SEMINAR ON ELECTRIFICATION

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JAPANESE NATIONAL RAILWAYS
JAPAN INTERNATIONAL COOPERATION AGENCY

CONTENTS

CHAPTER 1

OUTLINE OF ELECTRIFICATION

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1-1 Effect of Electrification

1-1-1 Present Condition of Electric Traction in Japan

The present condition of electric traction in Japan is shown in Table 1-1. Of the JNR's total route length of 22,597 km (of which 1,176 km belong to the Shinkansen line), 9,611 km are electrified, accounting for 42.5% of the total route length. The traffic volume by electric traction accounts for 84% of the total, showing that the JNR's main means of transportation is based on electric traction.

Direct current of 1,500 V was invariably used for electrification until 1957. However, with successful commercial applications of alternating current, electrification by this current has expanded rapidly, accounting for a half of the total electrified route length at present. With private railways, of their total route length of 5,599 km, 4,907 km, or 88% of the total, are electrified, cover almost all major routes (operating mainly on 1,500 V direct current). The sections of the JNR under electrification work at present total 1,888 km, including the Tohoku and Joetsu Shinkansen lines (scheduled to be open in 1982 with a total route length of 831 km). When these sections are completed, the total electrified route length will be 11,500 km (electrification ratio of 49.1%).

The share of railways in Japan's traffic volume in fiscal 1979 was about 40% in terms of passenger-km and about 10% in terms of ton-km. Since electric traction are the main means of transportation for passengers, electric cars number about 35,000, accounting for 75% of the total passenger cars.

As regards locomotives, almost all of them are for freight trains except for long-distance sleeper trains.
(See Tables 1-2 and 1-3.)

Table 1-1 Electrified Route Length by Type

(unit: km)

	DC		AC (1ϕ)		Total	Route km in service	Electrification ratio
	Under 1500 V and others	1500 V	20 kV	25 kV			
JNR		4965	3470	1176	[8435] 9611	[21421] 22597	[39.4] 42.5
Private railway	1147	3747	(600 V) 13		4907	5599	87.6
Total	1147	8712	3483	1176	14518	28196	51.5

(Under construction)

JNR		982	75	831	1888		

Figures in square brackets exclude the Shinkansen.

Table 1-2 Number of Cars by Type

(unit: car)

	Electric cars			Electric locomotives			Diesel cars	Diesel locomotives
	DC	AC·DC	AC	DC	AC·DC	AC		
JNR	12126	2988	(2415) 2582	1002	229	625	5038	2109
Private railways	17260	-	130	203	-	-	205	206
Total	29386	2988	(2415) 2712	1205	229	625	5243	2315

Figures in brackets indicate those on Shinkansen lines.

In addition to those shown above, the JNR owns 6,000 passenger cars and 100,000 freight cars.

Table 1-3 Domestic Passenger Transportation in Japan

(Fiscal 1979)

Means of transportation	Railway	Bus	Automobile	Aircraft	Others	Total
100 million passenger-km	3125	1083	3199	302	64	7773
Ratio %	40.2	13.9	41.1	3.9	0.9	100

Domestic Freight Transportation in Japan

(Fiscal 1979)

Means of transportation	Railway	Truck	Coastal shipping, etc.	Total
100 million ton-km	431	1729	2260	4420
Ratio	9.7	39.1	51.2	100

1-1-2 Progress of Electrification for the JNR

It was 1919 when electrification of the JNR emerged as Japan's energy policy. At that time, in view of the rapidly increasing demand for industrial coal, the JNR, which was consuming 12% of the total coal consumption, formed the view that a change be made to electric traction to save coal through hydroelectric power generation and decided to electrify its trunk lines and to construct hydroelectric power stations.

From then on, the efforts made by those concerned gradually bore fruit, though hindered by various obstacles including changes in policy, restricted funds and the stagnant period due to World War II. Thus, by the time the JNR was reorganized as a public corporation in 1949, it had electrified a total of 1,600 km.

Among the policies adopted by the JNR since it was reorganized as a public corporation, "Adoption of AC Electrification" and "Motive Power Modernization" need special mentioning.

After conducting a large-scale survey on the method of AC electrification based on a commercial frequency and a special high tension voltage, the method which was drawing attention as a new method of electrification for its advantages, the JNR decided to adopt it on a full scale. As a result, the first route based on this method came into being in 1957.

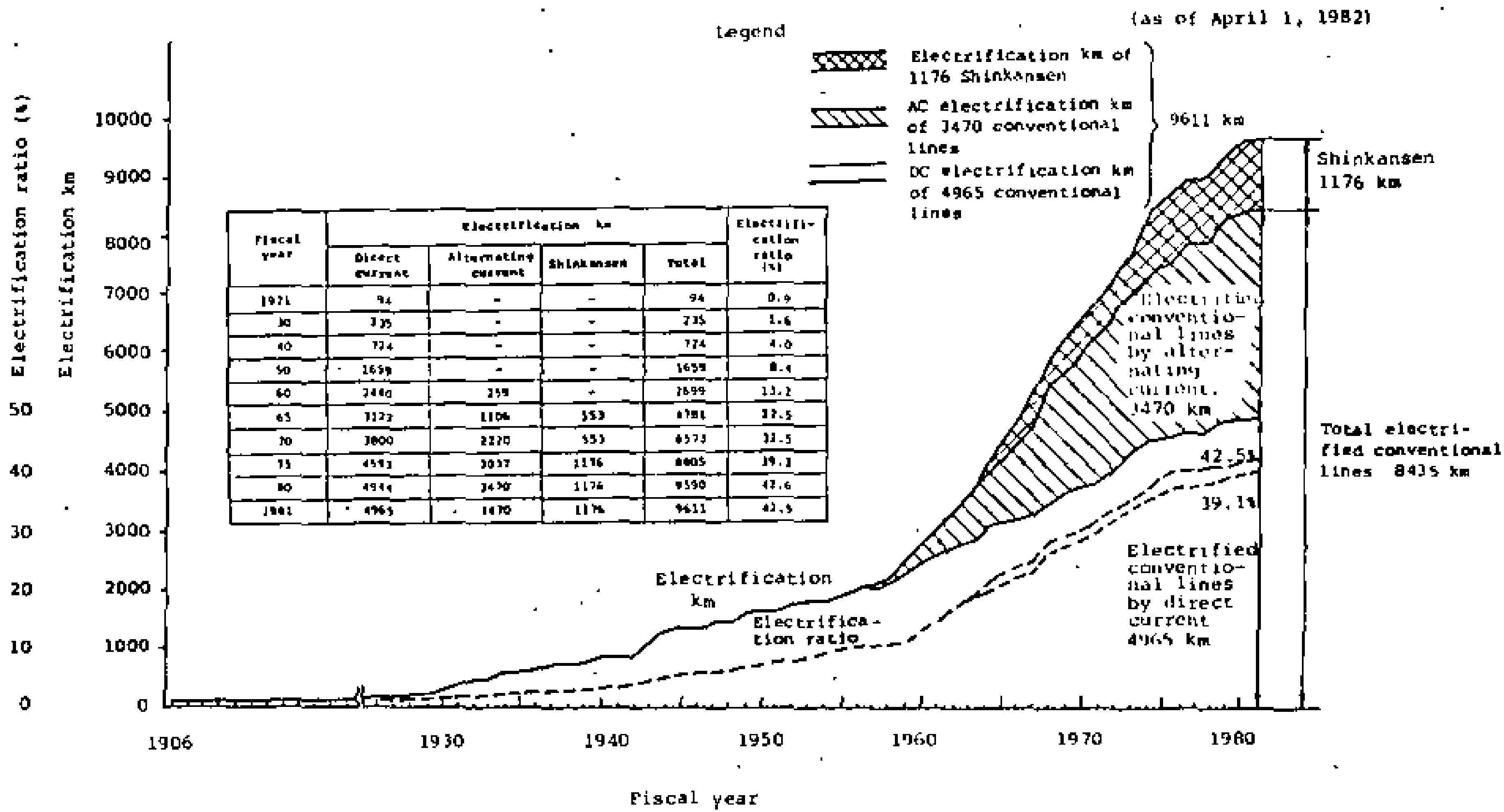
This successful electrification by 20 kV 60 Hz (Booster Transformer system) gave Japan's electric railways an opportunity to learn a great deal and the knowledge obtained had a great impact on a wide-ranging field of technology. The results of numerous technological advances thus brought about laid the foundation for the construction of the Shinkansen line seven years later in 1964.

The Motive Power Modernization Program formulated in 1959 stated: "The JNR must electrify 5,000 km of its unelectrified main routes and adopt diesel traction for other routes in 15 years' time at the latest, abolishing steam traction".

At that time, Japan's industry was undergoing extensive modernization through technological renovation and only the JNR was mainly based on antiquated steam traction. The program was formulated to meet the urgent needs for the modernization of transportation and streamlined management.

This program was carried out step by step under long-term planning by the JNR. As it had been planned, steam traction was completely abolished in fiscal 1975, and newly electrified lines amount to 5,100 km of its routes (excluding 1,180 km of the Shinkansen line).

The program thus achieved its goal and also produced additional results such as the development on a commercial basis of the Auto Transformer feeding system as a new electrification type. (See Fig. 1-1.)



Fiscal year	Electrification km				Electrification ratio (%)
	Direct current	Alternating current	Shinkansen	Total	
1921	94	-	-	94	0.9
30	735	-	-	735	1.6
40	774	-	-	774	4.0
50	1659	-	-	1659	8.4
60	2440	259	-	2699	13.2
65	3122	1106	553	4781	22.5
70	3800	2220	553	6573	32.5
75	4593	3037	1176	8805	39.1
80	4944	3470	1176	9590	42.6
1981	4965	3470	1176	9611	42.5

Fig. 1-1 Progress of Electrification by JNR

1-1-3 Effect of Electric Traction (Compared to diesel traction)

The changeover to electric traction not only has a merit in terms of cost because of the change in energy from oil to electricity but also improves railway management in numerous ways.

The effects of electric traction can be summarized as below.

(1) Effect due to Improved Car Performance

- Increased effect of infrastructure of railways -

The tractive capacity increases due to the characteristics of electric motor vehicles, thus increasing the transport capacity per train. The headway can also be reduced by fast acceleration and deceleration (increase in transport capacity).

These effects lead to an increase in the quantitative capacity of railways.

(2) Reduction in Running Costs.

- Running costs, e.g., power cost, repair cost, personnel cost, can be reduced. -

Since electric motor vehicles require lower power and repair costs, this economic merit can adequately cover the additional expenditure for maintaining electrification facilities.

In addition, it will be possible to reduce the number of crew members with the increased train speed and the increased tractive capacity.

(3) Increased revenue due to Improved Services

- Revenue is to be increased by providing comfortable transport services with the increased train speed and a low pollution level (no smoke, no smell, low levels of noise and vibration) -

The reduced transport time due to the increased train speed serves as a significant benefit for passengers, resulting in an increase number of users.

1-1-4 Effect of Improved Car Performance (Cases)

(1) Traction Characteristics

To show the difference in performance between electric and diesel locomotives, DL-DD51 and EL-ED75 models currently used by the JNR are compared below.

Table 1-4, Specifications of EL and DL

	Hydraulic type DL (DD51)	AC 20 kV EL (ED75)
Weight	81∿84 t	67.2 t
Service rating	2200 ps (1100 ps x 2)	1900 kW (475 kW x 4)
Axle arrangement	B-2-B	B-B

The traction characteristics of EL and DL show that EL is far superior than DL in traction, particularly in low and medium speed ranges. Moreover, when they are compared with regard to traction, assuming the speed to be constant (40 km/h), we find that EL is 1.8 times larger than DL (EL 18.9 t against DL 10.5 t). When they are compared in terms of balancing speed, assuming the traction to be constant (10.5 t), we find that EL is 1.6 times faster than DL (EL 65 km/h against DL 40 km/h).

Table 1-5 Comparison of EL and DL in Performance

	DL (DD51)	EL (ED75)	
Speed	40 km/H	40 km/H	65 km/H
Tractive effort	10.5 t	18.9 t	10.5 t

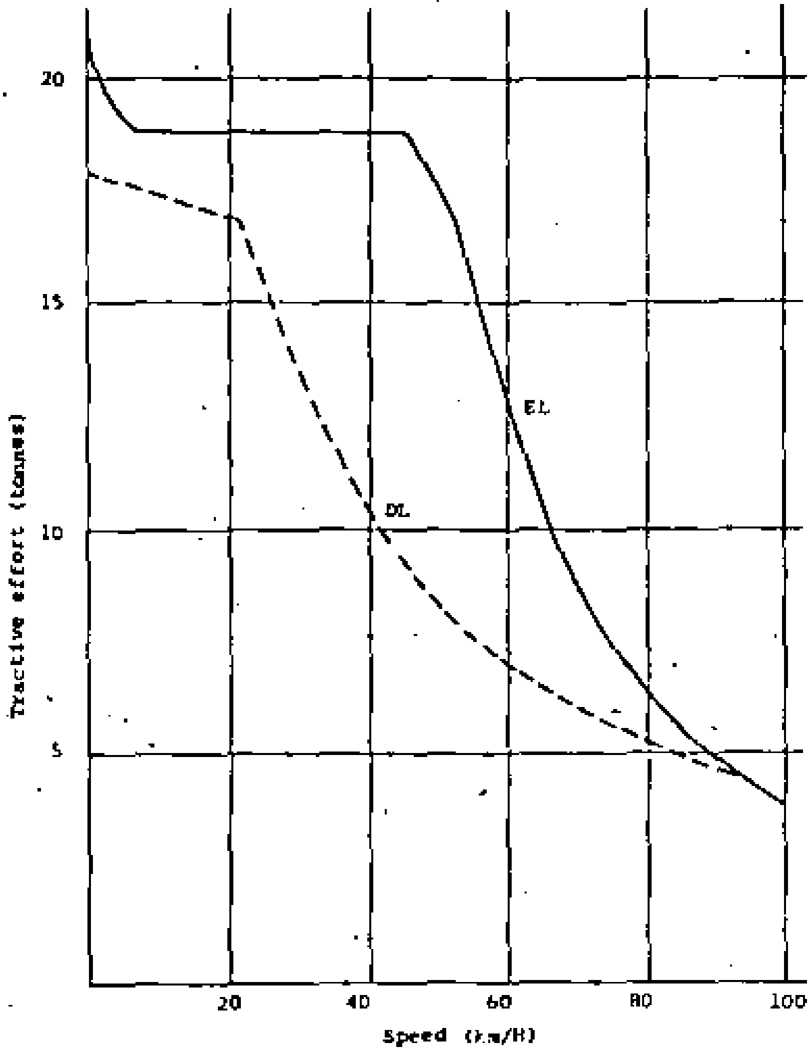


Fig. 1-2 Traction Characteristics of EL and DL

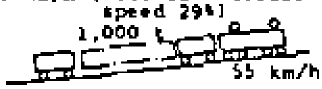
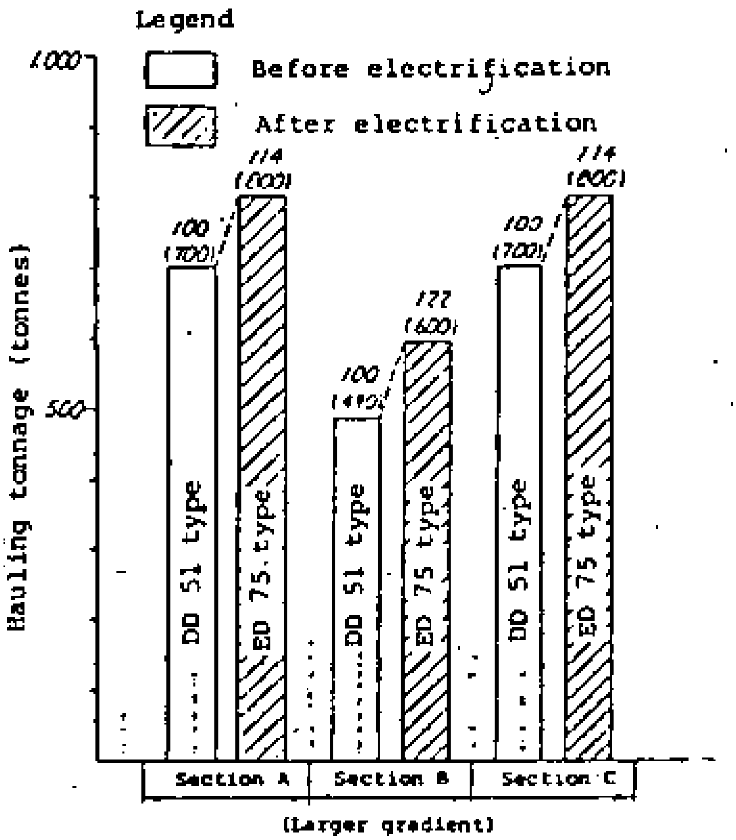
Gradient / Locomotive	Flat line	Gradient 10 ‰
EL	 1,000 t 78 km/h	78 km/h ⇨ 55 km/h (rate of decrease in speed 29%)  1,000 t 55 km/h
DL	 1,000 t 70 km/h	70 km/h ⇨ 29 km/h (rate of decrease in speed 59%)  1,000 t 29 km/h

Fig. 1-3 Comparison of Locomotive Performances
(An example of the balancing speed for a gradient)



Electrification of Ou line (November, 1975)

Fig. 1-4 Comparison of Traction Capacities before and after Electrification

(2) Improvement in Speed

As regards the improvement in speed by electrification, the JNR records show that standard traveling time was shortened about 10~15% after electrification. (See Fig. 1-5.)

Moreover, since electric cars produce fast acceleration and deceleration, the headway on high density sections can be reduced. Fig. 1-6 shows the improvement in accelerating capacity.

1-1-5 Reduction in Running Costs

(1) Reduced Power Cost

Since the product of the power consumption rate and the unit price of power determines the power cost, it is necessary to take these two factors into account when comparing power costs. The power consumption rate fluctuates according to various factors

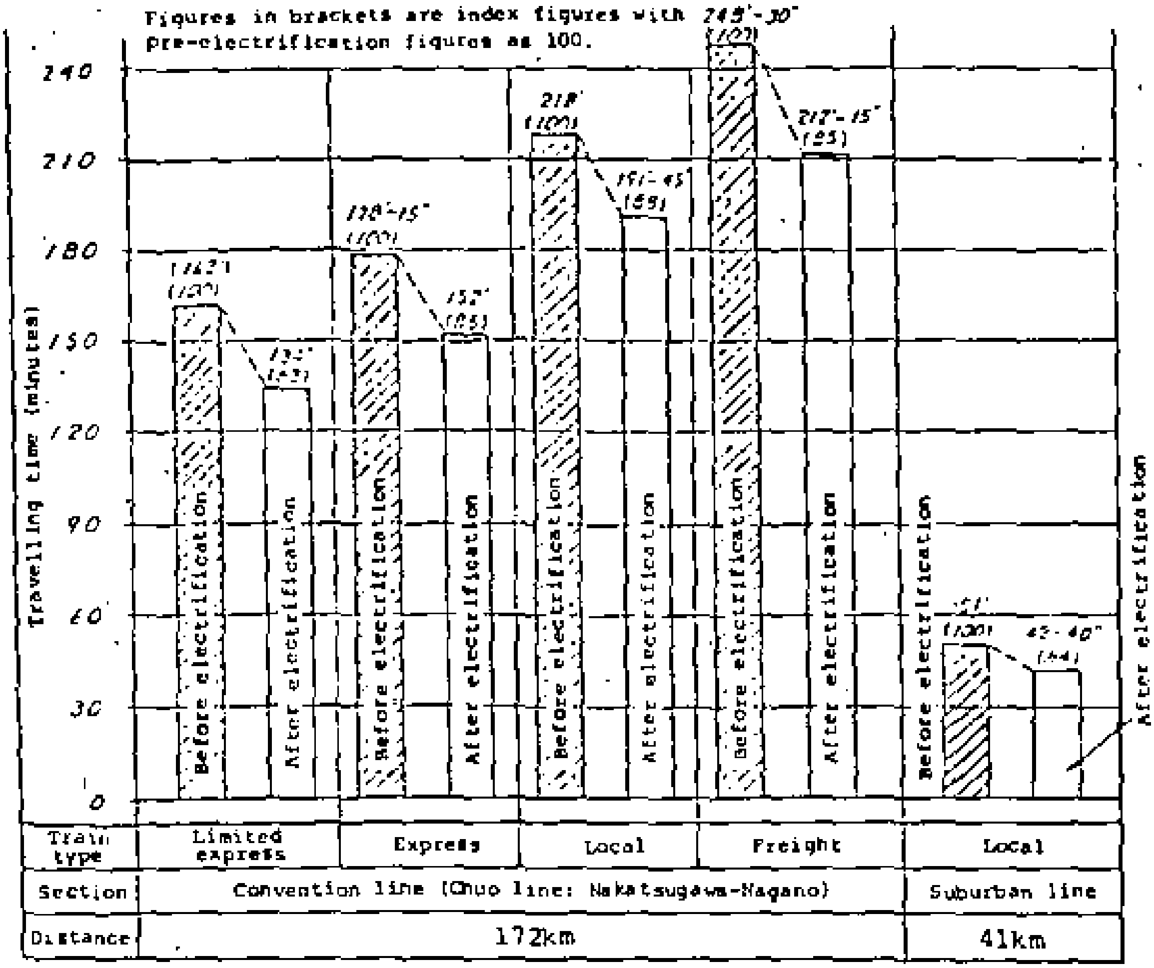


Fig. 1-5 Improvement in Standard Traveling Time by Electrification

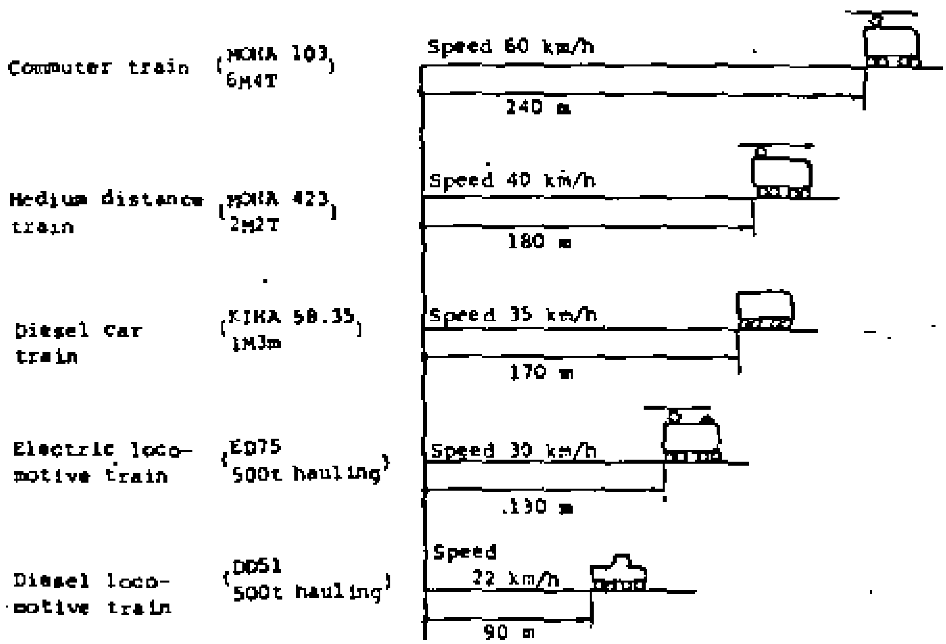


Fig. 1-6 Comparison in Accelerating Performance
(30 seconds after start)

including the train type, the speed, the track condition, etc.. However, an average figure for the JNR as a whole is used here for macroeconomic comparison.

Since the unit price of power greatly varies according to the energy situation in the country concerned, it cannot be applied universally. The unit price of power for the JNR is used for the data here.

Table 1-6 Comparison of Power Costs

(Passenger)

	Power consumption rate	Unit price of power	Power cost	Ratio
Electric car	1.67 kWh/Car km	17 Yen/kWh	28 Yen/Car-km	57
Diesel car	0.64 ℓ/Car-km	78 Yen/ℓ	50 Yen/Car-km	100

(Freight)

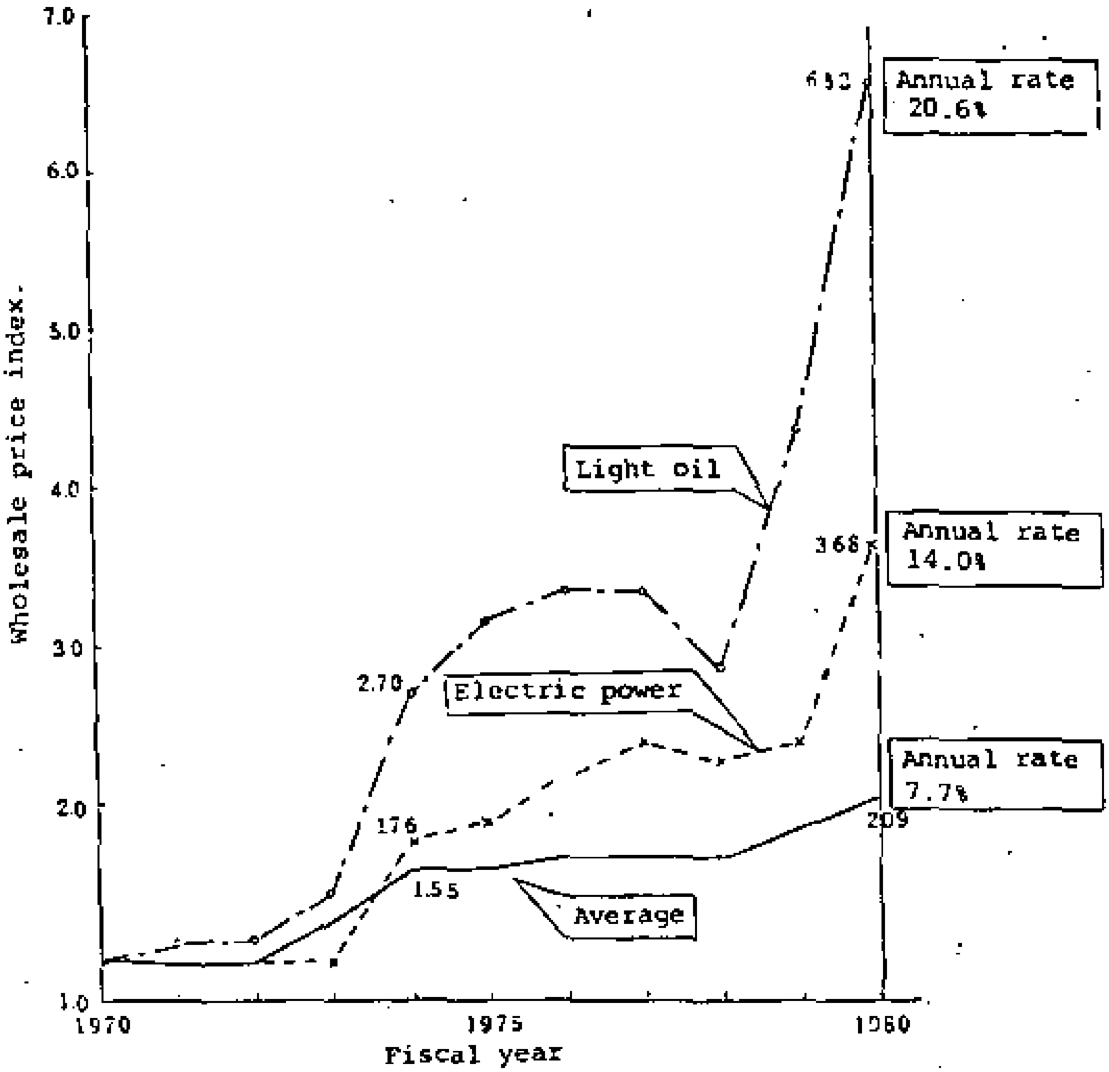
Electric locomotive	2.2 kWh/10^2 Ton-km	17 Yen/kWh	37 Yen/100 km Ton-km	48
Diesel locomotive	1.0 ℓ/10^2 Ton km	78 Yen/ℓ	78 Yen/100 Ton-km	100

The unit prices are for fiscal 1980.

As Table 1-6 shows, the power cost per car-kilometer of electric cars is about 40% lower than that of diesel cars, while the power cost per hauling weight kilometer for electric locomotives is about 50% lower than that of diesel locomotives, showing that the power cost is lower with electric motor vehicle with the JNR.

Needless to say, the unit prices of electric power and light oil are greatly affected by crude oil prices. Consequently, the above-mentioned relative relations of the power cost also fluctuate.

Fig. 1-7 shows the rate of increase in unit price for electric power and light oil in the last decade. There was a marked difference in the rate of increase between the two, i.e., 14% per



Note: Bank of Japan Wholesale Price Index.

Fig. 1-7 Changes in Energy Prices

year for electric power and 21% for light oil. As a result, the merit of using electricity has been increasing in recent years in Japan. With the recent commercialization of regenerative cars by means of thyrister chopper control, the energy consumption efficiency of electric cars will further improve. (The problem of energy will be dealt with in detail in 1-2.)

(2) Reduced Car Maintenance Cost

In general, the car maintenance cost for diesel cars tends to be higher than electric cars because of a large number of parts including those which need to be replaced due to wear and also because of a high degree of accuracy required in assembling the engine, the torque convertor, etc. Car maintenance is carried out according to various inspection standards.

Table 1-7 compares electric cars with diesel cars in terms of annual maintenance cost (personnel and material costs) based on the JNR records. If the annual total running km is the same with both of them, the unit maintenance cost of electric cars is about 50∿70% of diesel cars, showing the good economy of the former.

Table 1-7 Comparison of Maintenance Costs per a Car

	Electric car (direct current; suburban type) 6M (120 kW × 4) 4T		Diesel car (commuter type) 180 ps × 2	
Maintenance cost (1,000 yen/year)	(45)	5,900	(100)	13,000

	Electric locomotive 425 kW × 6		Diesel locomotive Liquid type 1100 ps × 2	
Maintenance cost (1,000 yen/year)	(73)	16,500	(100)	22,600

Figures in brackets are index figures.

(3) Other Effects

The improved car performance due to electrification increases the train speed and reduces the train hour (decrease of 5∿10% with the JNR). As a result, the operational efficiency of crew members improves and it is possible to reduce the personnel cost. (See Fig. 1-8.)

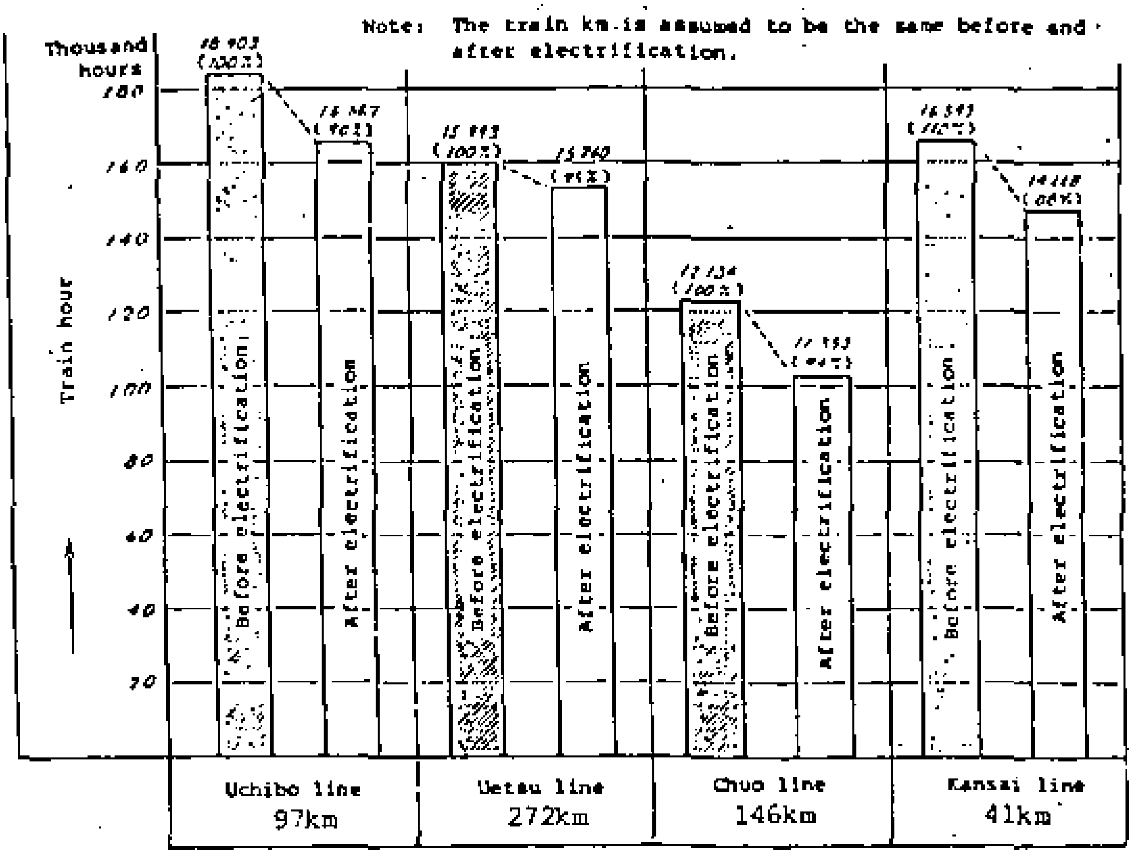


Fig. 1-8 Comparison of Passenger Train Hours before and after Electrification

Furthermore, the JNR was able to combine or abolish car sheds after electrification because of the reduced number of cars and that of inspection and repair personnel. Such as incidental merit should also be considered.

(4) Increased Expenses due to Electrification

Electrification requires maintenance work for ground facilities. The recent JNR records are as shown below.

Maintenance personnel: 0.1 ~ 0.4 person/km
Material cost : 600 thousand yen/km

As regards the additional investment in electrification facilities, expenses such as depreciation and interest form additional expenditure. These expenses should be evaluated in relation to investment effects (1-1-7).

1-1-6 Increased Revenue due to Improved Services

It is considerably difficult in general to assess to what extent the revenue increased because of improved services. This section is intended to outline the results of an analysis of the passenger traffic induced by the increased train speed and the higher frequency resulting from electrification.

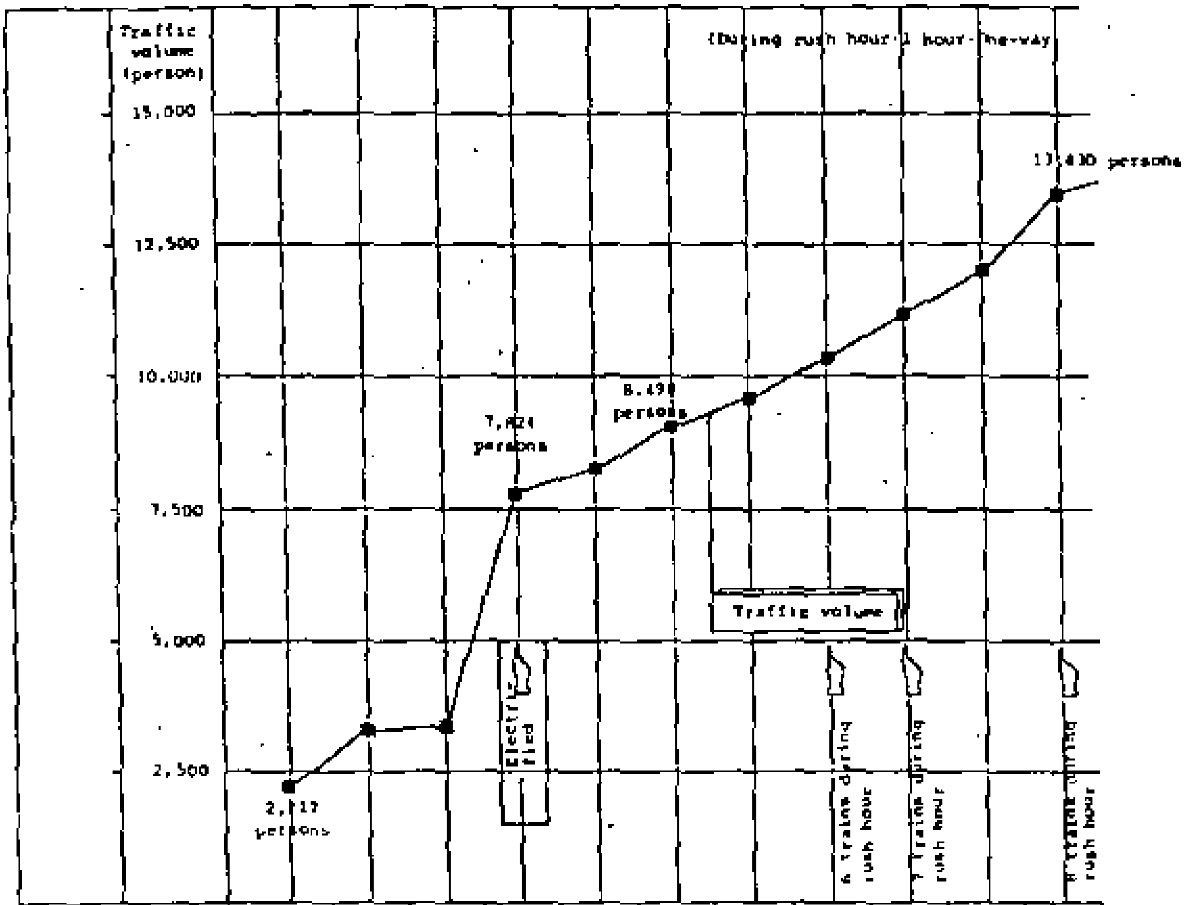
The induced effect was obtained by 1) forecasting the passenger traffic (passenger-km) without transport improvement and 2) obtaining the difference in percentage with the results of improved services. The induced effect on those sections where transport improvement was carried out was obtained as below.

	Ordinary passengers	Commuters
Electrified sections (9)	3 ~ 17%	2 ~ 14%
Unelectrified sections (4)	2 ~ 6%	0 ~ 6%

The above figures show clearly that the induction rate was higher on electrified sections with both ordinary passengers and commuters.

It can also be concluded in general terms that the induced effect of improved services on passenger demand tends to increase in proportion to the population density, the traffic density and the ratio of tourists in the section concerned.

Other results of the analysis also show that the effect of higher frequency on induction was large on commuter lines and that the induction rate was mainly dependent on the rate of improvement in train frequency. They also show that the effect of the higher train speed on induction was large on those trunk lines where the long-distance trains are important. (See Fig. 1-9.)



Fiscal year	'70	'71	'72	'73	'74	'75	'76	'77	'78	'79	'80
Traffic volume	2,217	3,310	3,360	7,874	8,293	8,998	9,493	10,320	11,092	11,882	13,430

Fig. 1-9 Changes in Traffic Volume due to Electrification and Increased Frequency (On Kansai Line)

1-1-7 Assessment of Investment Effect

The JNR has used the additional investment yield ratio to assess the effect of investment for electrification.

$$\text{Return rate of additional investment} = \frac{(\text{Increase in earnings}) - (\text{Expenses for electrical operation}) + (\text{Expenses for diesel operation})}{(\text{Investment for electrification}) - (\text{Investment for diesel operation})}$$

Expenses : power cost, personnel cost, repair cost, depreciation cost

Investment: ground facilities, cars

This return rate of additional investment ascertains the merit of investment statically at a point of a specific fiscal year. Accordingly, it does not take into account the fluctuations of economic factors relating to the effect of investment. Nor is it necessarily appropriate for ascertaining the overall effect of long-term investment. Therefore, the DCF method (discounted cash flow method) is mainly used at present.

(1) Method for Assessing Investment Effect (DCF method)

One of the characteristics of this method is that the future cost (or outflow) and benefit (or inflow) are discounted to present values for comparison. In this way the rate of discount can take into account the rate of inflation and factors of uncertainty in the future.

As regards indicators for assessing the effect, various methods are generally available to calculate 1) cost benefit ratio, 2) current net value and 3) internal rate of return. The JNR uses the internal rate of return method which is useful for ranking the investment efficiency.

After obtaining the internal rate of return γ_0 which satisfies the formula below, it is compared with the standard internal rate of return γ_B which can serve as the criterion for determining the feasibility of investment. If $\gamma_O > \gamma_B$, it can be concluded that the feasibility of investment is positive.

Here,

$$\gamma_O: \sum_{z=1}^{T} \frac{V_t}{(1+\gamma_O)^t} + \frac{S}{(1+\gamma_O)^T} - I_O = 0$$

V_t: $V_t = (R_{Nt} - R_{Ct}) - (O_{Nt} - O_{Ct})$

R_N: forecast earnings after investment

R_C: forecast earnings without investment

O_N: estimated expenses after investment (excluding depreciation cost and interest)

O_C: estimated expenses without investment (excluding depreciation cost and interest)

γ_O: internal rate of return

I_O: initial investment

T : project life

S : residual value of facilities after T years

(2) Example of Economic Calculation

Table 1-8 is the economic calculation of investment for electrifying a suburban line decided recently by the JNR. In this case, the rate of inflation for each factor is 0. This means that the effect of investment is most conservatively estimated in this case.

Table 1-8 Comparison of Electrification and Diesel Traction regarding Earnings and Expenses (million yen/year)

	Electrification (A)	Diesel traction (B)	Difference (A) - (B)
Total expenses	414	881	- 467
Power cost	183	281	- 98
Rolling stock maintenance cost	177	317	- 140
Ground facilities maintenance cost	32	0	32
Personnel cost	-	243	- 243
Miscellaneous cost	22	40	- 18
Increase in earnings	15	-	15

Personnel cost are for crew members and inspection and maintenance personnel.

Investment: ground facilities 3,100 million yen
rolling stock 2,200 million yen

Condition of transportation: about 4,000 train-km/day
about 16,000 car-km/day

Internal rate of return : 15%

1-1-8 Benefit of Investment for Electrification for the JNR

(1) Assessment of Previous Investment for Electrification

As described above, the effect of investment for electrification covers a wide-ranging field. It is therefore difficult to quantitatively assess everything. In particular, analysis of the effect on earnings poses a difficult problem. Accordingly, the effect of investment for electrification carried out up until now was calculated tentatively only on the basis of expenses which were ascertainable in figures.

As regards the method of calculation, on the assumption that all electrified sections of the JNR (a total of 8,435 km at present excluding the Shinkansen line) were operating on diesel traction, the expenses (repair cost, personnel cost, power cost and depreciation cost) were first obtained. They were then compared with those in the case of electric traction to obtain the difference.

The results are given in Table 1-9, which shows that electrification meant a saving of about 330 billion yen a year for the JNR, equivalent to as much as 11% of the total expenses of the JNR.

Though this assumption that the present electrified sections are operating on diesel traction was made in order to calculate the macroeconomic effect on expenses, it must be pointed out that this assumption is considerably unrealistic. For it is difficult in reality, for instance, to carry out transportation of such a high density as required for the Tokyo Metropolitan zone with diesel cars. That is to say, it can be concluded that the present burden of transportation cannot be carried out unless it is based on electric traction in a considerably large number of areas. Therefore, it must be emphasized here that the effect of investment for electrification is not only the reduction in expenses as calculated above but also the good services to compete with other means of transportation such as automobiles and aircraft.

(2) Benefit of Investment for Electrification
(Present state of the JNR)

Of the JNR's route length of 21,300 km (excluding the Shinkansen line), those sections of double-track and above total about 5,600 km, while electrified sections total about 8,400 km.

In the case of investment for electrification, the larger the traffic volume the higher the benefit of the section. Accordingly, the JNR electrified its main trunk lines of double-track except those sections with special conditions. There is no doubt

Table 1-9 Comparison of Expenses between Electric Traction and Diesel Traction

(Unit: 100 million yen/year)

	Electric traction Ⓐ	Diesel traction Ⓑ	Difference Ⓐ - Ⓑ
Expenses	3889	7178	- 3289
Maintenance cost	871	1696	- 825
Rolling stock	737	1696	
Ground facilities	134		
Personnel cost	871	1468	- 597
Rolling stock *1	605	1468	
Ground facilities	266		
Power cost	981	2122	-1141
Depreciation cost	1166	1892	- 726
Rolling stock *2	1063	1892	
Ground facilities	103		

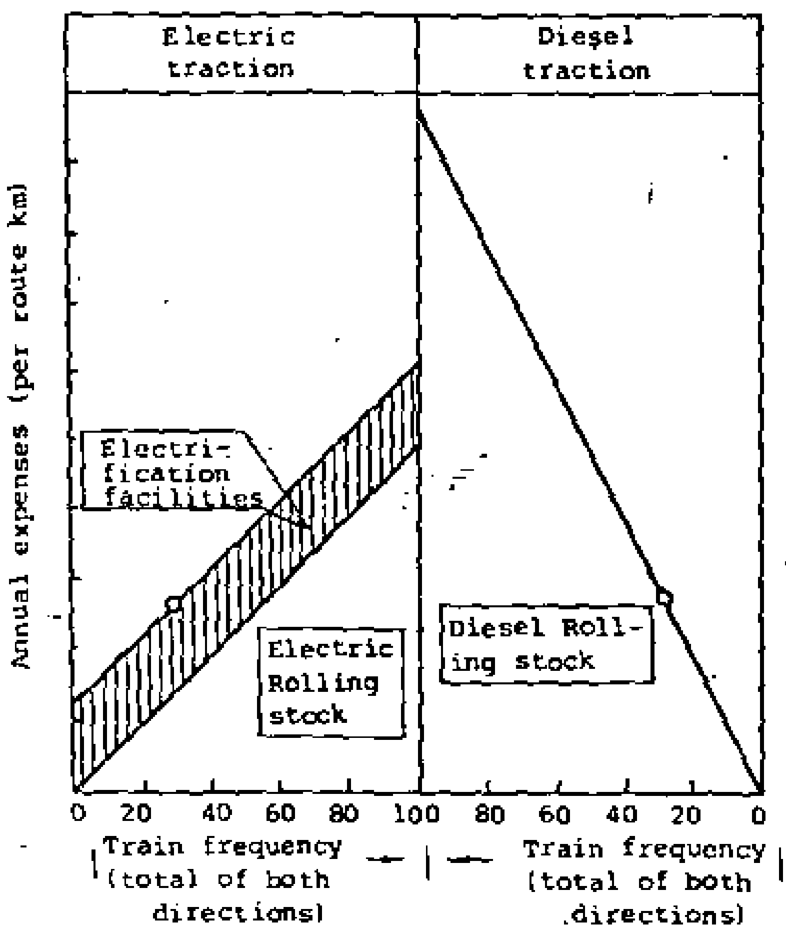
*1: Personnel cost (cars) is for inspection and repair personnel other than those personnel at Railway Factory.

*2: Based on purchase prices.

about the profitability of investment for electrification on those sections where the traffic volume makes it necessary to operate them on a double-track. Electrification by the JNR is now shifting to single-track sections.

The track capacity (the number of trains which can be operated per unit hour) depends on the nature of the section (the ratio between passengers and freight, the station interval, the signaling system, night trains, etc.). In the case of the JNR, it is about 80∿100 trains/day.

Fig. 1-10 presents in model form the expenses of electric traction and diesel traction (for single-track sections) with the number of trains as a parameter. This was prepared on the assumption that the expenses concerning cars are roughly in proportion to the traffic volume and those concerning electrification facilities roughly at a constant value to the traffic volume.



Expenses: personnel, maintenance, power, depreciation and interest costs

Fig. 1-10 Comparison of Annual Expenses and Train Frequency

Fig. 1-11 shows these expenses in terms of unit expenses per train frequency (excluding interest). The two systems show the same running cost at the train frequency N_0. However, investment for electrification cannot be justified for the benefit of this size of traffic volume. The economy of investment for electrification can be approved if the traffic volume (N_1) increases further and the size of the benefit (B_{N1}) seems to guarantee an appropriate and sufficient return for investment.

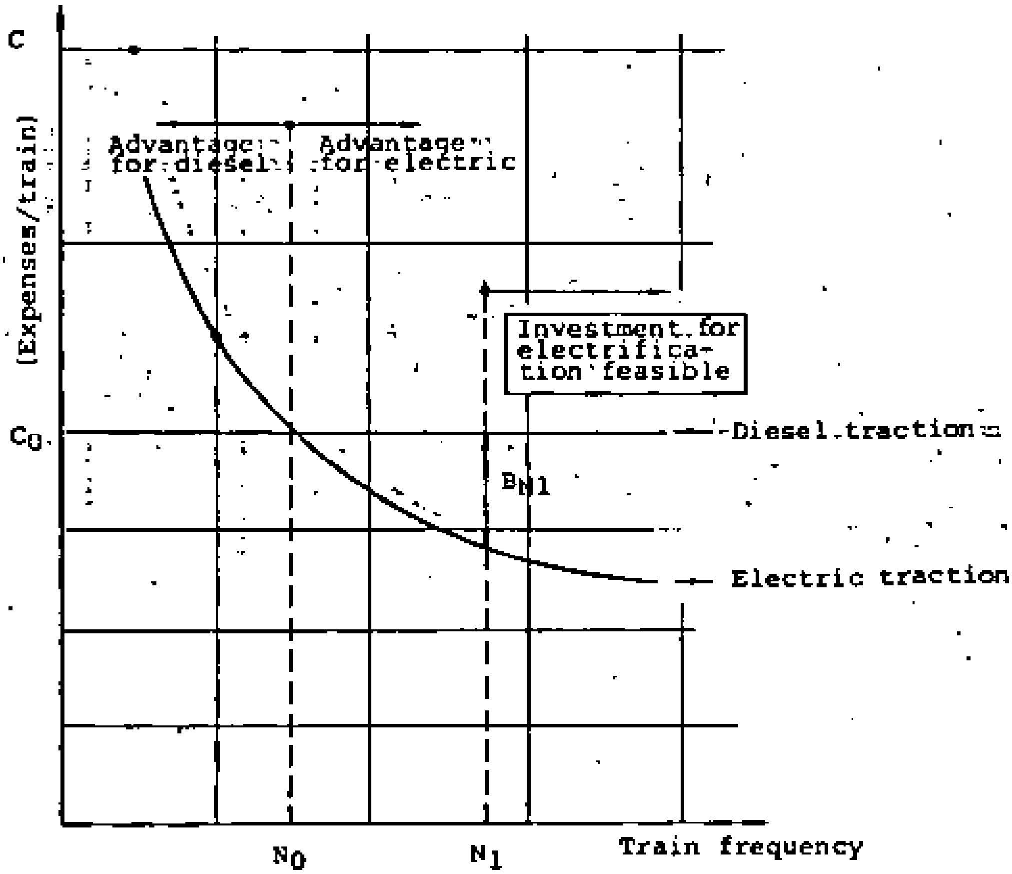


Fig. 1-11 Comparison of Expenses per Train and Train Frequency

In order to increase the benefit of investment for electrification, the JNR's engineers have made every effort to reduce the investment cost for electrification and maintenance cost.

As a result of these efforts and fluctuations in economic factors due to the oil crisis, the range of profitability in investment for electrification has extended in the case of the JNR, i.e., sections with a train-frequency of around 60/day ten years ago to those with a frequency of 30∿40/day. The JNR intends to continue to make efforts to reduce costs in every sector in order to increase the benefit of electric traction.

1-1-9 Conclusion

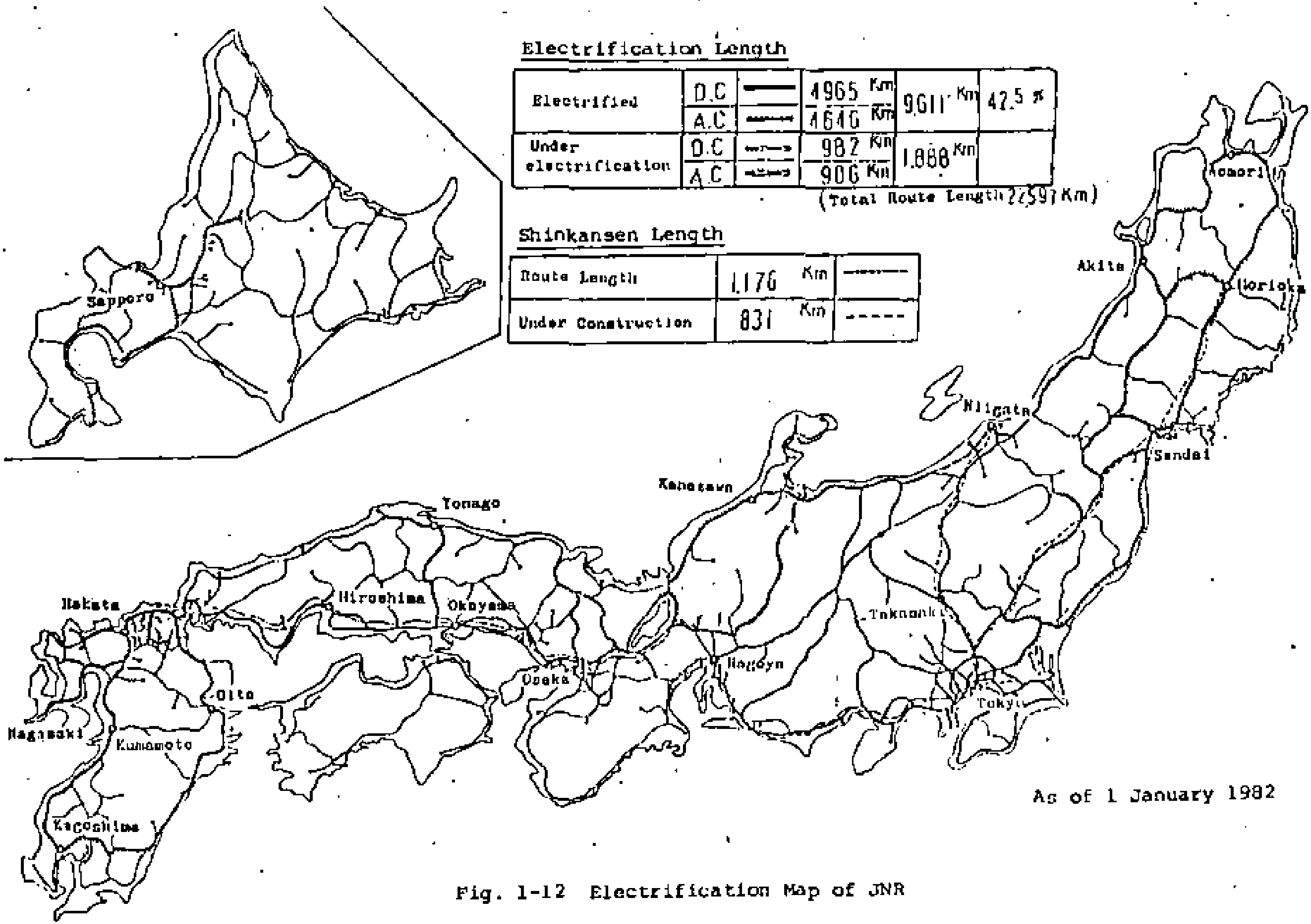
The effect of electric traction in the case of the JNR has been described above mainly by comparing it to diesel traction.

The JNR has a total of 9,600 km of electrified sections at present; it will exceed 10,000 km when 800 km of the Tohoku and Joetsu Shinkansen lines go into service this year. (See Fig. 1-12.)

Almost all of these electrified sections were completed one by one as Japan recovered from the devastation left by World War II, taking a total of about 30 years. Electrification at the initial stage of reconstruction was a means to increase the transport capacity in response to a rapidly increasing demand for transportation. After the Japanese economy assumed a somewhat settled tone, it was to improve services so that more attractive services could be provided. After the wave of increasingly rapid motorization began to affect railway management in Japan, it became an important management improvement policy, placing the emphasis on the reduction of transport costs.

The effect expected from electrification has thus changed in weight in response to changing circumstances. However, we became convinced from experience that the unchangeable usefulness of electrification lies in that it strengthens the characteristics of railways as a system of public transport such as mass transportation, rapid transportation, comfortable, safe and inexpensive means of transportation.

The contents of this chapter entitled "Effect of electrification" are inseparable from economic values unlike technical themes



Electrification Length

Electrified	D.C	———	4965 Km	9611 Km	42.5 %
	A.C	—·—·—	4646 Km		
Under electrification	D.C	—▪—▪—	982 Km	1,888 Km	
	A.C	—▫—▫—	906 Km		

(Total Route Length 22,597 Km)

Shinkansen Length

Route Length	1,176 Km	————
Under Construction	831 Km	- - - - -

As of 1 January 1982

Fig. 1-12 Electrification Map of JNR

for Chapter 2: Feeding system and following chapters. Accordingly, it should perhaps be added here that the figures given in this chapter values ascertained amid the actual environment of Japan including the economy, society, culture, etc.

1-2 Electrification and Energy

1-2-1 Outline of Supply and Demand for Energy in Japan

Energy consumption in Japan increased with its economic growth, but remains almost at the same level since the oil crisis in 1973, reaching 390 million tons in 1979 when converted and totaled in terms of oil.

The supply of energy in Japan is characterized by its high reliance on imports 86% (in Fiscal Year (1979)- and heavy dependence on oil (71%), especially as seen by the situation where almost all of the oil is imported.

In view of the anticipation that oil supply will become more and more difficult to obtain it is now the most important and urgent national problem to get the energy saving measures thoroughly implemented in every field of activity, and strongly promote the development and introduction of substitute energy for oil in order to reduce dependence on oil.

1-2-2 Energy Consumption in the Field of Transportation

The total amount of energy consumed by Japan's domestic transport systems in fiscal 1979 was 568,000 billion kcal, accounting for 14.6% of Japan's total energy consumption of 3,900,000 billion kcal (equivalent to 390 million tons of oil at a conversion rate of 10,000 kcal to a kilogram). As the breakdown in Table 1-10 shows, oil supplied a total of 533,000 billion kcal, or 24.4% of the total domestic oil consumption, and electricity supplied 37,000 billion kcal, or 2.8% of the total domestic consumption.

Electricity is generated from diversified sources such as oil, LNG, coal, atomic power and hydraulic power as primary energies.

However, since oil supplied 52% of the total power generated, the oil energy consumed by the transport section actually amounted to 552,000 billion kcal, or about 19% of the total domestic oil energy consumption of 2,890,000 billion kcal.

Table 1-10 Energy Consumption by Source Fiscal 1979

Source of energy			Domestic consumption Ⓐ	Domestic transport systems: Consumption Ⓑ	Domestic transport systems: % Ⓑ/Ⓐ
Total		①+②+③	3900	568	14.6
Oil	Total	①	2186	533	24.4
	Gasoline	(10,000 kl)	(3451) 297	(3421) 294	99
	Light oil	(10,000 kl)	(2158) 199	(1318) 121	61
	LPG	(10,000 t)	(1227) 147	(174) 21	14
	Kerosene, jet oil	(10,000 kl)	(2737) 244	(296) 26	11
	Heavy oil	(10,000 kl)	(8145) 806	(715) 71	9
	Other types of oil		491	-	-
Electricity (100 million kWh)		②	(5548) 1359	(153) 37	2.8
Other energies		③	356	-	-
Electricity generated with oil		④	704	19	
Total oil energy		①+④	2890	552	19.1

Consumption unit: 1,000 billion kcal (equivalent to 100,000 tons of oil).

Figures in brackets are actual figures.

Notes: 1) Source: Resources and Energy Agency, Comprehensive Energy Statistics

2) 52% of electricity is estimated to be supplied by oil-fired generation

Fig. 1-13 shows the percentage of traffic volume (passenger-km and ton-km) and the energy consumption shared by each of the transport means as classified broadly into passenger and freight services.

The share of railways in Japan's traffic volume in fiscal 1979 was about 40% in terms of passenger-km and about 10% in terms of ton-km. In the same year they consumed about 39 x 10^{12} kcal of energy, or about 7% of the total energy consumed by domestic transport system. Accordingly, in rough figures, railways in Japan carried about 30% (passenger-km and ton-km) of the total traffic volume, consuming about 7% of the total energy consumed by the

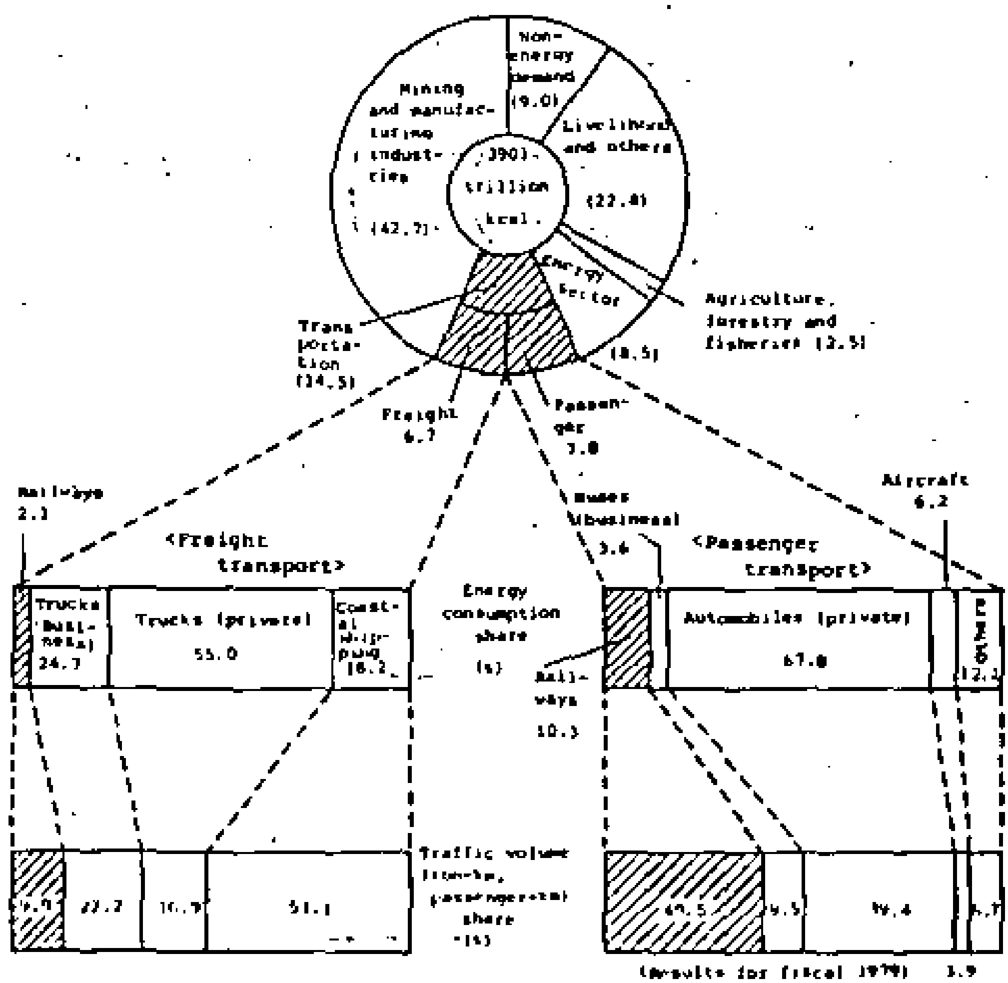
entire transport sector. These figures indicate that Japan's railways provide transportation of high energy efficiency.
(See Table 1-11.)

Table 1-11 Traffic Volume and Energy Consumption

(Fiscal 1979)

	Domestic total Ⓐ	Railways Ⓑ	(Ⓑ/Ⓐ %)	JNR Ⓒ	(Ⓒ/Ⓐ %)
Passenger traffic volume (10^8 passenger-km)	7709	3125	(40.5)	1947	(25.2)
Freight traffic volume (10^8 ton-km)	4418	431	(9.8)	423	(9.8)
Energy consumption (10^{12} kcal)	597	39	(6.5)	26	(4.4)

Source: Traffic volume from the Ministry of Transport statistics



Note: In the circular graph, figures in brackets show shares.

Fig. 1-13 Energy Consumption in the Transport Sector

1-2-3 Energy Consumption Characteristics by Various Means of Transport

Table 1-12 shows the energy consumption units by various means of transport as calculated from the actual results recorded in 1977.

From the macroscopic point of view, it can be said that the transport means of good energy efficiency are railways and buses for passenger traffic, and railways and ships for freight transportation. Table 1-13 shows the energy consumption units as analyzed in further detail on passenger transportation. These energy consumption units are largely affected by technological elements concerning the propulsion efficiency of the transport means themselves as well as by the elements based on the conditions of use, namely the load factor (seat-load factor or freight-load factor).

Table 1-12 Consumption Units of Operating Energy by Various Transport Means (Fiscal Year 1977)

(1) Passenger traffic

Items / Transport means	Traffic volume (100 million passenger-km)	Energy consumption (10 billion kcal)	Energy consumption unit (kcal/ passenger-km)	Index number ("Railway" taken as 1)
Railways	3,123	3,162	101	1
JNR	(1,997)	(2,028)	(101)	
Private railways	(1,126)	(1,134)	(101)	
Buses	1,046	1,483	142	1.4
Automobiles	2,640	20,405	773	7.7
Airplanes (Domestic)	236	1,673	708	7.0

(2) Freight traffic

Items / Transport means	Traffic volume (100 million ton-km)	Energy consumption (10 billion kcal)	Energy consumption unit (kcal/ ton-km)	Index number ("JNR" taken as 1)
JNR	406	576	142	1
Trucks	1,431	19,896	1,390	9.8
(Business)	(800)	(5,364)	(670)	(9.8)
(Private)	(631)	(14,532)	(2,304)	(16.2)
Ships (Internal)	2,023	5,348	264	1.9

Table 1-13 Consumption Units of Operating Energy in Passenger Traffic

Kinds of transport means		Energy consumption unit (kcal/passenger-km)	Number of occupants (persons/car)	Capacity (persons/car)
JNR	Shinkansen	140	45	89
	Commuter electric trains	50	80	140
	Local diesel trains	180	30	-
Private railways	Urban high-speed railways	100	64	-
	Local passenger railways	160	33	-
Buses	Business (General)	220	14	74
	" (Chartered)	80	37	54
	" (Express)	140	25	40
	Private	100	16	25
Automobiles	Business	1,270	0.8	4~5
	Private	740	1.4	4~5

On the other hand, there is a problem with such simple comparisons based on macroscopic average values, when considering that each means of transport offers a variety of transportation services. In this sense, we wish to make some analyses on energy consumption rates (or specific energy consumptions) on the basis of some concrete examples.

(1) Comparison of Various Interurban High-speed Transports with Respect to Energy (Case 1)

We wish to make a comparison of the representative interurban high-speed transportation with respect to consumption units. The section between the two biggest cities of Japan, Tokyo and Osaka (about 500 km in distance) is a section of the most active flow of passengers in Japan. Table 1-14 shows the energy consumption of three principal means of transport which are used between these two cities - JNR Shinkansen railway, airway and super-highway.

Table 1-14 Comparison of Energy Consumption in the Route between Tokyo and Osaka (Passenger traffic)

		Shinkansen (Hikari-16 cars)	Airplane (B747-SR)	Airplane (DC-10)	Automobile (2000 cc)
1	Route, Distance	Between stations 515 km	Between airports 530 km	Between airports 530 km	Between city centers 550 km
2	Number of seats	1,430	500	326	5
3	Energy consumption (One-way)	20,200 kWH	*1 13,100 ℓ	*1 9,800 ℓ	61 ℓ
4	Conversion factor	2,450 kcal/kWH	8,900 kcal/ℓ	8,900 kcal/ℓ	8,600 kcal/ℓ
5 (3x4)	Energy	49.5 x 10^6 kcal	116.6 x 10^6 kcal	87.2 x 10^6 kcal	52.5 x 10^4 kcal
6	Average number of users	930 passengers	415 passengers	271 passengers	*2 2 passengers
7 (6/2)	Coefficient of utilization	65%	83%	83%	40%
8 (5/6)	Energy consumption per person (Ratio)	53,200 kcal /passenger (1.0)	281,000 kcal /passenger (5.3)	322,000 kcal /passenger (6.1)	263,000 kcal /passenger (4.9)
9 (8/1)	Energy consumption unit (Ratio)	103 kcal/passenger-km (1.0)	530 kcal/passenger-km (5.1)	607 kcal/passenger-km (5.9)	477 kcal/passenger-km (4.6)
Time	Traveling time / Waiting, Access etc.	3H10M / 5M	1H / 1H30M	1H / 1H30M	6H20M / 30M

*1 Not including access energy to airport.

*2 Assumed value (the national average is 1.4.)

Although it may be necessary to take into consideration the time required to cover the distance, the energy consumption units to airplanes and automobiles are 5 to 6 times as large as that of Shinkansen.

In Fiscal Year 1977 the Shinkansen carried 29 billion passenger-kms, consuming electric power of 1.6 billion kWh, which corresponds to 440 thousand kℓ (2.8 million barrels per year) of heavy oil, supposing the electricity is wholly produced by steam-power generation. If this amount of traffic volume had been carried by airplanes or automobiles, 5~6 times as much jet fuel or gasoline would have been needed, which fact will prove effectiveness of Shinkansen railways for oil saving.

(2) Comparison of Various Urban Transports with Respect to Energy (Case 2)

The Tokyo Metropolitan Traffic Area and the Kinki Traffic Area are the two biggest urban areas of Japan, which include the population of 24 million and 24 million residents respectively in a circle each with the radius of about 50 km. Table 1-15 shows the traffic volumes by various transport means in Fiscal Year 1976 in these two urban traffic areas. In both of the areas, the mass transport means such as high-speed railways and buses have a high share of 75% to 70%, and automobiles have only a small share. It can be considered that this is because in these two big cities the railway networks, both national and private, have been well developed since early stages and also because the improvement and expansion of high-speed railways was actively undertaken, including the construction of subways in the center of city to keep pace with the recent centralization of population.

Table 1-15 Passenger Traffic Volume by Various Means of Transport

(Million passengers)

Transport means	Tokyo metropolitan area	%	Kinki area	%
Total	16,060	100.0	8,065	100.0
High-speed railways	9,522	59.3	4,298	53.3
JNR	4,112	(25.6)	1,165	(14.4)
Private railways	3,606	(22.5)	2,331	(28.9)
Subways	1,804	(11.2)	802	(10.0)
Buses & others	2,505	15.6	1,361	16.8
Hired cars, taxicabs	885	5.5	488	6.0
Automobiles (Private)	3,148	19.6	1,918	23.9

Next, the energy consumption by various transport systems in two metropolitan zones was analyzed. In analyzing the amount of energy, the concept of so-called life cycle energy, including not only kinetic energy for transport vehicles used previously, but also maintenance and control energy for transport facilities and transport vehicles, construction energy for infrastructure and manufacturing energy for cars, was adopted. Furthermore, access transportation to railways was also taken into account to compare door-to-door total energies.

Table 1-16 shows the results of the analysis. When the door-to-door total energies are compared, we find that the energy efficiency of electric trains is 12 times higher than automobiles (private) and 3.5 times higher than buses. In other words, a well arranged network of electric railways forms the framework of transportation in metropolitan areas in Japan (a total of about ...

Table 1-16 Energy Consumption by Passenger Transport Systems in Metropolitan Areas

Item \ Transport			Electric car (commuter type)	Bus (large)	Automobile (private)
Kinetic energy kcal/km		1	4,200 kcal/car-k	3,400 kcal/car-k	1,000 kcal/car-k
Maintenance and control energy "		2	1,390 "	730 "	120 "
Construction energy "		3	200 "	60 "	20 "
Car manufacturing energy "		4	230 "	220 "	100 "
Total energies	1 + ... + 4	T	6,020 "	4,410 "	1,240 "
Average number of passengers	Passenger/car	N	80.4	15.8	1.4
Energy unit kcal/passenger-km.	Kinetic 1 / N	E1	52 <1.0>	215 <4.1>	714 <13.7>
	Total T / N	E2	75 <1.0>	280 <3.7>	890 <11.8>
	Door-to-door	E3	80 <1.0>	280 <3.5>	890 <11.8>

Figures in < > are inter-system index figures with the minimum value being 1.0.

3,200 km in Tokyo and Kinki regions), supplemented by bus services, forming an extremely energy-saving transport system. Needless to say, in provincial cities where mass transport systems are not so complete as in metropolitan areas, the degree of dependency on automobiles (private) and buses is bound to be high.

(3) Long Distance Freight Transportation (Case 3)

In the case of freight transportation, various transport systems are likely to compete in the field of long distance transportation. In this case study, the energy consumption for the transportation of sundries between Tokyo and Osaka, the section with the heaviest freight flow in Japan, was calculated on the basis of the route currently operating and transport conditions (transport equipment, operating schedules, etc.). In order to ascertain the effect of the load factor on energy consumption, it was calculated for three load factors: actual factor, 100% and 50%.

The results given in Table 1-17 show that the energy efficiency was highest for electric railways and container vessels while the energy consumption of freight ferries was about two times more and that of trucks about three times more.

Table 1-17 Energy Consumption by Freight Transport Systems

(Unit: 10^4 kcal/ton)

Area \ Load factor \ Transport system		Electric railways	Trucks (11t)	Shipping: Freight ferries	Shipping: Container vessels
Tokyo ~ Osaka	100%	4.5	15.3	12.1	4.8
	50%	6.4	27.5	21.9	8.7
	Record	<1.1>5.5 70%	<3.3>18.4 * 80%	<2.4>13.2 * 90%	<1.0>5.7 * 90%
	Distance KM Time H.M.	555 10°36'	547 10°24'	680 20°35'	680 32°0'
Maximum freight load t		465	11	2600	2600

Figures in < > are index figures with container vessels as 1.

* Estimates

1-2-4 Trends in Energy Consumption with the JNR

The energy consumption by transport systems as a whole has been outlined above. This section is intended to describe the condition of energy consumption with the JNR.

The JNR pushed forward the changeover from steam locomotives to electric or diesel traction over a long period of time. As a result, steam traction was completetdly abolished in fiscal 1975. The adoption of electric or diesel traction was extremely effective for improving railway management, i.e. increasing the transport capacity, improving services and reducing transport costs; it also resulted in a significant reduction in energy consumption.

Fig. 1-14 shows the long-term trends in traffic volume (weight × distance) and energy consumption by type of traction. Though the total traffic weight (A curve) increased by 2.3 times between fiscal 1950 and 1978, the total energy consumption (B curve) decreased by 18%. As a result, energy consumption rate (C curve) decreased to about 1/3 (energy productivity improving by about three times). This is due to the fact that while the energy efficiency of steam locomotives is several %, that of diesel and electric cars is 3∿4 times higher.

As regards the energy for operating JNR trains there was a shift from coal to electricity or oil until fiscal 1975 and then on from oil to electricity. As a result, the total energy consumed by the JNR in fiscal 1980 amounted to 8.1 billion kwh of electricity and 630 million liters (4 million barrels) of light oil. At the rate of 2,450 kcal to the kwh and 9,200 kcal to the liter of light oil, electricity accounted for as much as 77% of the total energy consumed for operating JNR trains.

* Conversion of electricity into calories:

  1 kwh=2,450 kcal. This means that electric energy of 1 kwh=860 kcal was obtained by oil fired generation at an energy conversion efficiency of 35.1% (record of the electric power companies in Japan for fiscal 1964). (860 ÷ 0.351 = 2450.)

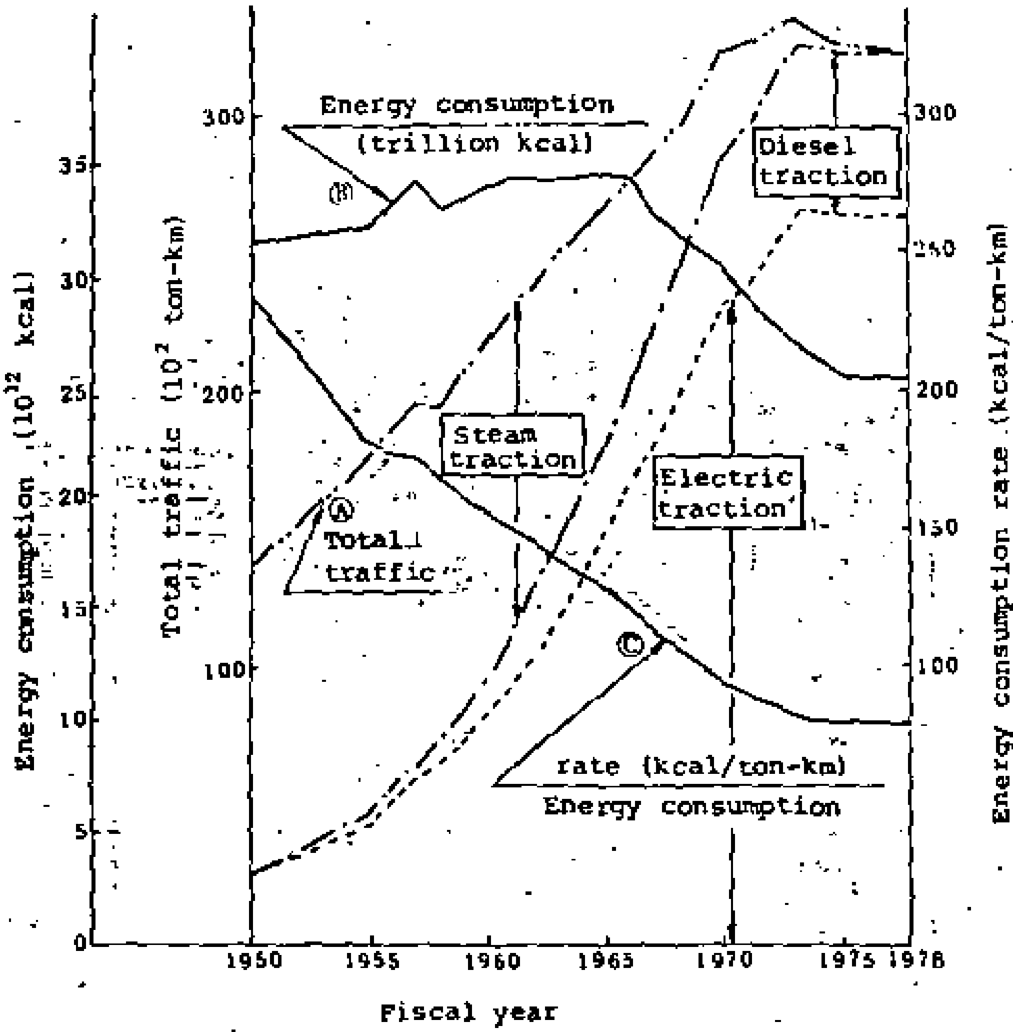


Fig. 1-14 Long-term Trends in Energy Consumption (JNR)

1-2-5 Trends in the JNR's Energy Costs

As Fig. 1-15 shows, the ratio of energy cost in the JNR's operating costs (personnel cost, power cost, repair cost, business cost and taxation) fell every year from 20% in fiscal 1950, reaching the bottom at 4% in fiscal 1978. This was due to the fact that while electrification and diesel traction described above reduced the energy cost and the unit energy cost per unit traffic volume decreased because of stable unit prices of electricity and light oil, the rate of increase in personnel cost, repair cost, etc. continued to be at a high level.

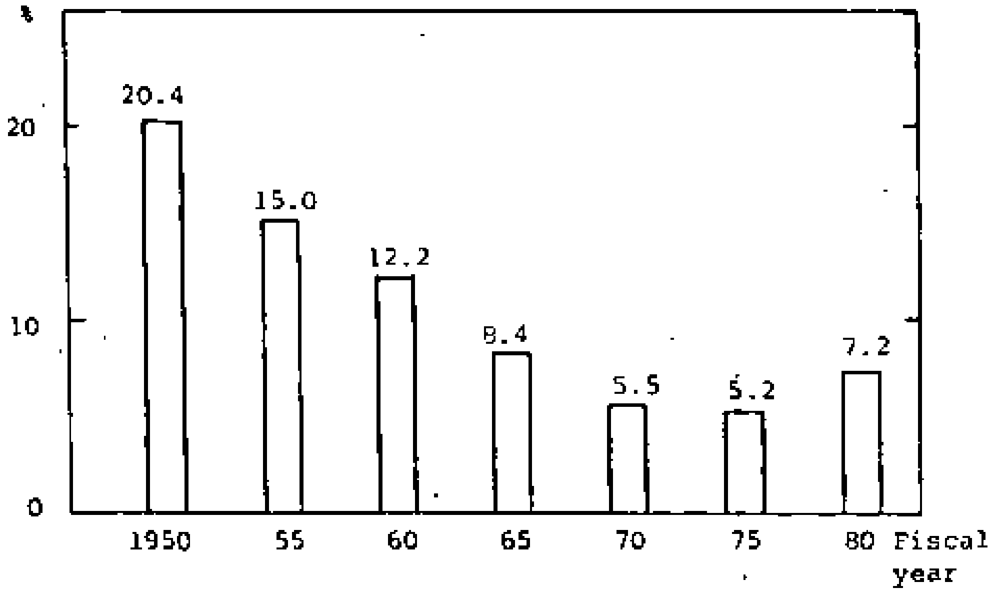


Fig. 1-15 Trends in (energy cost)/(operating costs) (JNR)

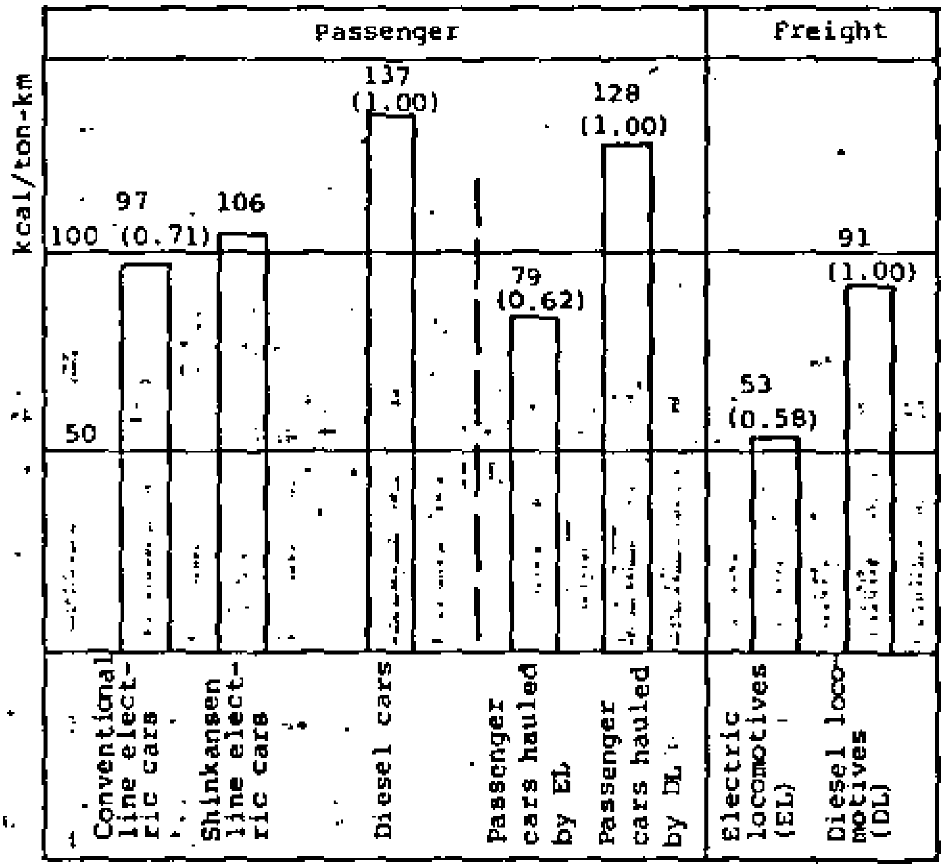
After the oil crisis of fiscal 1973, the rate of increase in energy cost rose rapidly. Compared with fiscal 1973, the unit price of electricity in fiscal 1980 was up by 3.9 times and that of light oil by 5.3 times with the result that the total energy cost went up by 4 times. Consequently, the ratio of energy cost in operating costs turned upward, rebounding to 7.2% in fiscal 1980.

It should be pointed out here, however, that even during the period from fiscal 1970 to 1980 when crude oil prices showed an abnormal rate of increase (annual rate of 34%), the rate of increase in unit prices of electricity was 14% per year, relatively low compared to 21% for light oil. This shows that electricity has more resistance to increases in crude oil prices, providing us with valuable information for our future selections.

1-2-6 Comparison of Electric and Diesel Traction in Energy Consumption

Transportation of the JNR can be classified into five types for passenger and two types for freight. Fig. 1-16 shows the

Fiscal 1978



Car weight-km: 1 ton × 1 km

Figures in brackets show the ratio of electric cars to diesel cars.

Fig. 1-16 Energy Consumption Ratio by Type of Traction (kcal/car weight-km)

basic units of energy consumption in macro terms according to this classification.

Apart from the Shinkansen lines with the train speed greatly different from others, in the case of passenger trains, the energy consumption ratio of electric cars is about 30% lower than diesel cars. With locomotive-hauled trains, the energy consumption rate of electric locomotives is 40% lower than diesel locomotives (diesel locomotives of the JNR are all of the diesel hydraulic type).

Since the energy consumption of trains is not determined only by the engine efficiency of the energy used but is also affected by the speed, stopping frequency, conditions of routes, traction efficiency, etc., all trains do not necessarily show the above differences in energy consumption. However, they seem to be appropriate figures in macro terms.

1-2-7 Energy-saving and Oil-saving Effects of Electric Traction

(1) Energy-saving Effect

The energy-saving effect and cost-saving effect of electric traction were tentatively calculated in macro terms.

Assuming that the already electrified sections excluding the Shinkansen lines (about 8,400 km as of the end of fiscal 1980) were all diesel sections, the required energy was calculated as about 309 × 10^{11} kcal as shown in Table 1-18. This is a saving of

Table 1-18 Energy-saving Effect of Electrification

	Present condition (1980)			All diesel traction
	Electric	Diesel	Total	
Traffic weight-km (10^9 ton-km) ①	185	43	228	228
Power consumption (10^6 kwh, 10^6 ℓ) ②	5770 (KWH)	635 (ℓ)		3355 (ℓ)
Energy consumption (10^{11} kcal) ③	141	58	199	309
Energy saving (10^{11} kcal) [Saving ratio %]			Δ 110 (36%)	
Unit power prices ④	17 (Yen/KWH)	78 (Yen/ℓ)		
Power cost (100 million yen) ④×②	981	495	1476	2617
Saving in power cost (100 million yen) (Saving ratio %)			1141 (44%)	

Rate of energy conversion: 1 kwh=2450 kcal, 1ℓ=9200 kwh about 110 × 10^{11} kcal (equivalent to 1.1 million tons of oil) compared to the actual record for fiscal 1980, which was 199 × 10^{11} kcal. This means a large saving of 36% compared to the case of non-electrification. This also means a saving in energy cost of about 114 billion yen/year (at price in fiscal 1980).

(2) Oil-saving Effect

Japan's total power generation (excluding private generation) in fiscal 1980 was 514 billion kwh. The composition of primary energies used was as shown below.

Breakdown of Primary Energy Resources Used for Power Generation (fiscal 1980)

Oil	Hydraulic	Atomic	LNG	Coal	Others	Total
44.0	16.6	16.0	15.0	4.4	4.0	100.0

As the table above shows, the degree of dependence on oil was as much as 44%. Based on the view that oil prices will continue to be at a high level in the future, Japan's power operators are pushing forward with the diversification of energy sources (atomic power, coal, LNG, hydraulic, geothermy, etc.). Of course, this policy of changing the source of energy is faced with many difficulties such as delays with the construction of power plants, e.g., atomic and coal-fired, because of environmental problems. However, the power operators have set positive goals on the basis of the national policy for stable supply of electricity.

Let us examine the effect of electrification from the viewpoint of oil-saving. If the energy-saving effect of electrification is 30%, the amount of oil required will be reduced from 100 units for diesel traction to 70 units even if the power is entirely supplied by oil-fired thermal power generation. Since Japan's dependence on oil for its electric power is 44%, the shift to electric traction will reduce the amount of oil required to 31 (0.7 × 0.44).

If the degree of dependence on oil falls to the 20% mark in the future (target figure for fiscal 1990-1995), the amount of oil required for electric traction will decrease to 14, resulting in the oil-saving ratio of 86%. (See Fig. 1-17.)

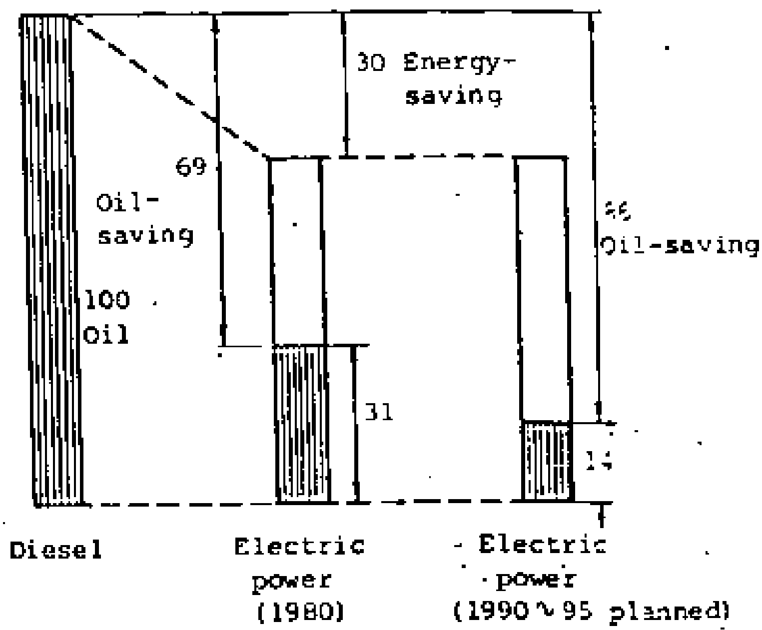


Fig. 1-17 Oil-saving Effect of Electrification (JNR)

Thus, it is clear that electrification of railways is an effective means of saving oil which is constantly becoming scarce in the world.

(3) Effect of Power Regeneration Effect

The DC electric cars with chopper control by thyristor produce a large power-saving effect as they have no power loss by resistor during powered operation and, in addition, the kinetic energy of the car is converted into electric energy during braking and regenerated on the catenary side.

Commercialization of chopper control cars in Japan is most advanced with urban transport such as subways and about 1,600 cars were already in use as of the end of fiscal 1979, producing stable results.

The JNR completed the development of faster chopper control cars because of the necessity of regeneration in a higher speed range compared to subway cars and began placing them in service from fiscal 1980. As the number of these cars increases in the future, they are expected to result in a power-saving effect.

As the JNR operates about 8,000 cars in the two major metropolitan transport zones of Tokyo and Kinki, if they are all changed to chopper-control cars, an annual saving of power is expected to be about 500 million kWh. Moreover, since power-regenerating cars based on chopper control techniques can fully make use of the characteristics of electric railways, the economy of electric traction is expected to further improve in the future.

The application of chopper control techniques to AC electric cars will be dealt with under Theme 8.

1-2-8. Conclusion.

With the oil crisis providing an impetus, the development of the energy problem began to exercise a serious influence on the economy and society of the nation. The core of measures to cope with the problem of the limited deposits of fossil fuels which emerged at a global level, seems to be how to switch over to alternative energies with little confusion as possible while using the limited resources with a maximum efficiency.

The transport sector is faced with the same problem. However, in the case of transport systems using oil as the fuel, it seems to be considerably difficult to switch over to alternative energies compared with the industrial sector. Accordingly, the main task in the transport sector for the time being will be an "efficient use of energy".

It is a well-known fact that among the various modes of transportation, railways can serve as an economical transport system if their characteristics of mass transportation and speed can be fully utilized and that they have the merit of a high energy efficiency. In particular, as the data in this section have fully proved, electric traction has a high efficiency even among railways.

The difference in power cost due to the difference in the types of traction naturally varies according to the prices of oil products and of electricity in the country concerned. In the case of Japan, however, even electricity using imported oil as the main fuel is under more favorable conditions than diesel traction based on light oil.

Finally, some comments on the outlook of the energy problem are in order.

First, on the outlook of energy-saving. It will be difficult to achieve such a drastic improvement in energy efficiency as has been accomplished by the JNR during the process of shifting the energy source from coal to electricity or oil. However, there seems to be a possibility of improving the energy efficiency by 10∿20% through the extension of electric traction, adoption of electric regenerating cars and technological development in the future.

As regards the trends in power cost, the past trend that the rate of increase in cost is lower for electric power than for light oil, is expected to continue as mentioned earlier. Furthermore, since demand for light oils such as light oil and kerosene increases, their prices are expected to be at a higher level than heavy oils. As a result, the advantage of electric energy in terms of cost is also expected to increase.

It is to be stressed in conclusion that in the field where railways can prove their characteristics, input of necessary energy should not be spared. Rather, it is important to make efforts to increase the use of railways by providing better services. This will in the end contribute to energy-saving in the transport industry as a whole.

1-3 Education and Training concerning Electrification

1-3-1 Maintenance of Electrification Facilities

The way of maintenance for electrification facilities seems to be dependent not only on the accumulation of techniques by railways, the average skills of personnel available and their level of technological knowledge but largely on the level of development of electrical industries in the country concerned.

In Japan, during the period when the capacity of domestic businesses was small, the scale of electrification facilities was also small. During this period, both the construction and repairs of electrification facilities, which are now entrusted with private businesses, were carried out under the direct management of the JNR. These facilities expanded drastically in the last two decades or so. At present, large-scale replacement or renovation, and overhauling of technically advanced equipment are entrusted with private engineering or manufacturing businesses.

Maintenance work by the JNR personnel consists in daily inspection and resulting simple repairs, emergency repairs and breakdown repairs.

The reliability of equipment and facilities has markedly improved in recent years due to technological advances. Such sharing of maintenance work by private businesses and the JNR seems to be not only contributing to more efficient railway management but resulting in an appropriate distribution of skills and technical labor for the society as a whole.

1-3-2 Training of Maintenance Personnel

Training of maintenance personnel for electrification facilities in Japan is carried out at two stages; training of recruits and training of maintenance foremen. As regards the training of recruits, they acquire basic electrical knowledge and also learn the configuration of electrification facilities and the function of each component. The training is intended to train their ability to operate, handle and inspect equipment used daily under the direction of maintenance foremen.

Training of foremen is given to those who have about five years' experience in maintenance. It is intended to train their ability to direct not only the operation, handling and inspection of equipment but also the detection and repairs of breakdowns and the formulation of inspection plans.

These maintenance foremen are expected, in addition to the above, to be upgraded to maintenance managers capable of controlling a group of maintenance foremen and of participating in the formulation of equipment renovation plans or new system plans (management personnel of Railway Operating Division).

Accordingly, the scope of education and training concerning electrification facilities is not limited to specific equipment but covers wide-raning techniques. Though they are classified into two categories, power facilities and signal and communication facilities, each curriculum is formed in such a way that the trainees will understand all equipment.

Training is provided in the form of lectures with textbooks and practical training with educational equipment. The contents of courses, the training period, etc. in the field of technical training for electrification facilities will be given in the following sections.

As regards the training of managers, planning personnel of Railway Operating Division, etc., special training courses are not provided at present. However, they acquire technical know-how effectively by taking part in electrification work and conducting adjustment or testing of various facilities.

1-3-3 Case 1: Training Curriculum for the Trainees Recruited for the Maintenance of the Shinkansen Lines, Mishima Technical Training School, A Branch of the Central Railway Training School

Those recruited for the maintenance of the Shinkansen lines are placed on duty after completing a three-month training course.

Table 1-19 outlines the part of the curriculum relating to technical training.

The scope of recruit training covers mainly basic technical points, handling of equipment and the inspection procedure with lectures and practical training conducted on a priority basis.

Table 1-19 Curriculum for the Electric Section (Shinkansen)

	Items	Hours (H)	Contents
Electric power	(Lectures)		
	1. Electricity in general	21 H	DC and AC theories
	2. Substation	46 "	Explanation of equipment, electric interlocking
	3. Overhead contact system	28 "	Composition, incidental equipment
	4. Feeding system	37 "	Feeder, switches, arresters, etc.
	5. Lighting and power equipment	3 "	Lighting, etc.
	6. Electric inspection car	3 "	
	Subtotal	138 H	
	(Practical training)		
	7. Handling of tools and gauges	24 H	
	8. Repair of overhead contact system	24 "	
	9. Restoration of broken catenary line	12 "	
	10. Inspection and adjustment of equipment	60 "	
	Subtotal	120 H	
	Total	258 H	

	Items	Hours (H)	Contents
Signal and communication	(Lectures)		
	1. Electricity in general	21 H	
	2. Transmission theory, etc.	15 "	
	3. Signal facilities	56 "	ATC, CTC interlocking system, track circuit, etc.
	4. Communication facilities	48 "	Carrier transmission system, train radio, etc.
	5. COMTRAC	3 "	
	6. Electric inspection car	3 "	
	Subtotal	146 H	
	(Practical training)		
	7. Signal facilities	36 H	Various types
	8. Communication facilities	37 "	Various types
	Subtotal	73 H	
	Total	219 H	

1-3-4 Training and Facilities at Chiba Railway Training School

A marked decrease in the intensity of maintenance work by the JNR personnel due to the contracting of repair work to private businesses and fewer breakdowns of equipment due to technological advances resulted in the merit of a large labor-saving effect. On the other hand, since the number of opportunities for the JNR personnel to directly handle equipment decreased, it became necessary to take measures to maintain and improve their skills and technological level.

Accordingly, such a step as to conduct education and training between works by utilizing the facilities for practical training is taken throughout the country. For instance, the Chiba Railway Training School under the Chiba Railway Operating Division is provided with various educational equipment shown in Table 1-20 so that each one of the 500 electric personnel can receive practical training once a month.

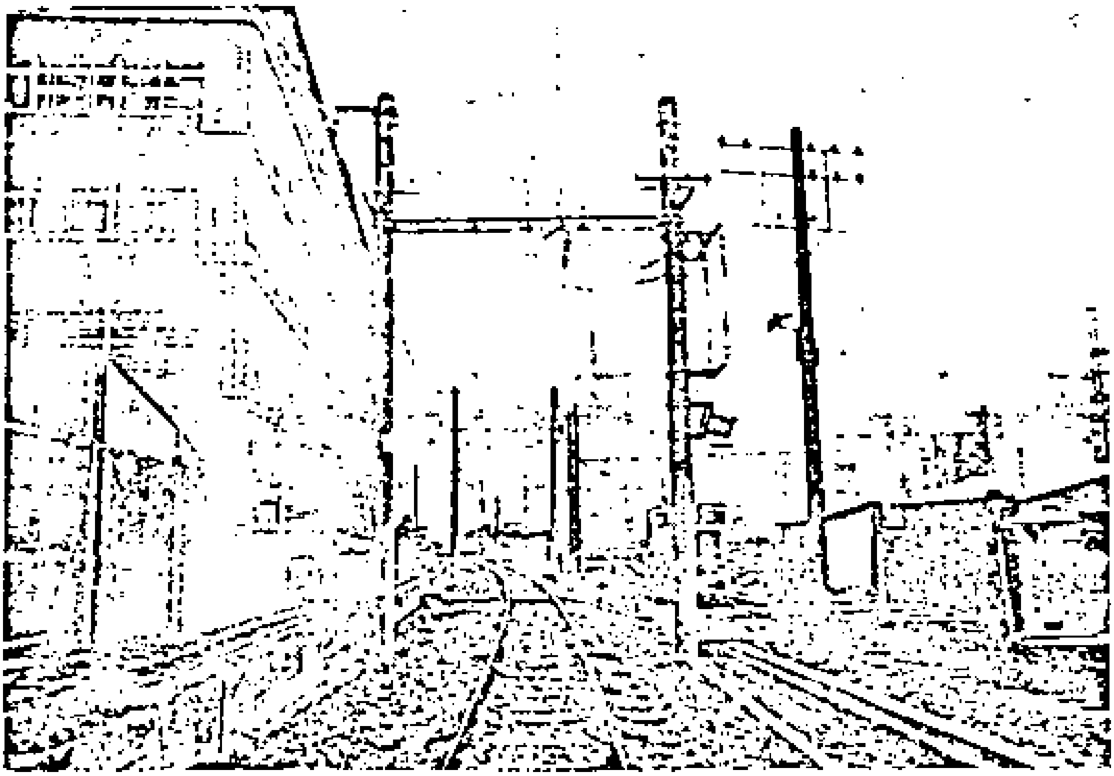
Table 1-20 Equipment for Practical Training

Electric power equipment		Signal and communications equipment	
1	Centralized remote control device	1	Relay interlocking machine
2	Substation interlocking panel, etc.	2	Electric switch machine
3	High speed circuit breaker	3	Track circuit
4	High voltage distribution panel	4	CTC device
5	Disconnecting switch	5	Cable carrier telephone system
6	Electric pump	6	Data transmission system
7	Others	7	Facsimile
		8	ITV
		9	Agent set for automatic seat reservation system
		10	Others

In addition, overhead contact system for training is provided for each maintenance section as shown in Fig. 1-18 for skill training under such training items as shown in Table 1-21. These training facilities are fully utilized for the training of new recruits.

Table 1-21 Guide for Practical Training

Training facilities	Scope of training
Supports	Installation and removal of temporary masts. Installation of temporary stays. Installation of temporary beams. Repairing of damaged masts and beams.
Insulators	Replacing of insulators on feeder and messenger wire. Replacing of side anchor insulators of the span type.
Catenary line	Adjustment of height, displacement and sagging. Restoration of broken contact wire. Restoration of broken messenger wire. Replacing of hangers and droppers. Inspection and replacing of connectors. Installation of hinged pull-off arms. Replacing of hinged pull-off arms and side anchors. Replacing of insulators and connecting rods of fixed extermination. Inspection and replacing of wood sections. Inspection and adjustment of automatic tensioning device. Restoration of broken wiring of automatic tensioning device.
Feeder	Wiring connection. Restoration of broken feeder. Branching and anchoring feeding lines.
Disconnecting switch	Inspection of disconnecting switch and adjustment of the control mechanism. Emergency repairing of disconnecting switch when not accepting input.
Crossing warning signs	Inspection and adjustment. Restoration of broken span lines.



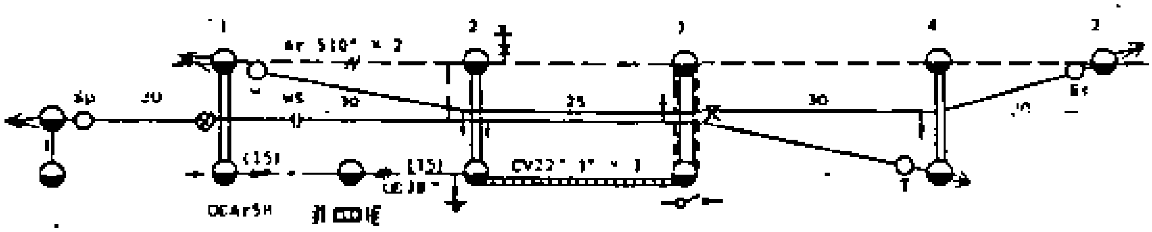


Fig. 1-18 Overhead Contact System for Training

1-3-5 Training Curriculum for Inspector Foreman at the Central Railway Academy (Job: Chief inspector)

The Central Railway Training School provides skill training (two months) for those selected by examination, who have more than five years' experience, necessary for being upgraded to chief inspector.

Below is an outline of the section of the curriculum relating to technical training.

(1) A.C. Electrification System (Lecture: 1-hour)

(a) Outline

(b) Classification

(c) Benefit of A.C. electrification system

- Comparison of A.C. electrification system and D.C. electrification system
- Various kinds of A.C. electrification system

(d) Problems

- Inductive disturbance
- Unbalance of power source

(2) A.C. Feeding Circuit (Lecture: 2-hours)

(a) Power system

(b) Feeding circuit configuration

- Scott connection and modyfied woodbridge-connection
- Substation (SS), Sectioning post (SP), Sub-sectioning post (SSP)

(c) Protection of feeding circuit

- Ground fault, short circuit fault

(3) Location of Substations (Lecture: half an hour)

(4) Overhead Contact System (Lecture: half an hour)

(a) Characteristics of overhead contact system

(b) Conditions required of overhead contact system

- Current capacity
- Mechanical strength, electrical strength

(c) Various types of overhead contact system

(d) Vehicle gauge and structure gauge

(5) Substation Facilities (Lecture: 38-hours)

(a) Power receiving equipment (Lecture: 12-hours)

- A.C. disconnecting switch
- A.C. circuit breaker
- Instrument transformer
- Lightning arrester

(b) Transformers (Lecture: 12-hours)

- Feeding transformer
- Distribution transformer

(c) Feeding equipment (Lecture: 6-hours)

- Feeding circuit breaker

(d) Protective relaying system (Lecture: 4-hours)

- Protection of power receiving equipment
- Protection of transformers
- Protection of feeding equipment
- Calculation of fault current

(e) Remote control apparatus for substation

- Various types (especially, TEKKEN-B type)

(6) Components of Overhead Contact System (Lecture: 30-hours)

(a) Supports

- Pole and mast
- Stay and strut
- Hinged cantilever and beam
- Insulator

(b) Catenary system (Lecture: 10-hours)

- Messenger wire
- Contact wire
- Hanger and dropper
- Connector and feeder fitting
- Hinged pull-off
- Tensioning equipment

(c) Feeding system (Lecture: 5-hours)

- Feeder
- Feeding network
- Switchgear
- Voltage drop

(d) Return circuit (Lecture: 2-hours)

- Composition
- Negative feeder
- Booster transformer
- Auto-transformer

(e) Protective equipment of overhead contact system

- Lightning arrester
- Overhead earth wire for flashover
- Gap arrester

(f) Maintenance of overhead contact system (Lecture: 2-hours)

(7) Signal Facilities (Lecture: 17-hours, Practice: 3-hours)

(a) Track circuit (Lecture: 9-hours, Practice: 3-hours)

- Outline
- Component
- Types
- Measurement practice

(b) Signal apparatus (Lecture: 8-hours)

- Significance and objectives
- Types and characteristics
- Signal
- Relay

(8) Communication Facilities (Lecture: 12-hours, Practice: 12-hours)

(a) Wire transmission (Lecture: 5-hours)

- Telecommunication cable
- Induction and the countermeasure for it

(b). Protective device (Lecture: 5-hours)

- Fuse, gap, arrester
- Earthning device

(c) Carrier-frequency equipment (Lecture: 2-hours, Practice: 12-hours)

- Outline
- Measurement practice

CHAPTER 2

FEEDING SYSTEM

CHAPTER 2. FEEDING SYSTEM

In this Chapter, the simple and AT feeding systems will be described mainly, but for the sake of reference, the BT feeding system will also be described briefly.

2-1 Characteristics of Feeding Systems and Comparisons between Them

2-1-1 Types and Features

Table 2-1 shows the types and features of the AC feeding systems, their circuit configurations and applicable districts.

(1) Simple Feeding System

The simple feeding system is the most fundamental one, comprised of contact wire and rails. But, as its variation, an NF simple feeding system with a negative feeder (NF) extended along and connected to rails every several kilometers by NF connecting wires is available. This system is advantageous in that with NF provided, it is possible to detect an insulator flashover occurring in the feeding circuit with ease and thus protect the circuit and reduce the feeding circuit impedance.

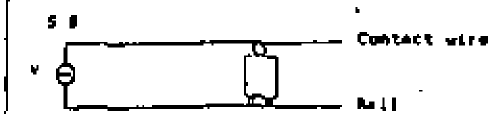
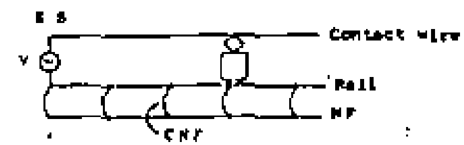
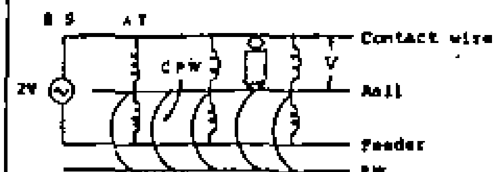
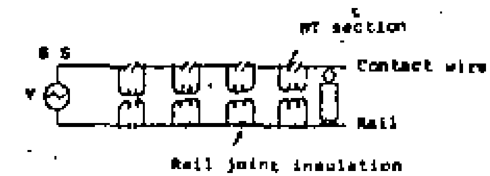
The simple feeding system features a simple circuit configuration. Thus it is economical with respect to the feeding circuit and permits easy maintenance. But its shortcoming is that it has the return circuit current flow through the rail over the whole section. Thus, the inductive interference on telecommunication lines is appreciable, and the rail potential is higher than in any other feeding system.

This system is the most extensively used in the world, and JNR is employing it in some sections.

(2) AT Feeding System

The AT feeding system is a system having a higher feeding voltage from the substation than that in the catenary line and

Table 2-1 Types and Features of AC Feeding Systems

Names		System diagrams	Features	Application: JNR	Application: Overseas
Simple feeding system	① Basic type (T-R)		1. Simplest feeding circuit configuration. 2. Telecommunication induction characteristic not good. 3. Protective measures required for insulator flashover, etc. 4. Theoretically higher rail potential than in other feeding systems.	Part of conventional lines	Used extensively in France, England, the Soviet Union, China and other foreign countries.
	② With NF (T-R-NF)		1. With NF provided, the feeding circuit impedance and rail potential are reduced compared with the basic type ①. 2. For telecommunication induction, more effective in shielding than the basic type ①.		
③ AT feeding system (AT: Auto Transformer)			1. Suitable for supply to large capacity loads on account of higher feeding voltage (SS send-out voltage) than catenary line voltage. 2. Longer SS interval than the other feeding systems. 3. Free from sections such as BT section. 4. AT interval is around 10 km.	Conventional lines Sanyo Shinkansen Tohoku/Joetsu Shinkansen	Part of the U.S.A. (25 Hz), France (TGV) and part of the Soviet Union.
BT feeding system (BT: Booster Transformer)	④ With NF		1. Greater telecommunication induction reducing effect. 2. BT section required. 3. BT interval around 3~4 km.	Conventional lines Tokaido Shinkansen	Part of England Part of France Part of Sweden
	⑤ Without NF		1. BT characteristics implemented, yet NF omitted. 2. Somewhat worse telecommunication induction reducing effect than ④ with NF. 3. Rail joint insulation required. 4. Insulator flashover and other protective measures required.	—	Norway Part of England Part of France Part of Sweden

dropping it to a necessary catenary line voltage by auto transformers (AT) installed about every 10 km along the track for supply of power to electric motor vehicles.

The AT feeding system in JNR has a feeding voltage from the substation two times the catenary line voltage, but by changing the winding ratio of the AT, it is possible to increase the feeding voltage.

This system is fitted for supply of large power as the voltage fed from the substation is high (two times the voltage fed to electric motor vehicles). Further, on account of less feed current from the substation, that is, 1/2 of the current in the simple feeding system, this system has less voltage drop due to feeding circuit impedance and allows installation of substations at greater intervals.

Greater substation intervals are advantageous particularly when the source of power is located far away. In such case, the total construction costs, including transmission lines, are lower than for the simple feeding system.

Further, as the load current is boosted by AT's on the left and right sides, the induction voltage to long telecommunication lines is set off, while the current flow in the rails is limited, so that the system is distinguished in the effect of decreasing the inductive interference.

The AT interval is determined in consideration of the telecommunication induction reducing effect, rail potential and voltage drop in feeding circuit, but it is 10∿15 km normally.

On the other hand, it is required to install AT's of a capacity of 1/3∿1/4 of the train load capacity at every 10∿15 km along the railway line and also provide a feeder of the same insulation level to that of the contact wire over the whole line, so that the circuit configuration is more complex than that of the simple feeding system.

(3) BT Feeding System

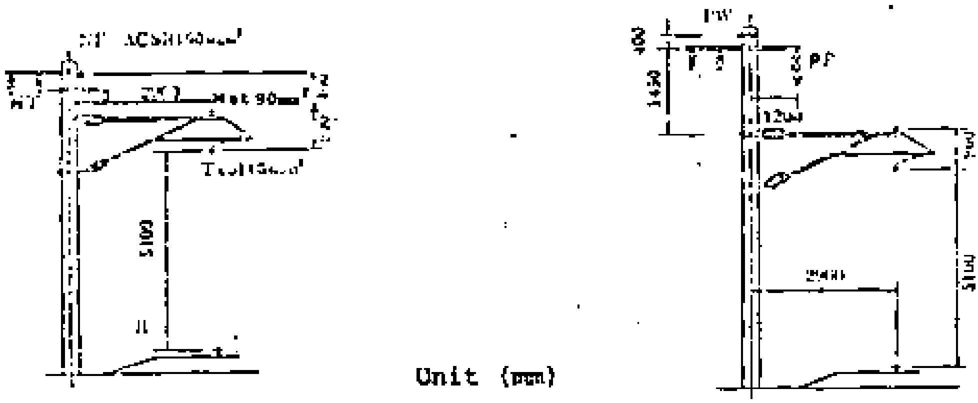
This BT feeding system has booster transformers (BT) installed every several kilometers (about 4 km) to boost the return current flow in the rails. The current flow to earth is thereby reduced so that the communication induction reducing effect is great.

This system includes two types: simple BT feeding without NF; and current boosting to NF with NF provided. The former is simple but is considerably inferior to the latter in its telecommunication induction reducing effect but not as much as that of the simple feeding system. Further, across the rail joint insulators, a BT secondary terminal voltage is produced so that when a train passes, shortcircuiting and opening by wheels occur repeatedly, resulting in poor maintenance of the insulators. Thus, the system is used where the load current is not so large.

As disadvantages of the BT feeding system, a complex feeding circuit configuration due to BT sections and greater feeding circuit impedance than that in the simple feeding system may be cited. Further, greater arc occurs at the booster section with increasing load current when a train passes so that some arc suppressing measures are also required.

2-1-2 Feeding Circuit Configuration and Assembling

The kind of electric wire varies with the load condition of electric motor vehicle, but examples in the JNR conventional lines are illustrated in Fig. 2-1.

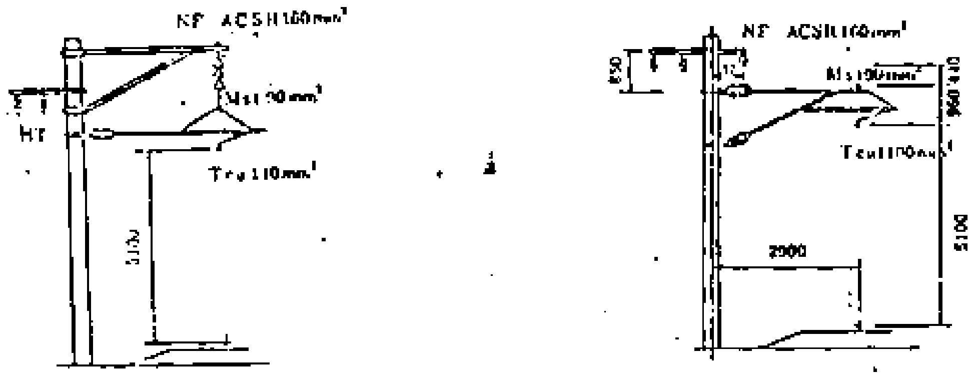


Unit (mm)

(a) (T-R only) simple feeding system - with NF deleted from this diagram

(b) (NF sideway) simple feeding system

(d) AT feeding system



(c) (NF immediately above) simple feeding system

(e) BT feeding system

Fig. 2-1 Feeding Circuit Assembling and Kinds of Wire

2-1-3 Feeding Circuit Impedance

The feeding circuit impedance also varies with the kind of wire and the assembling, but for the sake of reference, its approximate values as different with the feeding circuit types in JNR are shown in Table 2-2. As seen from the table, the impedance of the AT feeding circuit is small, at 1/3∼1/4 of the other feeding system.

Table 2-2 Impedance of AC Feeding Circuits

Feeding systems	Districts classification	Frequency [Hz]	Impedance [Ω/km]
Simple feeding system	Conventional line	50	0.241+j0.493
AT feeding system	Conventional line	50 60	0.111+j0.176 0.111+j0.212
	Shinkansen	50 60	0.040+j0.185 0.040+j0.209
BT feeding system	Conventional line	50 60	0.286+j0.684 0.286+j0.822
	Shinkansen	50 60	0.210+j0.660 0.210+j0.790

Next, the impedance characteristics from the substation to the load point will be described. In the case of the simple feeding system, the impedance seen from the substation is linear to the distance, as shown in Fig. 2-2. But, in the cases of the AT and BT feeding systems shown in Figs. 2-3 and 2-4, the impedance seen from the substation is not linear to the distance. It should be noted that in the AT feeding system, it is a wavy curve and that in the BT feeding system, it is stepped. The values of impedance of the AT and BT feeding systems shown in Table 2-2 are, for the AT feeding system, those of shortcircuiting impedance between the contact wire (T) and the feeder (F) and, for the BT feeding system, between the contact wire (T) and the negative wire (NF). The impedance of the simple feeding system and that of the AT feeding system will be described in detail in Section 2-2.

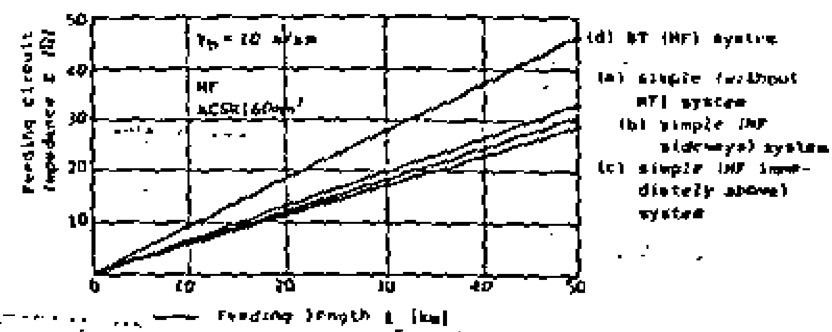


Fig. 2-2 Impedance Characteristic of the Simple Feeding System

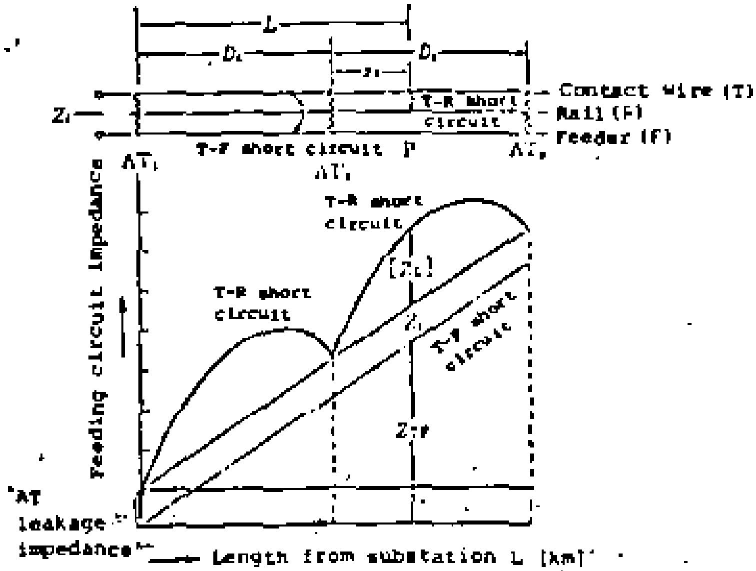


Fig. 2-3 Impedance Characteristic of AT Feeding Circuit

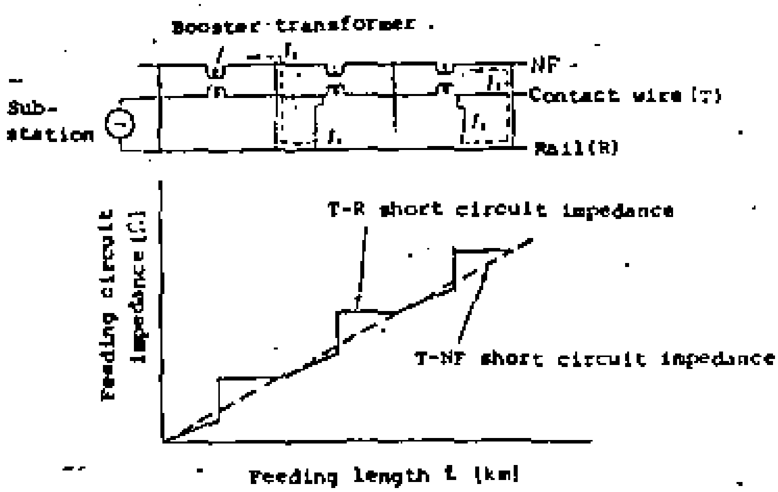


Fig. 2-4 Impedance Characteristic of BT Feeding Circuit

2-1-4 Substation Interval

When the feeding circuit impedance is smaller, the voltage drop of the feeding circuit is also smaller for the same load current. Consequently, it is possible to increase the substation interval.

For example, if the feeding circuit impedance is reduced to 1/3, the feeding length can be increased three times for the same load. However, if the substation interval is increased, there will be an increasing number of trains in the section subject, of course, to the train density so that the substation interval can hardly be increased exactly in inverse proportion to the feeding circuit impedance.

Table 2-3 shows a yardstick of the substation interval for the respective feeding systems.

Table 2-3 Feeding Systems and Substation Interval

	Substation interval	
	High load capacity and density district	Low load capacity and density district
Simple feeding system	30 km	50 km
AT feeding system	60 km	100 km
BT feeding system	20 km	30 km

2-1-5 Telecommunication Induction Characteristics

While the telecommunication inductance will be described in detail in Chapter 6, the following may be cited as matters to be considered in the selection of the feeding system, that is, induction dangerous voltage for fundamental waves and induction noise voltage on harmonics.

These values are governed by various conditions, as shown in Table 2-4 and are, therefore, hardly determined generally. Here, in order to see what differences would be produced by the type of the feeding system, calculations were made of model circuits which were of the same conditions except the feeding system.

Fig. 2-5 shows curves of the fundamental wave induction voltage in a long telecommunication line over the whole length of the feeding section for each of the feeding systems on a load current of 200A. As seen, the AT feeding system is about 1/5, and the BT feeding system is about 1/8, of the simple feeding system.

Table 2-4 Factors Affecting Telecommunication Induction

Items		Induction dangerous voltage	Induction noise voltage
Natural condition	Earth conductivity	○	○
Power circuit	Feeding system	○	○
Telecommunication line	Extension	○	○
	Separating distance to feeding circuit	○	○
	Parallel length to feeding circuit	○	○
	Relative position to feeding circuit	○	○
	Balancing degree		○
	Shield coefficient	○	○
Current conditions	Fundamental wave current {Load current, Fault current}	○	
	Equivalent disturbing current		○

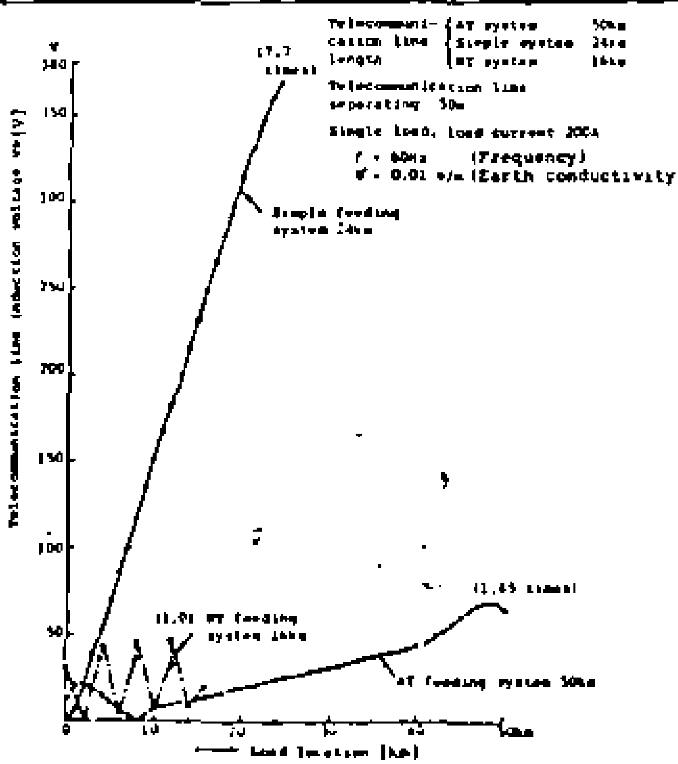


Fig. 2-5 Induction Voltage in the Respective Feeding Systems

Fig. 2-6 shows the changing induction voltage as a function of the length of telecommunication line with the value of induction voltage for 1 km of the telecommunication line taken as a unit.

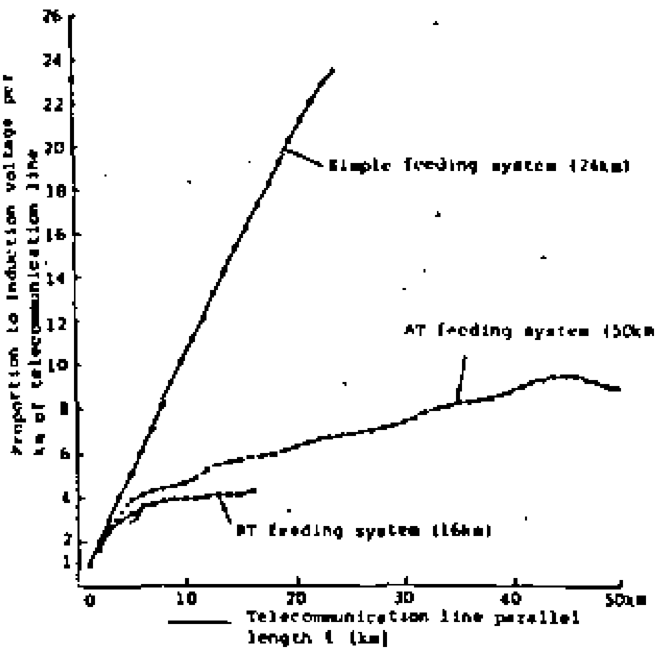


Fig. 2-6 Telecommunication Line Length versus Induction Voltage of the Respective Feeding Circuits
(Mean value of the maximum induction voltage per km of telecommunication line taken as standard 1)

Figs. 2-7 and 2-8 show the noise voltage characteristic by the same procedures respectively. That is, Fig. 2-7 shows the curves of LE induction noise voltage on a long telecommunication line over the whole length of the feeding section, and Fig. 2-8 shows the changing noise voltage with the length of telecommunication line in multiples of the value of noise voltage over 1 km of the telecommunication line.

These Figs. 2-5 through 2-8 indicate without exception that the simple feeding system is not good in telecommunication induction characteristics. Therefore, before the simple feeding is employed, it is necessary to examine these telecommunication induction characteristics carefully.

It should be noted that in the calculation of Figs. 2-5 through 2-8, the earth conductivity is taken as 0.01 s/m (mean value in Japan). It is thus important to understand the earth conductivity exactly in choosing the feeding system.

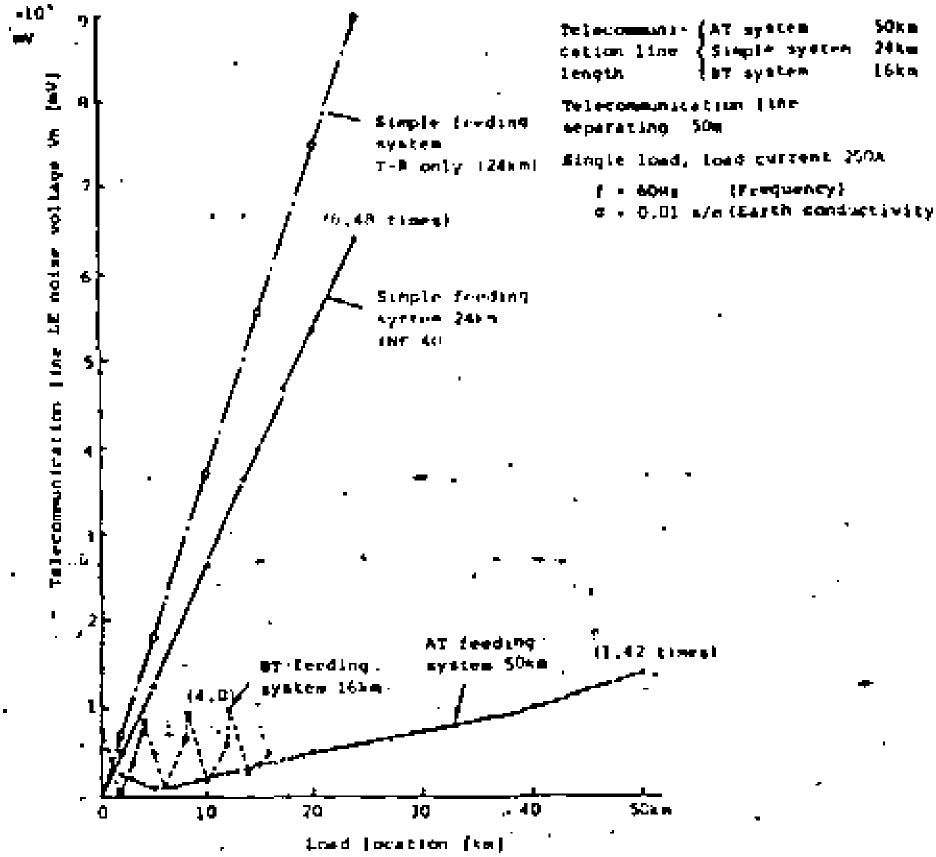


Fig. 2-7 LE (Line-Earth) Noise Voltage in the Respective Feeding Systems

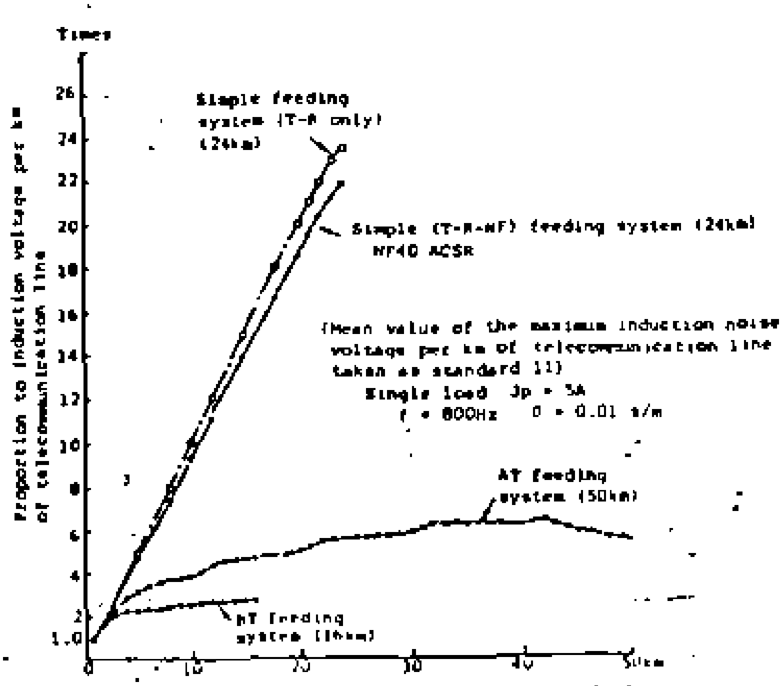


Fig. 2-8 Telecommunication Line Length versus Induction Noise Voltage of the Respective Feeding Systems

2-1-6 Construction Costs

Table 2-5 shows the ground electrical equipment construction costs by type of the feeding system, with the values equivalent to km obtained from the overall construction costs and expressed in indexes against the construction costs of the simple feeding system taken as 100.

Conditions for calculation of the construction costs are approximately as follows, and the respective feeding systems were designed under the same conditions.

Electrification section:	400 km
Track:	Single track
Train output:	3,000 kW (Electric locomotive)
Highest train speed:	100∿120 km/h

The construction costs are, of course, subject to change with changes in these conditions, but they may be taken as a basis for measurement.

Further, the numerals express the characteristics of the feeding systems respectively. That is:

(1) The transmission line construction costs are the lowest with the AT feeding system which permits greater substation intervals, followed by the simple and BT;

(2) The substation equipment costs are also in the order of the AT feeding system, requiring less substations for the same reason given above, simple and BT; and

(3) The contact wire construction costs are the lowest for the simple feeding system which is the simplest system, followed by BT, having NF of class 3 kV insulation and AT feeding system, having feeder of 30 kV insulation and non-insulation protective wire (PW).

The foregoing economical comparison has been made of the power equipment only. Actually, however, economy must be

Table 2-5 Approximate Construction Costs of the Feeding Systems (per km)

Feeding systems	Unit costs (per km)				Remarks
	Transmission line	Substation	Overhead contact system	Total	
Simple feeding system	19	41	40	100	(1) Transmission line, 77 kV, 2 circuits, 5 km (2) SS interval, 40 km (3) Catenary, Heavy simple. (4) Feeding circuit impedance, 0.5 Ω/km
		50	50	100	
AT feeding system	7	31 (24)	46 (53)	84	(1) Transmission line, 154 kV, 2 circuits, 2 km (2) SS interval, 100 km (3) Catenary, Heavy simple (4) Feeding circuit impedance, 0.2 Ω/km
		38 (30)	57 (65)	95	
BT feeding system	25	54	46	125	(1) Transmission line, 77 kV, 2 circuits, 5 km (2) SS interval, 30 km (3) Catenary, Heavy simple (4) Feeding circuit impedance, 0.8 Ω/km
		67	57	124	

Note 1. BT installed at 4 km intervals.
2. AT installed at 10 km intervals and included in substation work.
3. Parenthesized indicating AT as work of overhead contact system.
4. Single track.

considered comprehensively with the compensation for telecommunication induction, maintenance expense, etc. taken into account. That is:

(1) Where a number of communication lines are extended along the railway line, the simple feeding system is not economical in that it involves a greater amount of compensation for induction.

(2) When the maintenance cost is considered, the system requiring less substations such as AT feeding system is advantageous, but for the overhead contact system, the simplest simple feeding is advantageous, followed by AT feeding, and the BT feeding having many booster sections is rather disadvantageous.

2-2 Methods of Calculation of the Feeding Circuit Impedance and Voltage Drop

For analysis of the voltage and current distribution in the feeding circuit by electric car load, JNR has developed a multiline network analysis program (ATAC-P) with an electronic computer.

Here we describe methods of obtaining the feeding circuit impedance and voltage drop without using a computer.

2-2-1 Conductor Self Impedance and Mutual Impedance

Conductor impedances should be calculated according to the Carson-Pollaczek formula, but here, methods according to simplified formulas of reliable accuracy will be described.

(1) Self Impedance Zs of Ordinary Conductors

Zi: Internal impedance [Ω/km]

Ze: External impedance [Ω/km]

Ro,Ri: Internal resistance to DC, AC [Ω/km]

Lo,Li: Internal inductance to DC, AC [H/km] r : Radius of conductor cross-section [m]

ρ : Electric resistivity of conductor material [Ωm]

μs: Permeability of conductor material.

h : Height of conductor above ground [m]

f : Frequency [Hz]

σ : Earth conductivity [S/m]

$$Ro = \frac{\rho \times 10^3}{\pi r^2} \ [\Omega/km]$$

$$Lo = 0.5\mu s \times 10^{-4} \ [H/km]$$

$$x = 2\pi r \sqrt{2f\mu s \times 10^{-7}/\rho}$$

Fig. 2-9 shows curves of Ri/Ro and Li/Lo as a function of x, and the values of Ri and Li are obtainable from them.

$$Zi = Ri + j2\pi f Li \ [\Omega/km]$$

Ze is according to a simplified form of the Carson-Pollaczek formula.

$$\alpha = 2\pi \sqrt{2\sigma f \times 10^{-7}}$$

$$\beta = \frac{4\sqrt{2}}{3}\alpha h \doteqdot 1.8856\,\alpha h$$

$$Ze = 2\pi f \,[(0.5\pi - \beta) + j\,(2\,\ln\frac{2}{\alpha r} + \beta - 0.15443)] \times 10^{-4} \ [\Omega/km]$$

$$Zs = Zi + Ze \ [\Omega/km]$$

<Example>

Iron wire, $r = 0.008$ [m], $\rho = 1 \times 10^{-7}$ [Ωm], $\mu s = 100$, $h = 8$ [m], $f = 60$ [Hz], $\sigma = 0.01$ [S/m].

<Solution>

$Ro = 0.497$ [Ω/km], $Lo = 5.00 \times 10^{-3}$ [H/km]

$x = 5.51$, $Ri/Ro = 2.21$

$Li/Lo = 0.51$

$Ri = 1.098$ [Ω/km]

$Li = 2.55 \times 10^{-3}$ [H/km]

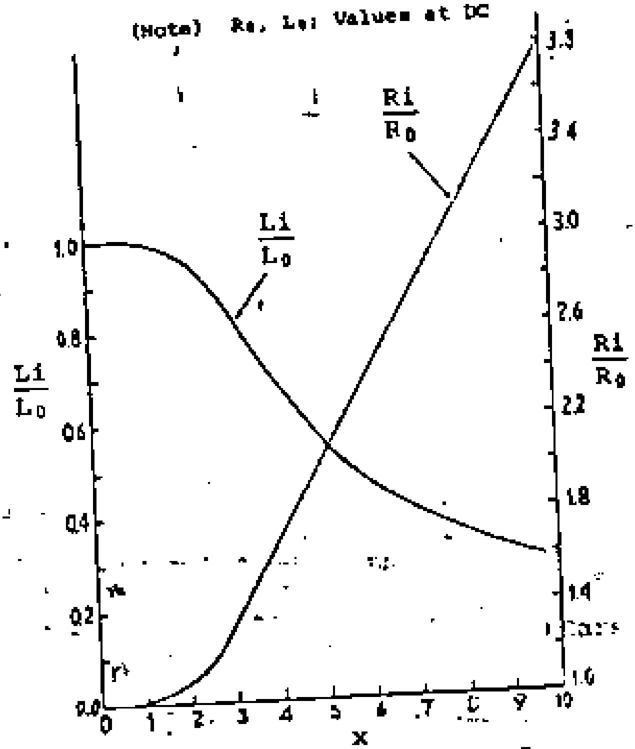
$Zi = 1.098 + j0.961$ [Ω/km]

$\alpha = 2.18 \times 10^{-3}$

$\beta = 3.29 \times 10^{-2}$

$Ze = 0.058 + j0.874$ [Ω/km]

$Zs = 1.156 + j1.835$ [Ω/km]



(2) Mutual Impedance Zm

Zm is according to a simplified form of the Carson-Pollaczek formula. The geometrical layout of two conductors is shown in Fig. 2-10.

b : Horizontal spacing between two conductors [m]

h_1, h_2 : Heights of conductors 1 and 2 above ground [m]

d : Distance between two conductors [m]

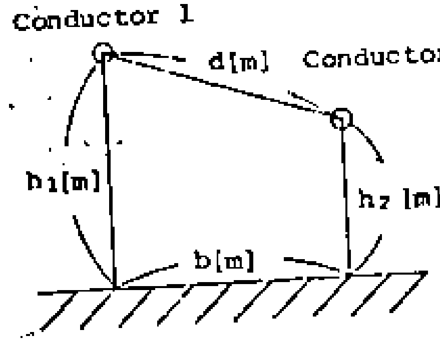


Fig. 2-10 Layout of Two Conductors

$$d = \sqrt{b^2 + (h_1 - h_2)^2}$$

$$\alpha = 2\pi\sqrt{2\sigma f \times 10^{-7}}$$

$$\beta' = \frac{2\sqrt{2}}{3}\alpha(h_1 + h_2) \doteqdot 0.9428\alpha(h_1 + h_2)$$

$$Zm = 2\pi f\{(0.5\pi - \beta') + j(2\ \ell n\frac{2}{\alpha d} + \beta' - 0.15443)\} \times 10^{-4} \ [\Omega/km]$$

<Example> b = 2[m]; h_1 = 6[m], h_2 = 8[m], f = 60[Hz],

$\sigma = 0.01$ [S/m]

<Solution> $d = 2.83\,[\mathrm{m}]$, $\alpha = 2.18 \times 10^{-3}$, $\beta' = 2.87 \times 10^{-2}$

$Z_m = 0.058 + j\,0.431$ [Ω/km]

(3) **Parallel Impedance of a Number of Conductors**

The rail is composed of 2 conductors, and catenary line is composed of 2~3 conductors of contact wire, messenger (and auxiliary messenger). Here, the method of obtaining the parallel impedance, which may be said to be an equivalent self impedance of a number of conductors, will be noted.

(a) Parallel Impedance of 2 Conductors Z_{p2}

Z_1, Z_2: Self impedances of conductors 1 and 2 [Ω/km]

Z_{12}: Mutual impedance between 2 conductors [Ω/km]

$$Z_{p2} = \frac{Z_1 Z_2 - Z_{12}^2}{Z_1 + Z_2 - 2Z_{12}} \quad [\Omega/\mathrm{km}]$$

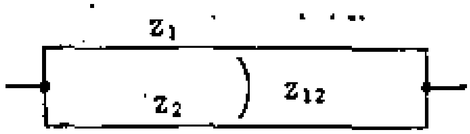


Fig. 2-11 2 Conductors Parallel

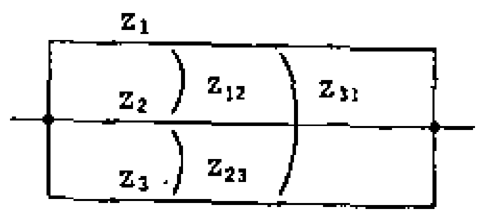


Fig. 2-12 3 Conductors Parallel

(b) Parallel Impedance of 3 Conductors Z_{p3}

Z_1, Z_2, Z_3: Self impedances of conductors 1, 2 and 3 [Ω/km]

Z_{23}, Z_{31}, Z_{12}: Mutual impedances across 3 conductors [Ω/km]

$$Z_a = Z_1 Z_2 Z_3 + 2Z_{23} Z_{31} Z_{12} - (Z_1 Z_{23}^2 + Z_2 Z_{31}^2 + Z_3 Z_{12}^2) \quad ([\Omega/\mathrm{km}]^3)$$

$$Z_b = (Z_2 Z_3 + Z_3 Z_1 + Z_1 Z_2) - 2(Z_1 Z_{23} + Z_2 Z_{31} + Z_3 Z_{12})$$
$$+ 2(Z_{12} Z_{31} + Z_{23} Z_{12} + Z_{31} Z_{23}) - (Z_{23}^2 + Z_{31}^2 + Z_{12}^2) \quad ([\Omega/\mathrm{km}]^2)$$

$Z_{p3} = Z_a / Z_b$ [Ω/km]

(4) Self Impedance of Rail

ℓ : Peripheral length of rail cross-section [m]

ℓ' : " " [in]

r : Equivalent radius of rail cross-section [m]

h : Height of rail above ground [m]

I : Current per rail [A]

f : Frequency [Hz]

Zi: Internal impedance of single rail [Ω/km]

Ze: External impedance " ["]

Zr_1: Self impedance " ["]

Ri: Internal resistance " ["]

Xi: Internal reactance " ["]

Zm: Mutual impedance between 2 rails ["]

Zr_2: Equivalent self impedance of 2 rails ["]

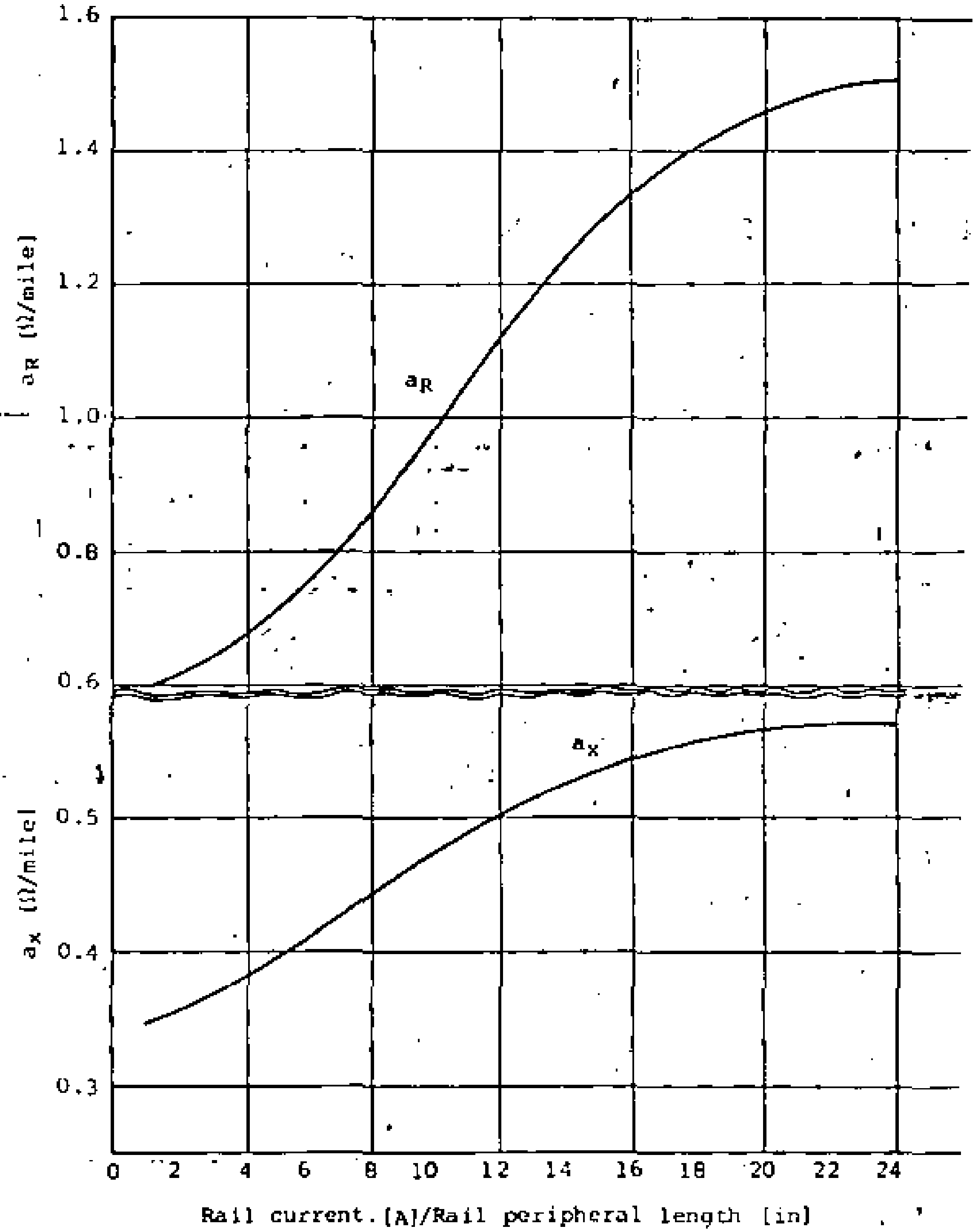
The internal impedance Zi of rail is according to a method of calculation devised by H. M. Trueblood. First, an assumed rail current I[A] is divided by the peripheral length of the rail ℓ'[in], and a_R and a_X are obtained from Fig. 2-13. Then,

$$Ri = \frac{0.015783\sqrt{f} \cdot a_R}{\ell} \ [\Omega/km]$$

$$Xi = \frac{0.015783\ f^{\frac{2}{3}}\ a_X}{\ell} \ [\Omega/km]$$

$$Zi = Ri + jXi \ [\Omega/km]$$

The external impedance Ze of rail is obtainable by the formula noted in paragraph (1), and the mutual impedance Zm between 2 rails by the formula noted in paragraph (2).



Note: 1 [inch] = 0.0254 [m]
1 [mile] = 1.6093 [km]

Fig. 2-13 Coefficients of Internal Impedance of Rail a_R, a_X (per rail)

Provided, $r = \ell/(2\pi)$ [m], and

$$Zr1 = Zi + Ze \quad [\Omega/km]$$

The equivalent self impedance of 2 rails is obtainable by the following formula having Zr_1 and Zm substituted for paragraph (3), item (a).

$$Zr_2 = 0.5\ (Zr_1 + Zm) \quad [\Omega/km]$$

<Example>

Rail 60 [kg/m], $\mu s = 70$, $I = 300$ [A], $\ell = 0.65973$ [m], $b = 1.13$ [m], $h = 0.5$ [m], $f = 60$ [Hz], $\sigma = 0.01$ [S/m]

<Solution>

$\ell' = 25.97$ [in], $I/\ell' = 11.55$ [A/in]

From Fig. 2-13, $a_R = 1.100$, $a_X = 0.498$

$$Ri = \frac{0.015783\sqrt{60} \times 1.100}{0.65973} = 0.204 \ [\Omega/km]$$

$$Xi = \frac{0.015783 \times 60^{\frac{2}{3}} \times 0.498}{0.65973} = 0.183 \ [\Omega/km]$$

$Zi = 0.204 + j\,0.183$ [Ω/km]

$r = \ell/(2\pi) = 0.1050$ [m], $d = b = 1.13$ [m]

$\alpha = 2.18 \times 10^{-3}$, $\beta = \beta' = 2.05 \times 10^{-3}$

$Ze = 0.059 + j\,0.679$ [Ω/km]

$Zr_1 = 0.263 + j\,0.862$ [Ω/km]

$Zm = 0.059 + j\,0.499$ [Ω/km]

$Zr_2 = 0.161 + j\,0.681$ [Ω/km]

2-2-2 Voltage Drop

A calculation model for the voltage drop is shown in Fig. 2-14.

Es: Power voltage [V]; Er: Load voltage [V]; Eo: Feeding circuit voltage drop [V]; I: Load current [A]; cosψ: Load power factor; and R + jx: Feeding circuit impedance [Ω].

The vector diagram on Er is as shown in Fig. 2-15.

$$Es = \sqrt{\{Er + I(R\cos\psi + X\sin\psi)\}^2 + \{I(X\cos\psi - R\sin\psi)\}^2} \text{ [V]}$$

In the foregoing formula, the second term is very small when compared with the first term so that

$$Es \fallingdotseq Er + I(R\cos\psi + X\sin\psi) \text{ [V]}$$

$$Eo = Es - Er \fallingdotseq I(R\cos\psi + X\sin\psi) \text{ [V]}$$

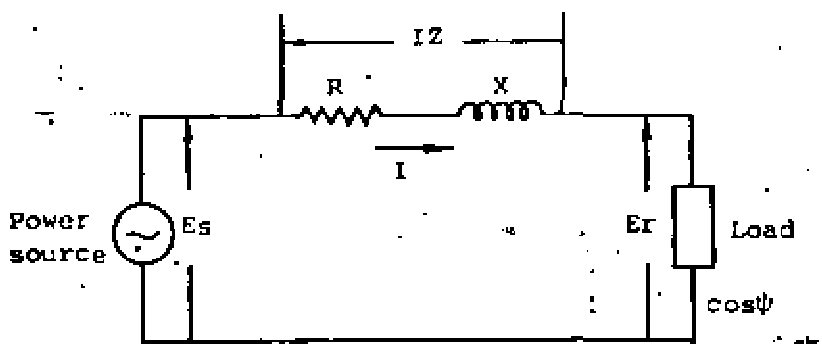


Fig. 2-14 Voltage Drop Calculation Model

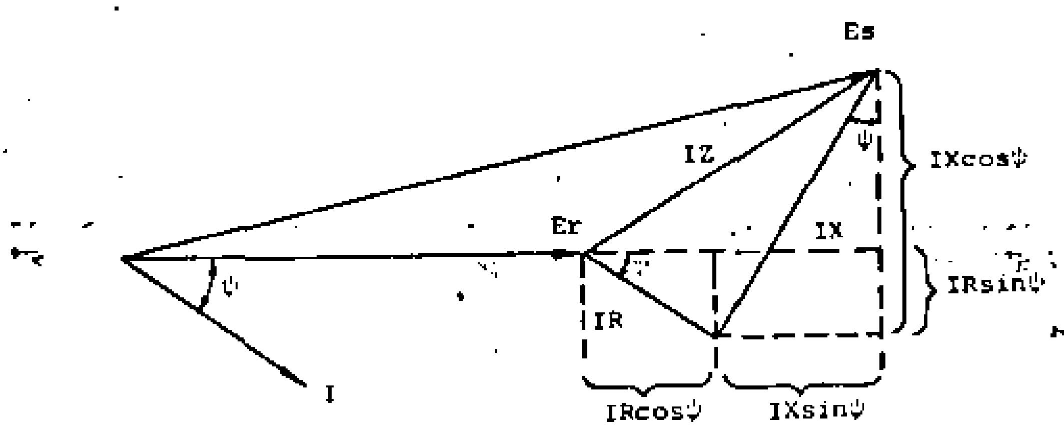
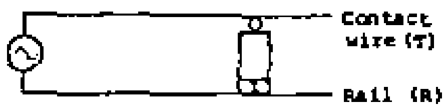


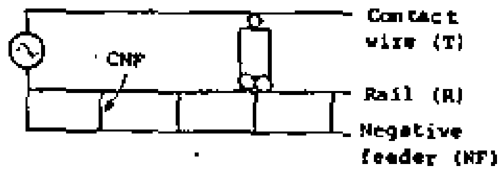
Fig. 2-15 Vector Diagram

(1) Feeding Circuit Impedance and Voltage Drop of Simple Feeding Circuit

The simple feeding system is a simple circuit system composed of contact wire (T) and rail (R), as shown in Fig. 2-16. But, as its variation, a system of extending a negative feeder along the rail and connecting NF to the rail every several kilometers by means of NF connecting wire (CNF) is also available. In this case, NF serves as a protective wire (PW).



(a) Basic type (T-R system)



(b) With NF (T-R-NF system)

Fig. 2-16 Simple Feeding System

Earth return impedances of conductors in a geometrical layout such as that shown in Fig. 2-17 and under the following conditions are shown in Table 2-6.

$f = 60$ [Hz]

$\sigma = 0.01$ [S/m]

Wires

- Messenger wire (M): St 90 mm^2
- Contact wire (T): Cu 110 mm^2
- Negative feeder (NF): ACSR 160 mm^2, 40 mm^2
- Rail (R): 50 kg/m

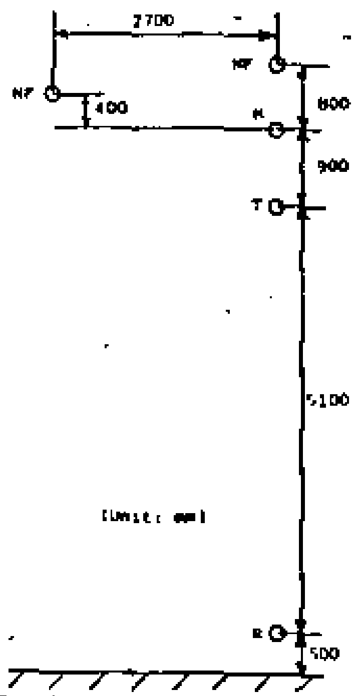
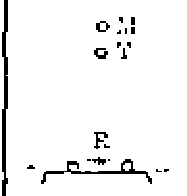
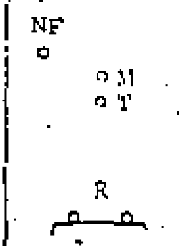
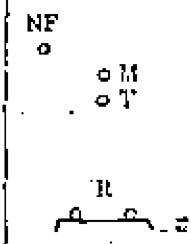
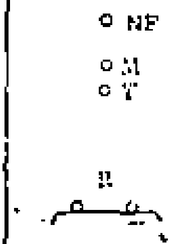


Fig. 2-17 Conductor Layout of Simple Feeding System

Table 2-6 Earth Return Self and Mutual Impedances of Simple Feeding System

NF location		None	Side		Immediately above
NF wire		—	ACSR160mm²	ACSR40mm²	ACSR160mm²
Configuration					
Self impedance [Ω/km]	Z_{TT}	$0.200 + j\,0.861$	$0.200 + j\,0.861$	$0.200 + j\,0.864$	$0.200 + j\,0.861$
	Z_{NN}	—	$0.235 + j\,0.901$	$0.761 + j\,0.932$	$0.235 + j\,0.901$
	Z_{RR}	$0.131 + j\,0.672$	$0.131 + j\,0.672$	$0.131 + j\,0.672$	$0.131 + j\,0.672$
Mutual impedance [Ω/km]	Z_{TN}	—	$0.058 + j\,0.434$	$0.058 + j\,0.432$	$0.058 + j\,0.490$
	Z_{TR}	$0.059 + j\,0.382$	$0.059 + j\,0.382$	$0.059 + j\,0.382$	$0.059 + j\,0.382$
	Z_{NR}	—	$0.059 + j\,0.370$	$0.059 + j\,0.365$	$0.059 + j\,0.366$

If the leak-to-ground admittance Y_b[S/m] of the rail is neglected the feeding circuit impedance Z[Ω/km] is:

In the case of no NF,

$$Z = Z_{TT} + Z_{RR} - 2Z_{TR} = 0.213 + j\,0.772 = 0.801\angle 74.6° \; [\Omega/km]$$

or

With NF (immediately above),

Z_T, Z_N, Z_R: Equivalent self impedances of T, NF and R [Ω/km]

$$Z_T = Z_{TT} + Z_{NR} - Z_{TN} - Z_{TR} = 0.142 + j\,0.358$$

$$Z_N = Z_{NN} + Z_{TR} - Z_{TN} - Z_{NR} = 0.177 + j\,0.427$$

$$Z_R = Z_{RR} + Z_{TN} - Z_{TR} - Z_{NR} = 0.071 + j\,0.414$$

Assuming that T-R is shortcircuited at point CNF,

$$Z = Z_T + \frac{Z_N Z_R}{Z_N + Z_R} = 0.202 + j0.571 = 0.606\angle 70.5°$$

However, if Y_b is great, part of the current flow in rail and NF flows to the ground so that the feeding circuit impedance decreases.

The approximate values of Y_b are shown in Table 2-7. In Table 2-8 are shown the computed values of the feeding circuit impedance Z [Ω/km] with Y_b assumed as 0.02 ∿ 10 (S/m), CNF interval as 4 km and length ℓ to the short-circuiting point as 10 or 40 km.

Table 2-7 Approximate Values of Leak-to-ground Admittance of Rail Y_b

Weather	Leak-to-ground admittance Y_b [S/km]	
	Conventional lines	Shinkansen
Fine	0.2 ∿ 0.5	0.002 ∿ 0.01
Rain	1.0 ∿ 2.0	0.1 ∿ 0.2

Table 2-8 Feeding Circuit Impedance Z

NF location	NF wire	Y_b [S/km]	Z [Ω/km]	
			ℓ = 10 km	ℓ = 40 km
None	—	0.02	0.743∠72.6	0.688∠73.2
		0.2	0.694∠72.8	0.671∠74.2
		2.0	0.673∠74.0	0.669∠74.5
		10.0	0.667∠74.5	0.667∠74.6
Side	ACSR 160 mm²	0.02	0.644∠72.0	0.609∠72.2
		0.2	0.624∠72.2	0.604∠72.8
		2.0	0.612∠72.7	0.602∠73.0
		10.0	0.608∠73.1	0.601∠73.0
	ACSR 40 mm²	1.0	0.644∠71.3	0.635∠71.6
Immediately above	ACSR 160 mm²	0.02	0.616∠70.9	0.581∠71.1
		0.2	0.599∠71.2	0.577∠71.6
		2.0	0.589∠71.7	0.576∠71.7
		10.0	0.584∠71.9	0.576∠71.8

With Y_b taken into account in this way, the feeding circuit impedance to $\ell = 40$ km is reduced by 14～17 percent with no NF and by 4～5 percent when NEs are provided.

<Examples of calculation of voltage drop>

Voltage drops when the feeding circuit and electric car load are as shown in Fig. 2-18 will be calculated. The conditions of calculation are assumed to be: power voltage, 30 kV; power source impedance, 0.2+j2% under 10MVA base; feeding transformer; 5MVA, j7.5%; series capacitor, 80% compensated; feeding circuit impedance; $0.577\angle 71.6°$ (= 0.1821 + j0.5475) Ω/km in the case of NF immediately above, $Y_b = 0.2$ S/m and $\ell = 40$ km in Table 2-8; electric car power factor, 0.8; and electric car current, 150A at 6 km point, 100A at 18 km point and 200A at 23 km point.

(a) Voltage Drop at Power Source Vs

$$\text{Power source impedance } Zs = \frac{(0.002 + j0.02) \times 30^2 k^2}{10M} \times 2$$
$$= 0.36 + j3.6 \ [\Omega]$$

$$\Sigma I = 150 + 100 + 200 = 450 \ [A]$$

$$Vs = 450 \times (0.36 \times 0.8 + 3.6 \times 0.6) = 1102 \ [V]$$

(b) Voltage Drop in Substation V_T

$$\text{Transformer impedance } Z_T = \frac{j0.075 \times 30^2 k^2}{5M} = j13.5 \ [\Omega]$$

$$\text{Series capacitor impedance } Zc = -0.8Z_T = -j10.8 \ [\Omega]$$

$$V_T = 450 \times (13.5 - 10.8) \times 0.6 = 729 \ [V]$$

(c) Voltage Drop in Feeding Circuit V_L

$$\text{Feeding circuit impedance } Z = 0.1821 + j0.5475 \ [\Omega/km]$$

Voltage drop per ampere kilometer

$$Z_L = 0.1821 \times 0.8 + 0.5475 \times 0.6 = 0.47418 \ [V/(A \cdot km)]$$

$$V_L = 0.47418\ (150\times 6 + 100\times 18 + 200\times 23) = 3462\ [V]$$

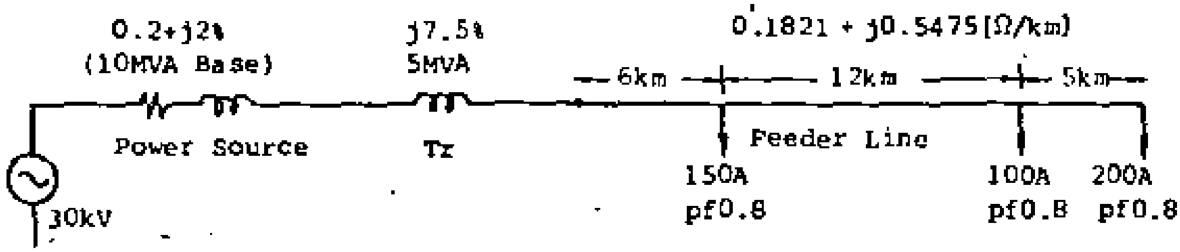


Fig. 2-18. Voltage Drop Calculation Model

(d) Minimum Pantograph Voltage Vp

Total voltage drop $\Delta V = V_S + V_T + V_L = 5293$ [V]

$Vp = 22 - 5.3 = 16.7$ [kV]

(2) AT Feeding Circuit Impedance and Voltage Drop

(a) Precise Calculation Method

The AT feeding circuit is comprised of a number of conductors including T (contact wire), F (feeder), R (rail) and PW (protective wire) so that in order to obtain exact voltage and current distributions, computer simulation must be resorted to.

Here, the method of obtaining the fundamental characteristics of the AT feeding circuit relatively precisely by paper calculation will be described.

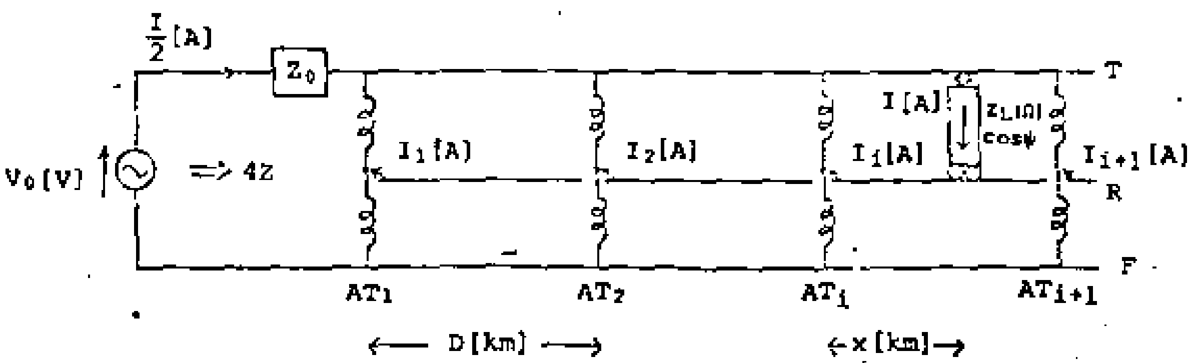


Fig. 2-19 AT Feeding Circuit Model

V_o: Power source voltage [V]

Z_o: Power source impedance [Ω]

Z_L: Electric car impedance [Ω]

I : Electric car current [A]

$\cos\psi$: Electric car power factor

I_i: AT_i boosting current [A]

D : AT interval [km]

x : Spacing between electric car and AT on power source side [km]

$d = X/D \ (0 \leq d \leq 1)$

Z_{AT}: AT leak impedance based at low voltage side [Ω]

Z_{TT}, Z_{FF}, Z_{RR}: Self impedances of T, F and R [Ω/km]

Z_{TF}, Z_{TR}, Z_{FR}: T-F, T-R and F-R mutual impedances [Ω/km]

Z_T, Z_F, Z_R: Equivalent self impedances of T, F and R [Ω/km]

$Z_T = Z_{TT} + Z_{FR} - Z_{TF} - Z_{TR}$

$Z_F = Z_{FF} + Z_{TR} - Z_{TF} - Z_{FR}$

$Z_R = Z_{RR} + Z_{TF} - Z_{TR} - Z_{FR}$

$A = Z_T + 2Z_R$

$B = Z_T + Z_R$

$G = Z_T + Z_F + 4Z_R$

$H = Z_T Z_F + Z_T Z_R + Z_F Z_R = BG - A^2$

When the electric car is positioned between AT_i and AT_{i+1}, the feeding circuit impedance Z_ℓ [Ω] based at low voltage side from the power source to the electric car is given by the formula

$$Z_\ell = 0.25Z_o + Z_{AT} + D\{(i-1)H/G + Bd - A^2d^2/G\} \quad [\Omega]$$

<Example of calculation of voltage drop>

Calculations are made for the Sanyo Shinkansen feeding circuit of a geometrical configuration of conductors such as shown in Fig. 2-20 having PW neglected and under the conditions shown below.

V_0 = 30 [kV]

D' = 10 [km], x = 7 [km]

$\dot{I}$ = 100 [A], $\cos\psi$ = 0.8

Z_0 = 1.2 + j7.6 [Ω]

Z_{AT} = 0.1 + j0.4 [Ω]

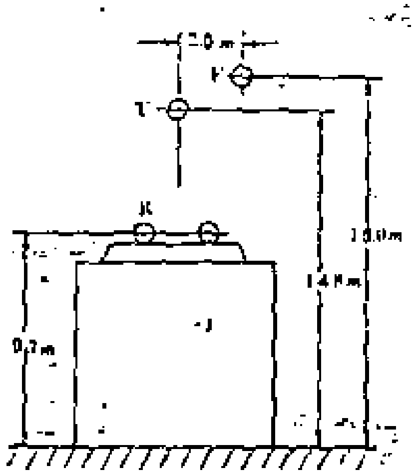


Fig. 2-20 Simplified Conductor Layout of AT feeding Circuit

1) Conductor wires

T (Contact wire)

M :	St	180 mm^2
AM:	Cu	150 mm^2
T :	Cu	170 mm^2

F (Feeder): Aℓ 200 mm^2

R (Rail): 60 kg/m

2) Self and mutual impedances [Ω/km]

Z_{TT} = 0.1192 + j0.7522

Z_{FF} = 0.2036 + j0.8847

Z_{RR} = 0.1618 + j0.6709

Z_{TF} = 0.0568 + j0.3953

Z_{TR} = 0.0574 + j0.3877

Z_{FR} = 0.0571 + j0.3410

3) Equivalent self impedance [Ω/km]

Z_T = 0.0621 + j0.3102 (0.3164 $\angle$ 78.7°)

$Z_F = 0.1471 + j0.5361$ $(0.5559 \angle 74.7°)$

$Z_H = 0.1041 + j0.3375$ $(0.3532 \angle 72.9°)$

4) Combined impedance

$A = 0.2703 + j0.9852$

$B = 0.1662 + j0.6477$

$C = 0.6256 + j2.1963$

$H = -0.4210 + j0.2376$

$H/C = 0.0496 + j0.2058$

$(Z_T + Z_F)/4 = 0.0523 + j0.2116$

$A^2/C = 0.1166 + j0.4419$

The feeding circuit impedance $Z_\ell[\Omega]$ based at low voltage side (Vo/2 side) is given as

$$Z_\ell = (0.1 + 1.662d - 1.166d^2) + j(0.4 + 6.477d - 4.419d^2) \ [\Omega]$$

As shown in Fig. 2-21, Z_ℓ $[\Omega]$ as a function of x [km] is given in a parabolic form projecting upward.

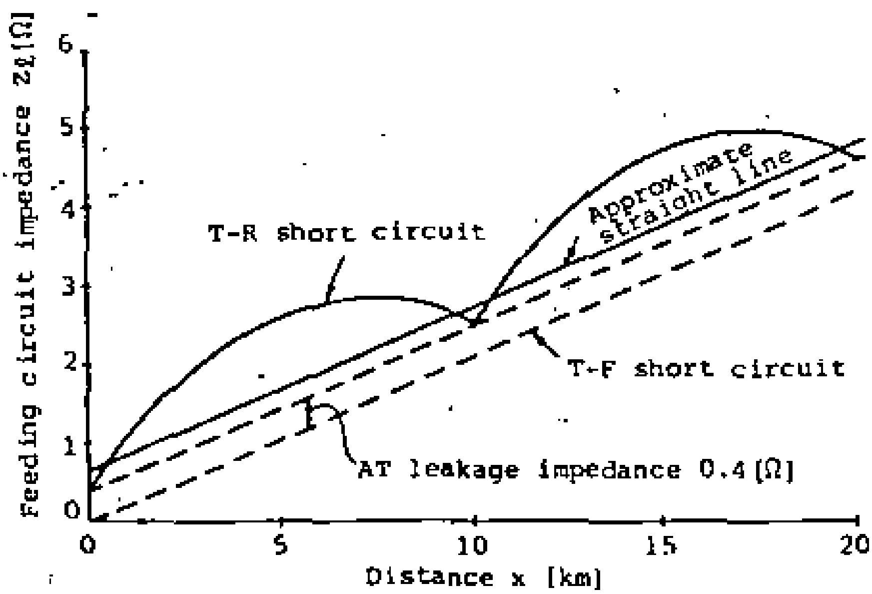


Fig. 2-21 Feeding Circuit Impedance versus Distance (simplified equivalent circuit)

The total impedance $Z[\Omega]$ from the power source to the electric car is given as

$$Z = (1.2 + j7.6)/4 + Z_\ell$$

$$= (0.4 + 1.662d - 1.166d^2) + j(2.3 + 6.477d - 4.419d^2) \ [\Omega]$$

When $x = 7$ [km] ($d = 0.7$),

$$Z = 0.9921 + j4.6686 \ [\Omega]$$

Then, the maximum voltage drop = 3595 [V]

$$\Delta V = 1000\,(0.9921 \times 0.8 + 4.6686 \times 0.6)$$

and the pantograph voltage,

$$V_p = V_o - \Delta V = 30 - 3.6 = 26.4 \ [kV]$$

In the case of a number of trains, or where PW is present or where the double track has inbound and outbound feeding circuits tied, analysis is not possible unless computer simulation is employed. For reference, the feeding circuit impedance characteristic obtained through precise simulation of the Sanyo Shinkansen feeding circuit is shown in Fig. 2-22.

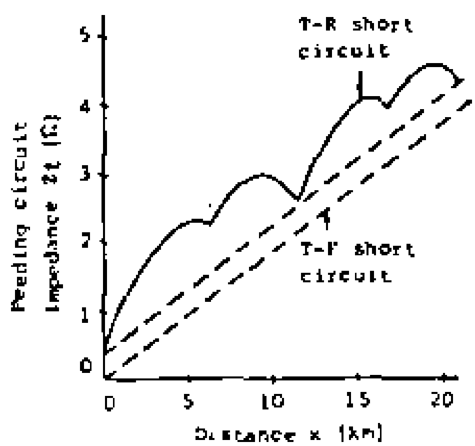


Fig. 2-22 Feeding Circuit Impedance versus Distance (Sanyo Shinkansen)

(b) Simple Calculation Method

A simple calculation method will be derived upon the drawings and calculation formulas in subparagraph (a).

Referring to Fig. 2-21, the increment of impedance for 1 section of AT is H/G, and it may be approximated as

$$\frac{H}{G} = \frac{Z_T Z_F + Z_T Z_R + Z_F Z_R}{Z_T + Z_F + 4Z_R}$$

$$= \frac{1}{4} (Z_T + Z_F) - \frac{(Z_T - Z_F)^2}{4\,(Z_T + Z_F + 4\,Z_R)}$$

$$\fallingdotseq \frac{1}{4} (Z_T + Z_F)$$

Further, it is difficult to handle continuation of parabolas, the approximate straight line shown in Fig. 2-21 is used. This line crosses the original paraboia at point d = 0.05 (or x = 0.5 km in Fig. 2-21).

Accordingly, the feeding circuit impedance Z[Ω] at low voltage base from the power source to a point x'[km] distant is given as

$$Z \fallingdotseq 0.25\,Z_O + Z_{AT} + 0.05D\,(B - 0.05A^2/G) + 0.25\,(Z_T + Z_F)\,x'\,[\Omega]$$

Further, the 3rd and 4th terms of the foregoing formula are handled as a scalar, and for the impedance angle, that of $(Z_T + Z_F)$ will be used as a representative value.

<Example of calculation of voltage drop>

Except the electric car current and power factor, the conditions are the same with those for the example of calculation in subparagraph (a).

$Z_T + Z_F = 0.2092 + j0.8463 = 0.8718 \angle 76.1°$

$Z_T \fallingdotseq 0.3164 \angle 76.1°$

$Z_F \fallingdotseq 0.5559 \angle 76.1°$

$Z_R \fallingdotseq 0.3532 \angle 76.1°$

$B = Z_T + Z_R \fallingdotseq 0.6696 \angle 76.1°$

$$A^2/G = \frac{(Z_T + 2Z_R)^2}{Z_T + Z_F + 4Z_R} = \frac{(0.3164 + 2 \times 0.3532)^2}{0.3164 + 0.5559 + 4 \times 0.3532} \angle 76.1°$$

$$= 0.4578 \angle 76.1°$$

$$Z = 0.25(1.2 + j7.6) + (0.1 + j0.4) + 0.05 \times 10(0.6696 - 0.05 \times 0.4578) \angle 76.1° + 0.25 \times 0.8718 \angle 76.1° \times x'$$

$$= (0.478 + 0.0524x') + j(2.614 + 0.2116x') \ [\Omega]$$

1) Electric car: 22 km point, 527A, power factor 0.6.

$$\Delta V = 527 (1.6308 \times 0.6 + 7.2692 \times 0.8)$$

$$= 3560 \ [V]$$

$$V_p = 30 - 3.6 = 26.4 \ [kV]$$

According to the computation, V_p = 26.3

2) Electric car: 3 km point, 553A, power factor 0.6; and 18 km point, 976A, power factor 0.8.

$$\Delta V = 553 (0.6532 \times 0.6 + 3.2488 \times 0.8) + 976 (1.4212 \times 0.8 + 6.4228 \times 0.6)$$

$$= 6519 \ [V]$$

$$V_p = 30 - 6.5 = 23.5 \ [kV]$$

According to the computation, Vp = 23.4 [kV].

2-3 Sectioning and Its Operation

The range of supplying power to trains from a substation is normally to the midpoint (sectioning post) to the adjacent substation on each side, forming a relatively long section (in the case of AT feeding, 25 km～50 km on one side). Therefore, if the feeding range of a substation is long, the power feed has to be interrupted over a long section in the event of a catenary failure or for maintenance work, causing a serious influence to the train operation.

2-3-1 Outline of Sectioning

In the AC feeding system, the feeding section becomes long and has the feeding circuit constructed as shown in Fig. 2-23 generally.

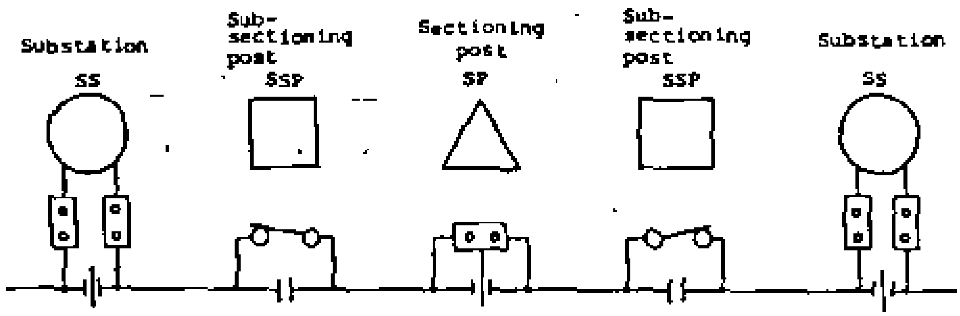


Fig. 2-23 Feeding Circuit Configuration

In general, the substation has feeding made by directions, and when the feeding voltage phase differs from direction to direction, a dead section (or, in some cases, changeover section) is provided to prevent contact.

The sectioning post located at the midpoint between substations has a dead section (or, in some cases, changeover section) provided to prevent contact between different power sources as there is a phase difference of voltage between the two substations.

Further, a sub-sectioning post is provided at the midpoint between the substation and the sectioning post for sub-sectioning the section in the event of an accident or for maintenance work. However, where the number of trains is small enough that sub-sectioning is not required, no sub-sectioning post is provided.

In the case of the AT feeding system, sub-sectioning or sectioning posts are provided at the locations of AT.

2-3-2 Sectioning Post

As shown in Fig. 2-23, the sectioning post confronts the different powers by a dead section (or, in some cases, changeover section) and sections them so that there will be no contact. However, if the powers from the left and right substations are of the same votlage phase (or of a phase difference within 5°) and frequency, it is possible to close a breaker for extension and thus decrease the voltage drop and power loss of feeding circuit. If either the left or right substations is dead while the different powers confront each other, the extension breaker is closed to extend the feeding.

Usually, a protective relay for feeding circuit is not provided in the sectioning post. However a protective relay might be installed for improvement of protective ability in the case of extended feeding, if necessary. When the equipment of the sectioning post fails, the feeding breaker of the substation is opened by the interlinked breaking device.

For short-circuiting of the dead section, a disconnecting switch for extension, which is more economical than the breaker, may be used. But, when the disconnecting switch for extension is operated, or when a fault is detected in the extended section, the feeding breaker in the substation has to be once opened to set the disconnecting switch to open under the no pressure condition. Consequently interlocking circuit becomes complex and takes much time.

2-3-3 Sub-sectioning Post

The sub-sectioning post is a switching post provided for the purpose of separating a worked section or fault section. When the equipment of the sub-sectioning post fails, the feeding breaker of substation is opened by the interlinked breaking device as in the sectioning post.

2-3-4 Tie Equipment

In the sectioning or sub-sectioning post, tie equipment (tying the up and down feeding circuit) is provided to reduce the feeding circuit impedance and pantograph arc in the crossover section.

2-4 Protection of Feeding Circuit

2-4-1 Protection from Substation

When a short-circuiting or insulation fault (grounding fault) occurs in a feeding circuit, it is required that the fault is detected immediately at the substation so that an OFF instruction is given to the feeding breaker to reduce damage to the equipment and catenary line to a minimum and, at the same time, prevent spreading of the fault to sound section.

If such protective devices fail to operate promptly, the fault point may have damage increased by the fault current, or if the short-circuiting current is of large value and long duration, stem insulators of the catenary line will be damaged, with much time reuqired for recovery.

In selecting protective devices, it is important to grasp the composition, distribution of voltage and current, etc. of the feeding system to be protected and take the most exact measures. The following may be listed as the items to be considered.

1) Normal load characteristic

2) Analysis of the phenomena of the fault

3) Characteristics of protective relays

4) Characteristics and choice of instrument transformer

5) Characteristics of breakers

6) Control source

(1) Protective Systems

Protective systems employed by JNR include the following:

(a) Distance Relay (44F)

This is a relay which detects faults from the difference in the region of the load characteristic and fault characteristic of the feeding circuit and is thus actuated, and it is used for main protection.

(b) AC ΔI Type Fault Selective Device (50F)

This is a relay which detects faults from the difference between the increment characteristic of the load current and that of the fault current and is used for back up protection.

(c) Overcurrent Relay (51F)

This is an ordinary relay actuated by an overcurrent. It is used as backup protection for detection of a high resistance fault and in a section of a relatively short feeding distance (as in yard or car shed).

When these protective relays are used, care must be exercised so that they will not be actuated falsely by even harmonics current contained in an exciting inrush current flowing in AT when pressurized in an AT feeding circuit or that flowing in the vehicle transformer when an electric car rushes into a new feeding section, or harmonics generated by commutation or thyristor control of an electric car.

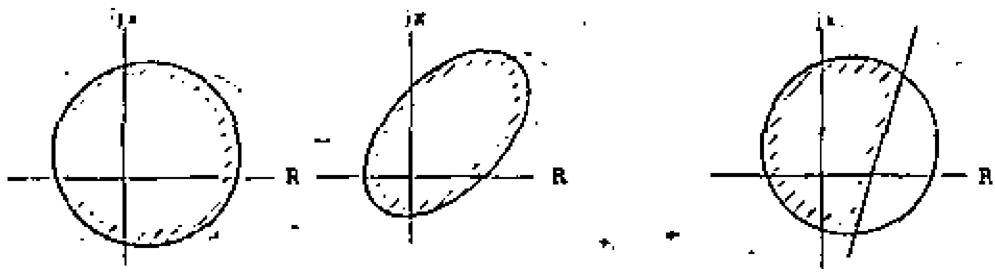
(2) Distance Relay (44F)

For protection of the AC feeding circuits from short-circuiting and grounding fault, the distance relay system is employed. This system is designed to operate the impedance at all times from the feeding voltage and current and, from the impedance, discriminate the load current and fault current from each other.

At the initial state of AC electrification, the offset mho type (electromagnetic movable type) distant relay shown in Fig. 2-24 (a) and the arc light type (rectifying type) shown in Fig. 2-24 (b) which have been used for protection of three-phase power systems were used generally.

These are useful where the electric car load is small and selection of the load current and fault current is made with ease. But, as the electric car load increases so that the fault current is hardly distinguished from the load current, these types must have a blind applied as shown in Fig. 2-24 (c).

Thereafter, from 1964, semiconductor stationary type distance relays having a parallelogram protection characteristic have come to be used (Fig. 2-25). The parallelogram protection characteristic permits protection in the same detecting sensitivity over the whole feeding section and has good discriminating characteristics between load current and fault current so that it is an ideal one.



(a) Offset mho type (b) Arc light type (c) Offset mho blind type (Formerly used in Tokaido Shinkansen)

Fig. 2-24 The Change of Protective Characteristics of the Distance Relay

Further, the fault detecting time is less than 100 ms, but it has an instantaneous operating characteristic (50 ms or less) in the large current region.

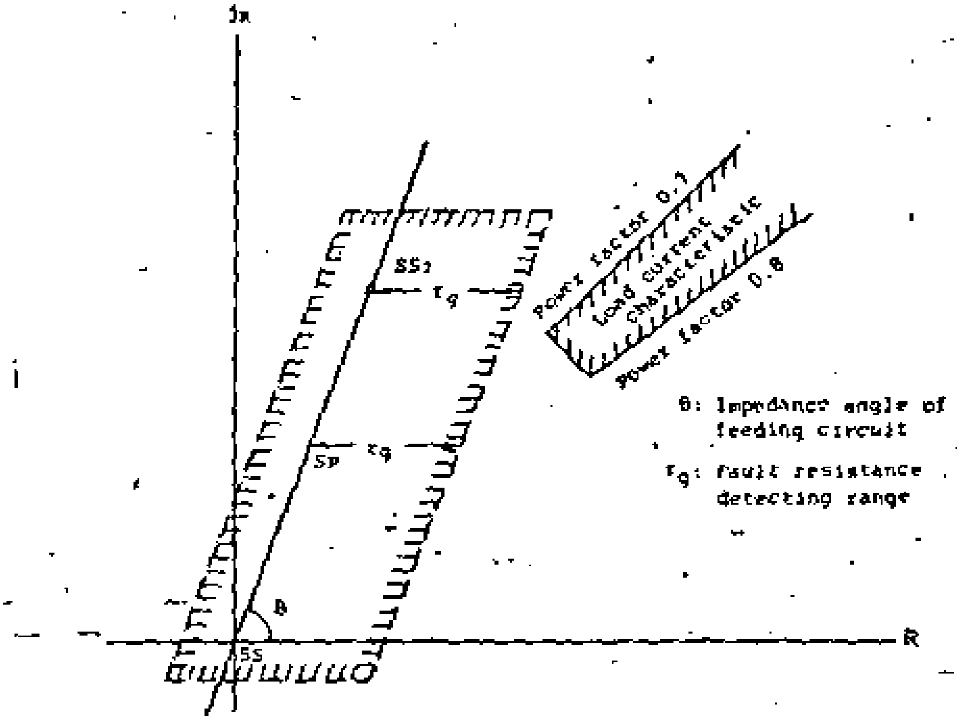


Fig. 2-25 Protective Characteristic of Parallelogram (stationary) Distance Relay

(3) AC ΔI Type Fault Selective Device (50F)

Since the protection of AC feeding circuits is very important, JNR developed an AC ΔI type fault selective device which detects a fault in the use of sharp change of the fault current as backup protection for the distance relay.

The principle of detection in this relay is as follows.

(a) From the regional difference between the variation ΔI of the load current and ΔI of the fault current, the fault current is detected selectively.

(b) For the exciting inrush current to AT and one to the electric car transformer at the time of passing the dead or changeover section, the content of the second harmonic component in the waveform is checked, and when it is 15 percent or more, operation of the relay is restrained.

(c) Deducting the third harmonic current variation ΔI_3 contained in the laod current from the fundamental wave current variation ΔI_1 in a certain rate, if ΔI_3 is contained in a large quantity, the current is determined as the load current and raise the operating current value of 50F.

Thus, the relay has no unnecessary operations caused by the electric car current variation, while it is actuated exactly by the feeding circuit fault current containing less harmonics at a low set value, and its operating speed is less than 50ms.

Fig. 2-26 is a block diagram of the harmonic restraint ΔI type 50F, and Fig. 2-27 illustrates protective ranges of the main protection (44F) and backup protection (50F).

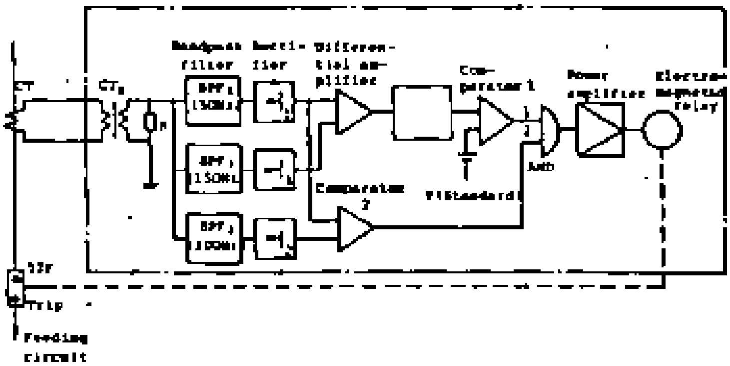


Fig. 2-26 Block Diagram of Harmonic Restraint ΔI Type 50F.

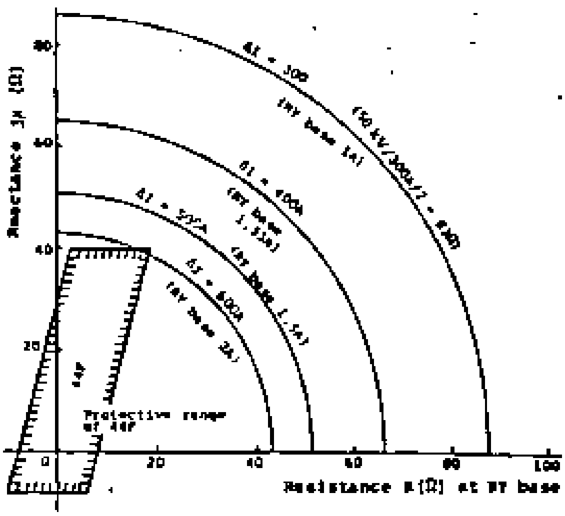


Fig. 2-27 44F Characteristics and 50F (ΔI) Protective Ranges

(4) Protection when Upbound and Downbound Feeding Circuits are Tied

Tying the up and down feeding circuits at an intermediate point or the end of the feeding circuit is effective for reduction of the voltage drop of feeding circuit by an electric car or and of the differential voltage in the section at the time of an electric car crossing over the up and down track. But, particular care must be exercised from the point of view of protection.

(a) Seen from the substation, the fault point resistance appears greater than it is really.

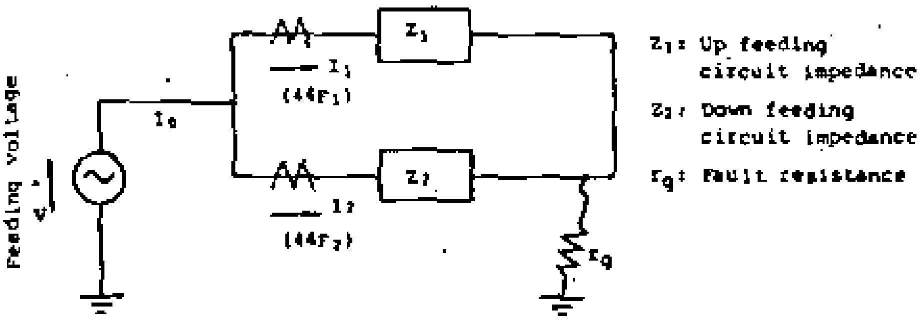


Fig. 2-28 Circuit Diagram Having Fault with Resistance (in tie feeding)

Fig. 2-28 shows the circuit grounded at the fault resistance rg in tie feeding, then the impedance seen from 44F$_1$ is given as

$$Z = Z_1 + (Z_1 + Z_2)/Z_2 \cdot rg \quad \text{.................} \quad (2.4.1)$$

so that the fault resistance rg appears to be $(Z_1 + Z_2)/Z_2$ times greater. Particularly, in the case of a fault at the tie point ($Z_1 = Z_2$), it appears to be 2 times greater than when not tied.

(b) In an extended feeding system, the feeding circuit impedance appears to be greater than it is really.

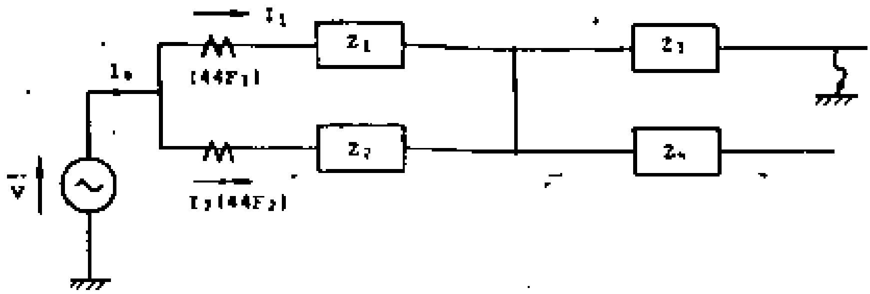


Fig. 2-29 Impedance in Extended System Appearing to be Greater

In a system having the further side of the tie opened as shown in Fig. 2-29, the impedance seen from 44F1 is given as

$$Z = Z_1 + (Z_1 + Z_2)/Z_2 \cdot Z_3 \quad \text{.................} \quad (2.4.2)$$

If the up and down feeding circuit impedances are equal ($Z_1 = Z_2$),

$$Z = Z_1 + 2Z_3 \quad \text{.............................} \quad (2.4.3)$$

so that the impedance Z_3 beyond the tie appears to be 2 times greater.

Consequently, if the relays are set without the foregoing consideration in the tie feeding, then when the fault point has a greater resistance rg or when a fault occurs at a point far beyond the tie, it is outside the protective range and cannot be detected, developing in serious trouble. Utmost care should, therefore, be exercised.

2-4-2 Easily Protected Circuit Formation

(1) Circuit Formation and Fault Current Route

The feeding circuit extends over a long seciton, and its faults take various forms in various degrees from purely metallic short-circuiting where the contact wire is broken and comes into contact with the rail to short-circuiting to grounding fault a large grounding resistance when the feeding wire comes into contact with trees.

Insulation faults are largely flashover to contact wire supports, substation equipment, steel structures, frames, etc. and generally have the grounding resistance at the fault point enter the circuit in series, as shown in Fig. 2-30, so that it is difficult to detect them.

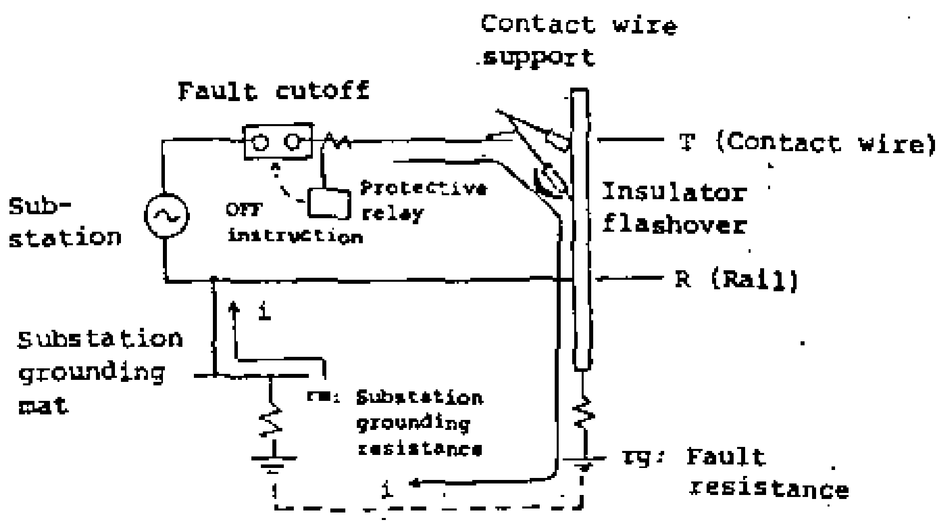
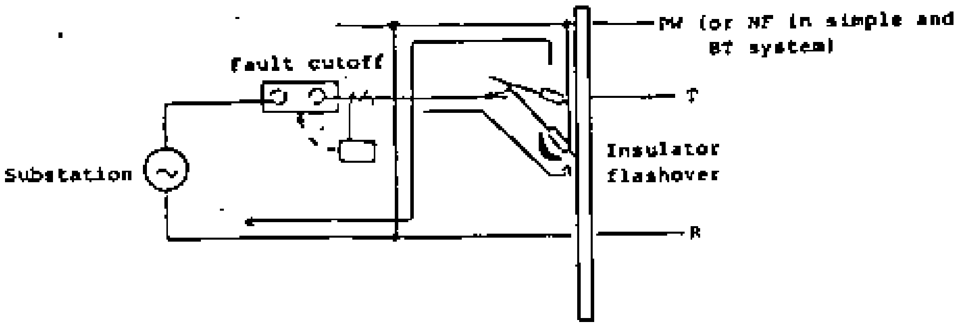


Fig. 2-30 Insulation Fault

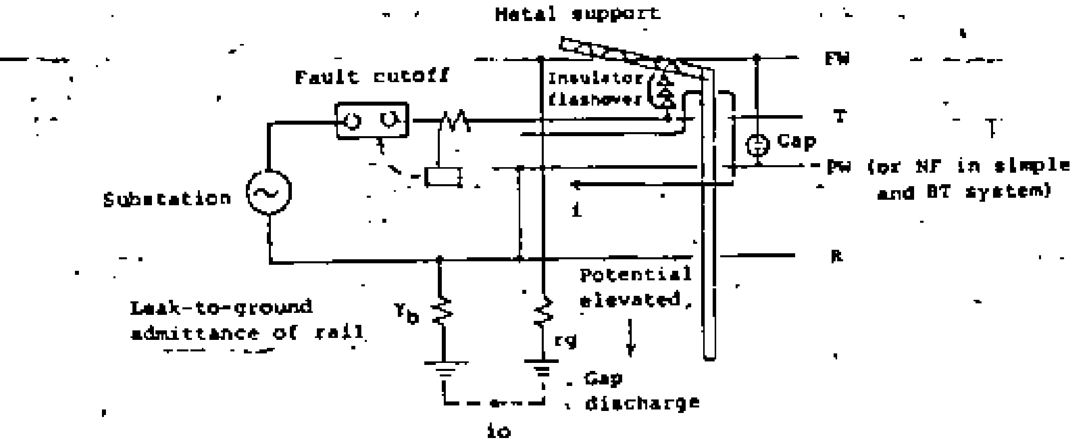
Thus, methods permitting protective detection with ease and exactness by forming the feeding circuit so that as many faults as is practical are reduced to metallic short-circuiting faults are employed.

(a) By Protective Wire (Fig. 2-31 (a))

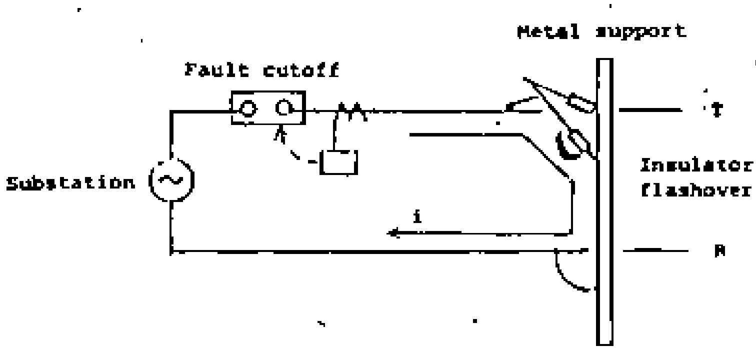
This method is to metal short-circuit the flashover fault to a protective wire by a pole arrangement as shown in Fig. 2-32 and is applied to ordinary sections.



(a) Method by protective wire (PW)

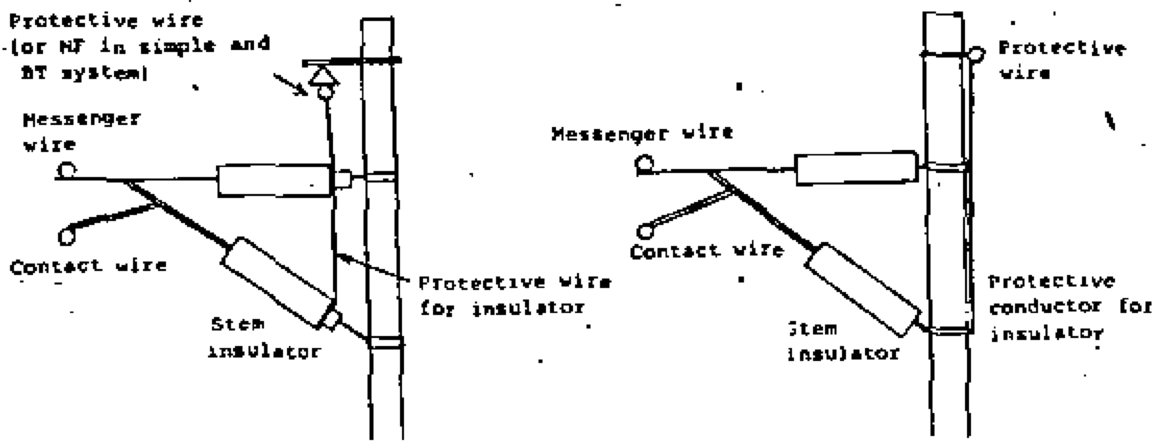


(b) Method by overhead earth wire for flashover (FW)



(c) Method of short-circuiting rail and metal support

Fig. 2-31 Examples of Easily Protected Circuit Formation



(a) Protective circuit by protective wire for insulator

(b) Protective circuit by protective conductor for insulator

Fig. 2-32 Examples of Pole Assembling around Protective Wire

(b) By Overhead Earth Wire (Fig. 2-31 (b))

This method is to use the overhead earth wire for prevention of lightning damage, and the grounding wire is connected to the protective wire with a protective gap. The method is used when the support is metallic (steel structure) and is applied mainly to large yards, etc.

(c) Connecting Support to Rail (Fig. 2-31 (c))

When the support is metallic (steel structure), this method is particularly useful, but JNR does not use it because of hazards to the signal track circuit and increase in the telecommunication induction.

(2) Insulation Fault Protective Discharger

In the case of JNR, the substation grounding mat and rail are not connected directly to each other because of hazards to the signal track circuit and the increase of the telecommunication induction. In such a case, the insulation fault in the feeding circuit or in the substation yard creates a high resistance current return circuit through the leak-to-ground admittance of rail so that reliable protection is not made possible.

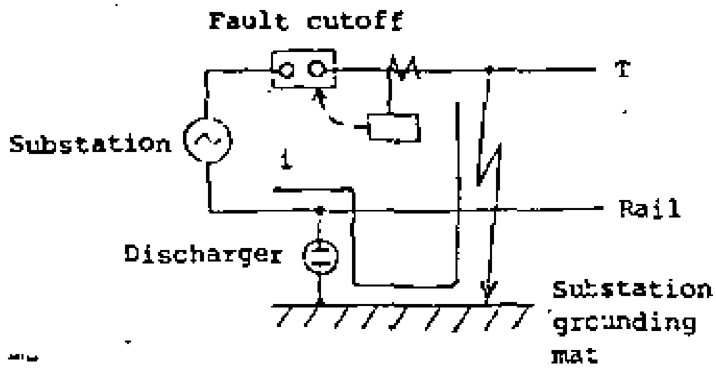


Fig. 2-33 Insulation Faults in Substation Yards

Thus, an insulation fault protective discharger is provided between the rail and the substation grounding mat, as shown in Fig. 2-33, which is adapted to discharge only when an abnormal voltage is produced between the rail and the substation grounding mat by the occurrence of an insulation fault so that the fault is detected with easy.

2-4-3 Fault Locator

The short-circuiting impedance seen from the substation of the BT feeding circuit is nearly linear to the distance. Thus, a system of ranging the distance by operating the impedance to the fault point was employed. But in this impedance detection system a ranging error was involved if resistance was present at the fault point. Then, a locator of the reactance detection system was developed which was only slightly affected by the resistance, and JNR is using this locator.

This system is also applicable to the simple feeding system, with little ranging error.

On the other hand, the short-circuiting impedance seen from the substation of the AT feeding circuit is not linear to the distance from the substation to the fault point except the contact wire (T) - feeder (F) short-circuiting but takes the form of projecting upward with the AT point as a node, as shown in Fig. 2-3. Consequently, the locator of the reactance detection system is very great in principle error and is not applicable practically.

In view of the foregoing, JNR developed for, and applied to, the AT feeding circuit a locator of AT neutral current ratio type.

(1) Reactance Detection Type Locator

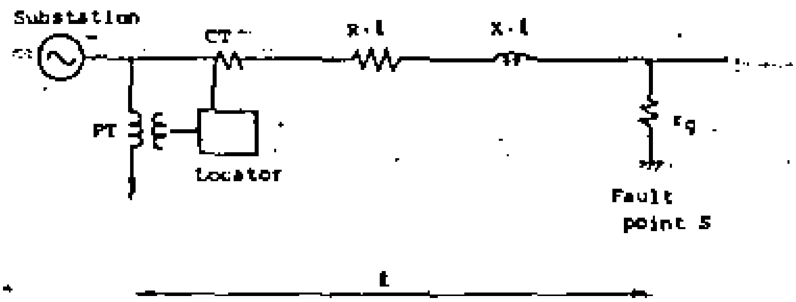


Fig. 2-34 Circuit Configuration

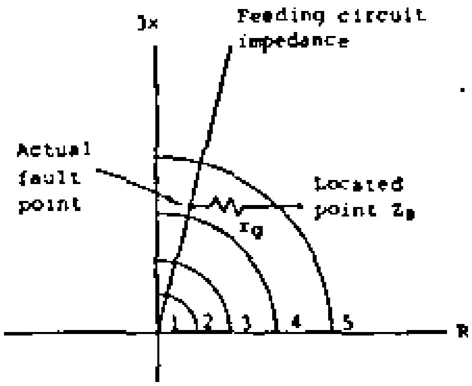


Fig. 2-35 Impedance Detection Type Locator

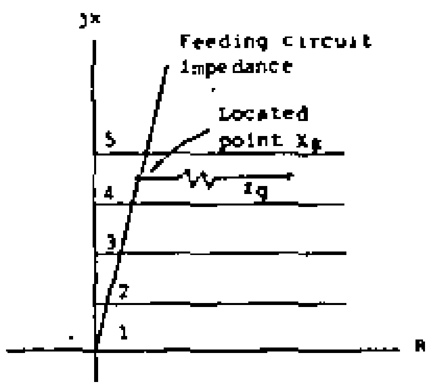


Fig. 2-36 Reactance Detection Type Locator

In the circuit of Fig. 2-34, the short-circuiting impedance seen from the substation is

$$Z_S = (R + jX) \cdot \ell + rg \quad \text{.......................... (2.4.4)}$$

Then, by comparing it with the known line impedance (R+jX), the distance ℓ from the substation to the fault point can be obtained.

However, according to the impedance detection system, if resistance is present at the fault point, there is the possibility that principle error will give rise to a fault in region 4 as in region 5, as seen from the R-X diagram of Fig. 2-35.

Then, as the system least affected by the resistance at the fault point, the reactance detection system locates the fault point through operation of the reactance. That is,

$$X_S = X \cdot \ell \quad \text{.................................. (2.4.5)}$$

Thus, through comparison with the known reactance (X), it is possible to obtain the distance ℓ to the fault point.

This may well be illustrated in the R-X diagram of Fig. 2-36, and it will be seen that the detection is free from the effect of the fault resistance rg.

(2) AT Neutral Current Ratio Type Locator

(a) Principle of AT Neutral Current Ratio Type Locator

In the AT feeding circuit, AT at each point serves as a source of power, and the size of the current at the neutral point of AT (called "booster current") represents the volume of power supply of said AT. If an insulation fault occurs in the vicinity of a certain AT point, the booster current of such an AT constitutes the greater part of the total fault current, and in the case of an insulation fault occurring at an intermediate point between AT's, these AT's across the fault point boost the total fault current proportionally.

presenting a form of the so-called parallel feeding between adjacent substations.

Accordingly, by measuring the values of booster current of AT's at the time of a feeding circuit fault simultaneously and through a simple calculation, it is possible to locate the fault point exactly. However, according to this system, it is not possible to locate short-circuiting faults of T and F which are fault phenomena of no power supply from AT. But, the feeding circuit faults are caused, for the most part, by the insulation fault (short-circuiting to PW) of T or F, and a T-F short-circuiting fault is very rare. Thus, in practical terms, this system is substantially free from trouble.

(b) AT Booster Current Ratio Characteristic

Fig. 2-37 shows the feeding distance and AT disposition taken along the horizontal axis and the AT booster current ratio along the vertical axis, and it will be seen that the AT booster current ratio and the distance from the AT to the fault point is in a nearly linear relationship, and in the JNR Shinkansen, this relationship is expressed substantially by the formula

$$X = L_n + \frac{H - 0.08}{0.84} D \ [\text{km}]$$

where X : Kilometerage of fault point starting from Tokyo;

L_n: Kilometerage of n-th AT starting from Tokyo,

H : AT booster current ratio $I_{n+1}/(I_n+I_{n+1})$;

D : Distance between AT_n and AT_{n+1} [km]; and

x : Distance from AT_n to fault point [km], or

$$x = \frac{H - 0.08}{0.84} D \quad [\text{km}]$$

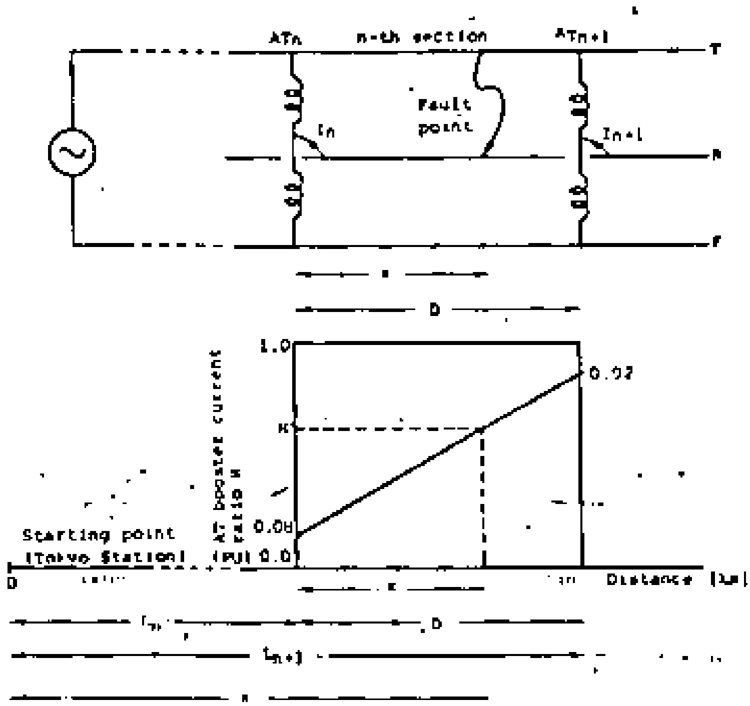


Fig. 2-37 Principle of AT Neutral Current Ratio Type Locator

In the Shinkansen, if a short-circuiting or insulation fault occurs in a feeding circuit, all of the AT booster currents in the circuit are measured and maintained automatically and are transmitted to the CSC (Central Substation Control) successively. At the CSC, a minicomputer computes the kilometerage of the fault point starting from Tokyo by the foregoing formula and indicates it.

(c) Points to be Noted for Operation of Fault Point Locator

From the experience gained in the Sanyo Shinkansen, the following may be listed as points to be noted in the operation of an AT booster current ratio locator.

1) When the 44F operates properly, but the AT booster current is small (500A or less), it is determined to be a T-F short-circuiting fault of the circuit, and calculate the fault point from the size of the fault current recorded automatically on the memory recorder in the substation.

2) Never compare the sizes of booster currents of the up and down AT's with each other and determine that the fault is in the circuit of greater current. In the case of a one wire insulation fault near the substation, it does not always follow that the booster current on the fault circuit side is greater. Determination of the fault circuit should properly be made by the operation of 44 of said section.

2-5 Coordination of Insulation

2-5-1 Principle for Coordination of Insulation

Coordination of insulation of the railway AC feeding circuit is composed of the three systems of substation, catenary line and electric car, and the insulators and insulating parts of the equipment in the respective systems must withstand the service voltage as well as abnormal voltage due to pantograph dewiring and breaker switching surge. Further, for the lightning abnormal voltage occurring in the feeding circuit, a lightning arrester and other protective devices should be used to reduce the voltage impulse abnormal so that the insulation strength of the equipment may be set as low as practicable thus making the insulation design of the system as a whole economical and reasonable.

2-5-2 Abnormal Voltage and Insulation Design

Values for abnormal voltage occurring in the AC feeding circuit are shown in Table 2-38. The crest value of the breaker switching surges occurring frequently is relatively low at about 60～70 kV generally. Therefore, the insulation design should be made with the lightning surge considered mainly.

The lightning surge riding on the feeding circuit as a progressive wave may be taken to be of the order of the flashover voltage of the feeding circuit insulator, with the crest value limited to about 300 kV. When such a progressive wave falls on an electric car, substation or sectioning post having an arrester provided, the wave front of the surge is, through arrester discharge, the impulse sparkover voltage of the arrester. It is reduced to 110 kV or less in the case of the electric car or 120 kV or less in the case of the substation, etc. so that elevation of the voltage on the equipment terminal is checked completely.

Then, if the allowance for coordination of insulation is assumed to be about 20 percent, the abnormal voltage is calculated as 110 kV × 1.2 = 132 kV for electric cars or 120 kV × 1.2 = 144 kV for substations, etc. Thus, the equipment has a sufficient allowance for basic impulse insulation level of 130 kV (for vehicle) or 150 kV (for substation, etc.).

Observe Figs. 2-38 and 2-39.

Table 2-9 Approximate Values of Abnormal Voltage Occurring in the Feeding Circuit

Items		Maximum service voltage	Abnormal voltage multiple	Abnormal voltage value
Abnormal voltage by switching surge		kV	Times 2.0 ∿ 2.5	kV 60 ∿ 70
Abnormal voltage by pantograph dewiring, etc.			1.5 ∿ 2.0	40 ∿ 60
Lightning surge voltage	Indirect lightning stroke	27.5	3.6 ∿ 5.5	100 ∿ 150
	Direct lightning stroke		11 ∿ 18	300 ∿ 500
Progressive wave voltage on catenary line			Insulator flashover voltage	250 ∿ 300

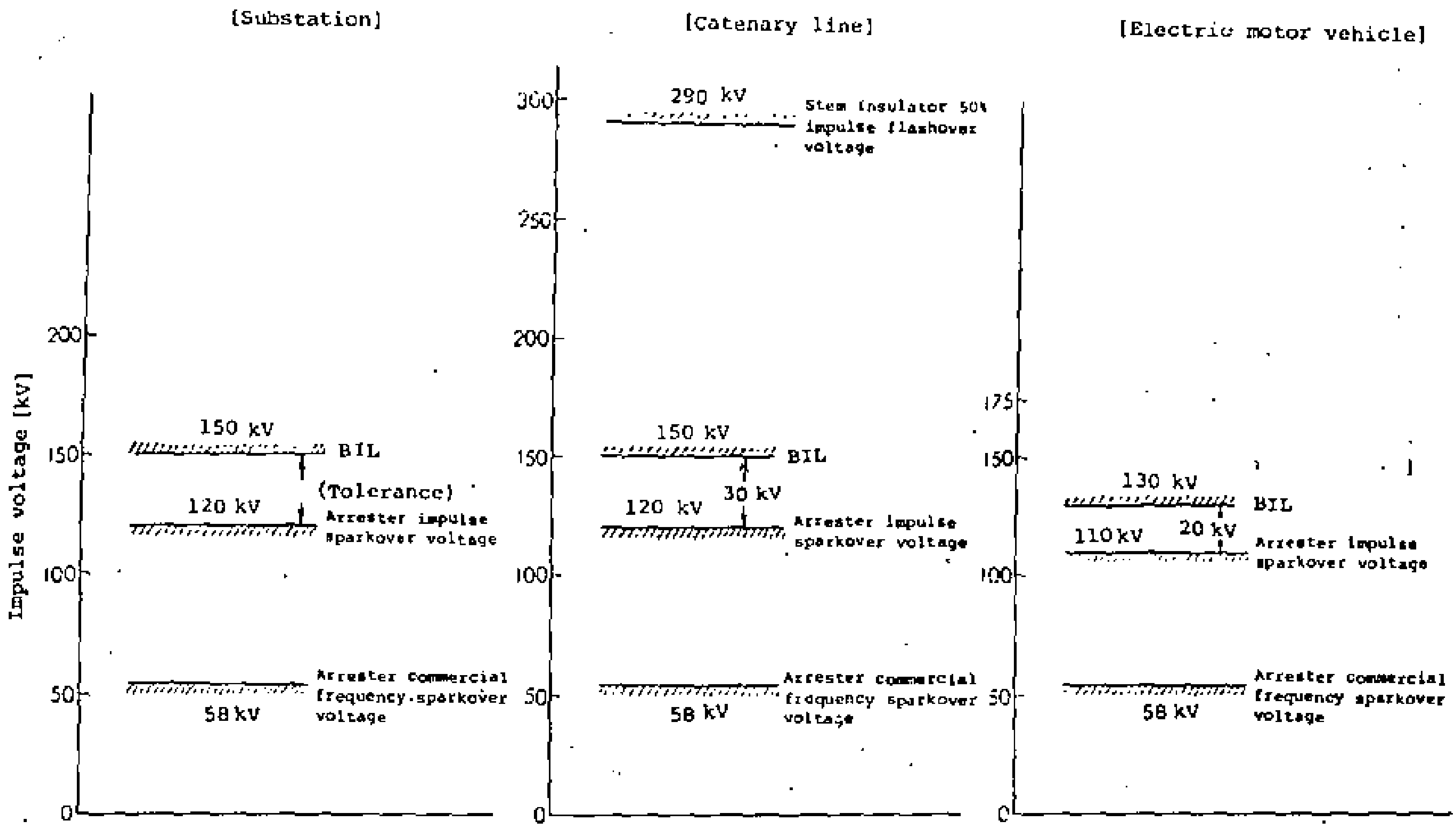


Fig. 2-38 Dielectric Strength of AC Feeding Circuit (25 kV)

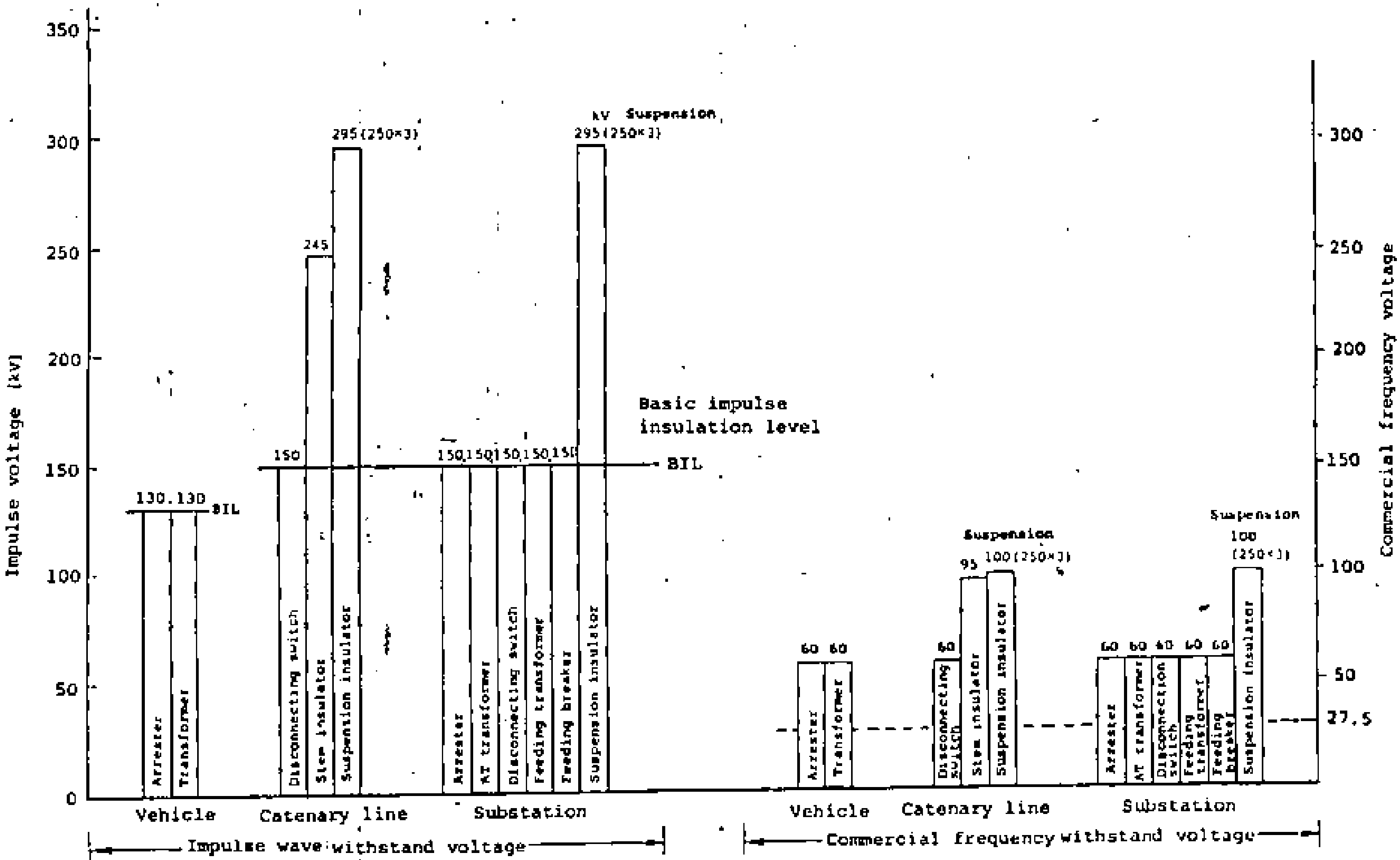


Fig. 2-39 Example of AC 25 kV AT Feeding System Insulation Design (feeding system)

2-5-3 Application of Protective Devices

Abnormal voltages are classified largely into two types: those due to the commercial frequency such as insulation faults in the substation and feeding circuit and those due to impulse waves such as lightning surge, and the following protective devices are applied.

(1) Commercial Frequency

Insulation faults in the substation and feeding circuit involve greater grounding current generally, resulting in greater elevation of the ground potential. Thus, for coordination of insulation for the equipment and weak electric circuits, dischargers (magnetic blowout type or carbon type) and horn gaps shown in Fig. 2-40 are used generally. Further, in the case of the AT feeding system, JNR designates the insulation class of the feeding bus twice that of the feeding circuit. Here, as a method of reducing it to the insulation class of the feeding circuit, a device of Fig. 2-41 is considered.

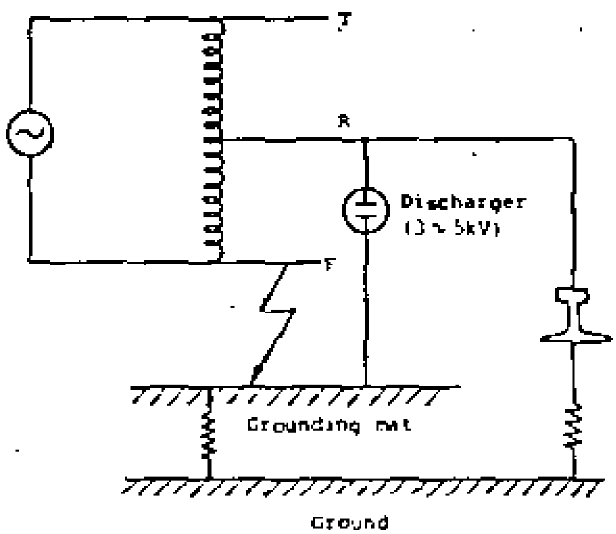


Fig. 2-40 Example of Protective System Using Discharger

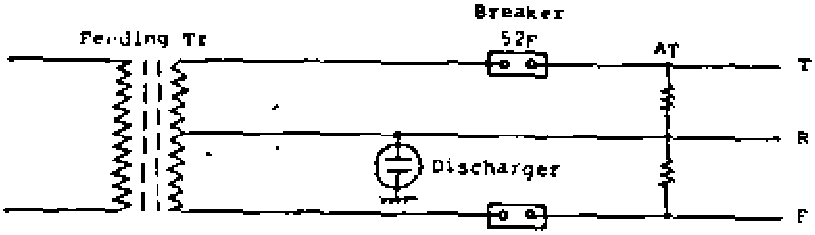


Fig. 2-41 Method of Connecting Feeding Tr Neutral Point to AT Neutral Point

(2) Impulse Wave

Abnormal voltage due to lightning is very great, and insulation withstanding such voltage is economically impossible. Lightning arresters are installed on electric cars, substations and sectioning posts as shown in Fig. 2-42. In areas of higher occurrence of lightning-storms, overhead groundinging wires are used for coordination of protection.

2-5-4 Choice of Grounding Resistance

(1) Feeding Substation

The grounding resistance of the substation must be so chosen that the equipment in the substation and information controlling weak electricity circuits coming in and out of the substation are not subjected to dielectric breakdown by the elevating potential of the grounding mat in the compound at the time of an insulation fault in the receiving or feeding system in the substation or discharge of the arrester, and for the potential, the commercial frequency and impulse waves are the objects of consideration of elevating the potential of the grounding mat.

(a) Elevation of Grounding Potential by Commercial Frequency

1) Feeding system insulation faults

At the time of an insulation fault of the feeding main circuit in the substation, a metal circuit is formed

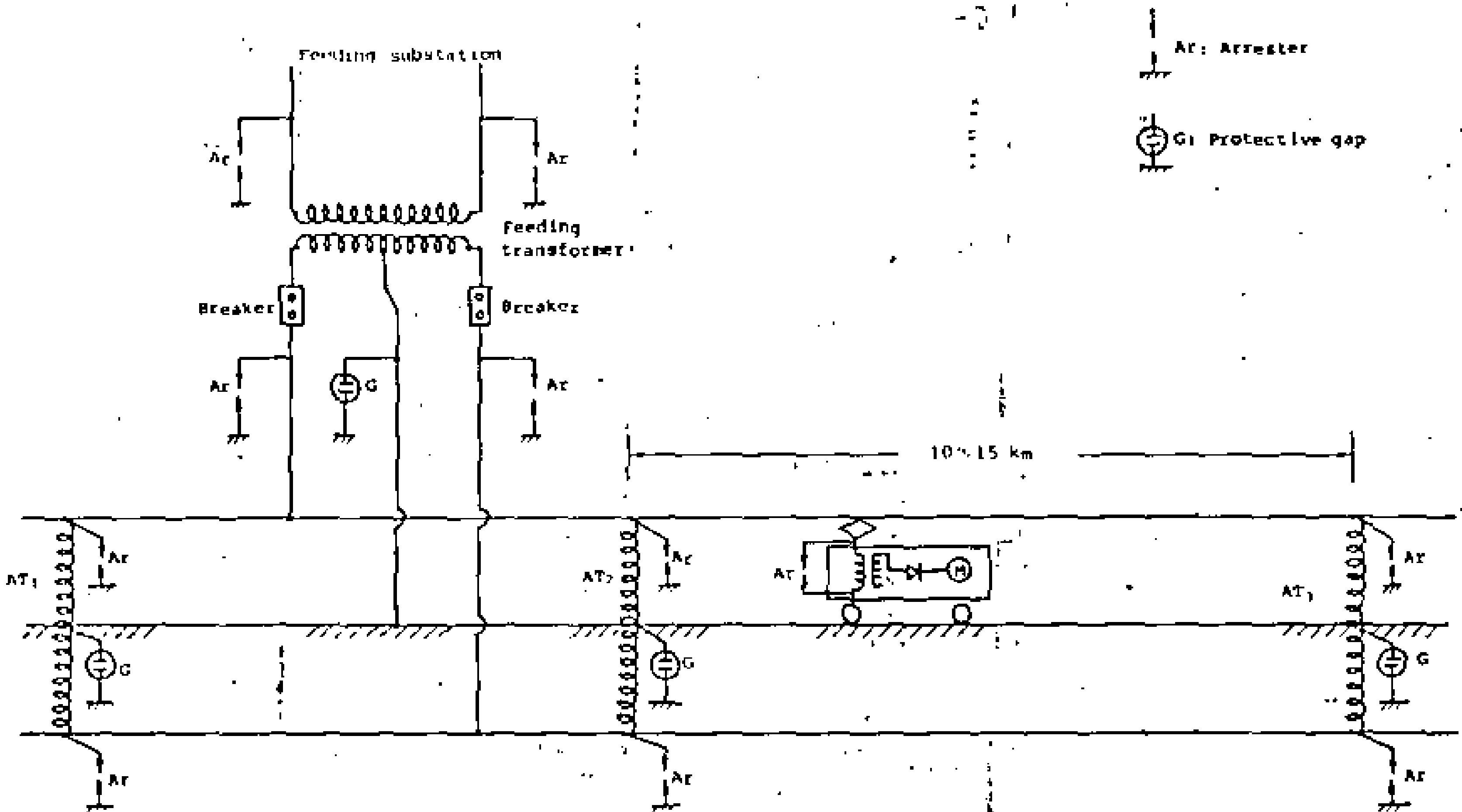


Fig. 2-42 Schematic Diagram of AT Feeding System Lightning Arrester Equipment

by a discharger (gap) provided between the substation grounding mat and the main transformer neutral point (rail or protective wire) to short-circuit the grounding resistance and suppress elevation of the grounding potential. The gap is set to a value (3∿5 kV) according to the insulation level of the equipment in the substation to insure coordination of the protection so that the grounding resistance does not rise over the gap value. Then, if the feeding failure only is taken into account, the grounding resistance value should not necessarily be decreased too much but be about 5Ω.

2) Receiving system insulation fault

Elevation of the grounding potential by a receiving system insulation fault in substation varies greatly with the method of treatment of the electric neutral point of the three phase transmission line, and in the case of a normally considered one wire insulation fault:

a) In a high resistance grounded neutral system, the short-circuiting current to ground is limited to about 200∿1000A by the resistance of the neutral point so that it will not be necessary to reduce the grounding resistance value too much; and

b) In a solidly grounded neutral system used jointly for substation grounding mat, the short-circuiting current flow into the grounding mat is as large as 10 kA, and in such a case, reduction of the grounding potential with the protective gap in the feeding system is not expectable, so that it is required to decrease the grounding resistance to a value at which coordination with the protective devices for the substation equipment and weak electricity circuits coming in and out of the substation is insured, and such a value is about 1Ω or less.

(b) Elevation of Grounding Potential by Impulse Wave

For elevation of the grounding potential in the case of discharge of the substation arrester by lightning, the protective effect of the feeding system protective gap is not expectable as in the case of the solidly grounded neutral system, so that the protective coordination with the weak electricity circuits coming in and out of the substation must have a grounding resistance value chosen in consideration of the lightning frequency, and the target value is 1Ω maximum.

As stated above, the resistance value of the substation grounding mat is governed mainly by the receiving grounded neutral system and impulse current, and in the solidly grounded system, the potential elevation by the commercial frequency at the time of a one wire short-circuiting is greater than that by lightning current, and in the high resistance grounding system, the grounding potential elevation is greater in the case of one wire short-circuiting than it is in the case of lightning current.

Accordingly, it is necessary to determine the grounding resistance value in consideration of the protective coordination with the substation equipment and weak electricity circuits coming in and out of the substation for both commercial frequency and impulse wave, and the target values are shown in Table 2-10.

(2) Sectioning Post, etc.

Sectioning and sub-sectioning posts cannot have an extra-high voltage three phase receiving system led in. Thus, at the time of a main circuit insulation fault, the protective coordination is maintained by a discharger (gap) as in the case of the substation feeding system protection. However, when the arrester discharges by lightning, the grounding potential rises with the lightning current so that the value of grounding resistance should be chosen in consideration of the protective coordination with the weak electricity circuits coming in and out of the substation, and the target values are shown in Table 2-11.

Table 2-10 Target Values of Substaion Grounding Resistance

Items	Receiving neutral grounded system	
	High resistance grounding	Solid grounding
Grounding mat resistance value	5Ω or less	1Ω or less
Short-circuiting current flows into grounding mat	About 1,000A (5,000V)	About 10,000A (10,000V)
Lightning current (Indirect lightning stroke)	2,000A or less (10,000V)	2,000A or less (2,000V)
Grounding potential at feeding circuit insulation fault (Gap)	$5k \times \sqrt{2} = 7,000V$	$5k \times \sqrt{2} = 7,000V$

Table 2-11 Target Values of Grounding Resistance for Sectioning Posts, etc.

Items	Target values
Grounding mat resistance value	5Ω or less
Lightning current (Indirect lightning stroke)	2,000A or less (10,000V)
Grounding potential at feeding circuit insulation fault (Gap)	$5k \times \sqrt{2} = 7,000V$

2-5-5 Coordination of Insulation with Weak Electricity Circuits

Should an insulation fault or arrester discharge occur in a substation or sectioning or sub-sectioning post, the grounding potential of the station rises, and the weak electricity cable lines coming in and out of the station receive the potential directly.

Thus, in the substation, etc., protective measures are taken against elevation of the grounding potential, and as such a measure, a protector system (with changeover fuse) and insulating transformer system by means of a control power (DC or AC used) are used mainly.

(1) Protector (with changeover fuse) System (DC used)

This system is applied when DC is used for control power, and its configuration is shown in Fig. 2-43.

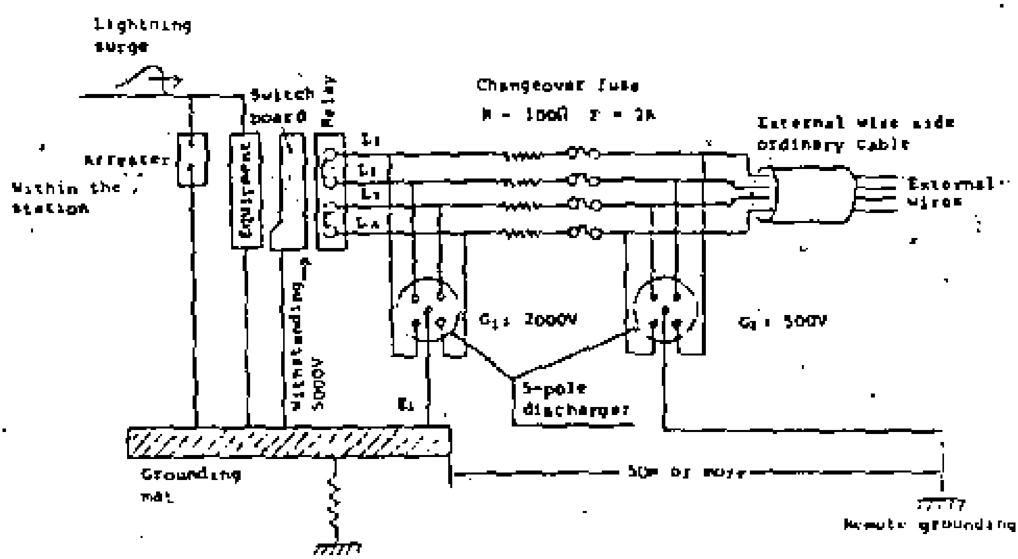


Fig. 2-43 Protector (with changeover fuse) System

When the grounding potential rises, the discharger (G_1) on the station side and discharger (G_2) on the external wire side are discharged to prevent a backward flashover accident of the weak electricity equipment such as the remote controller in the station. As G_1 discharges, the accident current flow in the external cable is limited by a current limiting resistor (R), while the circuit is cut off by a fuse (F), thus the cable line is protected. The discharger (G_2) is designed to check the dangerous voltage coming from the telecommunication cable to prevent danger to the human body.

This system has a circuit cut off for a short duration as the fuse is broken and resumes the circuit with automatic changeover of the fuse upon removal of the failure. In this respect it is a shortcoming, as control is suspended for about 10 seconds.

However, it is an economical system, and control interruption actually causes no hazard.

With respect to the set voltages of the dischargers, G1 is set at 2,000V or less for protective coordination with the equipment in the station, and G2 at 500V or less from the danger voltage applied to the telecommunication line. The remote grounding of G2 is to be installed at a location free from the influence of the insulation fault in the station as well as the rail potential elevation, and it is installed 50 m or more apart from the station grounding mat at right angles to the rail.

(2) Insulating Transformer System (AC used)

When AC is used for control power, an insulating transformer system shown in Fig. 2-44 is used.

The grounding resistance is so chosen that the value of elevation of the grounding potential at the time of an insulation fault in the substation, etc.

The weak electricity cable lines led out of the substation to the external wire side receive this potential elevation and they should be kept away from its influence. High voltage withstanding cables should be used to a point about 50 m or

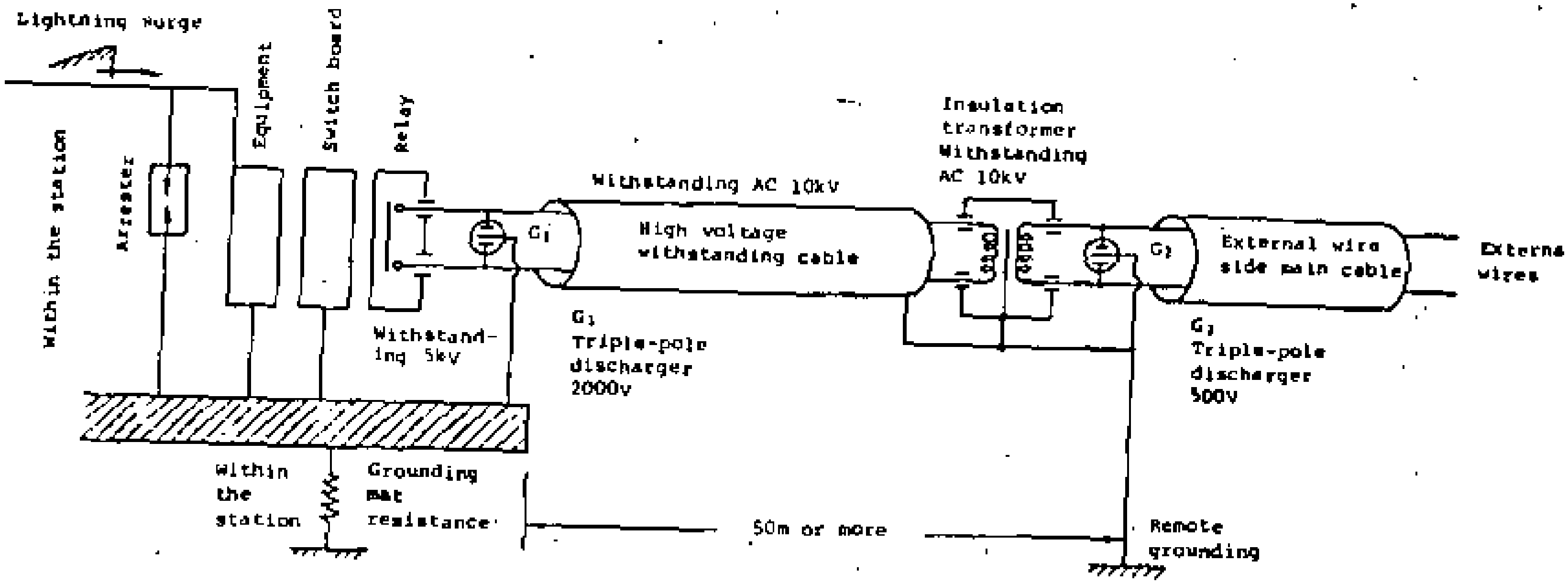


Fig. 2-44 Insulating Transformer System

more apart from the substation yard. Further, an insulating transformer is installed to insulate the shift of the abnormal voltage and safeguard it so that the grounding potential in the substation will not extend to the main cable side of the external wire.

This system has the control power coupled electromagnetically by the insulating transformer and thus has offers the advantage that the control is not interrupted at the time of an accident and is, therefore, highly reliable.

With respect to the dischargers, G_1 is used for decreasing the potential burden on the substation equipment and G_2 for reducing the dangerous voltage coming from the external wire.

For the insulation level of the insulating transformer and high voltage withstanding cable, AC10 kV is used.

2-5-6 Insulation Coordination Reference Table

An insulation coordination reference table of the AC feeding circuit is shown in Table 2-12.

Table 2-12 Insulation Coordination Reference Table

Items			Substation	Catenary line	Vehicle
Circuit voltage	Standard voltage Maximum voltage		25 kV 27.5 kV	25 27.5	25 27.5
Basic impulse insulation level	Impulse wave		150 kV	150	130
Arrester	Rated voltage		35 kV	35	35
	100% impulse sparkover voltage	Commercial frequency	58 kV	58	58
		Impulse wave	120 kV	120	110
	Residual voltage (at 10 kA discharge)		130 kV	130	110
	Place of installation		Feeding lead point, etc.	AT installation point of SS, SSP	Secondary side of pantograph
	Insulators		Commercial frequency wet withstanding voltage	Lightning impulse Withstanding voltage	50% flashover voltage
Insulators	Hinged cantilever stem insulator (general)		95 kV	245	290
	AT feeding wire suspension insulator 250 × 3		100 kV	295	355

2-6 Power Source

The load of an electric railway is characterized in that a rapidly fluctuating load is formed in a short time, with a great value. When the required power of the feeding substation for operation supplying this is received from the ordinary power system, the source voltage more or less fluctuates. Particularly, when the electric railway is of AC electrification, the load current as seen from the power source is single phase in most instances, resulting in greater fluctuation in the source voltage.

On the other hand, the customers in the conventional power system are demanding further improvements in the quality of voltage and frequency of electricity with the development of the automatic control of industrial equipment and spread of domestic electric products.

Therefore, in formulating a receiving plan for a feeding substation for operation, it will be necessary to examine beforehand what the extent of fluctuation of the source voltage is and thus form a supply system so that no adverse effects are caued to consumers in general. As fundamental measures for problems which are likely to occur, the following may be considered.

(1) The system should be so composed that the loads of a number of trains are integrated for smoothing the fluctuating current and balancing the three-phase current, while the power is received, as far as is practical, from a source of greater power short-circuiting capacity.

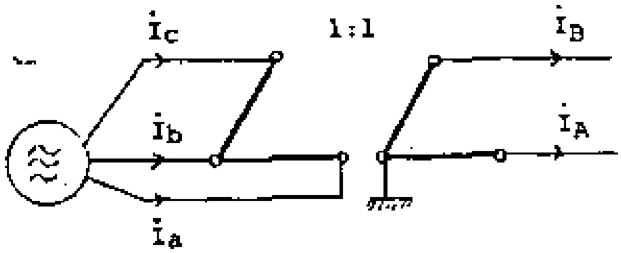
(2) The supply system should be isolated completely to form an exclusive transmission system.

(3) Balancing and compensating devices should be installed.

Here, calculation formulas will be sought in order to see how the source voltage is affected by the electric railway load. From the experience of JNR, complaints, etc. do not occur when the voltage fluctuation ΔV is suppressed below 4 percent.

2-6-1 Formula for Approximate Calculation of Voltage Drop in Single Phase and V-connection Feeding

When the feeding transformer connection and current distribution are as shown in Fig. 2-45.



$\dot{I}_a = I_A \epsilon^{-j\theta}$ $\quad$ $\dot{I}_b = -(I_A + I_B \epsilon^{j\frac{\pi}{3}}) \epsilon^{-j\theta}$

$\dot{I}_c = I_B \epsilon^{j\frac{\pi}{3}}$ $\quad$ θ = Angle of load power factor

Fig. 2-45 V-connection Transformer

The positive phase component I_1 and negative phase component I_2 of the primary current are obtainable as

$$\left.\begin{aligned} \dot{I}_1 &= \frac{1}{3}(\dot{I}a + a\dot{I}b + a^2\dot{I}c) = \frac{1}{\sqrt{3}}(I_A + I_B)\epsilon^{-j(\theta+\frac{\pi}{6})} \\ \dot{I}_2 &= \frac{1}{3}(\dot{I}a + a^2\dot{I}b + a\dot{I}c) = \frac{1}{\sqrt{3}}\{I_A\epsilon^{-j(\theta-\frac{\pi}{6})} - I_B\epsilon^{-j(\theta+\frac{\pi}{6})}\} \\ &\text{Provided, } a = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \end{aligned}\right\} \cdots (2.6.1)$$

Further, if these current flow to the source impedance, the voltage drop in the respective phases is given by formulas (2.6.2) where Z_1 is the positive phase component, and Z_2 is the negative phase component, of the source impedance.

$$\left.\begin{aligned} \dot{U}a &= \dot{I}_1\dot{Z}_1 + \dot{I}_2\dot{Z} \\ \dot{U}b &= a^2\dot{I}_1\dot{Z}_1 + a\dot{I}_2\dot{Z}_2 \\ \dot{U}c &= a\dot{I}_1\dot{Z}_1 + a^2\dot{I}_2\dot{Z}_2 \end{aligned}\right\} \cdots\cdots\cdots\cdots (2.6.2)$$

Now, obtaining the voltage of the respective phases after passage of the load current,

$$\left.\begin{aligned} \dot{V}'_{ab} &= \dot{V}_{ab} - (\dot{U}_a - \dot{U}_b) \\ \dot{V}'_{bc} &= \dot{V}_{bc} - (\dot{U}_b - \dot{U}_c) \\ \dot{V}'_{ca} &= \dot{V}_{ca} - (\dot{U}_c - \dot{U}_a) \end{aligned}\right\} \quad \cdots\cdots\cdots (2.6.3)$$

Further, taking the ratio of this voltage to that before the current flow,

$$\left.\begin{aligned} \frac{\dot{V}'_{ab}}{\dot{V}_{ab}} &= 1 - \frac{(\dot{U}_a - \dot{U}_b)}{\dot{V}_{ab}} \\ \frac{\dot{V}'_{bc}}{\dot{V}_{bc}} &= 1 - \frac{(\dot{U}_b - \dot{U}_c)}{\dot{V}_{bc}} \\ \frac{\dot{V}'_{ca}}{\dot{V}_{ca}} &= 1 - \frac{(\dot{U}_c - \dot{U}_a)}{\dot{V}_{ca}} \end{aligned}\right\} \quad \cdots\cdots\cdots (2.6.4)$$

If the rate of voltage drop is defined as expressed by formula (2.6.5) in order to see the extent of fluctuation by current flow of the voltage before the current flow

$$\frac{\Delta V}{V} = \frac{V - V'}{V} \times 100 = (1 - \frac{V'}{V}) \times 100 \ [\%] \quad \cdots\cdots\cdots (2.6.5)$$

then, from formulas (2.6.4) and (2.6.5),

$$\left.\begin{aligned} \frac{\Delta \dot{V}_{ab}}{\dot{V}_{ab}} &= \frac{(\dot{U}_a - \dot{U}_b)}{\dot{V}_{ab}} \times 100 \ [\%] \\ \frac{\Delta \dot{V}_{bc}}{\dot{V}_{bc}} &= \frac{(\dot{U}_b - \dot{U}_c)}{\dot{V}_{bc}} \times 100 \ [\%] \\ \frac{\Delta \dot{V}_{ca}}{\dot{V}_{ca}} &= \frac{(\dot{U}_c - \dot{U}_a)}{\dot{V}_{ca}} \times 100 \ [\%] \end{aligned}\right\} \quad \cdots\cdots\cdots (2.6.6)$$

are obtained.

Here, considering the source impedance as expressed by the formula (2.6.7),

$$\left.\begin{aligned}&\dot{Z}_1 = \dot{Z}_2 = Z\varepsilon^{-j\psi}\\&\text{where}\quad \psi = \tan^{-1}\frac{x}{r}\\&\qquad x:\ \text{Source side reactance; and}\\&\qquad r:\ \text{Source side resistance.}\end{aligned}\right\}\quad\cdots\cdots\quad (2.6.7)$$

By substituting formulas (2.6.2) and (2.6.7) for formulas (2.6.6) and arranging, formulas (2.6.8) are obtainable.

$$\begin{aligned}
\frac{\Delta\dot{V}'_{ab}}{\dot{V}_{ab}} &= \frac{100}{V}[I_A Z\{\varepsilon^{-j(\theta-\psi)}+\varepsilon^{-j(\theta-\psi)}\}+I_B Z\{\varepsilon^{-j(\theta-\psi)}-\varepsilon^{-j(\theta+\frac{\pi}{3}-\psi)}\}]\\
&\fallingdotseq \frac{100}{V}[2I_A Z\cos(\theta-\psi)+I_B Z\sin(\theta+\frac{\pi}{6}-\psi)]\\
\frac{\Delta\dot{V}'_{bc}}{\dot{V}_{bc}} &= \frac{100}{V}[I_A Z\{\varepsilon^{-j(\theta-\psi)}+\varepsilon^{-j(\theta-\frac{4\pi}{3}-\psi)}\}+I_B Z\{\varepsilon^{-j(\theta-\psi)}-\varepsilon^{-j(\theta-\pi-\psi)}\}]\\
&\fallingdotseq \frac{100}{V}[-I_A Z\cos(\theta-\frac{2\pi}{3}-\psi)-2I_B Z\sin(\theta-\frac{\pi}{2}-\psi)]\\
\frac{\Delta\dot{V}_{ca}}{\dot{V}_{ca}} &= \frac{100}{V}[I_A Z\{\varepsilon^{-j(\theta-\psi)}+\varepsilon^{-j(\theta+\frac{4\pi}{3}-\psi)}\}+I_B Z\{\varepsilon^{-j(\theta-\psi)}-\varepsilon^{-j(\theta+\frac{5\pi}{3}-\psi)}\}]\\
&\fallingdotseq \frac{100}{V}[-I_A Z\cos(\theta+\frac{2\pi}{3}-\psi)+I_B Z\sin(\theta+\frac{5\pi}{6}-\psi)]
\end{aligned}$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\quad (2.6.8)$$

provided, $V = |\dot{V}_{ab}|$

These are the formulas for calculation of the rate of source voltage drop by V-connection load. However, the reactance and resistance in the source impedance are in the relationship of $x \gg r$. Then, assuming

$$\psi = \tan^{-1}\frac{x}{r} = \tan^{-1}\infty = \frac{\pi}{2}\quad\cdots\cdots\cdots\cdots\cdots\cdots\quad (2.6.9)$$

formulas (2.6.8) are simplified as below.

$$\left.\begin{aligned}
\frac{\Delta\dot{V}_{ab}}{\dot{V}_{ab}} &= \frac{1}{V}\{2I_A Z\sin\theta + I_B Z\sin(\theta - \frac{\pi}{3})\} \times 100\ (\%) \\
\frac{\Delta\dot{V}_{bc}}{\dot{V}_{bc}} &= \frac{1}{V}\{I_A Z\sin(\theta + \frac{\pi}{3}) + 2I_B Z\sin\theta\} \times 100 \\
\frac{\Delta\dot{V}_{ca}}{\dot{V}_{ca}} &= \frac{1}{V}\{I_A Z\sin(\theta - \frac{\pi}{3}) + I_B Z\sin(\theta + \frac{\pi}{3})\} \times 100
\end{aligned}\right\} \quad \cdots\cdots (2.6.10)$$

Multiplying V to the denominators and numerators for expression of the source impedance in the short-circuiting capacity (Ps), formulas (2.6.10) are represented as shown in Table 2-13.

If this formula is generalized, the numerator is given as kVIsinα. If it is represented by Q, then

$$\frac{\Delta V}{V} = \frac{Q}{Ps} \quad \cdots\cdots\cdots\cdots (2.6.11)$$

It will be noted that the voltage drop rate is proportional to the reactive power of the load and is inversely proportional to the short-circuiting capacity at the point.

Table 2-13 Formulas for Approximate Calculation of Voltage Drop Rates by V-connection Load

Conducting conditions	I_A only conducted (× 100%)	I_B only conducted (× 100%)	Both I_A and I_B conducted (× 100%)
$\frac{\Delta V_{ab}}{V_{ab}}$	$\frac{2VI_A}{P_s}\cdot\sin\theta$	$\frac{VI_B}{P_s}\cdot\sin(\theta - \frac{\pi}{3})$	$\frac{2VI_A}{P_s}\cdot\sin\theta + \frac{VI_B}{P_s}\cdot\sin(\theta - \frac{\pi}{3})$
$\frac{\Delta V_{bc}}{V_{bc}}$	$\frac{VI_A}{P_s}\cdot\sin(\theta + \frac{\pi}{3})$	$\frac{2VI_B}{P_s}\cdot\sin\theta$	$\frac{VI_A}{P_s}\cdot\sin\theta + \frac{2VI_B}{P_s}\cdot\sin\theta$
$\frac{\Delta V_{ca}}{V_{ca}}$	$\frac{VI_A}{P_s}\cdot\sin(\theta - \frac{\pi}{3})$	$\frac{VI_B}{P_s}\cdot\sin(\theta + \frac{\pi}{3})$	$\frac{VI_A}{P_s}\cdot\sin(\theta - \frac{\pi}{3}) + \frac{VI_B}{P_s}\cdot\sin(\theta + \frac{\pi}{3})$

Further, what aspect the line voltage of the primary three-phase power source will present by varying the angle of the load power factor is illustrated in Fig. 2-46.

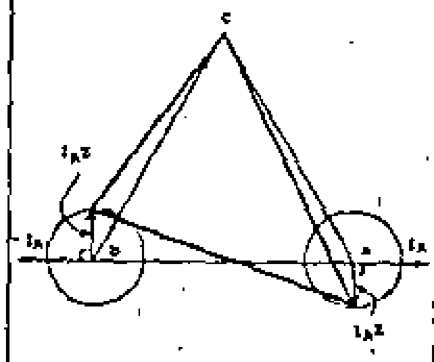
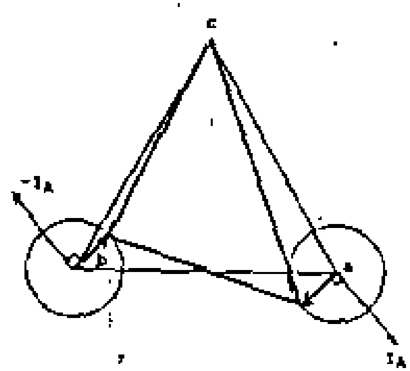
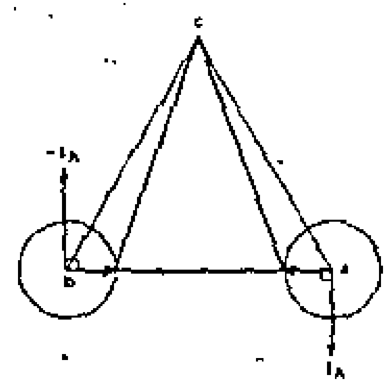
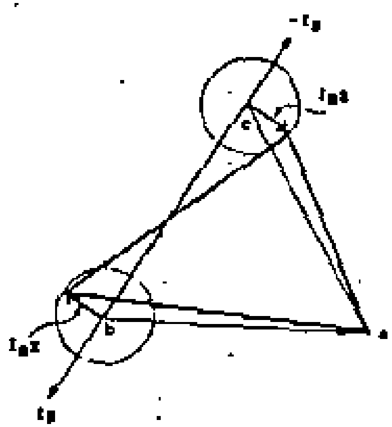
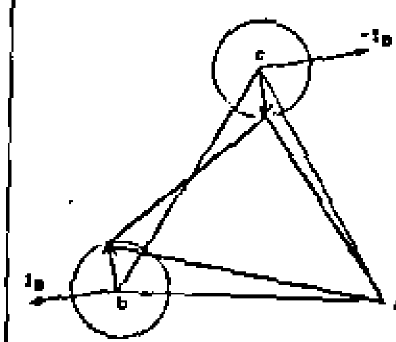
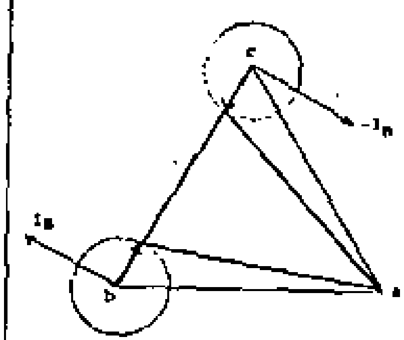
	Load power factor 1.00 (θ = 0)	Load power factor 0.71 ($\theta = \frac{\pi}{4}$)	Load power factor 0.0 ($\theta = \frac{\pi}{2}$)	Remarks
I_A only conducted				(1) The resistance component of the source impedance is assumed to be 0 so that the phase of the voltage drop IZ is delayed by π/2 over the current I. (2) If the resistance component of the source impedance is taken into account, IZ should be delayed by $\varphi = (\tan^{-1} \frac{x}{r})$.
I_B only conducted				(1) (2) } Same as above.

Fig. 2-46 Changing Vector of Voltage by V-connection Load

2-6-2 Voltage Unbalanced Factor versus Voltage Drop Rate

When the positive and negative phase components of the source impedance are taken as given by formula (2.6.7) and have the positive and negative phase currents of formulas (2.6.1) given respectively, the positive and negative phase voltages at this point are calculated, from the "fundamental formula for generators," as

$$\left.\begin{aligned}\dot{V}_1 = \dot{E}a - \dot{I}_1\dot{Z}_1 &= \{Ea - \frac{(I_A + I_B)Z}{\sqrt{3}}\cos(\theta + \frac{\pi}{6} - \psi)\} \\ &\quad + j\{\frac{(I_A + I_B)Z}{\sqrt{3}}\sin(\theta + \frac{\pi}{6} - \psi)\} \\ \dot{V}_2 = -\dot{I}_2\dot{Z}_2 &= -\frac{Z}{\sqrt{3}}\Big[\{I_A\cos(\theta - \frac{\pi}{6} - \psi) - I_B\cos(\theta + \frac{\pi}{6} - \psi)\} \\ &\quad - j\{I_A\sin(\theta - \frac{\pi}{6} - \psi) - I_B\sin(\theta + \frac{\pi}{6} - \psi)\}\Big]\end{aligned}\right\} \quad (2.6.12)$$

On the other hand, the voltage unbalanced factor is defined as

$$U = \frac{|\dot{V}_2|}{|\dot{V}_1|} \times 100 \ [\%] \quad \cdots\cdots\cdots \quad (2.6.13)$$

then,

$$|\dot{V}_1| \doteq Ea \ \ [kV]$$

$$|\dot{V}_2| = \frac{Z}{\sqrt{3}}\sqrt{I_A^2 + I_B^2 - 2I_AI_B\cos\{(\theta - \frac{\pi}{6} - \psi) - (\theta + \frac{\pi}{6} - \psi)\}}$$

$$= \frac{Z}{\sqrt{3}}\sqrt{I_A^2 + I_B^2 - I_AI_B}$$

Accordingly, the voltage unbalanced factor is given as

$$u = \frac{|\dot{V}_2|}{|\dot{V}_1|} = \frac{Z}{V}\sqrt{I_A^2 + I_B^2 - I_AI_B}$$

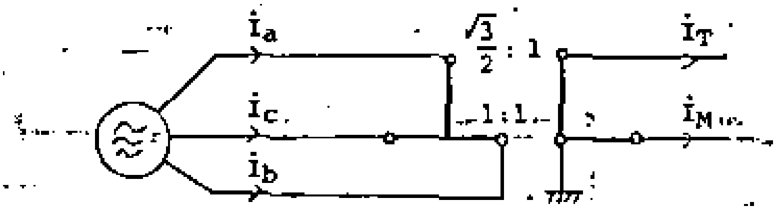
$$= \frac{V}{Ps}\sqrt{I_A^2 + I_B^2 - I_AI_B} \quad \cdots\cdots\cdots \quad (2.6.14)$$

provided, $V = \sqrt{3}$ Ea.

Now, comparing formula (2.6.14) with Table 2-13, it will be seen that although the maximum voltage drop rate is affected by the power factor angle θ, it is 2 times the maximum of the voltage unbalanced factor u. This means that if the instantaneous voltage unbalanced factor is allowed to go up to 3 percent, the instantaneous voltage drop rate is 6 percent.

2-6-3 Voltage Drop Approximate Calculation Formula in 3-phase/2-phase Connection

As a typical example of 3-phase/2-phase conversion, the transformer connection and current distribution in the case of use of a Scott connection transformer are shown in Fig. 2-47, and the results of calculation by the approximation formulas are noted in Table 2-14 for the sake of reference.



$$\dot{I}a = \frac{2}{\sqrt{3}} \cdot I_T \varepsilon^{-j\theta}$$

$$\dot{I}b = (-jI_M - \frac{I_T}{\sqrt{3}})\varepsilon^{-j\theta}$$

$$\dot{I}c = (jI_M - \frac{I_T}{\sqrt{3}})\varepsilon^{-j\theta}$$

Fig. 2-47 Scott Connection Transformer

$$\left.\begin{aligned} \dot{I}_1 &= \frac{1}{3}(\dot{I}a + a\dot{I}_b + a^2\dot{I}_c) = \frac{1}{\sqrt{3}}(I_T + I_M)\varepsilon^{-j\theta} \\ \dot{I}_2 &= \frac{1}{3}(\dot{I}a + a^2\dot{I}_b + a\dot{I}_c) = \frac{1}{\sqrt{3}}(I_T - I_M)\varepsilon^{-j\theta} \end{aligned}\right\} \quad \cdots\cdots\cdots\cdots (2.6.15)$$

Table 2-14 Formulas for Approximate Calculation of Voltage Drop Rate by Scott Connection Load

Conducting conditions	T-phase only conducted (× 100%)	M-phase only conducted (× 100%)	Both T- and M-phases conducted (× 100%)
$\frac{\Delta V_{ab}}{V_{ab}}$	$\frac{\sqrt{3}VI_T}{P_s}\cdot\sin(\theta+\frac{\pi}{6})$	$\frac{VI_M}{P_s}\cdot\sin(\theta-\frac{\pi}{3})$	$\frac{\sqrt{3}VI_T}{P_s}\cdot\sin(\theta+\frac{\pi}{6})+\frac{VI_M}{P_s}\cdot\sin(\theta-\frac{\pi}{3})$
$\frac{\Delta V_{bc}}{V_{bc}}$	0	$\frac{2VI_M}{P_s}\cdot\sin\theta$	$\frac{2VI_M}{P_c}\cdot\sin\theta$
$\frac{\Delta V_{ca}}{V_{ca}}$	$\frac{\sqrt{3}VI_T}{P_s}\cdot\sin(\theta-\frac{\pi}{6})$	$\frac{VI_M}{P_s}\cdot\sin(\theta+\frac{\pi}{3})$	$\frac{\sqrt{3}VI_T}{P_s}\cdot\sin(\theta-\frac{\pi}{6})+\frac{VI_M}{P_s}\cdot\sin(\theta+\frac{\pi}{3})$

2-7 Rail Potential

2-7-1 General

In the electric railway, the rail is designed as a return circuit and has an electric car current flow so that a rail potential is generated arising out of the product of the characteristic impedance of rail and the load current. Here, the size of the potential is dependent on

(1) Feeding circuit configuration,

(2) Value of the load current,

(3) Leak-to-ground admittance of the rail, and

(4) Location of the load.

As the rail potential increases, there is the possibility of electrification hazards to the passengers on the platform and track maintenance workers, or adverse effects such as insulation breakdown of the rail tie plate. Therefore, in planning electrification, it is necessary to estimate the rail potential and thus form an adequate feeding circuit.

As an element related to the rail potential in forming a feeding circuit, the following may be cited.

(1) Substation interval for simple feeding system,

(2) AT interval for AT feeding system, or

(3) BT and boosting wire interval for BT feeding system,

and in each case, the shorter the rail conducting distance, the smaller the rail potential.

Furthermore, the size of the leak-to-ground admittance Y_b [S/km] of rail has a great influence on the generation of rail potential. That is, by dispersing the grounding of rail, it is possible to reduce the rail potential generally, but as the leak-to-ground current increases, the induction to telecommunication lines increases greatly.

In JNR, the rail potential in the conventional AC electrified sections is 80V maximum or less so that no rail potential suppressing measure has been taken, and there have been no problems. In the Shinkansen, the load current is large, while the leak-to-ground admittance Y_b of rail is small, so that the rail potential rises up to about 500V in some cases. Thus, to prevent passengers from getting electric shocks, the rail is electrically connected to the iron structure of the station building to reduce the rail potential to 30V or less in the respective stations. Where the Shinkansen is located close to a DC railway circuit, the rail is grounded through a rail potential suppressor which blocks the DC stray current and passes AC only. This is a measure to prevent electrolytic corrosion of the iron structure of station building.

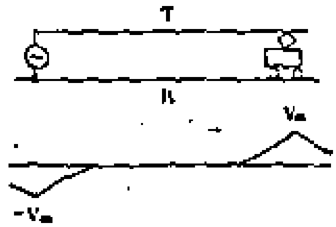
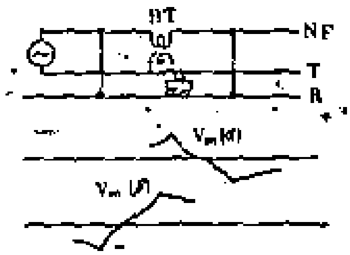
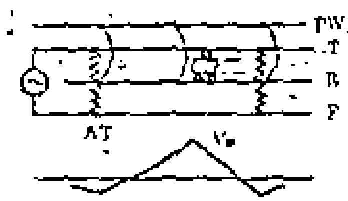
As a way of suppressing the rail potential in the double-track sections, the method of bonding the upbound and downbound rails every several kilometers (referred to as "cross-bond") is effective for reducing the rail potential and can reduce the rail potential nearly by half. This cross-bond method is employed wholly in the AT feeding circuits along JNR's Shinkansen.

2-7-2 Rail Potential Calculation Formulas

The rail potential is the highest at the load point at which the load current flows in and the boosting current point.

Table 2-15 shows the formulas for calculation of the highest value of rail potential in the respective feeding systems.

Table 2-15 Rail Potential Highest Value Generating Conditions and Calculation Formulas

AC Simple feeding system	At the maximum load at the remotest end Load point and substation point		$V_m = \frac{1}{2}(1-n_0) I Z_0 (1-e^{-\gamma \ell})$
BT feeding system	At the maximum load at booster transformer point Load point and boosting wire point		$V_m(0) = \frac{1}{2}(1-n_{00}) I Z_0 (1-e^{-\gamma \ell})$ $V_m(\ell) = \frac{1}{2}(1-n_0) I Z_0 (1-e^{-\gamma \ell})$
AT feeding system	At the maximum load at about the AT mid-point Load point		$V_m = \frac{1}{K_p} \cdot \frac{1}{2}(1-n_0) I Z_0 (1-e^{-\gamma \ell})$ $K_p \fallingdotseq 1.4$

$\gamma = \sqrt{Z_{RR} \cdot Y_b}$: Propagation constant of rail $n_0 = Z_{TR}/Z_{RR}$

$Z_0 = \sqrt{Z_{RR}/Y_b}$ [Ω]: Characteristic impedance of rail $n_{00} = Z_{RN}/Z_{RR}$

I[A]: Load current

ℓ[km]: Length from feeding point (substation, boosting wire or AT) to load point.

2-7-3 Aspect of Generation of Rail Potential in the Respective Feeding Systems

The aspect of generation of the rail potential will be described with respect to the simple and AT feeding systems.

a. Simple Feeding System

With respect to the simple feeding system which is composed of contact wire and rail only, the results of calculation of the rail potential, with the leak-to-ground admittance Y_b of the rail taken as a parameter, at the load points of a moving 100A single load, are shown in Fig. 2-48.

When Y_b is extremely small, the rail potential increases in proportion to the feeding length, but as Y_b increases, it rises exponentially to the feeding length and tends to saturate. For example, when Y_b is 1 S/km, the rail potential saturates at a feeding length of about 5 km and does not increase any more when the feeding length is extended further.

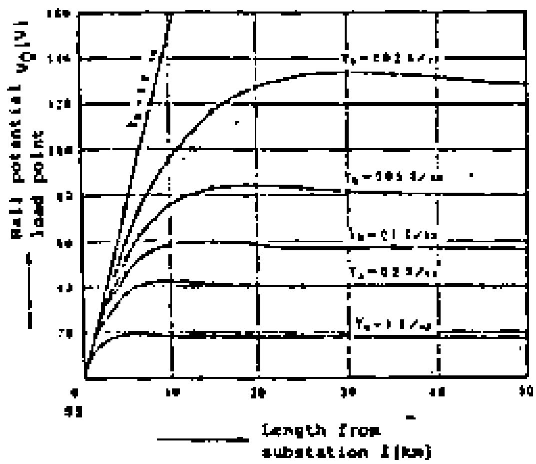


Fig. 2-48 Rail Potential in Simple Feeding System
(50[kg/m] rail, I=100[A]
single load [theoretical value])
(T-R simple feeding)

(2) Rail Potential in AT Feeding System

In the AT feeding system, the maximum rail potential in the absence of the protective wire (PW) is that of the load point when the load is located at the central position between AT's and takes a maximum load. When PW is provided, the rail potential is rather lower at the central point because of the shunt effect of PW but shows a maximum value at two points separated from the central point to the left and right.

Further, when Y_b is small, AT interval has a great influence on the rail potential, and at a minimum Y_b, the rail potential increases approximately in proportion to the AT interval. However, if Y_b is large, it shows a trend towards saturation for the AT interval as in the case of the simple feeding and does not rise over a certain value. This aspect is illustrated in Fig. 2-49.

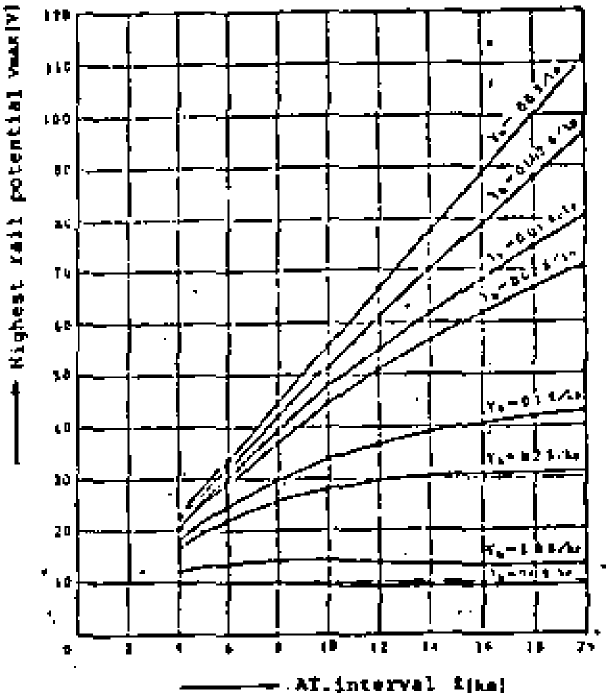


Fig. 2-49 AT Interval and Highest Rail Potential
(60[kg/m] rail, I=100[A] single load)
(Sanyo Shinkansen)

2-7-4 Approximate Numbers of Leak-to-ground Admittance of Rail

From the foregoing, it will be understood that the leak-to-ground admittance of rail affects the generation of rail potential greatly. Here, the value to be taken for Y_b in forecasting the rail potential presents a very difficult problem.

Y_b fluctuates greatly depending on the conditions of the rail tie plate and ballast, whether wooden or concrete sleepers are used, and depending on whether the weather is fine or rainy. When insulators are introduced in the rail tie plate as in the Shinkansen, Y_b takes a very small value. Table 2-16 shows the approximate numbers by district classification of the leak-to-ground admittances Y_b from the results of measurement in JNR.

Table 2-16 Approximate Numbers of Leak-to-ground Admittances of Rail in AC Electrified Sections

Weather	Leak-to-ground admittance Y_b [S/km]	
	Conventional line	Shinkansen
Fine	0.2 ∿ 0.5	0.002 ∿ 0.01
Rail	1.0 ∿ 2.0	0.1 ∿ 0.2

CHAPTER 3

SUBSTATION EQUIPMENT

CHAPTER 3. SUBSTATION EQUIPMENT

3-1 Composition of the Substation

The AC traction substation (hereafter referred to as substation) receives electric power from ordinary power networks of commercial power companies and supplies this to the overhead contact system after converting it in the feeding transformer to power suitable for operating electric vehicles. In addition to supplying stable power, a substation must be capable of swift and positive detection of trouble in the event trouble develops and must also possess necessary protective functions to cope with power failures. With the foregoing purpose in mind, a substation is composed of the following equipment.

(a) Power Receiving Equipment

Equipment to receive AC power from ordinary power networks.

(b) Transformer Equipment

Equipment to transform power received to operating power. The feeding transformer will be the principal equipment in the case of commercial frequency electrification systems.

(c) Feeding Equipment

Equipment to supply operating power to the overhead contact system.

(d) Common Equipment

Miscellaneous devices to control and operate various substation equipment.

Although various forms of substation equipment layouts may be considered such as for feeding systems, control systems etc., from the standpoint of both construction and maintenance, it will be advantageous to standardize wherever possible within the same electrification section.

JNR has standardized and is utilizing the AT feeding system with its numerous advantages as a feeding system, and the centralized remote control system for unmanned substation operation. An example of a substation equipment single diagram is shown in Fig. 3-1.

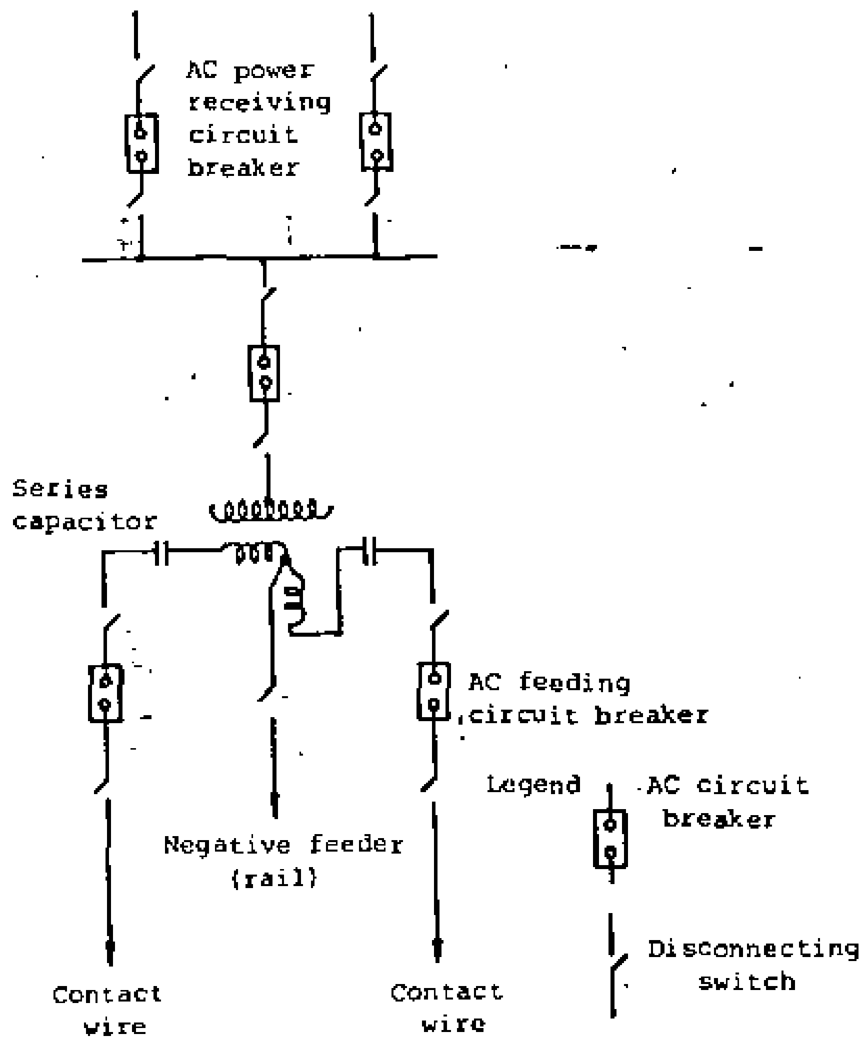


Fig. 3-1 Substation Equipment Single Diagram

(1) Location of the Substation

After deciding the type of feeding system, the electric vehicle output, track conditions, train operating conditions, and basic system of electrification, the substation is suitably located after taking into consideration interval, site and capacity.

(a) The substation equipment must possess sufficient capacity to withstand vehicle loads.

(b) Voltage drops due to vehicle loads should not adversely affect train operation.

(c) The substation must be provided with protective functions for swiftly and positively detecting the trouble and cutting off the power in the event short circuits occur in the feeding circuit due to trouble in the overhead contact system or in the vehicle.

(2) Interval of the Substation

a. Substation Interval

The interval of the substations is selected within the range that will enable maintaining minimum pantograph voltage in the overhead contact system and, moreover, enable swift and positive detection of fault currents that may be generated in the feeding circuit and thereby protect against power failures by cutting off this current.

As voltage drop is small in the AT feeding system, greater interval will be possible between the substations.

In the case of JNR's AT feeding system, substation interval and the range of voltage fluctuation in the overhead contact system are set as follows.

(a) Conventional line (Standard voltage 20 kV)

Interval approximately 100 km   22 - 16 kV

(b) Shinkansen (Standard voltage 25 kV)

Interval approximately 50 km   30 - 22.5 kV
(20 kV momentarily)

b. Assumed Load for Calculating Voltage Drop

Although train operation curves (speed, time and current curve based on distance) by car type are used to calculate assumed loads when carrying out estimated calculation of voltage drop, here we shall consider that the operation curve has already been drawn up and that its characteristics have been mastered.

The following items will therefore become involved in the method of selecting the load.

(a) Substation interval and track grade

(b) Feeding circuits by single or double

(c) Extended feeding and tie feeding (tying up and down feeding circuits) in double track feeding circuits.

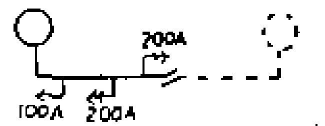
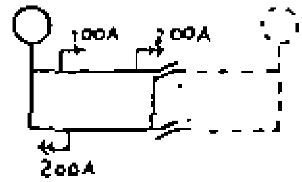
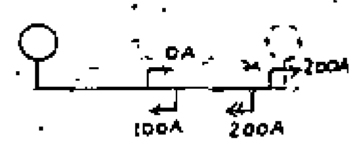
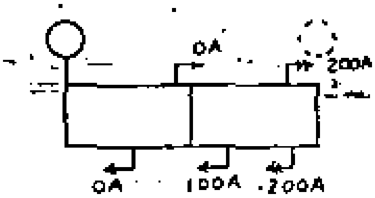
As may be noted by the example shown in Table 3-1 of the load condition when maximum voltage drop is assumed in the feeding circuit, the probability of minimum voltage developing is generally greater when heavy loads exist near the end of the feeding circuit.

If a time belt with the worst condition is selected from the time schedule shown in Fig. 3-2 as an example, and load assumption carried out, a load distribution diagram may be created as shown in Fig. 3-3.

As an AC feeding circuit is generally feeding from one substation, assuming that electric vehicle loads are constant, the further the train is from the substation, the higher the voltage drop. As voltage drop therefore becomes higher with increases in the product of the load current times the distance to the load point (Amp-km), a time with this kind of load should be selected from the time schedule when making load assumptions.

Fig. 3-3 shows the load distribution of a time belt with maximum voltage drop during normal feed with 4 trains running in the same feeder section at the same time of 8:15 (point "K"). Of these 4 trains, both up and down trains (trains 2 and 3) start

Table 3-1 Load Conditions and Composition of the Feeding Circuit (Feeding from One Substation)

	Single track	Double track
Normal feeding	*1)  	*3) 
Extended feeding	*1), *2)  	*3), *4) 
Load condition	*1) When the train is at a far point from the substation and the current is large. *2) When additional number of trains are in during extended feeding	*3) When large current loads exist at the same time on both up and down circuits with the trains at a far point from the substation. *4) In extended feeding, to be tie feeding during one substation stoppage.

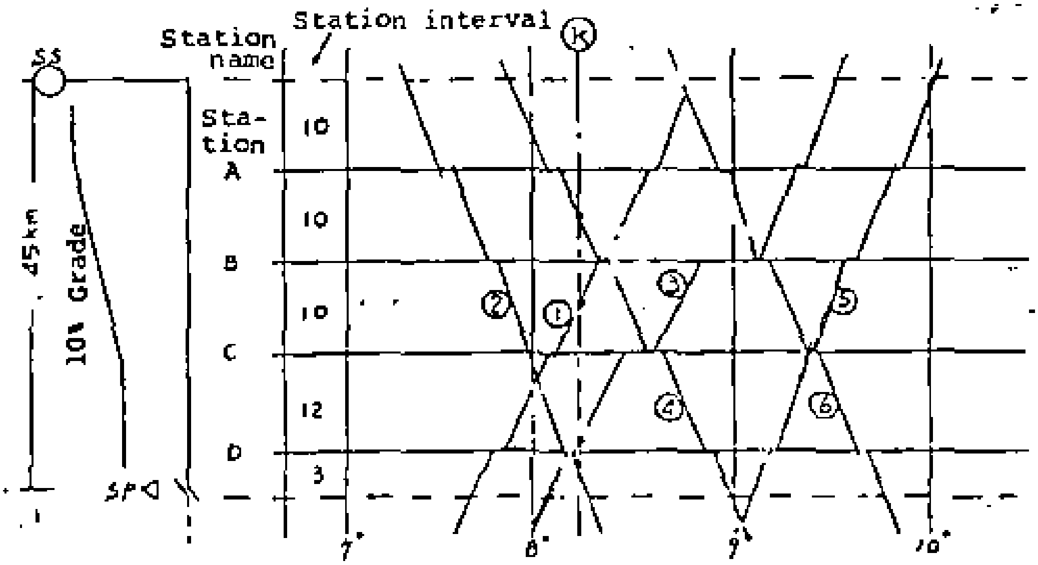


Fig. 3-2 Train Diagram

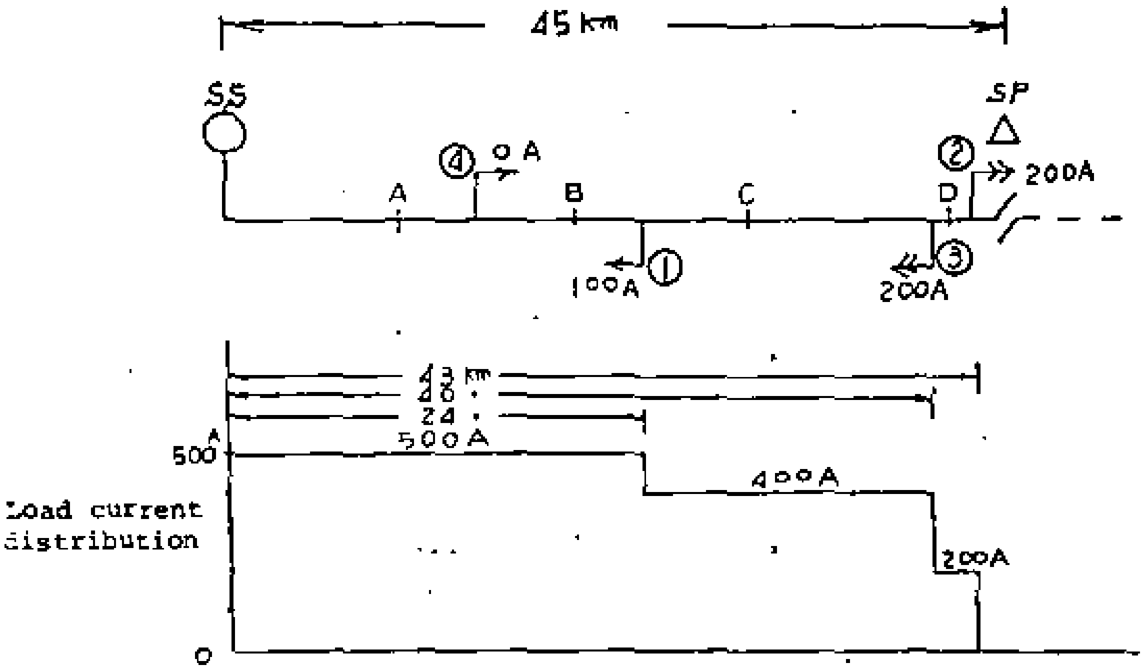


Fig. 3-3 Load Distribution Diagram

simultaneously at station D at the end of the feeding circuit and train 1 is at an up-grade between stations B and C. With the powering load of this train added, Amp-km becomes greatest and voltage drop becomes maximum.

Although the foregoing load assumption is for normal feed, it will be necessary to carry out extension of feeding when stopping the substation in the event of trouble or for power failure or maintenance work. However, load assumption may be carried out in the same manner.

In relation to protective systems for feeding circuits, refer to paragraph 2.4 "Protection of Feeding Circuits".

(3) Location of the Substation

In relation to the location of the substation, select an appropriate site in compliance with the planned spacing explained above and based on maps and on-site surveys taking the following into consideration.

(a) Where feeder source is easily available near the railway tracks.

(b) Where equipment may be carried in and out easily.

(c) Near receiving power source and where receiving power lines are easily laid.

(d) Where there is no fear of floods, land slides, land slips or avalanches.

(e) Away from factories emitting noxious gases.

(f) Noise countermeasures will be necessary in areas where equipment and station noises will become a problem.

(g) Where maintenance and inspection can be conveniently carried out.

(h) Where the dead section of the train tracks can be laid nearby.

(i) Where the ground resistance is below the rated value.

(4) Capacity of the Substation

The capacity of the substation must be greater than the maximum hourly output obtainable with the assumed load and furthermore must be capable of withstanding maximum instantaneous output. There may also be instances when the operation of the substation must be stopped due to trouble or for inspection of the equipment and, in these instances, it will be necessary to consider the degree of power available according to the degree of importance of maintaining train operation. For example, in important main lines where the failure of a substation must not affect train operation, it will be necessary to provide a dual system of power receiving equipment and transformers to improve the reliability of the power supply and thus lessen the chance of substation failure. In addition, when a substation fails and train operation is maintained by extended feeding from a neighboring substation, the capacity of the substation will differ according to whether operation is to be restricted and, if so, to what extent.

a. Calculation of the Maximum Hourly Output

The hourly output is calculated by obtaining the assumed load curve from the interval of the substations, the characteristics of the electric car, the condition of the tracks and the operating timetable and by calculating the maximum hourly output taking into consideration the power factor of the substation. Although the methods of calculation available are the method employing operation curves and the method using power consumption factor, it will generally be more convenient to use the power consumption factor method when obtaining approximate substation loads.

Power consumption factor will differ according to speed, acceleration, type of car, distance between stations and track condition. The following methods are available to obtain this value.

(a) Prepare electric car operation curves according to type of train and use this as basis for calculation.

(b) Estimate from usage performance of similar districts.

(c) Energy calculated from other motive energy.

Although (a) is the calculating method with the highest degree of accuracy, the process is very complicated so it is applied only when the operation plan has been established and detailed studies become necessary.

In (b) the power consumption factor of similar districts from track grade and transport conditions are used when existing electrified districts are available.

The power consumption factor by track condition in JNR is shown in Table 3-2.

Although (c) is a method of estimating maximum hourly power by converting from coal and petroleum energy, method (b) is generally used for the power consumption factor.

If we multiply the power consumption factor obtained in this manner times hauling weight and train kilometres according to car type of the trains running in the substation district per hour according to the timetable times the trailing load, load curves per hour for the day can be prepared and the maximum value will become the maximum hourly power.

As one example, if (1), (2) and (5) of the operation schedule in Fig. 3-2 are each considered pick up passengers train, the power consumption factor of an average 10‰ grade track will be 33 (kwh/1000 t-km) from Table 3-2. Also, if we consider (3), (4) and (6) as pick up goods train, the power consumption factor will be 20 (kwh/1000 t-km) from the fact that track conditions are the same as in the foregoing.

Table 3-2 Power Consumption Factor of Various Forms of Tracks (Japanese National Railways Example)

Unit: (kwh/1,000 t-km)

No.	Range of application	Electric car			Passenger train		Goods train	
		Limited express	Express	Local	Express	Local	Express	Local
1	Level track	25	27	33	19	31	11	16
2	Average 5‰ grade track	27	30	33	20	31	11	17
3	" 10‰ "	30	32	35	21	33	14	20
4	" 25‰ "	30	40	-	36	53	22	35
5	" 30‰ "	-	45	-	-	-	-	38
6	Commuter train section (Average distance between stations 1 - 2 km)	-	50	60	-	-	-	-
7	Shinkansen (Track grade under 10‰)	*1 40	*2 46	-	-	-	-	-

Note: *1 (Superexpress Hikari)

*2 (Superexpress Kodama)

From the above, the substation load per hour will be as shown in Table 3-3. From the same table, the load curves per hour as shown in Fig. 3-4 are obtained.

Table 3-3 Substation Load Calculation Table

Time [h]	Power consumption factor [kwh/1,000 t-km]	Traction constant [t]	Train running distance [km]	Power/1,000 [kwh]	Total power [kwh]	Train
7	33	600	31	613.8		②
~	33	600	9	178.2		①
8	20	1,200	4	96.0		④
					888.0	
8	20	1,200	41	984.0		④
~	33	600	36	712.8		①
	20	1,200	25	600.0		③
9	20	1,200	15	360.0		⑥
					2,656.8	
9	20	1,200	30	720.0		⑥
~	20	1,200	20	480.0		③
10	33	600	45	891.0		⑤
					2,091.0	

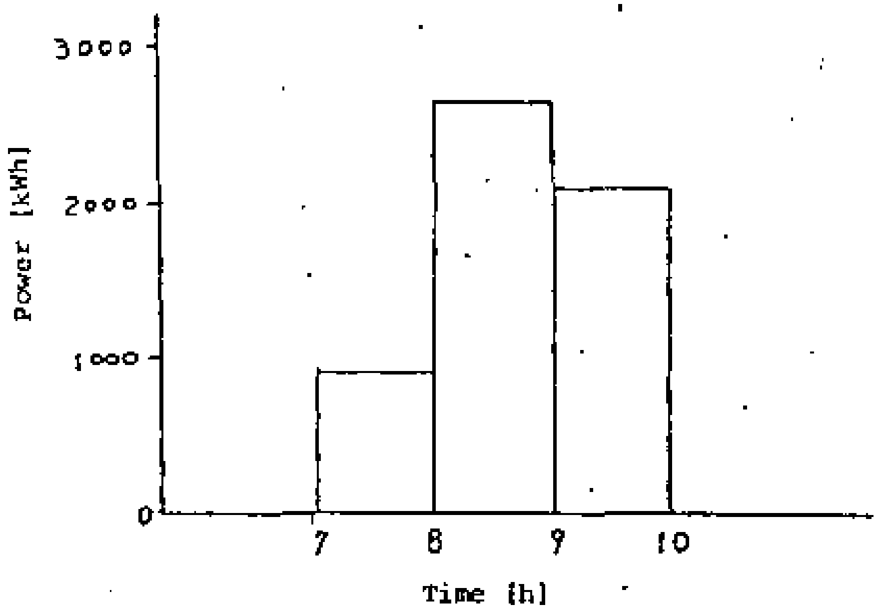


Fig. 3-4 Substation Load Curves by Time

b. Calculation of Maximum Instantaneous Output

When only 1 train enters the feeder range of 1 substation, the maximum output of this train will be used. In the case of multiple trains entering, the following method is used to calculate maximum instantaneous output.

(a) The instantaneous operating current of each train within the feeding district of the substation according to the train diagram are totalled and the maximum value obtained.

(b) As the relation in the following equation is theoretically possible between the maximum instantaneous output and the hourly output of every hour, the calculation method used by JNR to obtain maximum instantaneous output is to select a suitable value C from the performance of similar districts.

$$Z = Y + C\sqrt{Y} \quad \text{(3-1-1)}$$

Z : Maximum instantaneous output [kW]

Y : 1 hour output [kW]

C : Constant determined by the district

Although the value of C will be determined by the size and the waveform of the current per train, and the geographical position of the substation, in the case of JNR, it is within the range of 60 to 140.

c. Determining the Capacity of the Substation

When the maximum 1 hour output and the maximum instantaneous output are obtained, select suitable equipment such as transformers etc. from the rated values available and decide the capacity of the substation. However, as each output is in kilowatt values, taking load power factor into consideration, it will be necessary to convert these into kVA values.

Also, as capacity of the feeding transformer is determined by temperature rise, and as temperature rise will be affected by the thermal constants of the winding and the cooling oil, it will be necessary to consider its relation to the withstandable load. As the thermal constants of transformers are generally high, in most cases its capacity can be determined by the maximum 1 hour power. However, to prevent damage to the equipment from overcurrents due to troubles etc., it will be necessary to consider means of withstanding overloads. Specifications of JNR are drawn up to withstand loads equivalent to 300% of the rated current for 2 minutes of continuous usage. Lastly, by adding some allowance for future load increases to the capacity obtained by calculation, we determine the capacity of the substation.

3-2 Substation Equipment

(1) Power Receiving Equipment

The principal devices composing the substation equipment are power receiving disconnecting switch, power receiving circuit breaker, current transformer, and arrester. Counting devices for electric energy received and instrument transformers may also be installed if necessary.

The power receiving systems available are the 3 phase receiving and single phase receiving systems. Comparisons should be made between the regulation value of the effect that an unbalanced 3 phase voltage will have on the 3 phase power supply or the contract system in relation to receiving power with your power company and the economy of construction costs of the receiving equipment, and the most advantageous system should be used.

The greater the short-circuit capacity of the power supply of unbalanced 3 phase voltage, the smaller will its value be in relation to single phase of the same power. A large 3 phase short-circuit capacity will therefore be necessary at the power receiving point and it will be desirable to receive high voltages from a power supply with as large capacity as possible.

Due to the fact that train load is great in comparison with the shorting capacity of the power supply and as the contract rate for single phase power is considerably high, 3 phase power is used as a rule by JNR by using feeding transformers that reduces unbalancing of the 3 phase voltage.

The limit of the unbalancing factor of 3 phase voltage in Japan is designated by law to be under 3% at the receiving point of the substation in relation to a continuous average load for 2 hours.

(2) Transformer Equipment

The principal devices composing the transformer equipment are the feeding transformer, series capacitor, switching unit on the secondary of the transformer and a parallel capacitor. When necessary, control transformers, potential transformers and current transformers are provided.

We shall next discuss the unbalanced voltage resulting from the method of wiring of the feeding transformer.

a. Single Phase Wiring System

This is the most simple transformer and not only does it result in economical transformer equipment, it also leads to economical power receiving equipment. However, the unbalanced factor of the voltage is large and this factor may be calculated as follows.

$$K = \frac{P_A}{P_S} \times 100 \quad \text{......................} \quad (3\text{-}2\text{-}1)$$

Here, K: Unbalanced factor of the voltage [%]

P_A: Single phase transformer load [kVA]

P_S: Shorting capacity of the receiving system [kVA]

A wiring example is shown in Fig. 3-5.

b. V Connection System

This is a system in which 2 single phase electric powers are obtained from a 3 phase source by means of 2 single phase transformers. Although voltage unbalance is less than that in the single phase connection system, the 3 phase power source will be subjected to the same effect as a 50% single phase load in the event that the 2 single phase power loads are the same. The voltage unbalanced factor can be calculated by the following equation.

$$K = \frac{\sqrt{P_A^2 - P_A \cdot P_B + P_B^2}}{P_S} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3\text{-}2\text{-}2)$$

Here, P_A, P_B: Phase loads in the respective feeder sections [kVA]

K, P_S: Same as in Equation (3-2-1)

As a rule, JNR does not use this system from the standpoint of its effect on both the single phase connection system and the power source and also due to the high power contract system. The example of V connection system are shown in Fig. 3-6.

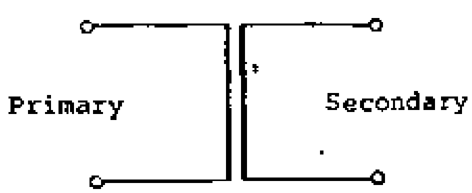


Fig. 3-5 Single Phase Connection Transformer

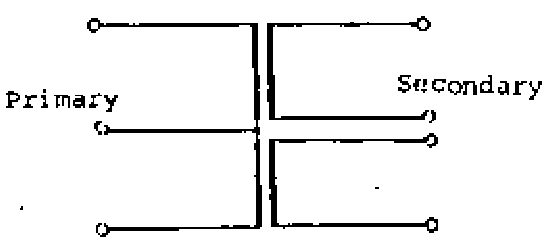


Fig. 3-6 V Connection Transformer

c. Scott Connected System

As shown in Fig. 3-7, this is a system to obtain 2 sets of single phase power of M phase (Main phase) and T phase (Teaser) from a 3 phase power source. In this system, when the 2 single phase power are the same, they act as a balanced 3 phase load on the 3 phase power source and acts to reduce the effect on the 3 phase power source. The voltage unbalanced factor may be calculated by the equation shown below.

$$K = \frac{|P_M - P_T|}{P_S} \times 100 \quad \text{......................} \quad (3\text{-}2\text{-}3)$$

Here, P_M, P_T: Power for each phase in the respective feeding sections [kVA]

K, P_S: Same as in equation (3-2-1)

This is most widely used by JNR as the standard system in resistance grounded neutral system power sources of under 154 kV.

d. Modified Woodbridge Connection System

As shown in Fig. 3-8, this is a system to obtain 2 sets of single phase power coordinates A and B from a 3 phase power source. This connection system has the same function as the Scott connection and moreover has an easily connectable neutral terminal on the primary side. It was developed as a system suitable for power sources of the grounded neutral system. The voltage unbalanced factor may be calculated by the same equation (3-2-3) as in the case of the Scott connection system.

In JNR, its "Shinkansen", which receives its power from a superhigh voltage (275 kV, 220 kV) solidly grounded neutral system power source, uses this as a standard system.

(3) Feeding Equipment

The principal devices composing the feeding equipment are the feeding circuit breaker, disconnecting switch, current transformer,

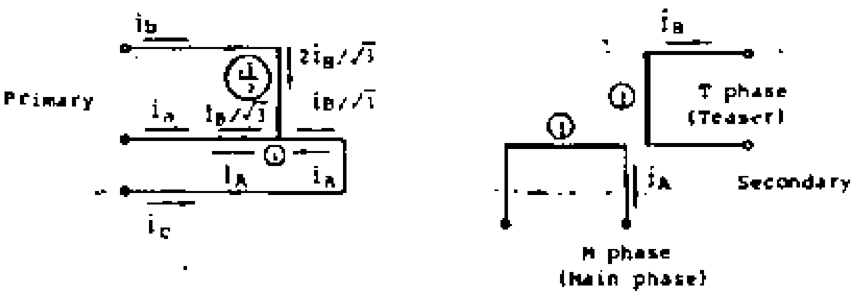


Fig. 3-7 Scott Connected Transformer

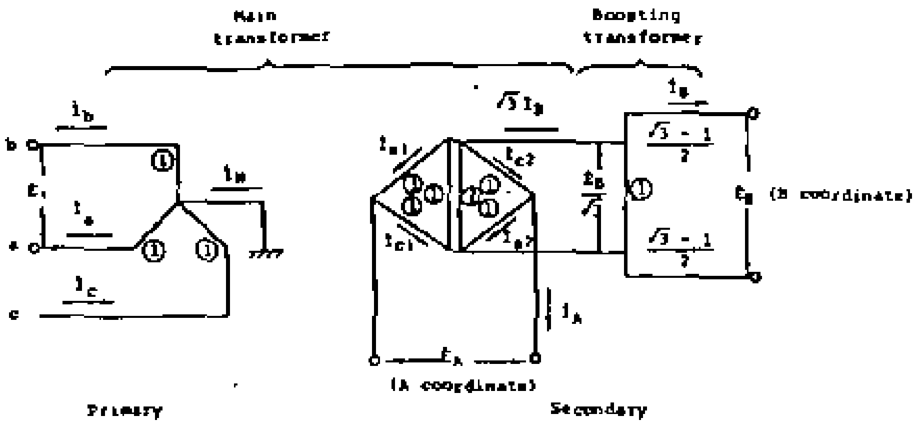


Fig. 3-8 Modified Woodbridge Connected Transformer

potential transformers and arresters. In addition, grounding fault protective discharges, changeover switches and AT are also provided where necessary. Consideration is also being given towards simplification of the equipment by providing the feeding transformer with AT functions in lieu of providing the substation with a separate AT system. This system has the following features.

Advantages

(a) Savings in cost for the AT deleted.
(Particularly where a number of circuits are fed from 1 substation)

(b) The class of insulation of the substation busbar can be lowered to that of the feeding circuit.

Disadvantages

(a) Induction to the communications line is 5 to 6 times greater than with a separate AT as it becomes a system approximating a simple feeding system in the first AT section.

(b) It will be necessary to reverse the voltage of the feeding transformer if desiring to connect the AT to the end of the feeding circuit when carrying out extended feed from an adjacent substation. It will therefore not be possible to carry on work when power failure occurs in the feeding transformer.

(c) Voltage drop will be high as the impedance of the feeding circuit will become 4 times when the feeding circuit breaker in the last substation is opened to avoid the reverse voltage in paragraph (b) during extended feed as it will be in AT-less condition at the end of the circuit. It will also be a problem point from the aspect of protection of the feeding circuit.

(d) It will be necessary to provide an intermediate tap on the secondary of the feeding transformer.

(e) AT neutral current ratio type locator cannot be applied.
Although installation of the AT in the substations is considered standard with JNR for the foregoing reasons, it will be possible to delete the first AT if any of the following conditions are satisfied.

(i) Sections where protection of communications is no problem.

(ii) When operation during extend feeding will not be inconvenient.

(iii) When AT neutral current ratio type locators are not applied.

In essence, it is a comparison between the savings in deleting the first AT and inconvenience in operation.

(4) Principal Devices

a. Take the following items into consideration when selecting the devices for the substation equipment.

(a) Standardization of Machine Specifications

If machine specifications are standardized, the advantages will be great as design and execution of the project can be carried out efficiently, control and maintenance will be simplified after commencement of operation, and as it will rationalize designing and manufacturing.

(b) Savings in Labor

Machines that will require minimum labor for control and maintenance should be selected.

(c) Reliability

Equipment with high reliability and minimum breakdown in relation to work conditions should be utilized.

(d) Equipment Environment

It will be necessary to consider the following measures in relation to devices installed in substations with poor environmental conditions.

(i) Measures to strengthen insulation against damage from salinity.

(ii) Soundproofing measures such as an enclosing structure against noise pollution.

(iii) Fire prevention measures where there is fear of fire.

(iv) Measures for providing space heaters and snow removal equipment in cold areas and against snow damages.

b. We shall now give an outline of the principal devices used in the various equipment of the substations.

(a) AC Circuit Breaker

The AC circuit breaker is an extremely important device to protect the substation equipments, catenary line and electric cars from damage by quickly cutting off the power when fault current flows. As AC circuit breakers have rated voltage, rated current, rated frequency, rated cut off current, rated restriking voltage, rated short-time current and rated breaking time, select suitable ratings corresponding to the usage conditions. Also, the percentage of success of reclosure of the circuit will be high if a high speed reclosing type AC circuit breaker is used as troubles developing in the catenary line end in momentary power failures in most cases. The AC circuit breaker (0 - 0.5 sec. - CO - 1 min. - CO) used by JNR has a percentage of success of about 80% in circuit reclosure.

According to the arc suppressing medium used, AC circuit breakers are available in the following types - oil circuit-breakers, air-blast circuit breakers, gas circuit breakers and vacuum circuit breakers. The advantages and disadvantages of the various types are shown in Table 3-4.

At the initial stage of electrification, JNR used the oil circuit breakers but, from the standpoint of labor involved in handling the insulation oil, air-blast circuit breakers were introduced. Due to problems in noise countermeasures and performance during short-distance cut off, gas circuit breakers, which have superior performance and require little maintenance, are currently used as standard equipment by JNR. Also, with the advancement of vacuum circuit breakers in recent years, these types are currently being used in certain quarters as changeover switches by utilizing their characteristics.

In selecting the type of AC circuit breaker, the most suitable type must be selected by taking into consideration noise countermeasures, conditions of place of installation, maintainability, and economy.

(b) Changeover Section

In relation to matching of different power sources in substation or feeder districts during AC electrification, we have the system in which the electric car is passed in notch-off condition by providing a dead section and a system whereby the electric car is allowed to power by in notch-on condition by providing a changeover section. The dead section system is generally used for slow speed operation but the changeover section is used for JNR's Shinkansen. A theoretical diagram of the changeover section is shown in Fig. 3-9.

Table 3-4 Types and Characteristics of Circuit Breakers

Type		Applicable voltage [kV]	Rated breaking current [kA]	Breaking principle etc.	Advantages	Disadvantages	Remarks
Oil circuit breakers	Tank type	3.6 ~ 300	12.5 ~ 31.5	1. Breaks path of electricity using insulating oil as the medium. 2. Insulating oil also insulates from ground (tank).	1. Anti soiling design of the bushing is easy. 2. CT can be built in. 3. Easily handled as construction is simple.	1. Oil deteriorates each time the breaker operates. 2. Labor required in maintenance due large quantity of oil used. 3. Unsuitable from point of fire prevention.	
	Insulator type	3.6 ~ 300	12.5 ~ 31.5	1. Same as above 2. Porcelain insulator will be used between the breaking portion and ground.	1. Amount of insulating oil is less (5 ~ 20%) compared to the tank type. 2. There are types in which CT can be built in.	1. Anti soil type design is difficult compared to the tank type. 2. Construction is slightly more complicated than the tank type.	
Gas circuit breaker		24 ~ 550	12.5 ~ 50	1. Breaks path of electricity by means of inert gases such as SF_6. 2. Both tank and porcelain insulator types are available.	1. Maintenance is easy. 2. Superior breaking performance. 3. Since the breaking portion is of unit construction, high voltage, high capacity circuit breakers can be produced by connecting units in series. 4. Suitable from the standpoint of fire prevention.	1. Gas leakage alarm monitor required. 2. There are units that require gas liquification prevention measures.	
Air blast circuit breaker		24 ~ 550	12.5 ~ 50	1. Breaking arc is quenched by blowing compressed air (15 ~ 30 kg/cm^2) 2. Insulation between the breaking portion and ground will be carried out by means of porcelain insulators.	1. Compact and light in weight compared to oil circuit breakers. 2. Maintenance is easy. 3. Same as above. 4. Same as above.	1. Noise is large when breaking current. 2. Equipment to supply good quality compressed air will be required. 3. Certain amount of problems exist in short distance breaking performance.	
Vacuum circuit breaker		3.6 ~ 168	12.5 ~ 40	1. Breaking of the electric path is carried out inside a high vacuum valve. 2. Same as above.	1. Maintenance is easy. 3. Is compact and light in weight. 3. Suitable from the standpoint of fire prevention.	1. Monitoring of the vacuum in the vacuum valve is not possible. 2. High voltage, high capacity units cannot be produced. 3. Opening and closing surge voltage is high.	

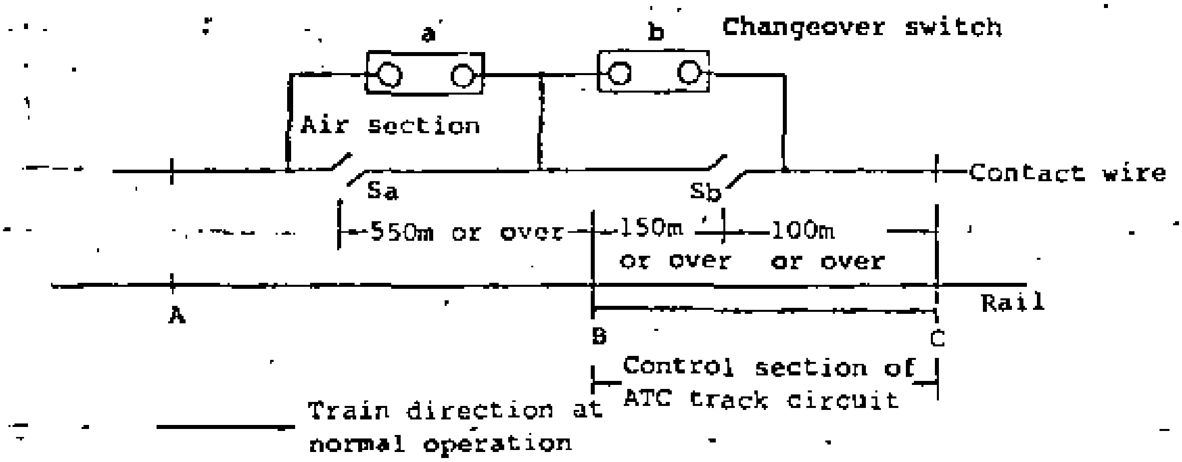


Fig. 3-9 Theoretical Diagram of the Changeover Section

Long life is demanded of the circuit breaker used in the changeover section as it operates each time a train passes and its frequency of operation is extremely great as it may operate 100 times in a single day. The air-blast circuit breaker was initially employed by JNR but considerable maintenance work was required in replacing the breaker components. With recent advancements in vacuum circuit breakers, plans are to use this type to attain a fixed cost of control and to improve maintainability by simply replacing the breaker valve.

(c) Power Capacitor

(i) Series Capacitor

Although series capacitors are generally inserted in the circuit in series to reduce voltage drops, it is particularly suited for use in AC circuits to compensate for voltage drops as the ratio of reactance in AC feeding circuits is high compared to conventional power distribution circuits and load fluctuation also severe. Although 100% compensation is carried out for the feeding transformer reactance in the substation, from the fact that abnormal phenomena are generated due to fractional harmonic vibrations, the compensation for feeding circuit reactance is under 80%.

Compensation voltage Vc due to installation of the series condenser may be expressed as follows.

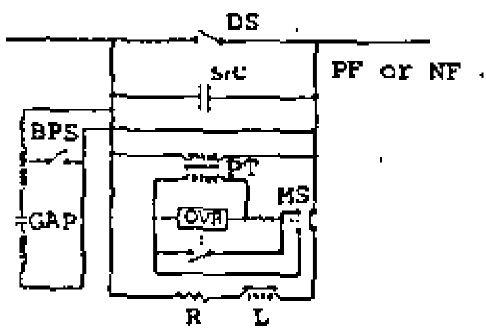
$$V_c = IX_c \cdot \sin\theta \quad \text{.........................} \quad (3\text{-}2\text{-}4)$$

Here, V_c: Compensating voltage due to the series capacitor

X_c: Reactance of the series capacitor

I : Load current

The composition of the series capacitor is as shown in Fig. 3-10.



SrC: Series capacitor unit

GAP: Discharge gap

BPS: Bypass switch

PT : Potential transformer

MS : Electromagnetic contactor

OVR: Over voltage relay

LR : Fractional harmonic inhibition unit

Fig. 3-10 Composition of the Series Capacitor

(ii) Parallel Capacitor

When purchasing electric power from a power company in Japan for operating electrical equipment, the basic portion of the charge will differ for each power company according to their contract rates for industrial, bulk and small electric power users. However, all have rate systems in which the load power factor is added. In other words, from the viewpoint that usage efficiency of the equipment will improve with improvements in the load power factor, the basic rate is premised on a standard power factor of 85%. If the power factor is higher than the standard percentage, a discount of 1% of the basic rate will be given for each 1% exceeding this value. If the power factor drops below the standard percentage, 1% of the basic rate will be added for each 1% below this value. Parallel capacitor are therefore installed as there is the possibility of reducing electric power charges by improving the load power factor.

(iii) Selection of the Capacity of the Parallel Capacitor

The capacity of the parallel capacitor is calculated from the power factor before the improvement and the power factor after the improvement. The desired percentage of the power factor after improvements is decided by taking into consideration the amount of reduction in the power rate and the cost of installation of the parallel capacitor. In other words, the parallel capacitor capacity K [kVA] will be as shown below.

$$K = P\{(\sqrt{\frac{1}{\cos^2\theta_1} - 1} - \sqrt{\frac{1}{\cos^2\theta_2} - 1}) \times \frac{1}{\alpha}\} \qquad (3\text{-}2\text{-}5)$$

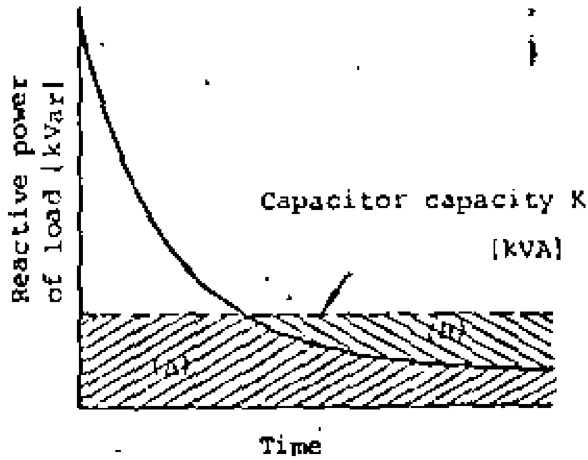
P : Average power [kVA]

$\cos\theta_1$: Power factor before improvements

$\cos\theta_2$: Power factor after improvements

α : Usage factor

α here indicates the percentage of usage of the parallel capacitor in fluctuating loads such as in the electric railways and is obtained from the reactive power - time curve in Fig. 3-11.



A: Range in which the capacitor is used effectively.

B: Range in which the capacitor is not used.

α: Usage factor of the capacitor.

$$\alpha = \frac{A}{A + B} \times 100 [\%]$$

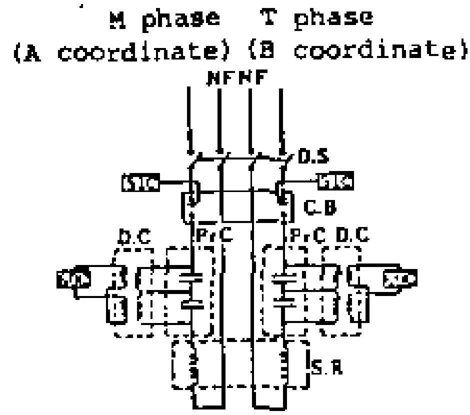
Fig. 3-11 Reactive Power - Time Curve

(iv) Composition of the Parallel Capacitor

As shown in Fig. 3-12, the parallel capacitor are generally installed on the busbar immediately below the secondary of the feeding transformer in the substation for each M phase (A coordinate) and T phase (Teaser) (B coordinate). The series reactor for M phase and T phase is a unit construction.

(d) Arrester

The arrester should be suitably selected after studying the rated voltage, spark over voltage, limited voltage and insulation. As to types of arresters, we have the carbonized silicon (Sic) element type which requires a series gap and the zinc oxide (ZnO) element type not requiring the series gap. Construction of both elements and voltage - current characteristics are shown in Fig. 3-13. As may be discerned from



DS: Disconnecting switch

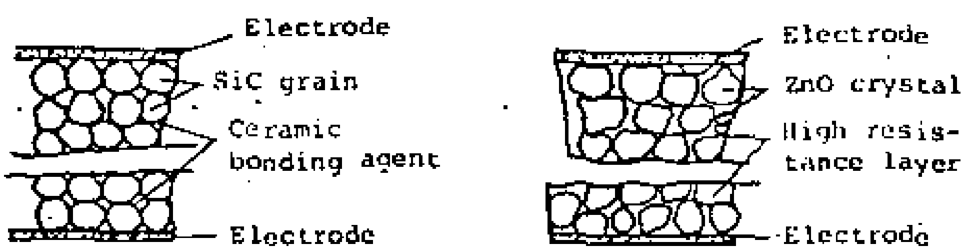
SR: Series reactor

CB: AC circuit breaker 51C } Protective relay

PrC: Capacitor unit 60C

DC: Discharge coil

Fig. 3-12 Composition of the Parallel Capacitor



(a) SiC element (b) ZnO element

Structure of the element

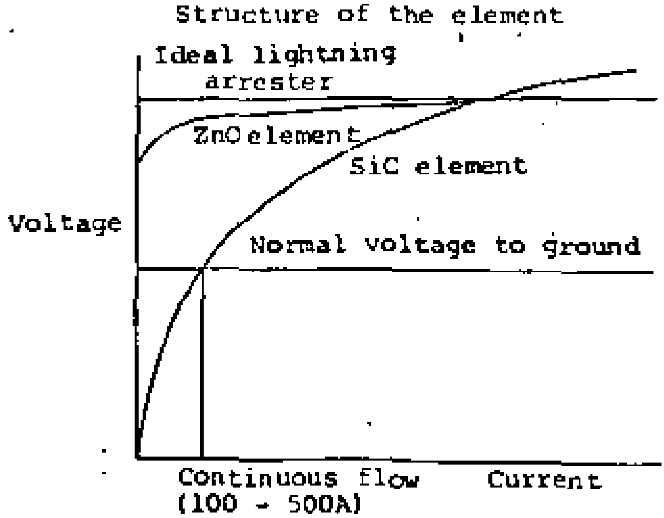


Fig. 3-13 Voltage - Current Curves of SiC and ZnO Elements

the diagram, the zinc oxide element type possesses almost ideal characteristics for arresters. This type has numerous advantages such as the capability of withstanding multiple lightning, withstanding soiling and the possibility of hot-wire washing, and moreover, is compact and light in weight.

(5) Control Unit

a. Power-board

Most of the power-boards used are generally open cabinet self-standing type of steel panel construction and is provided with a protective relay, switches, indicator lamps, indicator, test terminals, control wire connecting terminals and auxiliary relays. These devices are connected by means of an electrical interlocking circuit which carries out logical processing of the functions indicated in the essentials of electrical interlocking. When the logic to be processed is complicated and great in volume, not only will the auxiliary relay be used but sequencers may also be used. JNR is using sequencers in its Tohoku and Joetsu Shinkansen.

Also, when the substation is operated by centralized remote control, unmanned operation is normally carried out. However, it will be necessary to provide a changeover switch for the operating mode to enable manned operation of the power-board in the event of failure of the remote control unit. As shown in Fig. 3-14, JNR has standardized the composition of its power-board by systems taking into consideration functions and operations.

b. Remote Control Unit

The system of centralized substation control from one control point in which centralized monitoring and control is carried out on a number of substations from a remote control unit is highly more rational than for manned operation of each substation from the following standpoint.

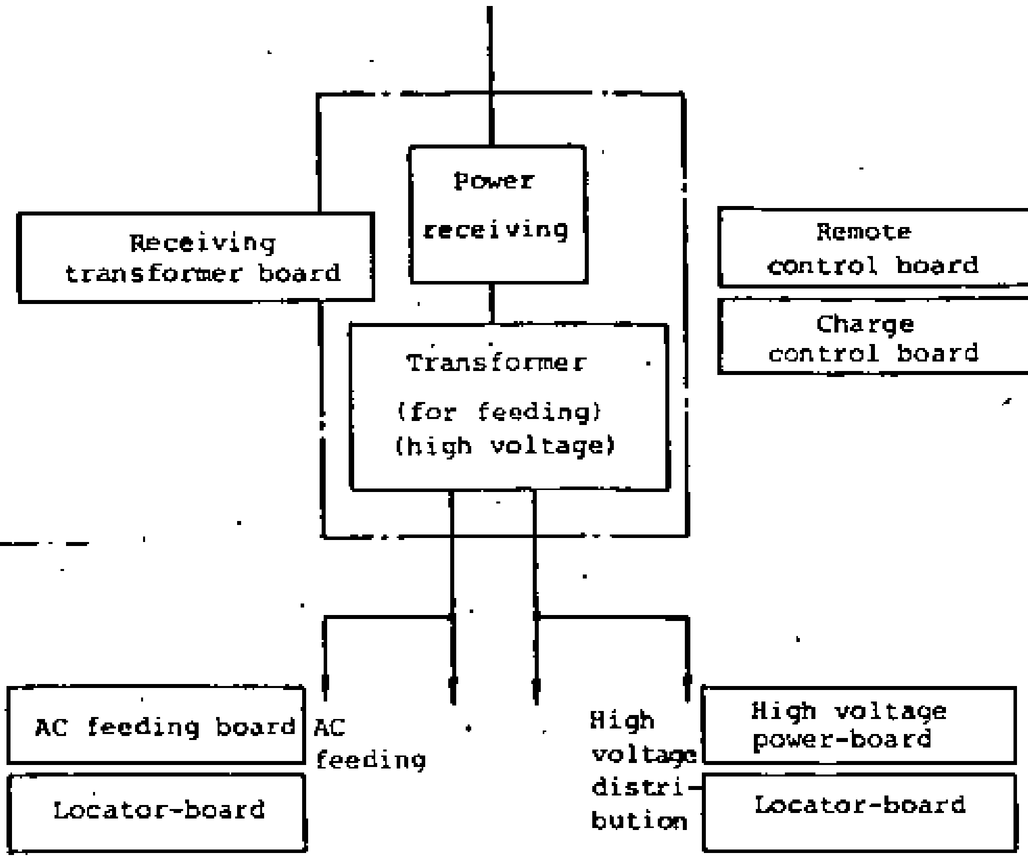


Fig. 3-14 Composition of the Power-Board in an AC Substation

(a) Manning of substations unnecessary

(b) Savings on labor expenses due reduction of operating personnel.

(c) Improvement in efficiency of operating the power system with centralized monitoring and control and also of processing accidents.

JNR is planning modernization of its electric power dispatch work by promoting a centralized control system with 1 management and 1 control place as a rule.

Conditions that a remote control unit must fulfill are as follows.

(i) Action must be absolutely positive with high reliability and no erroneous operation.

(ii) The number of communication circuits to be as few as possible.

(iii) Time required for signal transmission to be as short as possible.

(iv) Handling to be simple and maintenance easy.

(v) Price to be low

The Railway Technical Research Institute of JNR has developed the B, C, E, F, G, H, K and W type remote control units and are using each according to the features of the system. The general outline of each system is shown in Table 3-5. Items monitored by the remote control unit consist of indicating condition of the devices and serious trouble such as overloads and simple troubles such as drop in air pressure. Control items consist of automatic indication of ON OFF condition of each device, ON OFF of security locks, ON OFF of equipment test and these are automatically indicated at fixed hours together with the amount of power used.

JNR is also striving for a higher degree of modernization in electric power dispatch work by installing a substation interlock system provided with mutually adjacent interlock between the substations on both its Tohoku and Joetsu Shinkansen. It has also broadened its range of automatic control of its power system by developing and using an electric power control system (DECS) composed of the foregoing interlock system, a W type remote control system capable of transmitting lengthily worded maintenance information to the remote control unit, and a power information processing system using computers to process power information received from the foregoing lower systems.

Table 3-5 Outline of the Principal Remote Control Units of the Japanese National Railways

System name	Control style	Number of linked lines (plan)	Selection style	Controlling distance [km]	Number of places controlled	Number of items selected for 1 control place	Time required for 1 connection [ms]	Principal elements composing the circuit
JNR Type B	Centralized system (1:n)	4	Pulse code (2 circuit polarized combination system)	100	n=5	24	Approx. 2,500	Electromagnetic type relay (Wire spring relay)
JNR Type H	Centralized system (1:n)	4	Pulse code (Tone channel FS modulation 1,200	1,050	n=6	64	Approx. 100	H_2 Type: Transistor H_3 Type: IC
JNR Type K	Simplified centralized system (1:n)	2	Frequency selection (Tone channel)	20	n=5	8	Approx. 1,000	Mechanical oscillator, mechanical filter
JNR Type W	Centralized system (1:n)	4 × 2	Pulse code (Tone channel phase modulation 2,400 B/S)	200	n=14	255	Approx. 200	LSI multi processor

c. Fault Locator

In the case trouble develops in the feeding circuit or electric car, time required to investigate the fault point will be shortened if the fault point can be determined automatically. It will therefore have the advantage of shortening the power off time due to the fault and thus reduce its effect on train operation. The fault locator is a device that was developed for this purpose. The principal fault locators used by the JNR are the following 2 systems. Refer to paragraph 2-4 "fault locator" in relation to the theory.

(a) Reactance Measuring System

This is a system in which the reactance of the feeding circuit from the fault point to the point where the fault locator is positioned is measured and the measured value transmitted to the control office through the remote control unit. The supervisor at the control office then determines the fault point by checking a reactance map of the feeding circuit that were initially measured. This is an extremely useful system for simple feeding systems as the reactance of the feeding circuit and the distance are linearly proportional.

(b) AT Neutral Current Ratio Measuring System

In this system, the current is measured at the intermediate point of each AT circuit and this value is transmitted to the control office through the remote control system.

In the control office, computers automatically process operations and displays the number of kilos to the fault point on a CRT for the supervisor. The basic principle of this system is that the fault point in the section between AT systems will be in proportion to the ratio between the boosting current of the AT on both sides. Short-circuiting between the contact wire and the feeder can therefore not be measured. Due to the fact that practically all of the short circuit fault develops between the contact wire and rail since there is considerable space between the contact wire and the feeder on the poles, JNR is using this system in its AT feeder sections. The range of accuracy is considerably high and indicates in units of kilometers with errors of only several hundred meters.

d. Control Power Source

As the functions of the power-board and the remote control unit will come to a stop if the control power source discharges, the control power source governs the life or death of the control system. The power source must have sufficient voltage and capacity to operate the equipment positively and must be of high reliability. The general practice is therefore to provide a dual system AC power source using the power source from the control transformer and a spare power source.

For the DC power source, the general practice is to provide a floating charge system by connecting the battery control panel and the batteries in parallel. JNR is using a thyristor with the battery control panel to provide it with an automatic voltage adjusting function.

Enclosed type cubicle construction is used for small capacity batteries to reduce the space of the power-board room. Battery charging equipment is stored in the upper portion of the panel and batteries in the lower portion.

(6) Noise Countermeasures

If noise generated by the equipment in the substation affects the living environment of the residents in the area, that is, if problems of noise pollution arise, necessity will arise to reduce this noise by executing effective but economical soundproofing countermeasures at the source of the noise. Noise countermeasures will be studied in relation to the following devices.

a. Transformer

A typical device that is the source of noise in the substation is the transformer. The principal element in the cause of transformer noise is vibration originating from the magnetostriction of the iron core. Although the transformer noise level will differ in relation to the capacity, voltage and method of cooling, it is generally within the range of 70 ∿ 95 phons. It will therefore be necessary to lower this noise to the level requested by the area residents and the method generally used is to enclose the noise emitting transformer with concrete walls. Methods available according to the level of reduction necessary are to completely enclose the unit in a soundproof structure and to partially enclose it with walls. In noise counter-measures, appropriate designing should be carried out by studying the following items.

(a) Attenuation of Noise due to Distance

Attenuation of transformer noise due to distance may be calculated by the following equation.

$$dB_d = dB_s - 4.4 - 20 \log \frac{d}{\sqrt{A \cdot H}} \quad \cdots\cdots\cdots\cdots \quad (3\text{-}2\text{-}6)$$

dB_d: Noise value [phon] at a point d meters away from the measuring point of the noise source

dB_s: Noise value [phon] at noise source measuring point

d : Distance [m] from the noise source point to the measuring point.

$$d \geq K \sqrt{A \cdot H} \quad (K = 1.7 \text{ to } 2.0)$$

A : Width [m] of the transformer as viewed from the measuring point

H : Height [m] of the transformer

As the above method of calculation is not suitable when comparatively close to the noise source, it will be necessary to use separate experimental values in this instance.

(b) Amount of Penetration Attenuation with Walls

Although selection of the thickness and material when designing the structure of the soundproof wall will depend on the difference between the value of the noise level requested by the area residents plus the attenuated noise level due to distance and the value of the noise level generated by the transformer, for practical purposes, the attenuation value of the noise penetrating the wall can generally be obtained from the following equation.

$$T_L = \eta \times \{18 \log (f \cdot m) - 44\} \quad \cdots\cdots\cdots \quad (3-2-7)$$

T_L	:	Penetration loss	[dB]
f	:	Noise frequency	[Hz]
m	:	Area density of the wall	[kg/m^2]
η	:	Compensating constant for noise leakage	

Although η, which is noise leakage through penetrating parts such as bushings and piping due to solid-borne vibration transmitted directly to the wall, will differ according to the type of transformer and the soundproofing construction, it is generally between 0.6 to 0.8. The system of completely enclosing the transformer in a concrete structure is standard procedure with JNR and it has achieved attenuation values of between 20 to 25 phons.

b. Circuit Breakers and Disconnecting Switches

In most cases there will generally be no problem with circuit breakers and disconnecting switches as it will be intermittent noise with low frequency of operation. However, if the frequency of operation exceeds a certain extent, problems may arise with the area residents.

The noise level of circuit breakers is greater than that of transformers and in many cases problems arise particularly with air blast circuit breakers. In substations where noise problems exist, it will therefore be necessary to institute noise countermeasures such as using gas circuit breakers and moreover, housing this in a concrete structure as in the case of the transformer.

Although the noise level of disconnecting switches is generally low, problems may arise when high voltages are used as arcing noise is high when the charging current is released. In these cases it will be necessary to either soundproof the circuit breakers and disconnecting switches by GIS means or build an entirely indoor substation depending on the situation of the site of the substation.

The compressor should also be placed indoors if necessary for noise countermeasures.

3-3 Inspection of the Substation

(1) Maintenance Management of Equipment

Although initial stage trouble is generally prone to arise after start of operation of the equipment, troubles will decrease and it will enter a stable period after elapse of a certain period of time. Accidental troubles only will arise during this period but eventually wear, aging and deterioration of functions will advance with passage of usage time and, after a certain period, the percentage of trouble arising will commence to increase and the equipment will enter its superannuated period.

To enable the equipment to display its functions to the fullest, the following maintenance work and maintenance technology will be necessary to properly maintain the functions of the equipment and thus maintain maximum rate of operation.

a. Maintenance Work

(a) Check and inspection

(b) Lubrication, rust proofing, moisture proofing and repairs including painting

(c) Adjustment and replacement of components

(d) Repairs, remodelling and reclaiming

(e) Measuring, certifying and data recording

The above are all direct type work.

b. Maintenance Technology

(a) Maintenance management technique, management technology of test and measurement methods.

(b) Plans for spare parts, accessories and repair materials and measures for storage.

(c) Preparation of maintenance work standards, manuals, control index and control history.

(d) Plans and execution of stationing and training of maintenance personnel.

The above are indirect management technology.

(2) Maintenance Management Technique

Maintenance can be roughly divided into preventive maintenance and aftercare maintenance. Determining which maintenance method to apply will depend on an economic comparison between the costs necessary to carry out preventive maintenance and the losses that will arise with loss of function of the equipment due to the trouble if aftercare maintenance is carried out. This must be considered for each equipment or system. However, as loss of function is not permitted in most of the equipment in electric railways from the standpoint of securing operational safety in addition to economical reasons, it will be necessary to consider its effect on society from this standpoint.

With the view toward securing train operation and safety, JNR is carrying out preventive maintenance on all equipment except those that do not directly affect train operation. Aftercare maintenance is carried out on these equipment.

a. Preventive Maintenance

Preventive maintenance is maintenance carried out on equipment with deteriorated functions or showing signs of trouble to prevent trouble from arising during operation. Preventive maintenance measures available are periodical maintenance in which inspection and repairs are carried out periodically and occasional maintenance in which inspection and repairs are carried out when deemed necessary.

(a) Periodical Maintenance

This is a management technique in which a set period is provided during which planned stoppage of the equipment is carried out and maintenance work conducted. In this technique, inspection will generally be frequent and a number of maintenance personnel will be required based on the viewpoint of securing and maintaining equipment functions during the period from the initial inspection and repairs to the next planned inspection and repairs.

(b) Occasional Maintenance

This is a management technique in which equipment functions are measured, monitored and checked without setting any particular period and by carrying out maintenance if the functions exceed control limits of a preset index with mutual relations to function. As the idea of this technique is based on reliability engineering, mechanical inspection periods are not set and inspection is conducted when judged necessary to check equipment functions. In general, the number of inspections will therefore be few and the maintenance personnel also few.

b. Aftercare Maintenance

This is a management technique in which the trouble portion is traced after the equipment loses its functions due to the trouble and maintenance work carried out to restore these functions. Although it will not be necessary to carry out preventive maintenance on the equipment if aftercare maintenance is conducted and personnel can be reduced; on one hand, it has the disadvantage of causing the operational ratio of the equipment to become unstable and also result in high losses during stoppage.

To carry out rational equipment maintenance with fewer maintenance personnel, JNR has instituted an "electrical maintenance system modernization program" from 1971. The main points of this modernization program are as follows.

(a). Producing maintenance free equipment (high reliability)

(b) Introduction of centralized supervision system

(c) Introduction of substation inspection motorcar

(d) Application of new management maintenance techniques

(e) Improvements of the maintenance organization

It is also shifting to special maintenance based on a life control system by setting the life of the equipment and a limit value control system with alarm indications in relation to substation equipment also. 1 Point disconnecting switches and gas circuit breakers are being used and substation inspection motorcar are being introduced, and the past regular periodical maintenance is being discarded.

(3) Test and Measurement Unit

a. Substation Inspection Motorcar
(Substation equipment use)

To carry out checks of the power-boards in the substations of the JNR on an automatic basis, a substation inspection motorcar (for substation equipment) composed of measuring equipment installed on a motor vehicle (micro bus) is currently being used in a portion of the sections. (Fig. 3-15)

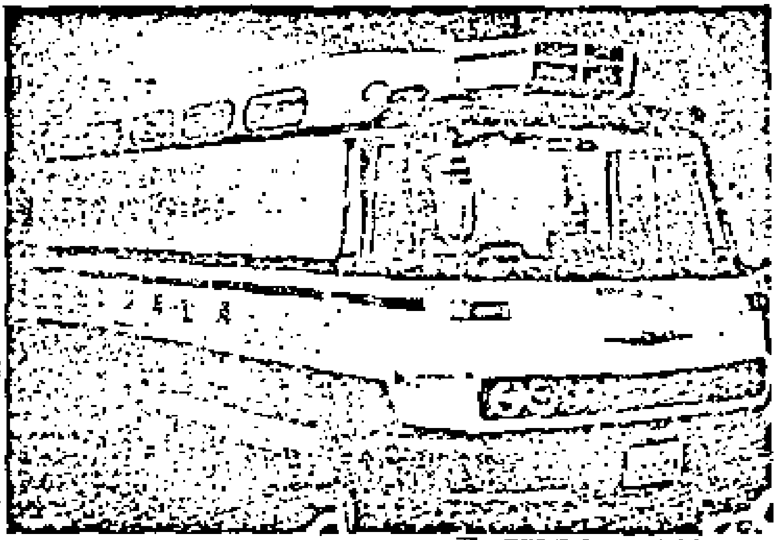


Fig. 3-15 Substation Inspection Motorcar
(for substation equipment)

This system is called "substation inspection motorcar" as the vehicle loaded with measuring equipment displays its mobile characteristics by going around the various substations or the feeder sections and testing and measuring the power-boards. The method used in checking and measuring the power-board is to connect the power-board to the car by means of cables (as couples are used, the power-board can be easily connected or disconnected). Then, by simple operation of the control panel, the protective functions and electrical interlock will be automatically checked against a fixed program and judgement of the overall functions will also be carried out.

Power-board inspection in the past required a high degree of technology, great care and much labor however, by mechanizing these processes, in addition to improving safety, there will be a great savings in labor in inspecting and measuring the power-board.

(a) Performance

(i) Power-boards to be inspected

The power-boards to be checked with this unit are standardized receiving and sending-boards, transformer-boards,

rectifier-boards, main-boards, feeding-boards and high voltage power-boards in substations, sectioning posts and sub-sectioning posts.

(ii) Types of Inspection

This unit is capable of carrying out "overall" inspection of the power-board and "inspection of the protective relay". The former is to check the overall functions of electrical interlock and the latter to check the functional characteristics of the protective relay itself.

* Overall inspection

Figure 3-16 shows the functions of the power-board according to the flow of command. As may be noted from this diagram, the operational commands received from the remote control unit and the electrical input from CT and PT are considered input signals and the ON OFF indications and trouble indications to be sent to the remote control unit after controlling and operating the devices are considered output signals.

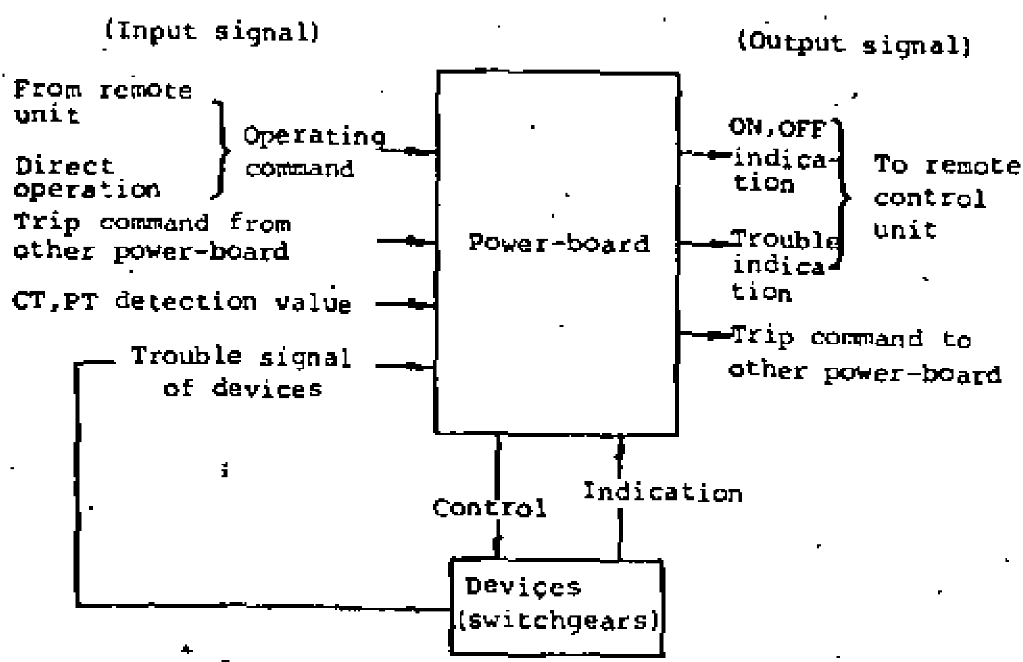


Fig. 3-16 Functions of the Power-board

In the "overall inspection", various types of input signals (operating commands, trouble detection signals, trouble current, voltage etc.) are supplied to the power-board and the overall functions of the power-board are judged by monitoring the output signals from the power-board.

* Protective relay inspection

As the "protective relay inspection" is to test the operational characteristics of the protective relay itself, this check is carried out only when necessary or when abnormality is discovered in the relay during the "Overall Inspection".

In this check, a drive power of arbitrary size is supplied by the test unit to the protective relay and the time required to function is measured. In this instance, adjustment of the amount of driving power and supplying this power are handled manually. All instruments necessary to carry out this operation are provided on the operating-board of the test unit.

(b) Composition of the Test Unit

Fig. 3-17 is a block diagram showing the general composition of this unit.

(i) Operating-board

This board is to start and stop the test and to monitor the test results. This unit is composed of the various switches, indicators, instruments and the reading unit for the inspection punch cards.

(ii) Logic-board

This board automatically advances the check according to a program. The logic control unit is composed of an electronic circuit employing IC.

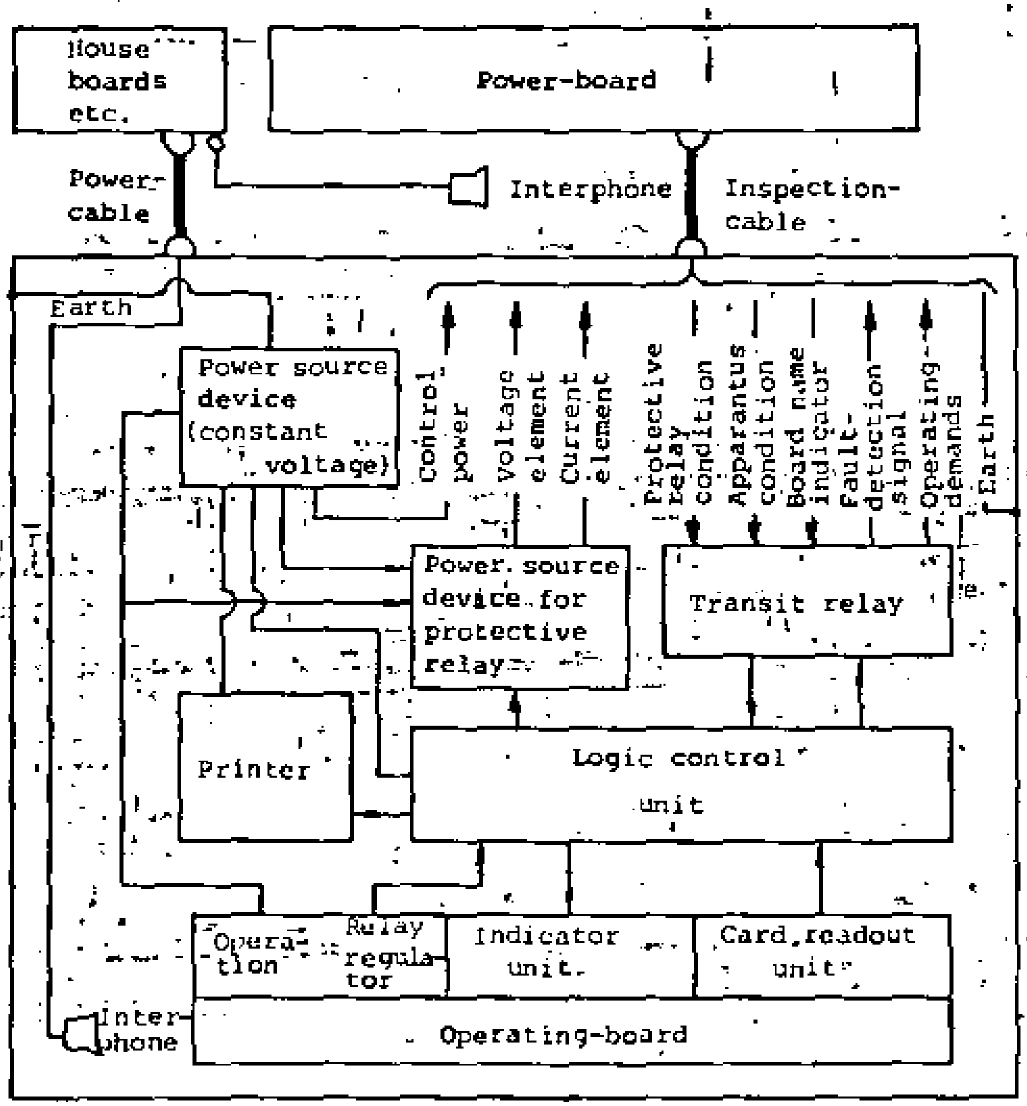
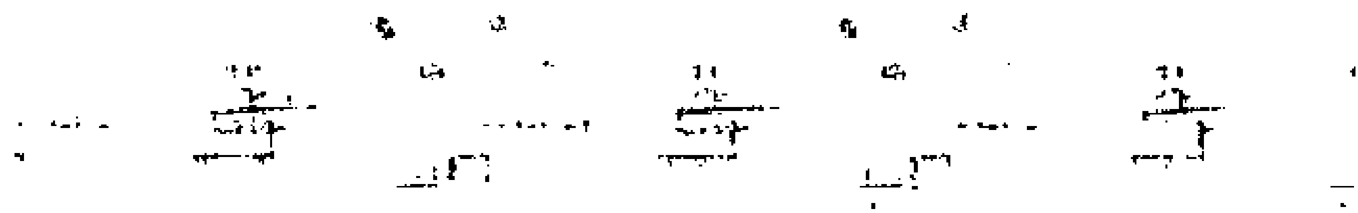


Fig. 3-17 Composition of the Mobile Type Automatic Test Unit for Substation Equipment (Inspection motorcar)

(iii) Power Supply-board

This board configures the various types of power required by the system and is divided into two boards, one to supply drive current to the protective relay and to supply the control power for the power-board and the other to supply power to the IC circuit.



(iv) Connecting Cable

This cable is to connect the power-board to be checked to the test vehicle and is composed of 120 (2 mm^2 × 22 + 1.25 mm^2 × 98) 600 V vinyl wires bundled and sheathed-in an insulator tube.

(v) Chassis

Considering the need to carry out efficient measurements while displaying its mobility by going from substation to substation loaded with test equipment, the vehicle selected was a popular micro bus of the 1,900 CC class.

(c) Method of Usage and Effect

As the protective relay and circuit breakers are operated actually during the power-board check, the main circuits are disconnected from the system and the power supply switch on the power-board is set to OFF when carrying out this check.

However, as control power is supplied to the power-board from inspection motorcar, the power-board will be checked in the same condition as when operating normally.

b. Automatic Verification

JNR has developed an automatic verification system which is more labor-saving than the mobile test vehicle and it has commenced to use this system in the substations of the Tohoku and Joetsu Shinkansen. This system solves the problem on a higher plane of the inability to set desired period of measuring as it is necessary for the test vehicle to move from one area to another and also the problem of the need for testing personnel.

As sequencers are used in the power-boards of the substations in both Shinkansen, a fixed type power-board verification system was developed which uses this information processing functions.

In this system, the relay circuit is continually observed by the sequencer and, in addition to using this to prevent erroneous controls originating in the input and output circuits of the sequencer, it has a unique self-analysis function such as carrying out verification of the protective relay from the control office through the remote control unit.

Automatic verification consists of the regular verification and the periodic verification.

(a) Regular Verification

In regular verification, input conditions to the sequencer of the relay and other devices are continually observed and when an irrational input condition is detected, the name and condition of the input are memorized and DEFECT DETECTED is displayed. Also, as there may be times when the sequencer does not carry out correct control depending on the type of defect, the control output of the sequencer is locked in this instance to prevent erroneous operation. In this manner, the functions in the regular verification are of extreme importance in improving the reliability of the control unit including the sequencer.

(b) Periodic Verification

Periodic verification is a system in which the protective relays and trouble relays of designated circuits are activated in successive order based on start commands from the operating board or the power information processing system and the action of these relays judged good or bad. In the case of the protective relay, the operating time and results of good or bad judgement are memorized in the sequencer and, in the case of the trouble relay, the name of the defective relay is memorized.

It will also be possible to measure the opening and closing time of the disconnecting switches and circuit breakers at the field post of the substations. In other words, if the devices are opened and closed in test condition, the operating time is automatically measured and the measured results and good or bad judgement for each operation are memorized in the sequencer unit.

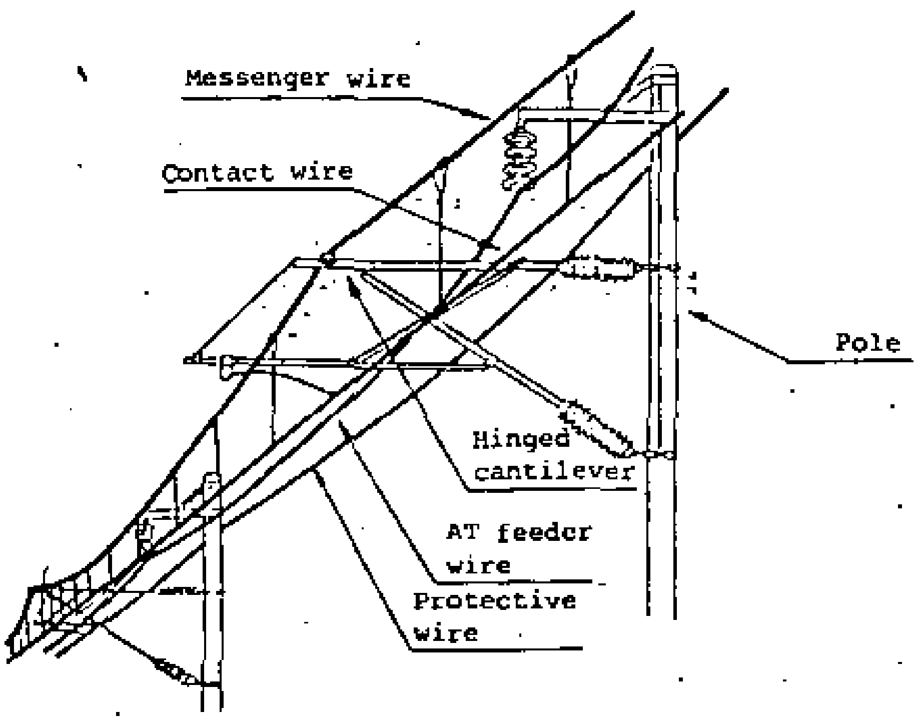
This system is a stationary substation type and moreover verification by remote control is also possible. As verification can be carried out at any time necessary and, as there will be no need to go to the site to carry out the process, the effect of this system on maintenance is extremely great.

The various data obtained from automatic verification are stored in the sequencer and this data is transferred to SMIS upon receiving transfer demands from the power information processing system after first communicating this to the control office. Overall processing of this information is then carried out in the SMIS.

CHAPTER 4

OVERHEAD CONTACT SYSTEM

The overhead contact system for electric rolling stock is an installation provided to supply power to electric rolling stock and basically comprises supports, feeder wire, protective wire and catenary line. The support includes a foundation, a pole, a hinged cantilever, a cross-arm and so on while the catenary line generically represents an assembly consisting of the messenger wire, the contact wire and the hanger.



The composition of overhead equipment for AT feeding system is as shown in the above diagram. Needless to say, this structural arrangement as well as the pole equipment should be made different if the feeding system is different.

Construction of the support is in most cases determined by the climatic conditions in the district and that of the catenary line determined by the operating conditions of electric rolling stock.

In the following are discussed some of the elements that should be taken into account for making such a structural selection.

4-1 Current-collecting Characteristics of Catenary System

Construction of the catenary system in JNR can be roughly classified into two types, one for the conventional lines and the other for the Shinkansen. For the conventional lines, there are further variations, each selectively used to meet such specific local requirements as load conditions and train speed and the environmental conditions of the district (especially the weather condition as strong wind prevails). Used with the Shinkansen is the overhead system especially featuring superb performance in high-speed operation.

Further, it should be so constructed that it can provide good current-collecting characteristics for long-term operation, and its capability to perform safely may not become impaired (due to deformation caused of wind, wear of the contact wire, and temperature difference between summer and winter, or due to accumulated fatigue of each catenary line member).

In view of the above, the factors which may be used to evaluate the current-collecting characteristics include:

(1) Contact loss
(2) Contact force between the contact wire and the pantograph
(3) Uplift at the respective portions in the span
(4) Stress of wires and fittings
(5) Deformation of the catenary line caused by wind
(6) Up-and-down movement of the pantograph
(7) Noise and radio wave interference

For each catenary line, these factors should be ascertained by means of theoretical calculations, simulation tests and on-the-site field tests.

4-1-1 Static Uplift of the Catenary Line

(1) Static Uplift near the Central Part of Span

Uplift (y) of load point on the string as shown in Fig. 4-1 can be expressed by

$$y = \frac{\left(\frac{S}{T} - \frac{x}{T}\right)\left(\frac{x}{T}\right)P}{\frac{S}{T}} \quad \cdots\cdots\cdots (1)$$

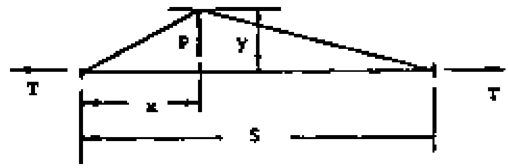


Fig. 4-1 Uplift of the Load Point

where,

y: uplift of the load point (m)

S: span (m)

T: tension of string (kgf)

P: upward force (kgf)

x: distance between the sustaining point and load point. (m)

Equation (1) is holding true in the case of a simple string, but even in the case of the catenary system, in general, in which two or three wires such as messenger wire, auxiliary messenger wire and contact wire, uplift is also calculated as a simple string with little errors, as shown in Fig. 4-2.

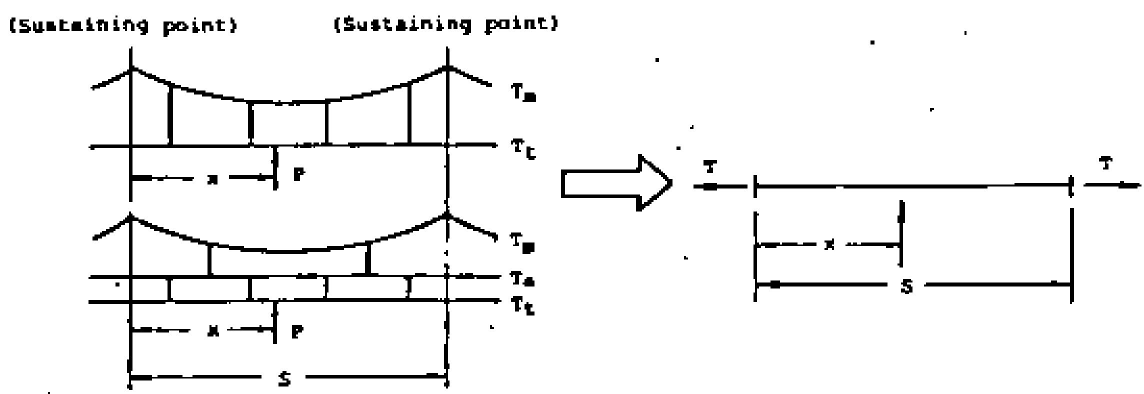


Fig. 4-2 Calculation Model of Uplift of the Catenary Line

That is, the whole tension of wires can be applied substitutionally to Equation (1). However, the static uplift of the catenary in case of load point near the sustaining point cannot be evaluated by Equation (1).

Moreover, the uplift at a hanger point can also be evaluated near the middle part of span, but a calculation value by the Equation (1) will be a little smaller than the real valve between the hangers.

(2) Static Uplift at the Sustaining Point

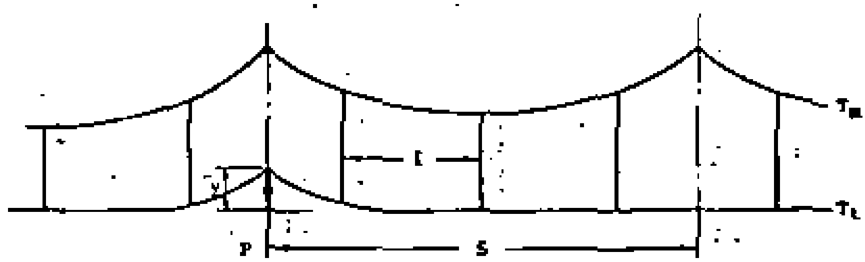


Fig. 4-3 Static Uplift at the Sustaining Point

Static uplift at the sustaining point can be expressed, in balance of force at both hanger points near the sustaining point and the load point according to the model shown in Fig. 4-3, by

$$y = \frac{P \cdot S}{T_t} \cdot \frac{(1 + \frac{T_m}{T_t})}{2(1 + 2n\frac{T_m}{T_t})} \quad \cdots\cdots\cdots\cdots \quad (2)$$

Where,

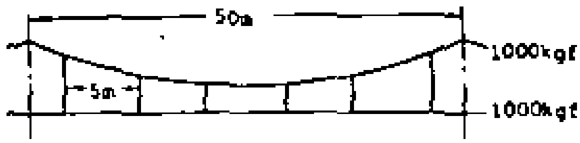
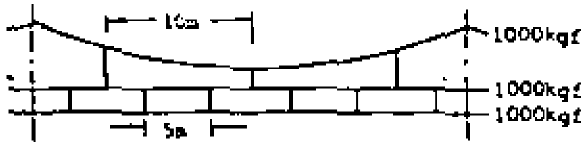
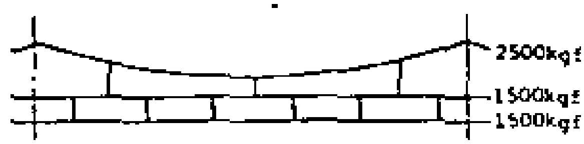
n: number of hangers, ℓ: distance between hangers

Other symbols are the same as in the Equation (1)

A typical static uplift of the contact wire evaluated under the Equations (1) and (2) is as Table 4-1.

Table 4-1 Static Uplift of Each Catenary Line

(When P = 6 kgf)

Catenary System	Schematic Structural Representation	Uplift (mm)	
		Sustain-ing Point	Center of Span
Simple		14	38
Compound		19	25
Heavy Compound		10	14

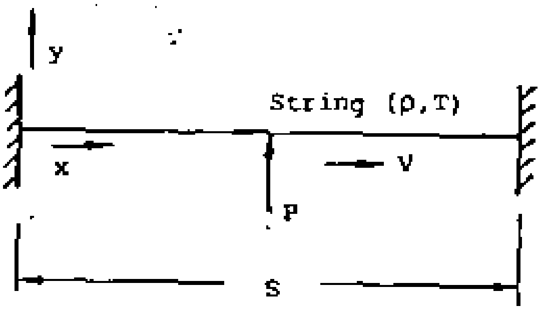
Relations between the static uplift and the current-collecting characteristics are not always definite, but generally a greater static uplift tends to make a dynamic uplift greater, which not only induces fatigue of catenary line members but also lessens clearance of pantograph and fittings, and from the difference of uplift at supporting point and mid-span can be inferred the up-and-down movement of the pantograph.

4-1-2 Dynamic Uplift of Contact Wire

(1) Basic Vibration of Catenary Line caused by Running of Train

Vibration of the catenary line is very complicated in spite of its structural simplicity. In order to ascertain an outline of catenary line vibration, it is important, therefore, to employ a model as simple as possible without losing essence of complex vibration. Followings are the catenary line's behavior when it is regarded as a simple string supported at either ends.

The calculation model is as shown in Fig. 4-4 and equation of the vibration of the string as the following Equation (3).



P: upward force

V: running speed

ρ: line density of the string

T: tension of the string

S: length of span

Fig. 4-4 Model of Catenary Line and Pantograph System

$$\frac{\partial^2 y}{\partial t^2} = C^2 \frac{\partial^2 y}{\partial x^2} + \frac{P}{\rho}\delta(x - vt) \quad \cdots\cdots\cdots \quad (3)$$

$C = \sqrt{\frac{T}{\rho}}$: Propagation velocity of vibration.

Solving Equation (3) as

$$y(t=0,\ x=x) = 0 \qquad y(t=t,\ x=0) = 0$$

$$\frac{\partial y}{\partial t}(t=0,\ x=x) = 0 \qquad y(t=t,\ x=S) = 0$$

the following Equation (4) can be obtained.

$$y = \frac{2P}{\rho S} \sum_{n=1}^{\infty} \sin \frac{n\pi}{S} x \left(\frac{\sin \beta_n t}{\alpha_n^2 - \beta_n^2} - \frac{V}{C} \cdot \frac{\sin \alpha_n t}{\alpha_n^2 - \beta_n^2} \right) \cdots\cdots \quad (4)$$

$$\alpha_n = \frac{n\pi C}{S} \qquad \beta_n = \frac{n\pi V}{S}$$

Equation (4) representing uplift of the catenary line may be expressed as shown in Fig. 5 as sum of the static uplift and the amount equivalent to free oscillation of the string.

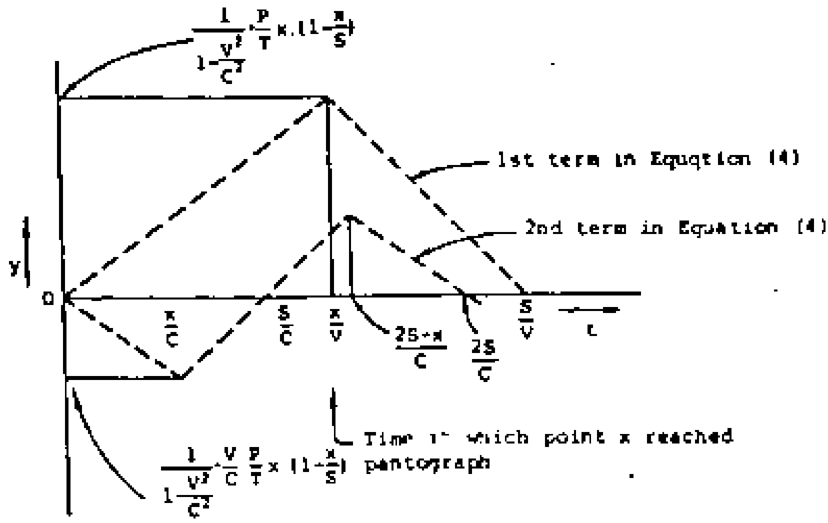


Fig. 4-5 Graphicalization of Equation (4)

Thus the uplift at the arbitrary point x can be obtained in a simple figure or as an algebraic sum. For example, the maximum uplift at x = S/4 can be obtained when the 1st and 2nd term of Eq. (4), x/V (x = S/4) and (2S-x)/C (x = S/4) respectively, are timingly coincided with.

$$\frac{S/4}{V} = \frac{2S - \frac{S}{4}}{C}$$

then, $V = C/7 = 14.3$ (m/s) 51 [km/h]

when let C be 100 (m/s)

Thus amount of the uplift, Y, can be obtained as

$$y = \frac{1}{1 - \frac{14.3^2}{C^2}} \{ \frac{P}{T} \cdot \frac{S}{4} \cdot \frac{3}{4} (1 + \frac{14.3}{C}) \} = 15 \text{ mm}$$

Fig. 4-6 compares the theoretical value with the experimental value for the catenary system with a large diameter (M: St 240mm^2, 2,500 kgf, Ax: PH200mm^2, 1,500 kgf, T: Gt 230mm^2, 1,500 kgf).

As seen from Fig. 4-6, the two sets of values coincide well which are sufficiently satisfactory for practical use of the results obtained from the theoretical equation.

By applying Equation (4), furthermore, a highly accurate analysis is done regarding the remaining vibration of the catenary system, the vibration of catenary system caused by several pantographs, overlapping, and the vibration of crossover etc.

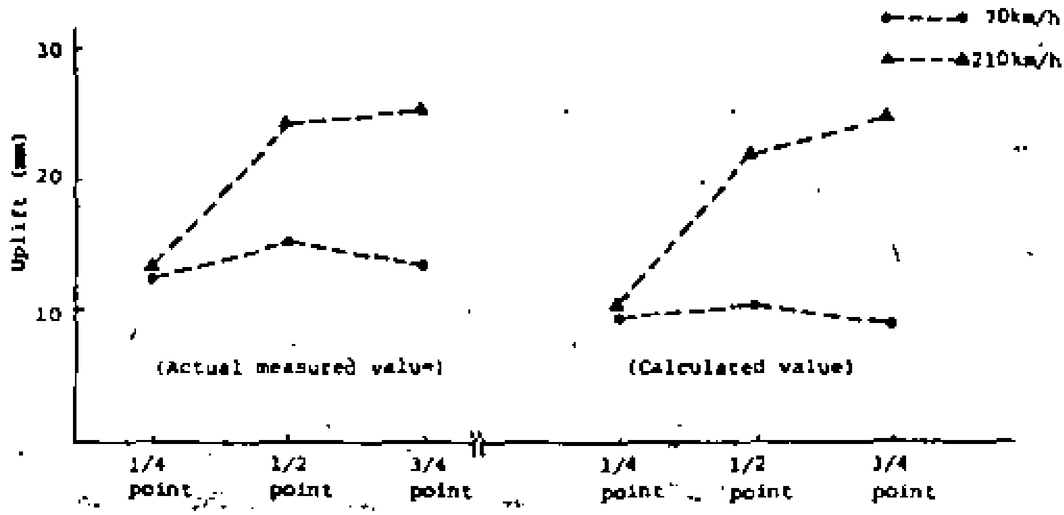


Fig. 4-6 Comparison of Actual Measured Value with Calculated Value

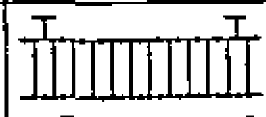
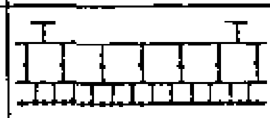
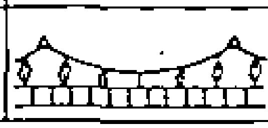
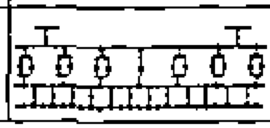
(2) Computer Simulation

In addition to the theoretical calculation method above, JNR does a great deal of analysis through computer simulation for solving complicated phenomena of current collection such as in the case of overlapping, hard spots, and deformed catenary systems.

A catenary line is composed of such fittings as droppers and hangers attached to wires such as contact wires and messenger wires, etc. Also the pantograph is a complicated assembly of a slider contacting the contact wire, a pan, retaining springs, a main frame, main springs, and dampers, etc.

It is almost impossible to analyze such complicated structures as they are, while the simulation method enables us to analyze the system as it is. For this purpose, a suitable model is therefore required. The following Fig. 4-7 illustrates the models of a main overhead system and a pantograph.

The most important thing in a simulation method is how well reality can be expressed; for this there is no other way than comparison with the test results using an actual vehicle.

Kind of system	Real installation	Analyzed model	Code
Simple - Heavy Simple			N.S H.S
Stitched Simple			S.S
Compound Heavy Compound			N.C H.C
Composed Compound			C.C

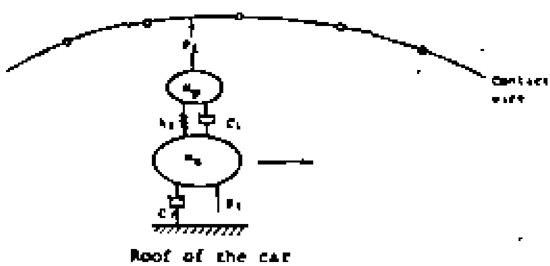


Fig. 4-7 Simulation Models of Overhead Contact System and Pantograph

Fig. 4-8 illustrates a comparison of the measured value by test with the result of simulation of the displacement of the crossover (main line and side line) in case of varied tensions of the overhead system. The results show how well the sets of oscillations coincide. The simulation method is firmly established with such a confirmation. Using this method, research is being done on the influence of speed, distance between pantograph and uplift on the overhead system. We are able to calculate the contact loss ratio, the pantograph's up and down motion, the contact force as well as the uplift through the simulation method, which is presently become an advantageous step in finding out the characteristics of the dynamic behavior of overhead system and pantographs.

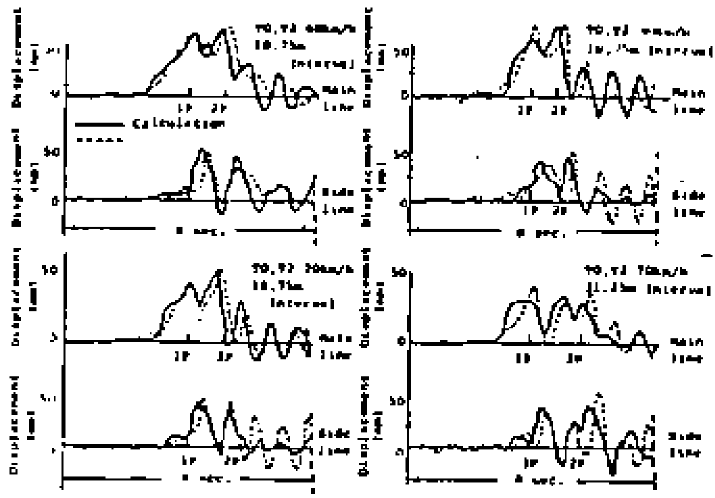
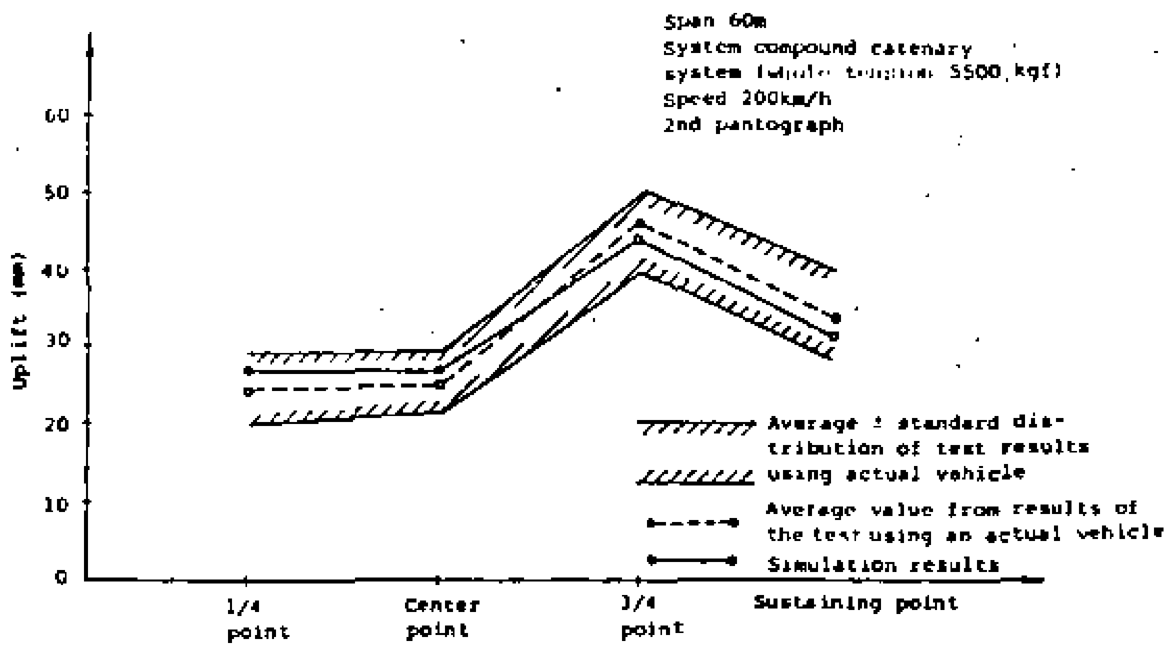


Fig. 4-8 Comparison of Measured Value with Simulation

For your reference, some of the analyses made by the simulation method are illustrated below.



Position within the span

Fig. 4-9 Measured and Simulated Uplift Values of Heavy Compound Catenary System

Fig. 4-8 shows a comparison of the uplift overtime, while Fig. 4-9 is a comparison of the maximum values of uplift at each position. In either case it can be seen that they coincide well with the measured values.

Fig. 4-10 illustrates a comparison of overhead systems used in JNR conventional lines through the simulation method. The uplift of the contact wire with high tension system is considered to be smaller than other systems, with less oscillation and to have a small high and low differences in the pantograph motion showing a smooth current-collection. It can also be seen that the vibration is more or less amplified and the variation of contact force becomes bigger by successive pantographs.

(3) Examples of Measured Data on Running Test

Figs. 4-11 and 4-12 illustrate examples of the measured data on simple catenary system and direct suspension system obtained by running a vehicle. The items measured on both systems are the locus of the pantograph, the contact loss, the contact force, the uplift and stress of the contact wire, etc., each being measured in accordance with their test purposes.

Measurements for the test were done by loading a real pantograph on the car applied of D.C linear motor, weighing about 3,000 kg called the Testing Power Collection System by which a real pantograph can move along a real overhead system for the test. The test performed by this device, which is now applicable only for running the car with one pantograph, makes it possible to change the speed, the pantograph upward force and the conditions of the overhead system.

Fig. 4-13 shows a comparison of the simple catenary system with the direct suspension system regarding the relations between speed and contact loss from several test results. There is no great difference between the two up to 120 km/h, but in the case of high speed, the contact loss of the direct suspension system

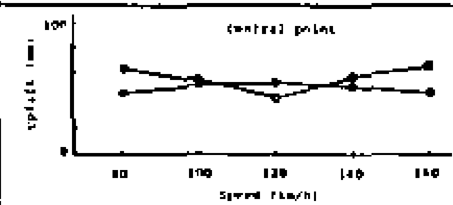
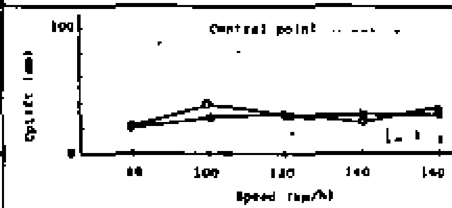
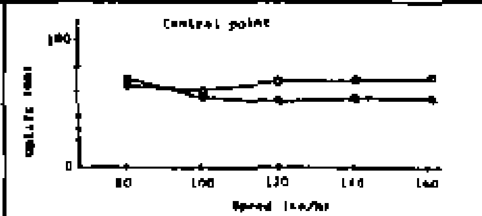
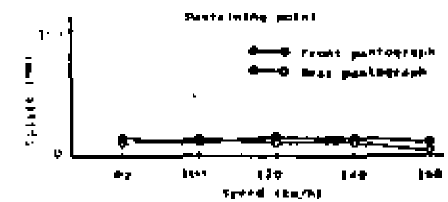
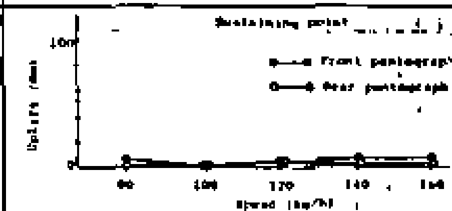
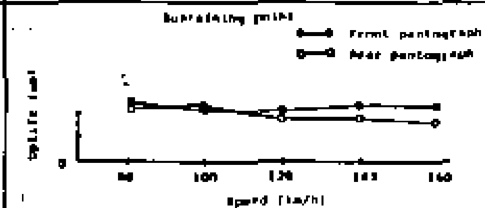
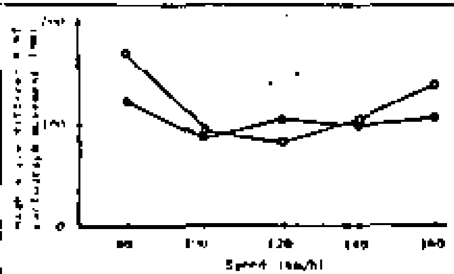
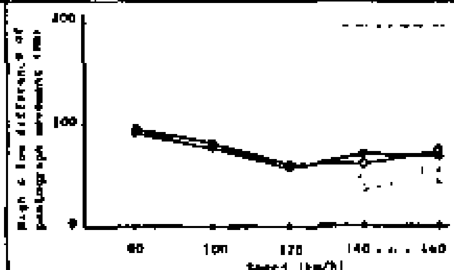
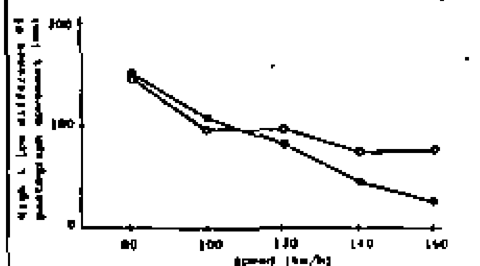
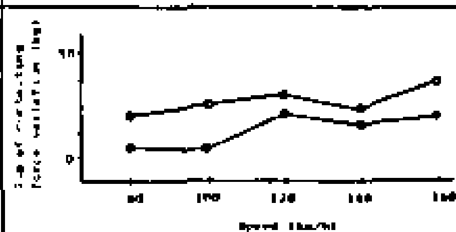
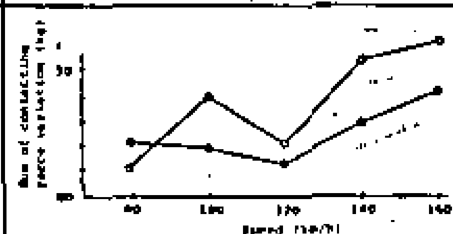
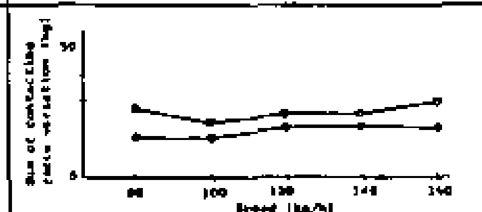
	Simple catenary	Heavy simple catenary	Stitched simple catenary
Calculation conditions	M: St 90mm² 1,000kgf T: Gt 110mm² 1,000kgf Span: 50m Distance between pantographs: 22.5m Static upward force of pantograph: 5.5kgf	M: St 135mm² 2,000kgf T: Gt 110mm² 1,000kgf Span: 50m Distance between pantographs: 22.5m Static upward force of pantograph: 5.5kgf	M: CdCu 60mm² 1,000kgf T: Gt 110mm² 1,000kgf Y line: Cu 38mm², 200kgf 10m Span: 50m Distance between pantographs: 22.5m Static upward force of pantograph: 5.5kgf
Dynamic uplift at the central point of the span			
Dynamic uplift at the sustaining point			
High and low difference of pantograph movement			
Average value of varied contact forces			

Fig. 4-10 Comparison of Overhead Contact System by Simulation

increases. The increased contact loss makes it impossible to supply the electric rolling stock with constant power, which results in producing an arc between the contact wire and the pantograph,-increasing abrasion.of the slider and contact wire. Of the current collection characteristics, the contact loss is very important as is the uplift of the contact wire, so a particularly careful test must be conducted in regard to new types of catenary systems. The JNR has been recently planning to introduce the direct suspension system in order to decrease the electrification cost. The following is an outline of the investigation.

The direct suspension system has messager wires. The demerits of this system are as follows.

(i) Difficulty in laying the system

(ii) Inferiority in current collection characteristics

(iii) Increase in stress of contact wire

The above demerits must be considered, and after confirming such characteristics through various kinds of tests, judgement for its practical use should be made.

(a) How to Set the Tension of Stitched Wire and How to Lay It

In both the case of a stitched simple catenary system and the case of a direct suspension system with stitch wire as shown in Fig. 4-12, it is important that the system height and the tension of the stitch are proper. The direct suspension system here is designed to relieve stress at the sustaining points using stitch wire with a spring.

L_{20} before laying must be a little longer than $L_{10}/2$ in proportion to the system height and wire stretching from tension. Considering this value for Lx,

$$Lx = \frac{h^2}{L_{11}} - \frac{L_{10}(T_0 - T_{11})}{2A_1E_1} - T_{21}\left(\frac{1}{K} + \frac{L_{20}}{A_2E_2}\right)$$

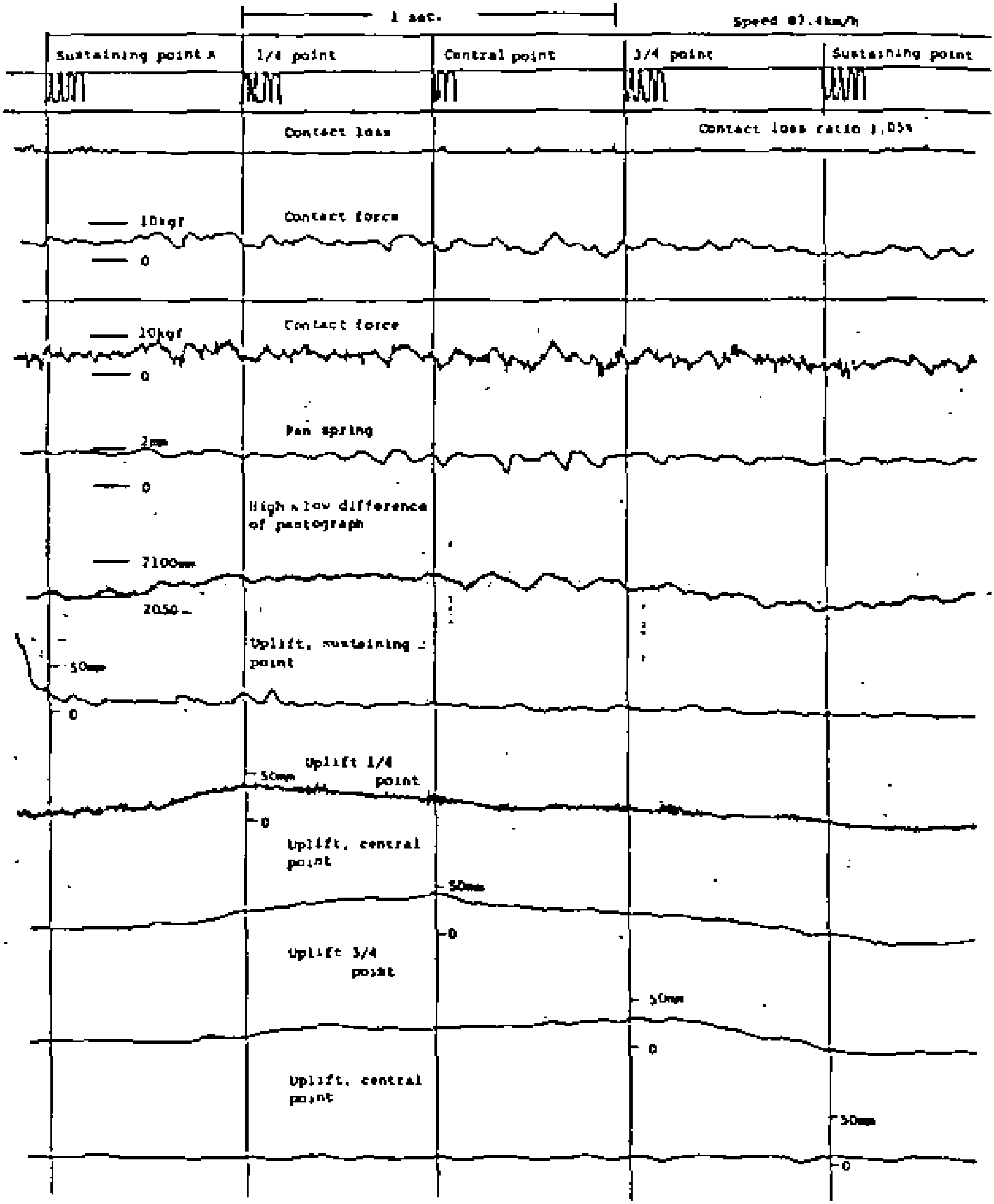


Fig. 4-11 Measurements of Simple Catenary System during Running Test

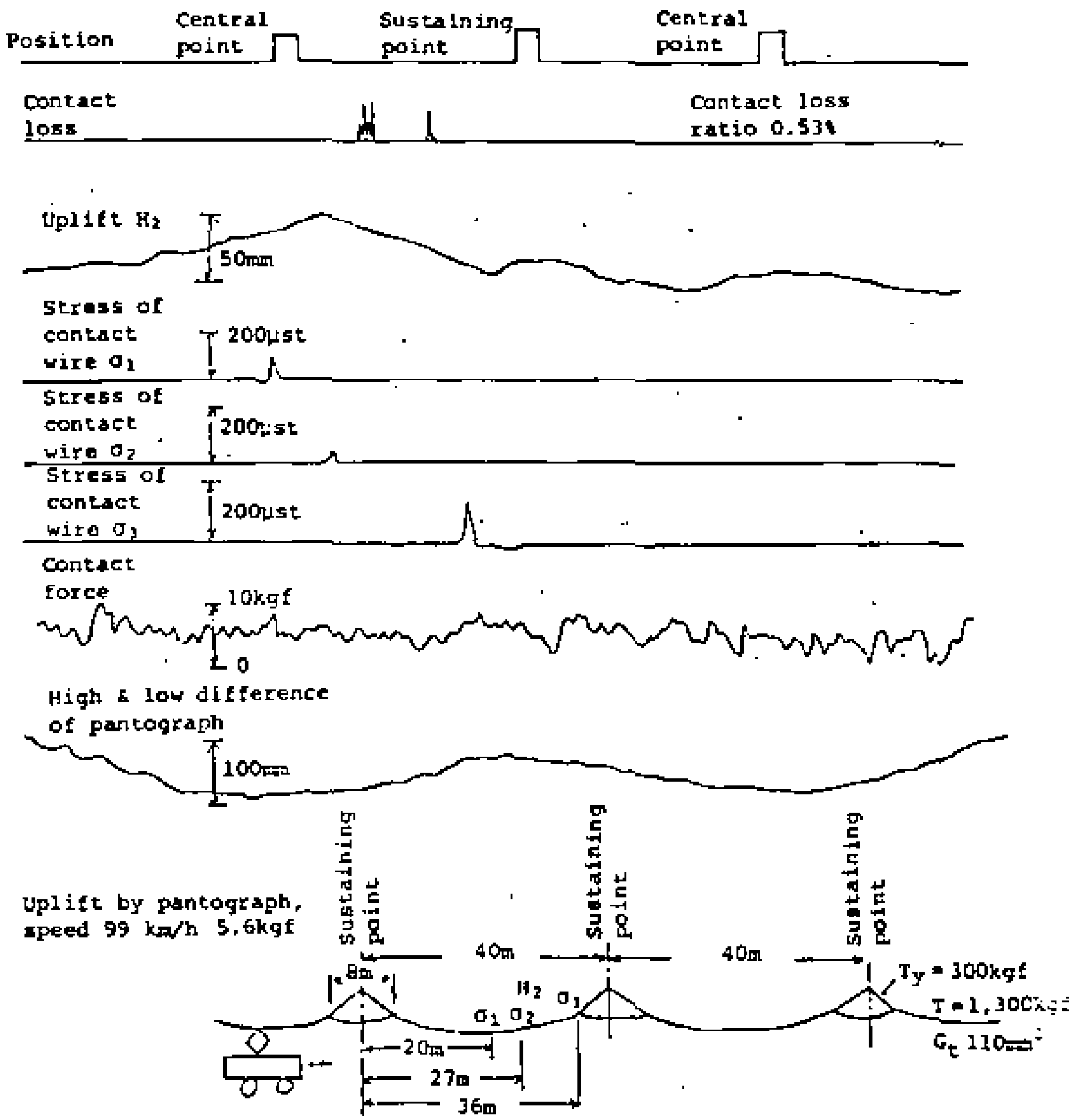


Fig. 4-12 Measurements of Direct Suspension System during Running Test

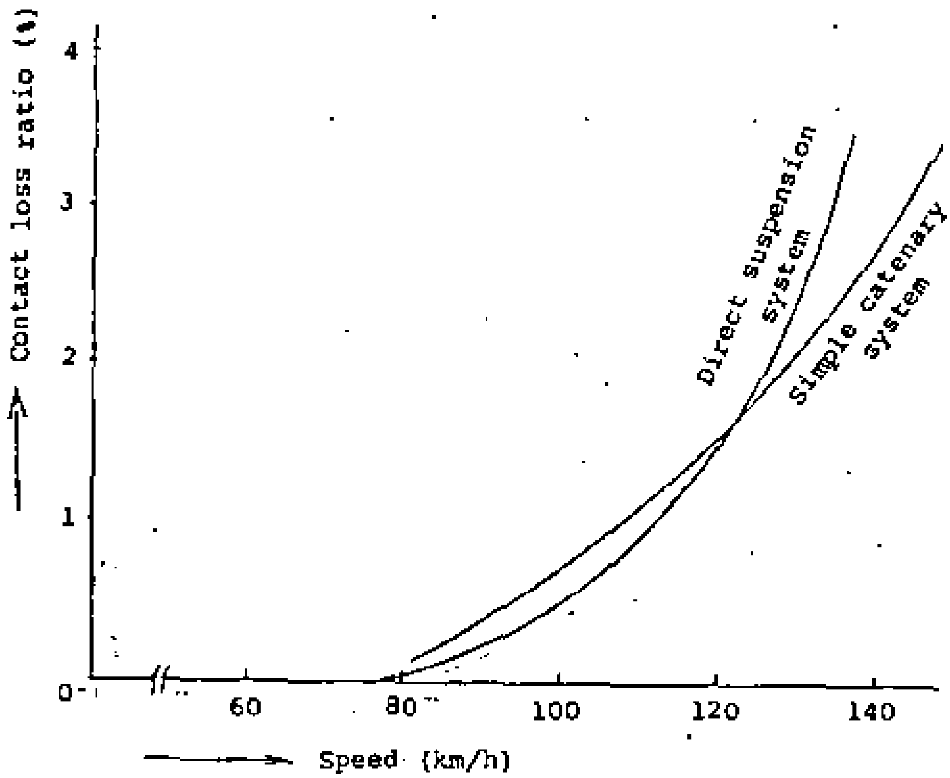


Fig. 4-13 Speed-Contact Loss Characteristics

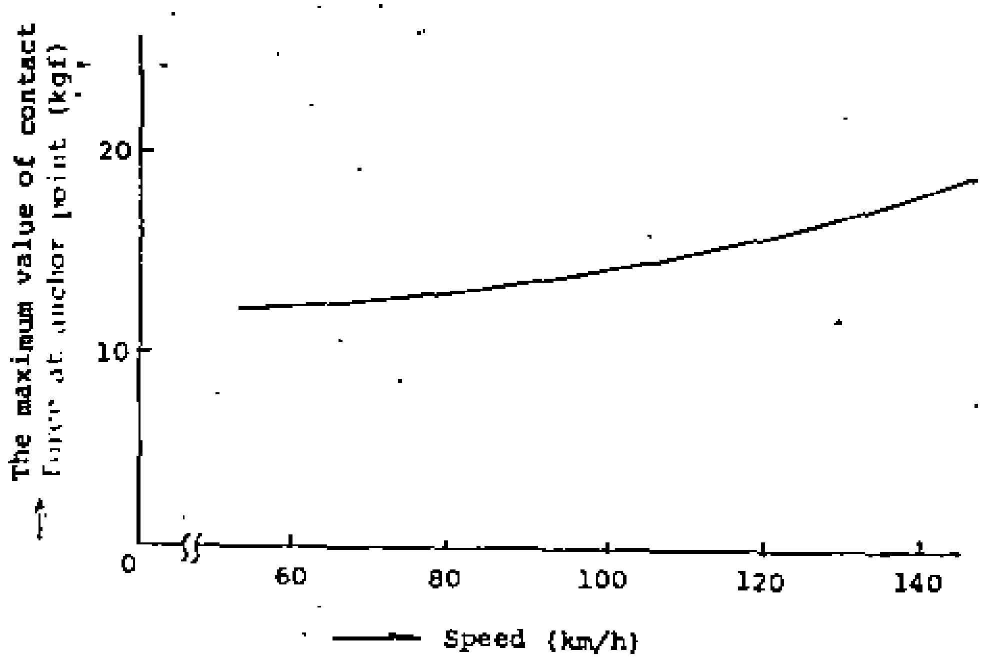


Fig. 4-14 Speed-Contact Force

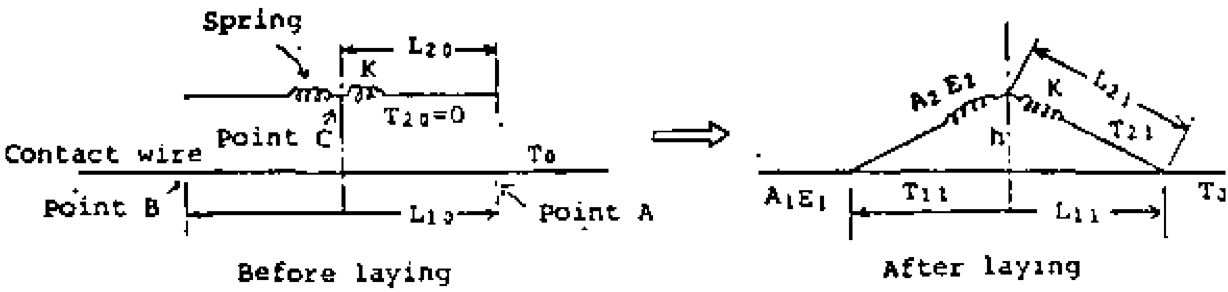


Fig. 4-15 Conditions for Installing Stitch Wire in Direct Suspension System

(b). Measuring the Contact Loss & Contact Force:

Figs. 4-13 and 4-14 show the results of the measurements related to the contact loss ratio of the direct suspension system and the maximum value of the contact force. These results show that both become higher with the speed. We have no authorized allowable limit related to these values, but a proper judgement must be made considering the number of trains (the number of pantographs passing through) and the maintenance conditions.

(c) Stress of the Contact Wire

For judging the conditions of the contact wire fatigue in the following description, the stress of contact wire is measured as shown in Fig. 4-16.

The stress is very different depending on whether the stitch wire has or does not have a spring, and it also increases with increased speed. In consideration of the results of these tests, the JNR has decided to start putting the direct suspension system into practical use.

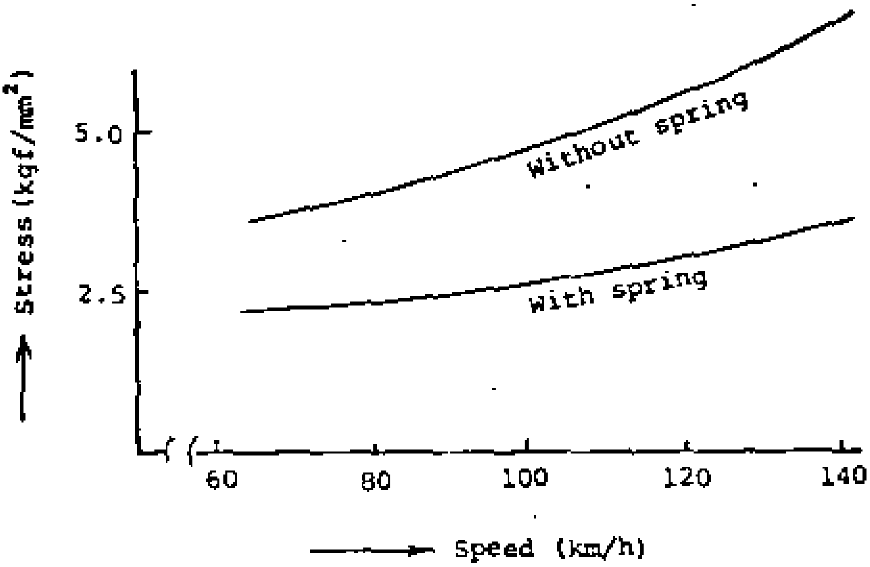


Fig. 4-16 Stress of the Contact Wire

4-2 Overhead Cont_ct System

4-2-1 Supporting Structure and Messenger Wires

(1) Supporting Structure

The JNR has rapidly developed its electrification since the end of World War II, using wooden poles mainly as the supports for the overhead contact system because of a shortage of materials, etc. However, concrete poles have come into use as the standard because wooden poles erected in moist land often rotted within a short period even after creosoting was applied, and because the mechanical strength of the wooden poles wasn't precise. Particularly in Japan, concrete poles are extensively adopted in areas of rich production of lime-stone which is the main component of concrete, and also the cost of concrete poles is extremely cheaper as compared with such steel products as iron poles, H-type steel poles and steel pipe poles, etc. Also maintenance is not necessary for anti-corrosion. Prestressed conrete poles (PC poles) are now being used for almost all overhead contact systems.

When the length and intensity are decided according to the conditions of their use, a proper selection from among the application list is made for their use. In general, the usage conditions of the poles are different, so a great many kinds of poles are required. But we are promoting reduction in production costs by planning standardization of the products and decreasing the number of kinds to a minimum.

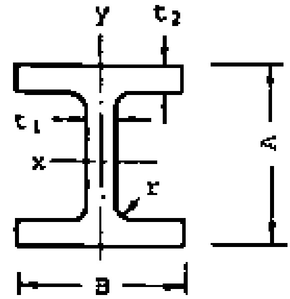
For your reference, Table 4-2 shows a list of applications of the poles for JNR's conventional lines.

Table 4-2 Applicable Poles

Length (m)	Bending moment (kgf-m)			Diameter (cm)
9	5,000			
10	5,000,	6,500		
11	5,000,	6,500,	7,500	35
12	5,000,	6,500,	7,500	
13			7,500	
14			7,500	

The minimum bending moment in this cable is 5,000 kgf-m. This is in close relation to Japanese climatic conditions, which is a major factor for the JNR applying 40 m/s for the calculation of intensity of the supporting structure. Considering the climatic conditions and catenary systems employed in foreign countries, the application of H-shape steel can also be considered as it generally, makes the design bending moment smaller. In this point, we are going to take up a few comparative examples relating to the 2nd class PC poles used for the JNR's overhead contact system and the 1st class PC poles & H-shape steel poles used for power distribution lines.

(a) Characteristics of Poles



Characteristics of H-shape Steel

	H mm	Size mm					Sectional area (cm^2)	Unit wgt. (kg/m)	2nd sectional moment (cm^4)		Radius (cm)		Sectional coefficient (cm^3)		Calculation moment (kgf·m)
	A × B	A	A	t_1	t_2	r			Ix	Iy	ix	iy	Zx	Zy	
I	150 × 150	150	150	7	10	11	40.14	31.5	1,640	563	6.39	3.75	219	75.1	3,600
II	175 × 175	171	174	6	9	12	41.74	32.8	2,300	791	7.43	4.35	269	90.9	4,400
III	200 × 150	194	150	6	9	13	39.01	30.6	2,690	507	8.30	3.61	277	67.6	4,570

Characteristics of Prestressed Concrete Poles

Name	Length (m)	Edge caliber (cm)	Root caliber (cm)	Height of sustaining point (m)	Design load (kgf)	Height, load point (m)	Design bending moment (kgf·m)	Reference weight (kg)	Remarks
P10-19-350	10	19	32.3	1.7	350	8.05	2,818	670	1st class
P10-19-500	10	19	32.3	1.7	500	8.05	4,025	705	1st class
10-35-NS,000	10	35	35	1.7	621	8.05	5,000	1,220	2nd class

(b) The Standard Pole Assembly and Design Bending Moment

The size of each part of the standard assembly for the purpose of calculation of intensity is as shown in Fig. 4-17. Also, Table 4-3 shows examples of calculations of intensity.

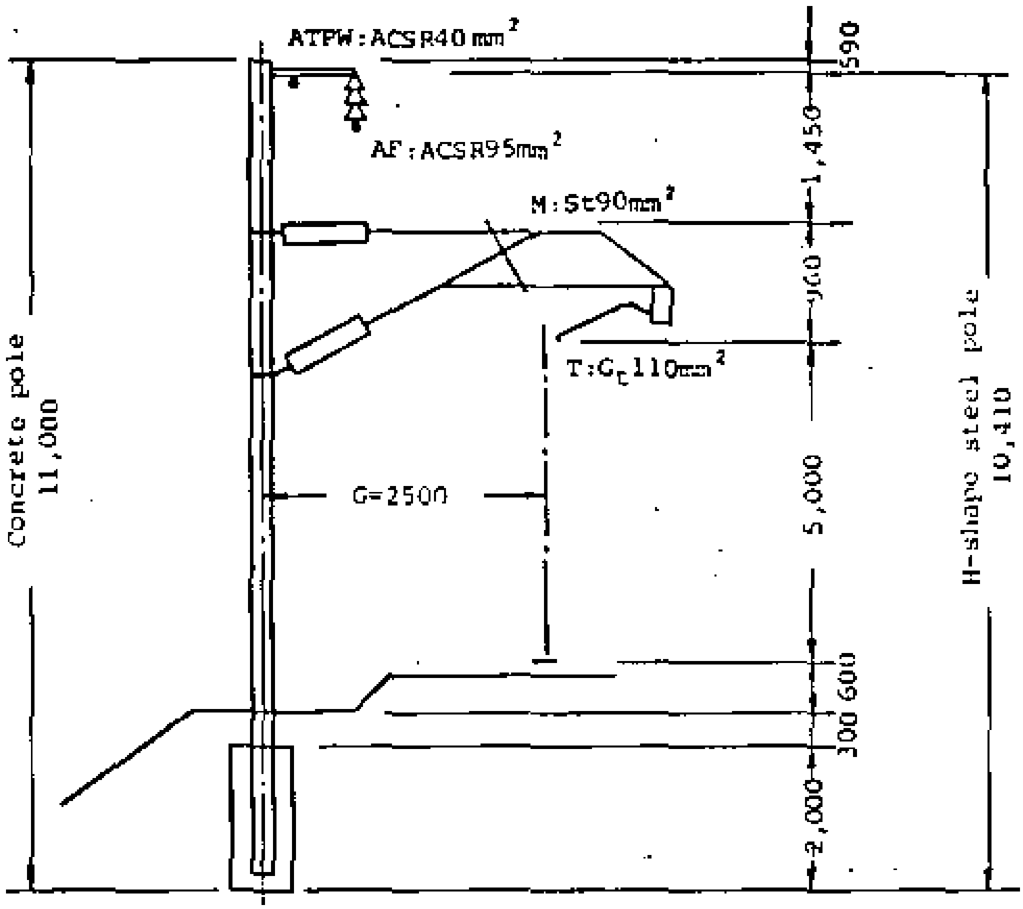


Fig. 4-17 Diagram of AT Feeder Type Standard Pole Assembly (Conventional Line)

In the case of a straight line part or the applicable wind velocity being small as shown in Table 2-1, the application of H-shape steel pole is also fully considered.

(c) Deflection of H-shape Steel Pole

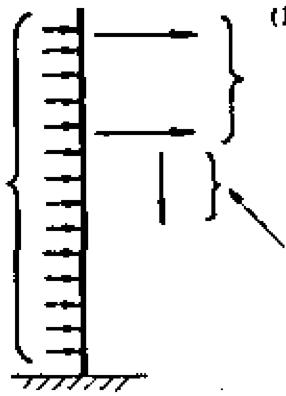
When the wind blows at 30 m/s, as in the JNR's regulations, the poles must not be deflected more than 50 mm at the height of the contact wire so that the contact wire will not come off the pantograph.

Table 4-3 Design Moments

Item \ Wind velocity	R=Straight line S=55m					R=600m S=50m					R=300m S=40m				
	Load (kgf)		Load point	Moment (kgf-m)		Load (kgf)		Load point	Moment (kgf-m)		Load (kgf)		Load point	Moment (kgf-m)	
	30	40		30	40	30	40		30	40	30	40		30	40
(Horizontal load)															
H-pole 150 × 150	138	246	4.1m	566	1,009				566	1,009				566	1,009
H pole 175 × 175	160	285	4.1	656	1,169				656	1,169				656	1,169
H pole 200 × 150	138	246	4.1	566	1,009				566	1,009				566	1,009
P11-19-500	99	176	4.4	436	774				436	774				436	774
P11-35-N5,000	138	246	4.4	607	1,082				607	1,082				607	1,082
Catenary line	71	127	6.48	460	821				460	821				460	821
ACSR 95*	42	74	8.41	353	622	38	68	8.41	320	572	30	54	8.41	252	454
ACSR 40*	27	48	8.41	227	404	25	44	8.41	210	370	20	35	8.41	168	294
(Sideways tension)															
Catenary line						140		6.48	907		223		6.48	1,445	
ACSR 95*						28		8.41	235		40		8.41	336	
ACSR 40*						14		8.41	118		20		8.41	168	
(Vertical load)															
Catenary line	84		2.5	210		76		2.5	190		61		2.5	153	
ACSR 95*	36		1.2	43		34		1.2	41		30		1.2	36	
Hinged cantilever	88		1.3	114		88		1.3	114		88		1.3	114	
(Design moment)															
H-pole 150 × 150				1,973	3,225				3,161	*4,379				*3,698	*4,832
H-pole 175 × 175				2,063	3,385				3,251	*4,539				3,788	*4,992
H-pole 200 × 150				1,973	3,225				3,161	4,379				3,698	*4,832
P11-19-500 (Class 1)				1,843	2,990				3,031	*4,144				3,568	*4,597
P11-35-N5,000 (Class 2)				2,014	3,298				3,202	4,452				3,739	4,905

(Note) The mark * indicates not applicable because the design moment exceeds the tolerance moment.

A test calculation of the deflection of H-shape steel pole is as follows.



As shown in the above diagram, the results calculated for the cumulated deflection caused by the three kinds of load are shown in Table 4-4.

Table 4-4 Amount of Deflection on the Position of Contact Wire at Wind Velocity of 30 m/s

(Unit: mm)

	Kinds of H-shape Steel Poles		
	150 × 150	175 × 175	200 × 15
(a) Deflection due to wind	11.2	8.0	6.0
(b) Deflection caused by concentrated load	25.8	18.4	15.7
(c) Deflection caused by eccentric load	28.7	20.5	17.5
Total	65.7	46.9	39.2

Table 4-4 shows the example of S = 55 m in a straight line, but part of the sideways tension should be further added in the case of a curved line. Although the H-shape steel pole is safe in terms of intensity as mentioned above, attention must be given to its larger deflection. Moreover, another demerit of the H-shape steel pole is that it is weaker than the concrete pole against buckling and twisting.

(2) Hinged Cantilever

Fig. 17 shows a standard pole of a AT feeding system for conventional lines. As you can see from this diagram, the catenary line is supported by the hinged cantilever. By a combination of the hinged cantilever with the automatic tension control system, the tension of the catenary line can always be kept constant. As the increase in the tension of the catenary line due to a change of temperature presents the danger of wires breaking, or a decrease in tension causing deterioration of the current collection characteristics, maintenance is of considerable importance in the management of the catenary line. In order to achieve better current collection characteristics and a decreased amount of maintenance, the JNR uses many hinged cantilevers.

(3) Materials of the Messenger Wires

The ideal messenger wire has the following two qualities.

(a) The contact wire hangs horizontally

(b) A portion of load current flows

Table 4-5 shows a comparison of each quality related to iron and copper alloy messenger wires used at one time or another by the JNR.

Table 4-5 Comparison of Iron Messenger Wire with Copper Messenger Wire

Item	Messenger wire made of iron	Messenger wire made of copper alloy
Anti-vibration fatigue Anti-wear characteristics	◎	○
Current capacity with the catenary line system	○	◎
Wave propagation velocity (of light & high tensionable)	◎	○
Corrosion	○ (Higher anti-corrosion by zinc plating)	◎
Production cost	◎ (Cheaper)	△ (Expensive)
Problems in the process of manufacture	○	△ (Difficulty of manufacturing alloy environmental pollution problem)

Note: ◎ Superior quality ○ Common △ Inferior quality

As shown in Table 4-5, neither the iron or the copper alloy can necessarily be considered the best selection because both have their respective merits and demerits. However, both of them may be judged advantageous under the individual country's special circumstances (for instance, high speed and multi-pantographs, electrical power sources, resources, and environmental pollution problems). The JNR mainly uses iron messenger wires taking these conditions into consideration.

(a) Vibration Fatigue Characteristics

Fig. 18 illustrates typical fatigue curves of iron and copper. Complete care must be taken in the actual selection of the materials because these fatigue curves vary in accordance with the component of the material and the processing degree.

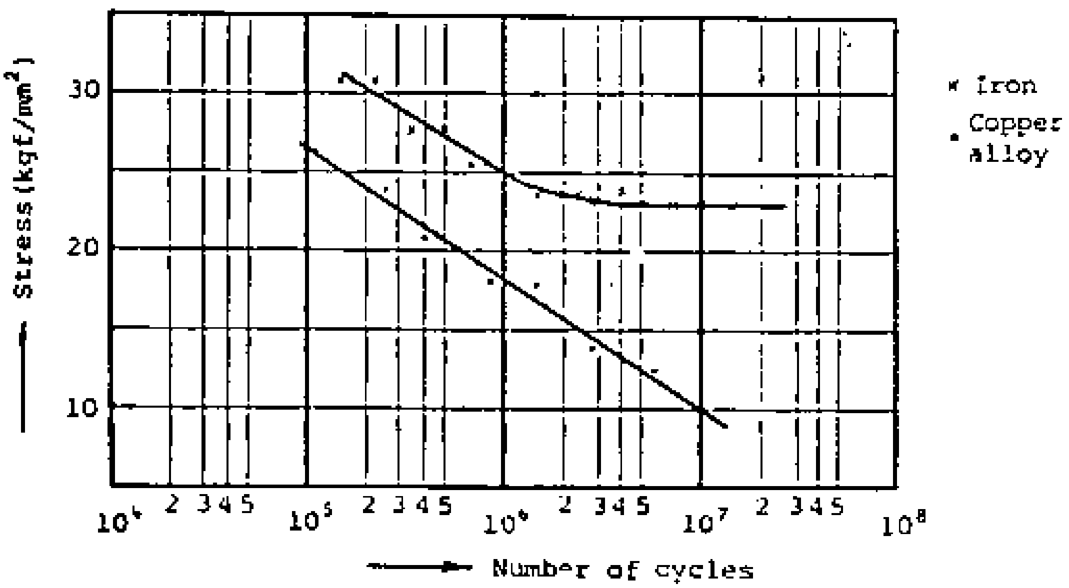


Fig. 4-18 Fatigue Curves (S-N Curve)

The stress which occurs by the passing of a pantograph or by the wind varies according to the overhead system and the speed, but it is actually measured in a range of about 5 to 10 kgf/mm^2. However, it is considered that stress exists in excess of the actual measured value because of the anticipated intensive stress caused by the occurrence of errors at the time of installation, wear or corrosion. Therefore, selection of the material must be made accounting for maintainability and reliability against fatigue.

(b) Current Capacity with the Catenary Line System

The electrical characteristics of the catenary line depend upon the train's driving conditions, which affect two factors, i.e. a rise in temperature of the contact wire and a voltage drop.

The maximum tolerable temperature of the contact wire in the JNR is 90°C considering softening characteristics, stretching characteristics at high temperature, stretching of the contact wire, and the design of the metal fittings. Based on this, Table 4-6 shows the calculated tolerable currents of catenary lines.

Table 4-6 Tolerable Currents of Catenary Lines

Kind of catenary lines			Current capacity (after contact wire is worn) (A)
Messenger wire	Auxiliary messenger	Contact wire	
CdCu 60mm^2	-	Gt 110mm^2 (8.5)	625
St 90mm^2	-	Gt 110mm^2 (8.5)	420
St 135mm^2	-	Gt 170mm^2 (9.5)	505
St 180mm^2	PH 150mm^2	Gt 170mm^2 (9.5)	1,085

Wind velocity 0.5 m/s, Amount of sun-shine 0.1 W/cm^2,
Heat radiation coeffcient 0.9
( ) shows the remaining diameter after abrasion of the contact wire.

In the case of the iron messenger wire, the current capacity decreases much as compared with the copper messenger wire, and considering the intermittent conditions which are characteristic of electric railway load, the peak value of the current capacity in Table 4-6 is several times tolerable. Even under heavy conditions of conventional line train operation in the JNR's A.C. electrification districts (20 kV, BT, average distances between the substations, 30 km), temperatures of contact wires composed of a simple catenary (St $90mm^2$ -Gt $110mm^2$) and a heavy simple catenary (St $135mm^2$ -Gt $170mm^2$) do not exceed the determined values.

However, in the case of an electric locomotive with a large capacity (including connected locomotives) on successive ascending slopes and at a far distance between the substations, the calculation of the catenary line system must be fixed calculating a rise in the temperature of the contact wire in proportion to the load conditions.

(c) Kinds of Messenger Wires and Voltage Drop

Regarding AT feeding system voltage drop very complicated calculations are generally required, so effects of the kinds of messenger wires on voltage drop must be compared on the basis of the actual measured values in the JNR's electrified districts. Table 4-7 shows a comparison of the kinds of messenger wire and their effect on voltage drop.

Table 4-7 Line Impedance

Line Impedance of BT Feeding System

Line	Section	Kind (mm^2)	Hz	Line impedance (Ω/km)	Voltage drop (V/A-km)
Joban	Fujishiro - Taira	T = Cu 110 M = CdCu 60 NF = Al 200	50	0.253 + j0.686 = 0.726	0.616
Tohoku	Sendai - Morioka	Ditto	"	0.286 + j0.682 = 0.738	0.638
Ou	Yonezawa - Yamagata	T = Cu 110 M = St 90 NF = Al 200	"	0.308 + j0.740 = [illegible]	0.690
Hokuriku	Fukui - Kanazawa	T = Cu 110 M = CdCu 60 NF = Al 200	60	0.288 + j0.844 = 0.893	0.737
Kagoshima	Moji-ko - Kurume	Ditto	"	0.265 + j0.732 = 0.810	0.651
Nippo	Kokura - Kozaki	T = Cu 110 M = St 90 NF = Al 200	"	0.311 + j0.851 = 0.936	0.777
Tokaido Shinkansen	Tokyo - Shin-Osaka	T = Cu 110 M = CdCu 80 M' = CdCu 60 NF = Al 300	"	0.311 + j0.790 = 0.817	0.643

Table 4-7 Line Impedance

Line Impedance of AT Feeding System

Line	Section	Kind (mm^2)	Hz	Line impedance (Ω/km)	Voltage drop (V/A-km)
Nihonkai Jukan	Murakami - Hirosaki	M = St 90 T = Cu 110 F = Al 95	50	0.1100 + j0.1890 = 0.2190	0.201
Tohoku Shinkansen	Omiya - Arikabe	M = St 180 M' = Cu 150 T = Cu 170 F = Al 300	-	0.0387 + j0.1712 = 0.1750	0.134
Kagoshima	Yatsushiro - Kagoshima	M = St 90 T = Cu 150 F = Al 95	60	0.1190 + j0.1962 = 0.2300	0.211
Sanyo Shinkansen	Okayama - Hakata	M = St 180 M' = Cu 150 T = Cu 170 F = Al 300	"	0.0370 + j0.2178 = 0.2210	0.160

As we have no example of systems using copper messenger wire in the AT districts of the JNR's conventional line, there is no such description in Table 3-7. However, because the voltage drop in the iron messenger wire in the BT district is a 15% larger than in the iron system and the voltage drop in the AT district is about 1/3 times as much as in the BT district, we can guess that there is little difference in voltage drop between the iron and copper system messenger wires in the AT district.

The voltage drop is very little in the AT district in view of the characteristics of the feeder circuit, causing no particular problems.

(d) Others

The wave propagation velocity C mentioned in the section on the dynamic uplift of catenary line is generally described as,

$$C = \sqrt{\frac{\Sigma T}{\Sigma \rho}}, \quad T: \text{ Tension}, \quad \rho: \text{ Wire density}$$

This is used as the index of the current collection efficiency, particularly of high speed efficiency. If C is large, occurrence of contact loss will also decrease to increase the current collection efficiency besides decreasing the dynamic uplift. T/ρ must be increased in order to enlarge C. That is, the wire with a small density and with a high tension is determined according to the quality of its materials. Iron is superior in quality with about twice the T/ρ and about 1.4 times the $\sqrt{T/\rho}$ of copper.

Next, regarding the problem of corrosion, copper is generally rather advantageous. In the rural districts where environmental conditions are good, even zinc plating steel twisting wire is sufficiently durable. When selecting the messenger wire, a thorough investigation into environmental conditions in the district must be carried out to determine the best method, such as changing the kind of wire in each area.

(4) Quality of the Contact Wire

A grooved hard copper wire is usually employed as the contact wire. Sizes are $85mm^2$, $110mm^2$ and $175mm^2$.

The $85mm^2$ is used for side tracks, the $110mm^2$ as the standard contact wire, and the $175mm^2$ for heavy compound and heavy simple contact wires. The material used was almost pure copper until recently, but an alloy contact wire mixing copper with tin was developed for the purpose of improving the anti-abrasion quality. When replacing the contact wire, this alloy-made contact wire is generally employed. The following table shows the characteristics of both.

Classification	Stretch strength (kgf/mm^2)	Conductivity (%)	Fatigue limit (kgf/mm^2)	Anti-wear ratio (%)
Pure copper contact wire	39 ∿ 40	99.4	15	100
Alloy contact wire with tin	43 ∿ 45	74 ∿ 80	17	50

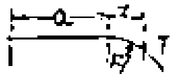
A TA contact wire with a longer length steel belt coated with aluminum at both ends is being developed now. At-the-site test results show it has good current collection characteristics and anti-abrasion characteristics, which leads us to expect its practical use in the near future.

4-2-2 Suspension System and Span

Based on past Japanese climatic conditions, the JNR has its set conditions such as "No destruction of the supports of the overhead contact system at a wind velocity of 40m/s (securing the safety factor that is fixed on each equipment), and possibility of smooth traffic operation even under a wind velocity of 30m/s" according to the calculated strength for the supports of the contact system. In this respect, considering the slack of the contact wires and jolting of the vehicles under strong winds, the maximum span was fixed so that the contact wire will not come off the pantograph. The conditions for fixing the span are as shown in Table 4-8.

Table 4-8 Conditions for Fixing the Span

Item	Value	Reference value (mm)
(1) Deflection of contact wire when no strong wind blows	Usually, 0 to 200mm	100
(2) Deflection of contact wire due to turning of the hinger canti-lever	Usually, 30 to 50mm	40
(3) Deflection of contact wire due to slack of the support	JNR provided as 50mm	50
(4) Deflection of contact wire due to turning of the base	———————	50

Item	Value	Reference value (mm)
(5) Amount of pantograph point removed by jolting of the vehicle	Different according to the width of the tracks and kinds of vehicles. JNR provided as 235mm	235
(6) Limit of pantograph's squeezing	 $X_0 = \{R^{\frac{2}{3}} - (P\cdot S/4T_t)^{\frac{2}{3}}\}^{\frac{3}{2}}$	750
(7) Limit of slack of contact wire by the wind	(7) = (6) - {(1)+(2)+(3)+(4)+(5)}	275

(7) in Table 4-8 may be compared in order to examine the relationship between the kinds of catenary lines and the span. The other items are almost fixed regardless of the kinds of catenary. Let's calculate the effect of Item (7) on the span regarding the simple and heavy simple catenaries employed by the JNR.

Item	Simple catenary	Heavy simple catenary
Kind of wire	M: St $90mm^2$ T: Gt $110mm^2$	M: St $135mm^2$ T: Gt $110mm^2$
Wind pressure load at 30m/s (W: kgf/m)	W_m: 0.675 W_t: 0.692	W_m: 0.844 W_t: 0.692
Tension (T: kgf)	T_m: 1,000 T_t: 1,000	T_m: 2,000 T_t: 1,000

In the case of Simple: $0.275 = \frac{S^2}{8}\cdot\frac{1,367}{2,000}$

$\therefore S = 56.7$ m

In the case of Heavy Simple: $0.275 = \frac{S^2}{8}\cdot\frac{1,536}{3,000}$

$\therefore S = 65.6$ m

The difference is about 9 m.

The span calculated here is based on the Reference Value in Table 4-8, and differs more or less by the values in Items (1), (2) and (6). But the difference of the maximum span is almost the same. Thus the span is allowed to be stretched 15% for contact wires with high tension, and an approximate 10% reduction of construction expenses under this method can be expected.

However, it is also possible to enlarge the span very greatly in the area where strong winds rarely blow. Nevertheless, as the height and intensity of supports must be increased because of the system height, it is impossible to expect economic advantages.

4-3 Maintenance of the Overhead Contact System

4-3-1 Considerations in Maintenance

Maintenance of the overhead contact system is considered preventive maintenance, taking into account the service life of the equipment to take necessary measures.

The two main factors of deterioration of the equipment are as follows.

(1) Caused by the equipment entering the over-age period and reaching the end of its service life.

(2) Caused by a provisional disorder in the equipment exceeding some limit value.

As the two functional types of deterioration have respectively different signs, different procedures must be taken.

We are managing the service life of the equipment whose functional loss is caused by the first factor, and performing a preventive maintenance of those whose functional loss is caused by the second factor through management of the limit value involved.

In the service life manageing method it is necessary to recognize the time before the equipment loses its function due to over-age and deterioration.

We have three ways of checking: "Establishing the service life", "Whole inspection", and "Sampling inspection".

Establishing the service life means a procedure in which the effective service life of the equipmet is determined at the time of installation, managing the passage of years till the time of their effective service life.

Regarding the equipment for which the service life can not be quantitatively checked because of a lack of data, the inspection should be carried out at the time presumed to be the "Over-age period" to judge the functional loss time caused by over-age and deterioration.

The inspection consists of two kinds, (1) Whole Inspection (2) Sampling Inspection. The whole inspection is conducted regarding equipment which can be efficiently inspected by inspection instruments.

Manual inspection, in principle, is applied for the sampling inspection to judge the remaining service life of the lot concerned to take the necessary steps according to the result of the inspection. The sampling inspection applied is mainly the method called the sampling inspection by variables which is carried out in quality control.

On the other hand, in the limit value management method, which is applied to maintain the catenary structure or catenary alignment, necessary action is taken when the limit value concerning each part occurs.

The performance of improved maintenance for accurate control and energy-efficiency are being planned using instrumental measurements.

4-3-2 Instrumental Inspection

The electric measuring inspection car installed with measuring inspection apparatus is employed by the JNR for instrumental inspection of the contact system equipment. The electric measuring inspection car performs inspections of the contact system equipment, which previously required much labor, by automatic measuring inspection at a regular operation speed to conduct efficient maintenance of the equipment.

The appearance and measuring apparatus of the electric measuring inspection car is shown in Photographs 1 and 2.

(1) Items Measured

The items measured for the overhead contact system are as follows.

1) Abrasion of the contact wire
2) Height of the contact wire
3) Deviation of the contact wire
4) Obstacles in the way of the pantograph driving
5) Hard spot

(a) Abrasion of the Contact Wire

Prevention of accidents involving braker contact wire should be planned by obtaining the abrased condition of the wire.

So far, measurement of the degree of abrasion of the contact wire has been manually carried out using a micrometer, resulting in point measurements. The abrasion of the contact wire can now be continually measured by practical use of the abrasion measuring apparatus for contact wire using a laser beam. Fig. 4-19 shows the principle of the contact wire abrasion measurement using a laser beam.

A single wavelength argon ion laser beam, as shown in Fig. 4-19 is turned toward the sliding surface of the contact wire through a revolving mirror then reflected from the contact wire to reach the photoelectric transducer which detects the abrasive condition of the wire. The reflected light from the contact wire involves sunlight, which is removed by an optical filter. The time duration

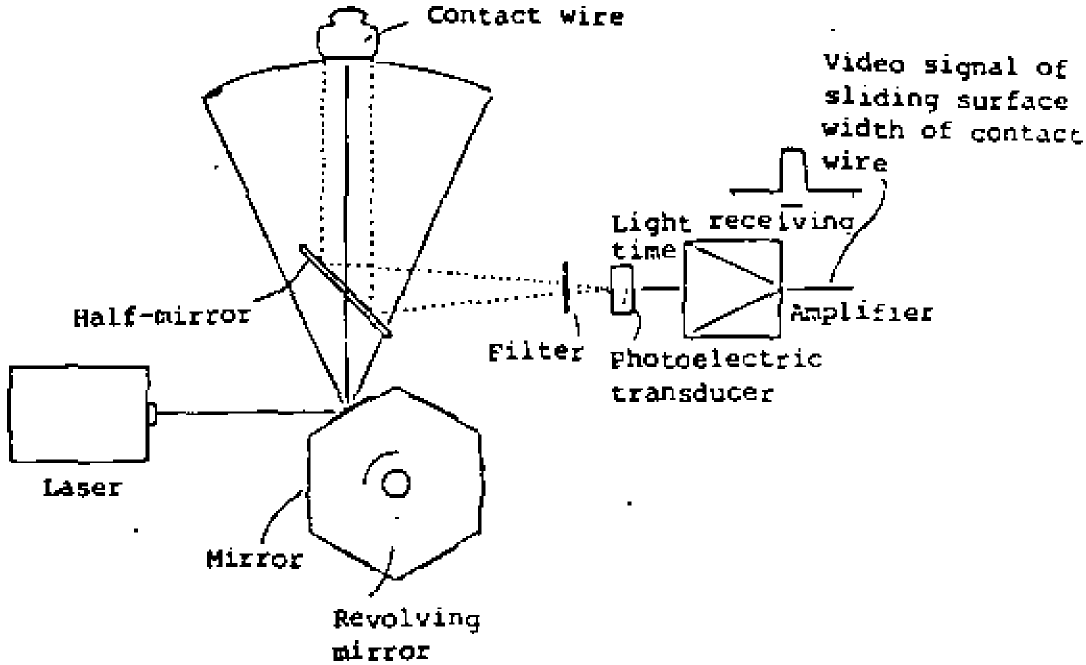


Fig. 4-19 Principles of Measuring Abrasion of Contact Wire with a Laser Beam

of the reflected light from the contact wire is in proportion to the width of the sliding surface of the contact wire, so this time duration is transformed into a voltage to measure the amount of abrasion of the wire.

The main characteristics of the contact wire abrasion measuring apparatus are as follows.

1) Can measure regardless daytime or night.

2) Four contact wires can be simultaneously measured.

3) Accuracy of measurement is 0.2mm

Fig. 4-20 shows an example of abrasion measurement of the contact wire.

(b) Height of the Contact Wire

The contact wire must be laid of a uniform height without extreme high and low difference to allow the a pantograph good current collection. Originally, measurement of the height and deviation of the contact wire was performed by gauge pole shown in Fig. 4-21.

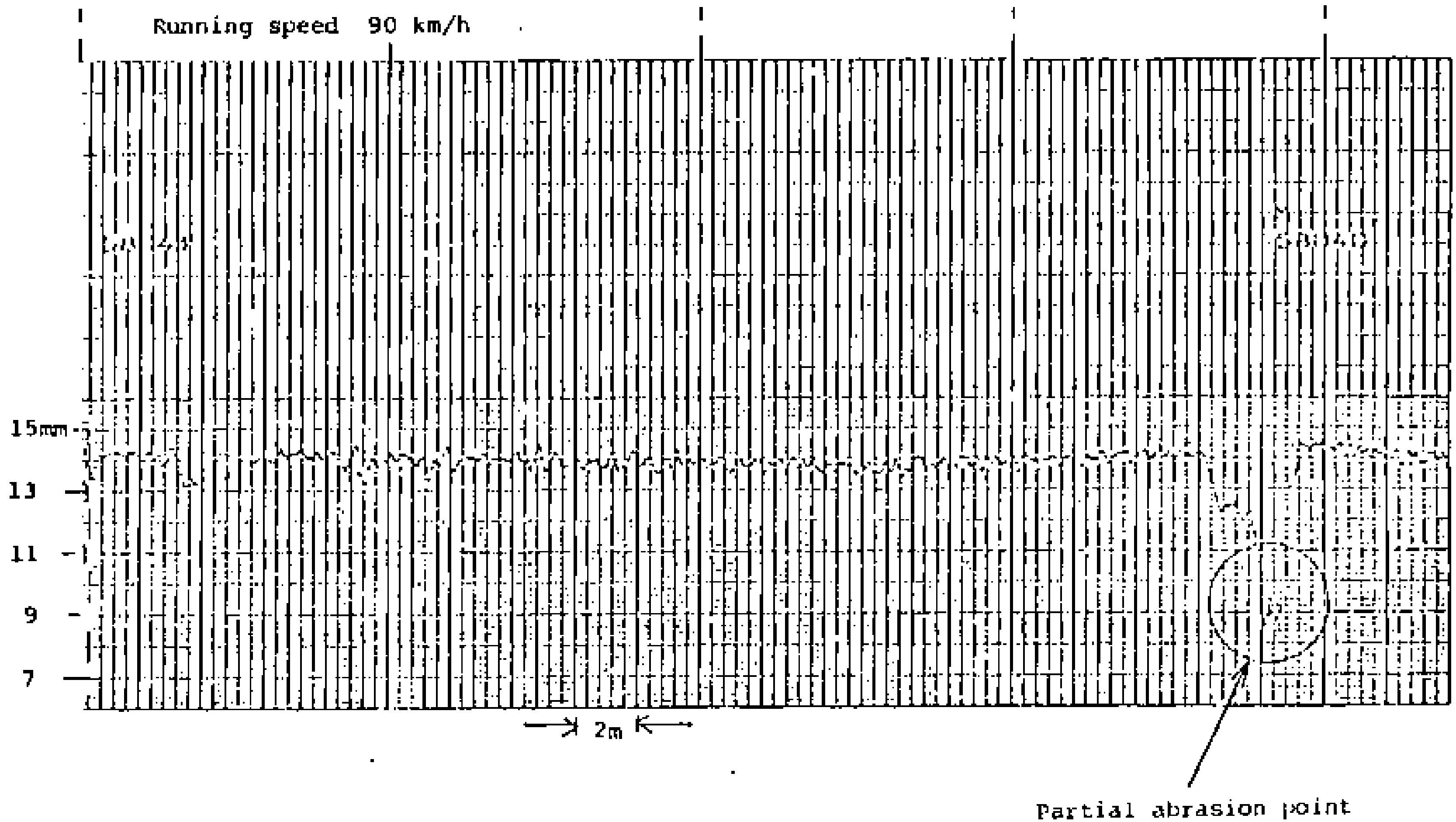


Fig. 4-20 Example of Measured Abrasion of the Contact Wire

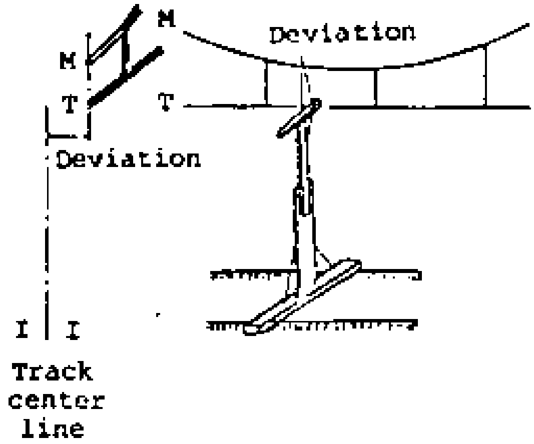


Fig. 4-21 Measuring by Gauge Pole

The dynamic height of the contact wire from the rails is measured by the electric measuring inspection car.

The principle of height measuring is shown in Fig. 4-22. The main shaft of the pantograph revolves through the up and down motion in accordance with the variance of the height of the contact wire.

The revolving angle of the main shaft of the pantograph is led to the potential meter installed on the roof of the measuring inspection car through the insulator to make the height signal.

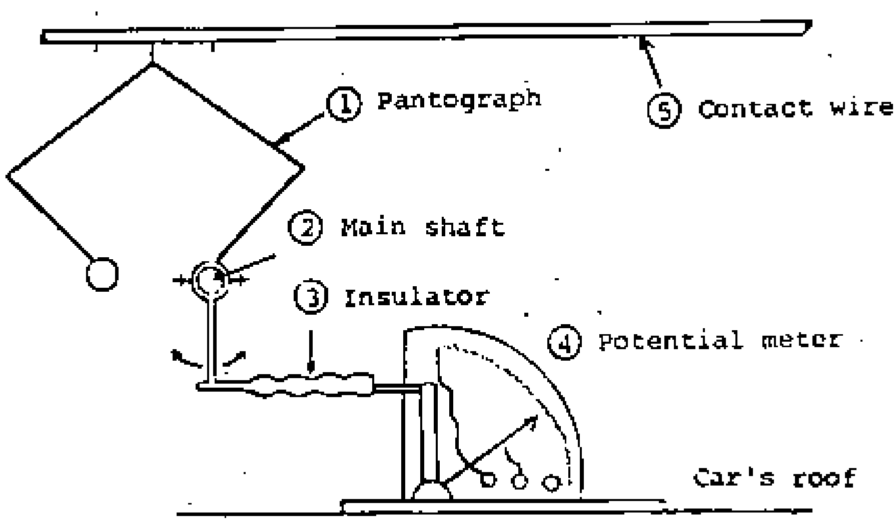


Fig. 4-22 Diagram of Measuring the Height of the Contact Wire

(c). Deviation of the Contact Wire

Laying the contact wire with a proper deviation is an essential condition for maintaining good current collection.

Measurement of the deviation is one application of the principle of the laser type abrasion measurement of the contact wire. The degree of deviation of the contact wire can be detected by measuring the time interval between the start of beam scanning and the time of reflection by the contact wire.

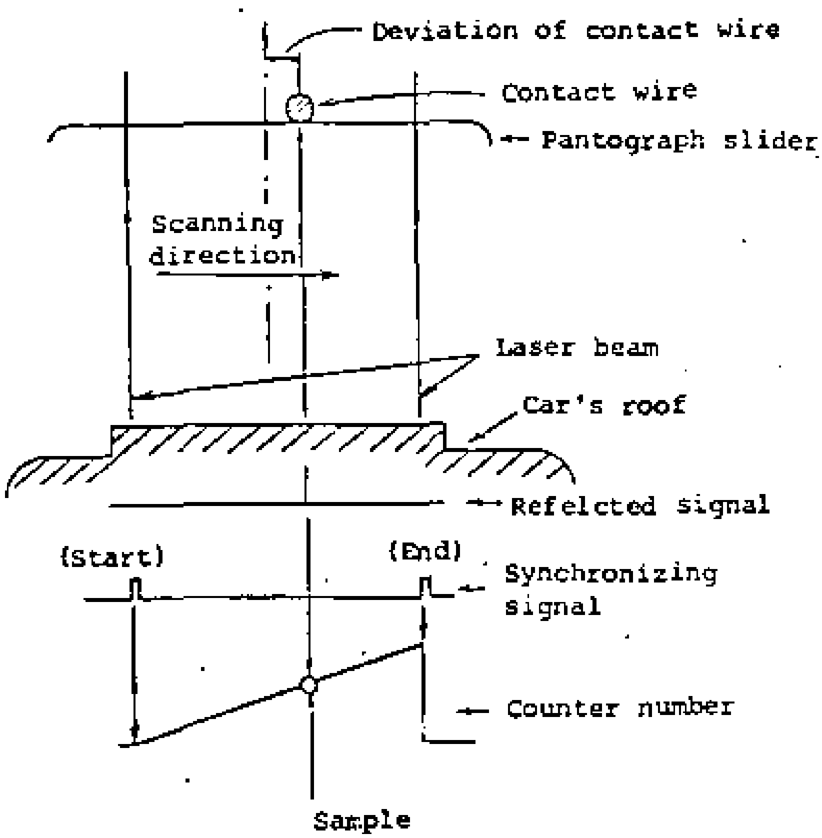


Fig. 4-23 Diagram of Principle of Measuring the Deviation of the Contact Wire

(d) Obstacles in the Way of the Pantograph Driving

The obstacle detector detects obstacles when the pantograph passes as well as wrongly fitted angles of the contact system fittings (stay braces, pull-off fittings).

The pan of the pantograph is equipped with an antenna with a micro-switch which gives a signal when the fitting of the contact system hits the antenna.

(e) Hard Spot

In the case of the contact wire having a partially heavy part, or having some bad points, the pantograph will be jolted causing contact loss or a partial wear of the contact wire.

The hard spot detector detects acceleration in the forward-backward and upward-downward directions given to the pan of pantograph by a wire strain gauge-type accelerometer on the reverse side of the pan.

(2) Data Process

The data measured and processed by the electric measuring inspection car are effectively utilized for maintenance and control of the overhead contact system to secure safety in traffic operation.

The electric measuring inspection car is equipped with data processing apparatus mainly composed of a mini-computer (memory capacity 32kW) for the purpose of immediate processing the measured data during operation.

The processed data is output in digital & analogue. The digital data is output by two terminal devices, (1) a high speed printer (whole data output at each span) and (2) typewriter (alarming data output).

Table 4-9 and Fig. 4-24 show the digital data and analogue data processed during operation.

Moreover, the entire data measured are recorded in a magnetic tape in analogue by the data recorder and are effectively utilized for time series control of the contact wire abrasion.

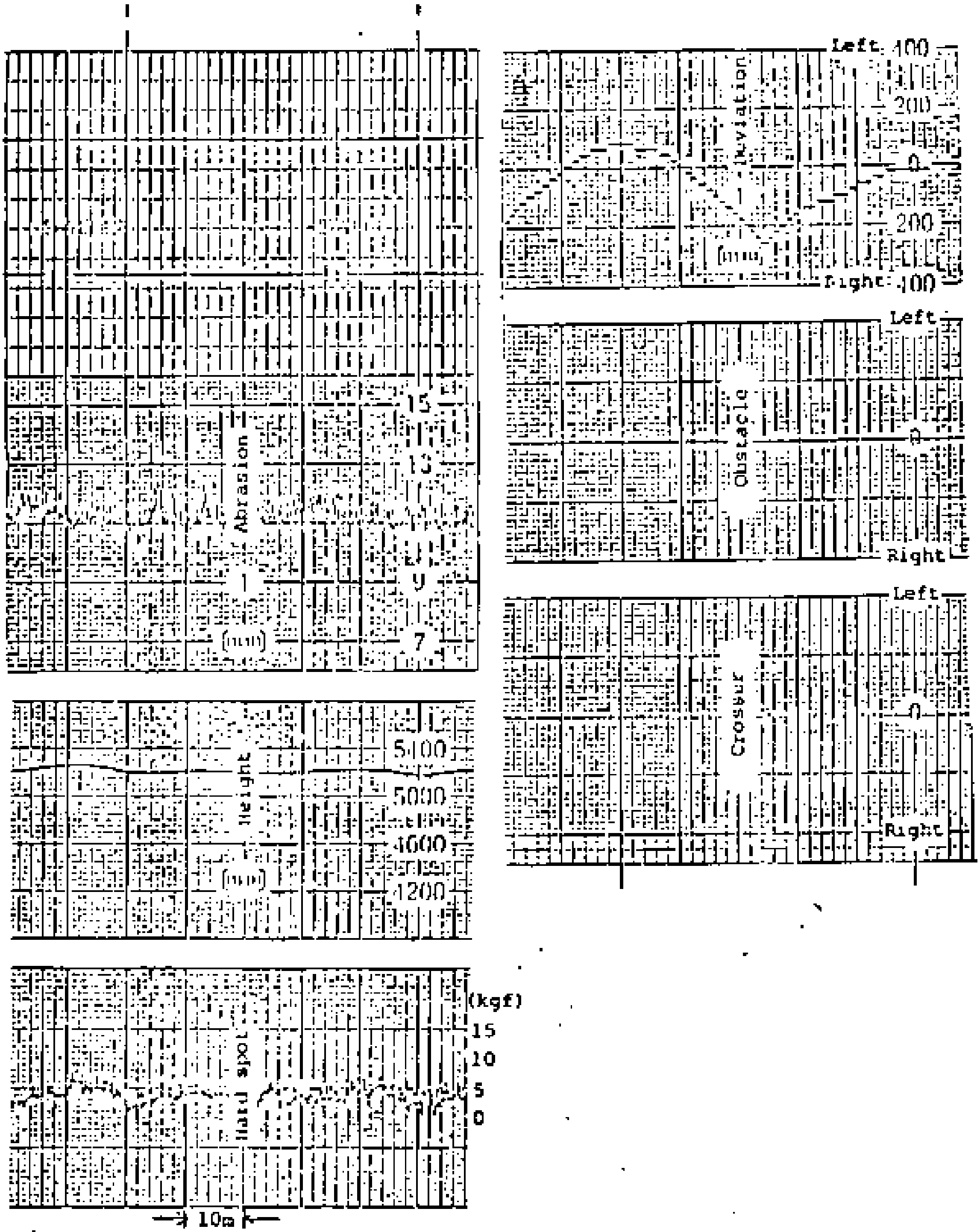


Fig. 4-24 Example of Output of Analogue Data by Electric Measuring Inspection Car during Operation (Running speed 90 km/h)

Table 4-9 Electric Measuring Inspection Car: Date Example of High Speed Printer Output

Date: 55.12.19 Name of line: UAK U Section code: 468312 Running direction: L Page: P-001

Station No.	Pole No.	Conditions 1/2	Span Standard F	M-1	Minimum value of abrasion (1CH)				Frequency distribution (1CH) P0	P1	P2	Average value (1CH) M-1	M-2	Minimum value of abrasion (2CH)			Frequency distribution (2CH) P0	P1	P2	Average value (2CH) M-2	Minimum value 3CH M-3	Minimum value 4CH M-4	Speed SPD	Hard spot		Dynamic slope of contact wire T	L(H)R	Deviation ID	Obstacle (division, antenna) L	S R	Crossover H	ID divisions	Overlap division Interval HE	Parallel length
*	02001F	//	297299	104	107	*	*	*	*	*	*	114	110	107	*	*	*	*	*	114	*	*	033	L1	01	20	37	01	*	*	*	*	*	*
*	01041F	//	239236	107	103	*	*	*	*	*	*	114	109	111	*	*	*	*	*	114	*	*	033	L1	01	*	35	01	*	*	*	*	*	*
*	040F	//	246261	106	106	*	*	*	*	*	*	112	111	115	*	*	*	*	*	119	*	*	037	L1	01	12	35	*	*	*	*	*	*	*
*	039F	//	256252	104	076	*	*	*	*	*	*	115	121	120	*	*	*	*	*	122	*	*	043	L1	01	06	35	*	*	*	*	*	*	*
*	038F	//	253257	119	117	*	*	*	*	*	*	120	119	120	*	*	*	*	*	121	*	*	045	L1	01	*	32	02	*	*	*	*	*	*
*	037F	//	255255	116	118	*	*	*	*	*	*	119	121	120	*	*	*	*	*	121	*	*	045	L1	01	09	31	09	*	*	*	*	*	*
*	036F	//	254250	113	113	*	*	*	*	*	*	120	117	112	*	*	*	*	*	121	*	*	045	L1	01	13	32	02	*	*	*	*	*	*
*	035T		229253	120	120	*	*	*	*	*	*	*	117	113	*	*	*	*	*	*	121	121	047	L1	01	24	33	15	*	*	*	*	20	100
*	034T		271273	111	*	*	*	*	*	*	*	*	111	*	*	*	*	*	*	*	115	113	047	L1	01	35	29	09	*	*	*	*	20	010
*	033F	//	272273	119	118	*	*	*	*	*	*	120	117	112	*	*	*	*	*	122	*	*	049	L1	01	06	27	10	*	*	*	*	*	*
*	032F	//	243233	118	115	*	*	*	*	*	*	121	120	120	*	*	*	*	*	122	*	*	049	L1	01	07	25	06	*	*	*	*	*	*
*	031F	//	282272	119	117	*	*	*	*	*	*	120	120	120	*	*	*	*	*	122	*	*	050	L1	01	14	32	07	*	*	*	*	*	*
	019F	///	406603	105	105	101	102	108	*	*	-	110	!	!	*	*	*	*	*	*	*	*	050	L1	01	32	04	06	*	*	*	*	*	*
	011F8	///	507 *	106	102	101	104	*	*	*	*	109	*	*	*	*	*	*	*	*	*	*	047	L1	01	13	*	05	*	*	*	*	*	*
	017FC	///	314312	100	104	104	*	*	*	*	-	110	*	*	*	*	*	*	*	*	*	*	045	L1	01	10	02	14	*	*	*	*	*	*
	016F	///	315315	104	103	102	*	*	*	*	*	109	*	*	*	*	*	*	*	*	*	*	047	L1	01	30	05	22	*	*	*	*	*	*
	015T	//	373370	105	103	*	-	*	*	*	*	*	*	106	107	*	*	*	*	*	*	*	047	L1	01	06	24	17	*	*	*	*	26	045
	014F	///	347342	103	105	103	*	*	*	-	*	110	*	*	*	*	*	*	*	*	*	*	046	L1	01	54	15	04	*	*	*	*	*	*
	013F	///	350 *	104	*	*	*	*	*	*	*	109	*	*	*	*	*	*	*	*	*	*	046	L1	01	*	12	*	*	*	*	*	*	*

P 1 110 H-LIM-OVER 170 1 H-LIM-OVER1 L/R 1-MINDO U/D 1 C H 1 L ??? R

468312 0097 * 1 * * * * 1 * 13 24 07 01 097 * * 1 * 097 * * * * * * * * 1 01

L 1 HATARI / R 1 J T L

01 * * * * * * * * * 01 * * * * * * * * * * 02 1

(3) Measurement Period

The electric measuring inspection cars are stationed in 7 groups on conventional lines throughout Japan.

The number of measuring inspections is 4 times a year in each district. In addition, two inspection cars are employed on the Tokaido & Sanyo Shinkansen Lines. The usual running speed is 210 km/h and the number of measuring inspections is once a week.

4-4 Mechanized Construction

Of the construction work related to the overhead contact system, the mechanized construction is to be done for the following items.

(1) Supports

New installation of electric poles
New installation of beams

(2) Catenary

Extension of messenger wire
Extension of auxiliary messenger wire
Extension of contact wire

(3) Feeder Wire

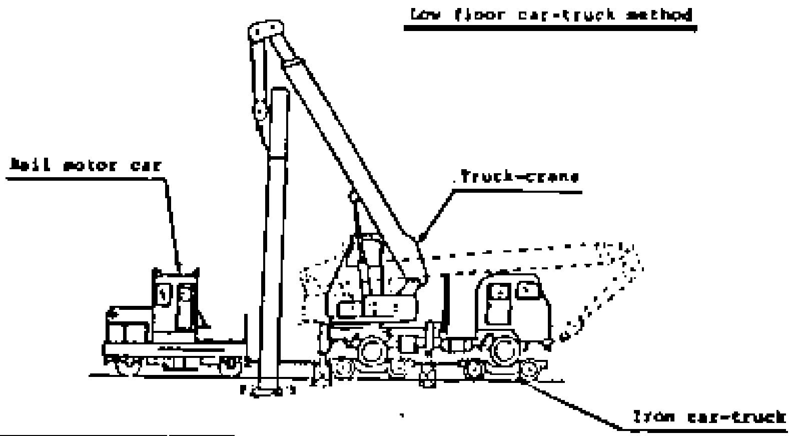
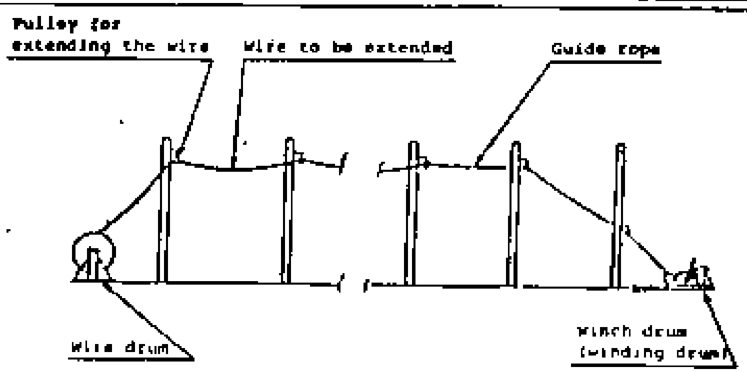
Extension of feeder wire

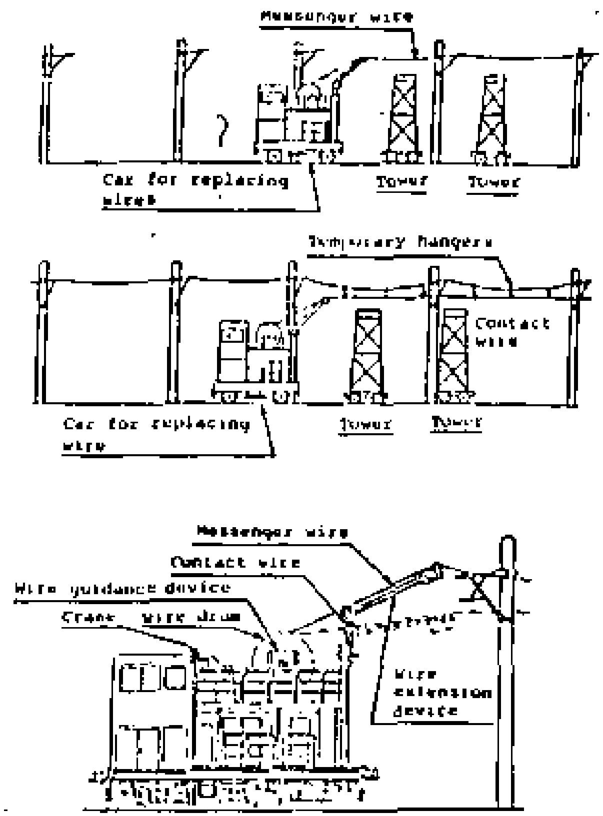
In addition, some construction work related to the cross-arms, insulators, or fittings for the contact wire is occasionally done using a construction car.

While details are indicated in the attached appendix, it is very convenient in the case of new pole installation on the conventional lines to use a truck-crane loaded on iron car trucks called low floor car trucks. In construction work on the extension of the contact wire on the Shinkansen, work is carried out using a combined party with a wire-extension car and a work car. As we are able to devise efficient and economical work through the mechanized construction method, safety of the work is attained.

Regarding the construction of a new Shinkansen contact wire or replacing a contact wire, mechanized construction is fully employed, and in the electrified construction on conventional lines as well, the mechanized construction method is adopted in districts where construction interval at night-time is available.

The Mechanized Construction Method of the Overhead Contact System (Electrification Work on Conventional Lines)

Classified equipment	Construction method: Mechanical type used	Construction method: Contents of the method	Diagram of work organization
Supports	Truck-crane, hanging-up load 5 tons to 10 tons	Mechanization of installation of electric poles and laying of beams 1. On-the-road method: Placing a truck-crane on the road or on the road bed, the poles or the beam are installed. 2. Low floor car-truck method: As shown in the diagram, a truck-crane is loaded on the iron car-truck (for electrical work), called the low floor car-truck, then is moved by towing of the rail motor car to erect the poles or lay the beam.	
Feeder	Winch, output: 5ps/1800rpm to 7ps/2000rpm	Mechanization of extension of the wire: After fixing pulleys onto each pole between the wire extension section, a guide rope is passed through the pulleys, then at the same time when one edge (pull-out side) of the guide rope is connected with the wire to be extended, the guide rope at the terminal end is wound by the winding drum. After the preparation is completed between the sections, the guide rope should be wound by the winch to extend the wire, braking the wiring drum and keeping in contact with it.	

Classified equipment	Construction method		Diagram of work organization
	Mechanical type used	Contents of the method	
Catenary	Rail motor car for electrical work (A car for changing the catenary) Loading weight; 3.5 tons Wiring tension; 0 to 3000kgf Crane capacity; 2.9 tons Wire guidance device; Up and down lift range; 4.2M to 7.0M Horizontal feed range; left & right 1.0M Output; 152ps/2000rpm	Mechanization of extending wires of the contact system; The car for replacing wires of the contact system and the towers for working (loaded on the car-truck for railways) are organized as shown in the diagram. 1. Extension of messenger wires After reaching the wire extension section, the messenger wire should be temporarily held to the terminating pole to be towed to the terminal edge being given a tension by the extending device of the car for wire extension. Then suspension of the wire is conducted at each support by the operation lever of the wire guidance device. The succeeding towers act as helpers for suspending the wire and for necessary realignment. 2. Extension of the contact wire After the contact wire is temporarily held to the terminating pole, the wire should be moved to the terminal edge giving a tension by extending the device of the car. Then the wiring extension should be done with temporary hangers and pull-off fittings at each span by the successive towers.	

Wire Extension on the Shinkansen

On the Shinkansen, "The Rail Motor Cars for Electrical Work" are used, as shown in Fig. 4-25, for the extension of the wires, new installation of hinged cantilevers, and adjustment of the catenary configuration. As described above, the mechanized construction work contributes to the safety of work progress in efficiency and in shortening the work hours as compared with the manual construction work of the past.

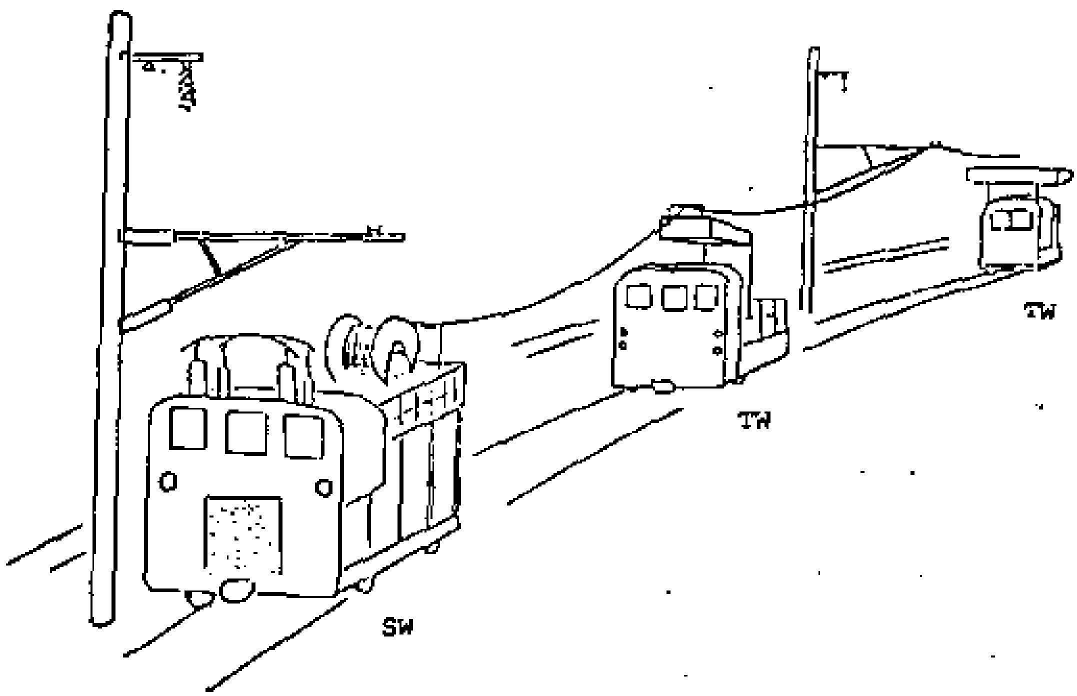
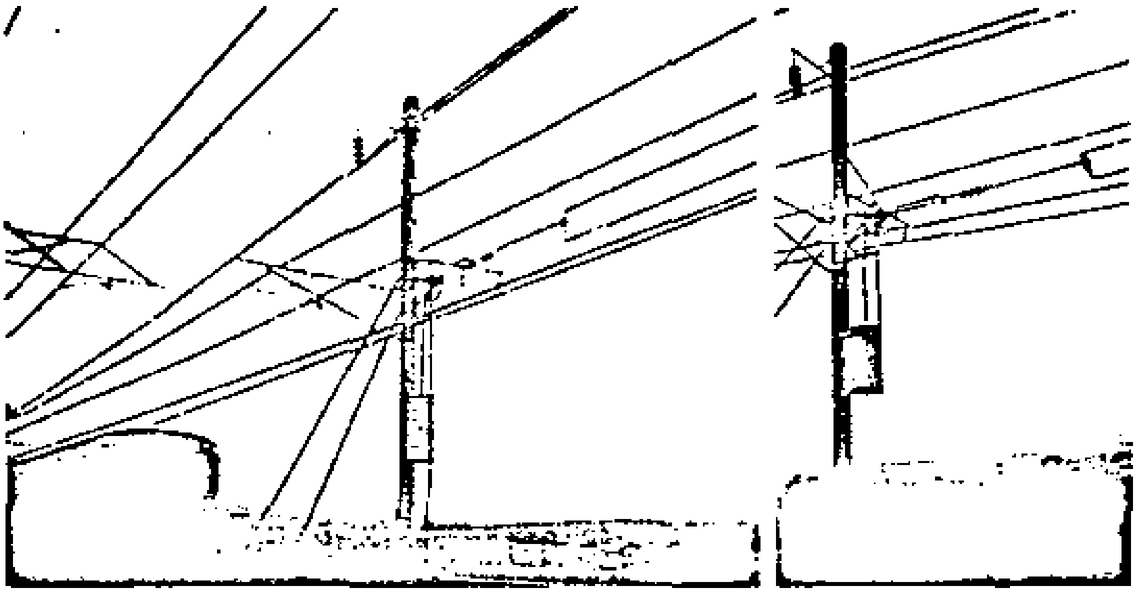


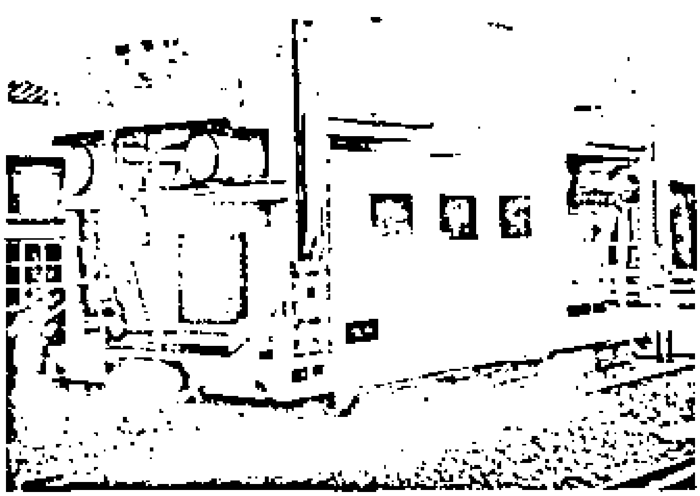
Fig. 4-25



20kV Heavy Simple Catenary Equipment of the AT Feeding System

TW

SW



SEMINAR ON ELECTRIFICATION

CHAPTER 5 ELECTRIFICATION AND SIGNALLING

CHAPTER 6 · ELECTRIFICATION AND COMMUNICATION

June, 1982

JAPANESE NATIONAL RAILWAYS
JAPAN INTERNATIONAL COOPERATION AGENCY

CONTENTS

CHAPTER 5

ELECTRIFICATION AND SIGNALLING

5-1 Automatic Signals

5-1-1 Train Operation and Automatic Block System

The section which can be occupied by one train is called a "block section". The tablet block system, tokenless block system, etc. are systems in which the conditions of the block section are set artificially. Namely, one section between a station and the next station is taken as one block section within which only one train can run.

The automatic block system is a system in which the train itself automatically sets the conditions of the block. The existence of a train is detected by the track circuit, and the signals are indicated on signal devices, thus the desired number of trains can run between two stations.

The automatic block system reduces the train interval to a minimum, therefore track efficiency (capacity) can be increased.

In the JNR, the following operation and safety system are adopted.

For double-track operation:	Automatic block system
For single-track operation:	Automatic block system Tokenless block system Table block system Others

5-1-2 Automatic Block System and Train Interval

In the automatic block system, the minium headway, that is the minium interval of time in which a train can be operated, greatly varies depending on the maximum speed, deceleration by brake, and signal indication system. As to the signal device, the allowable speed is determined in response to the signal indicators such as R (red) and Y (yellow). The train must be operated at such a speed that it can be decelerated with the manual brake starting from time the operator sees the signal indication and stopping at the position just in front of the signal.

Therefore, in cases of trains with low rates of deceleration or those running at high speeds, it may be necessary to increase the number of signal indication stages. The distance between the signal devices, namely the block section, is sufficient, if it is longer than the distance required to acknowledge the signal indication. There is no problem even if this is several kilometers.

As the result, there are signal indicating system such as two aspect section, three aspect section and four aspect section systems. According to the signal indicating systems, the minimum headway, namely the interval between the previous train and the following train, is determined.

The three aspect section system among those shown in Fig. 5-1 is generally used by the JNR. In the case of limited express trains with a maximum speed of 120 km/h and freight trains at 75 km/h (1,200 t hauling), the distance to carry out the signal indication is 600 m, and the distance between the signal devices is 1 to 1.5 km, the minimum headway is 3 to 5 minutes.

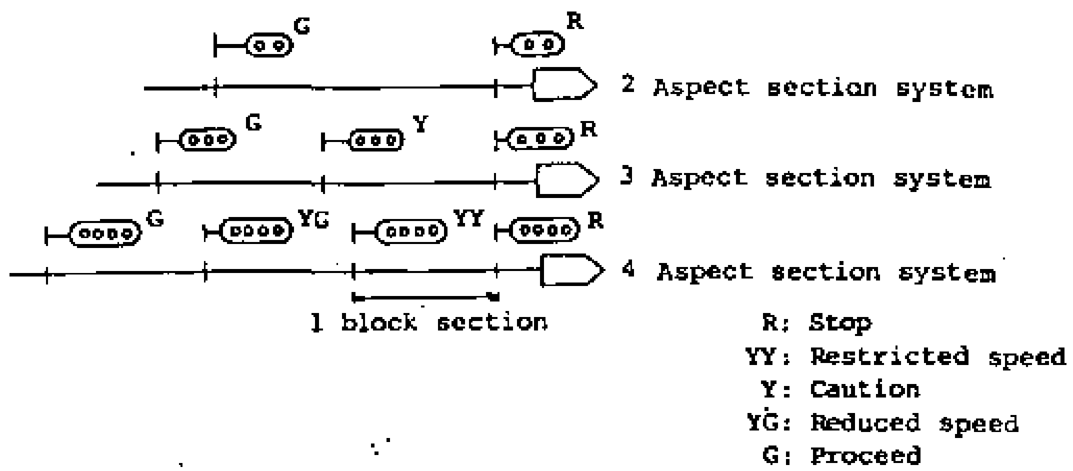
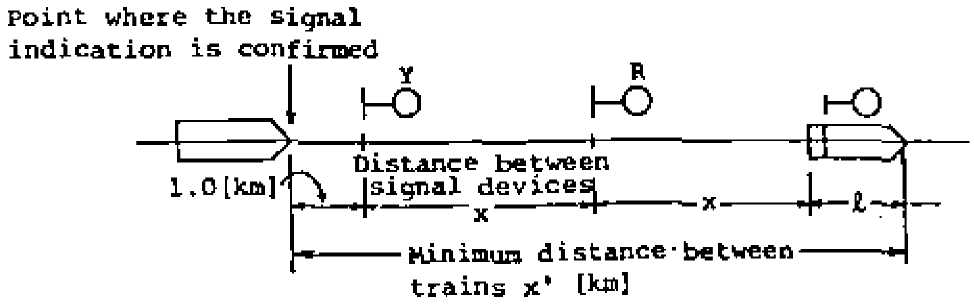


Fig. 5-1 Signal Indicating System

The relation between the minimum headway and the distance between signal devices in the three aspect section system, can be obtained approximately by the following formula (See Fig. 5-2).



Minimum distance between trains: $x' = 2x + \ell + 1$ [km]

Minimum headway: $y = \frac{x'}{v}$ [min]

of the train [km/min] v

Length of train: ℓ [km]

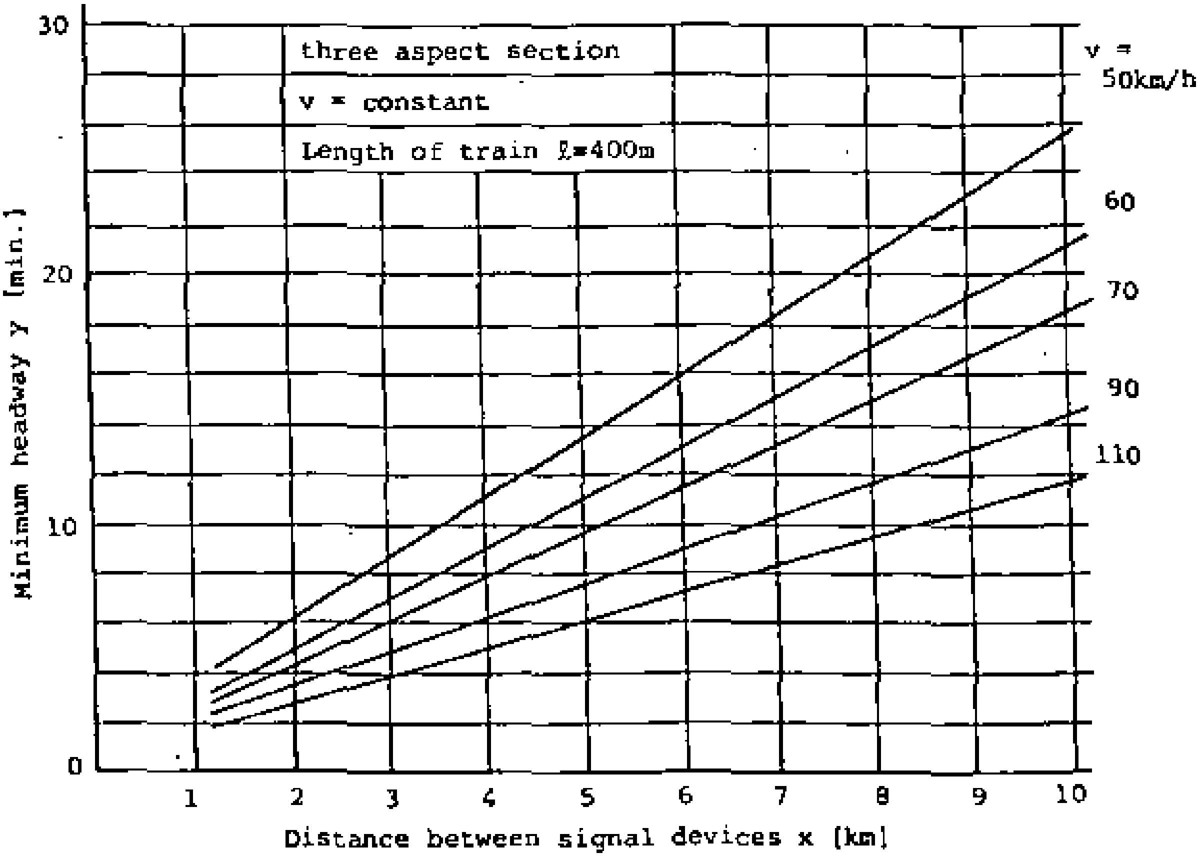


Fig. 5-2 The Relationship between the Minimum Headway and the Distance between Signal Devices in the Three Aspect Section System (approximate calculations)

Concerning the area near a station, there are various factors such as whether there are double tracks or a single track, whether the station is a stop or through one, etc. Therefore, it is recommended that a run-curve be drawn to obtain accurate positions of signal devices and the minimum headway. It is also desirable that the signal devices between the stations for an up-train and a down-train be installed at the same position.

5-1-3 Realization of Automatic Signal System

The following systems form the automatic signal (block) system.

Axle counter system
Check-in/Check-out system
Continuous track circuit system

The axle counter system and check-in/check-out system are the signal control systems which detect and memorize passing trains at the position where the signal devices are installed, with control circuits between the signal devices.

On the other hand, the continuous track circuit system controls the signal device which detects the existence of the trains. Further it is also a safety system as it is able to detect the rail breakages and other dangerous conditions for train operation, and causes the signal device to indicate "R".

Therefore the continuous track circuit system is the main system used in JNR's signalling.

5-1-4 Track Capacity

Track capacity means the maximum number of trains which can be operated in one day. The track capacity depends on the duty of the line operated, the condition of the equipment, the train speed and kinds of trains, etc. Thus it is very difficult to obtain an accurate figure for train capacity.

Conventionally, the track capacity has been generally considered as 80 to 90 trains for a single track, and 240 to 270 trains for a double track (both ways).

Concerning the "track capacity calculation formula" below, and its result, it is like an appeal of a patient when the diagnosis is closed condition of the track capacity. To judge the measures such as whether an interchange point or passing tracks should be newly constructed or whether a major operation such as additional construction of new line is necessary, a detailed examination into future transport demands, strain of train diagram, and the effects of improvement, etc. are necessary.

(1) · Single-track operation

$$N = \frac{1,440}{t + c} \times f$$

N : Track capacity (number of trains)

t : Average time of operation between stations for one train (Minute/number of trains)

c : Block time (minutes)

Automatic block system, Controlled manual block system & Tokenless block system	1.5 minutes
Other block systems	2.5 minutes

f : Track utilization efficiency — 0.6 as a rule

Example of calculations, in the case of the automatic block system:

$$N = \frac{1,140}{t + c} \times f = \frac{1,440}{7.5 + 1.5} \times 0.6 = 96 \text{ [number of trains]}$$

When,

$$t = \frac{\text{Time of total actual train operation between stations}}{\text{Number of schedule trains}} = \frac{623 \text{ [minutes]}}{83 \text{ [number of trains]}}$$

$$= 7.5 \text{ [minute/number of trains]}$$

This numerical formula is for the calculation between stations, and the answer is the number of trains when a standard diagram is made for each line. Therefore, it does not take into consideration connections with adjacent lines. The conditions of special express trains passing through, which has recently been increasing are also not considered. However, because this calculation is simple, it is useful for understanding the closed conditions of track capacity, and since further examinations are done from every angle in projects of increased trains or investment in equipment, this formula is widely used as a general objective.

(2) Double-track operation

$$N = \frac{1,440}{hv' + (r+u+1)v} \times f$$

N : One way track capacity; it must be calculated for each up-train and down-train.

h : Interval between the following high speed train; standard is 4 ∿ 6 min.

r : Minimum necessary interval between the low speed train previously arrived at the station and the high speed train later arrived at the station; standard time is 3 ∿ 4 min.

u : Minimum necessary interval between the high speed train previously departed from the station and the later low speed train leaving the station; generally 2.5 min.

v : Number of high speed trains (in percent)

$$= \frac{\text{(Scheduled number of high speed trains)}}{\text{(Scheduled number of one way trains)}}$$

v': Number of low speed trains (in percent)

$$= \frac{\text{(Scheduled number of low speed trains)}}{\text{(Scheduled number of one way trains)}}$$

Where the number of low speed trains means the number of trains except freight trains; and the number of high speed trains means the number of trains except freight trains and low speed trains.

f : Track utilization efficiency; although it depends on the section's nature, it is generally determined as 0.6 ∿ 0.75.

(Example of calculations)

The scheduled trains are divided by speed classification as in Table 5-1.

Table 5-1 Speed Classification and Number of Trains

Train mark	1	2	3	4	5	6	Total
Time of train operation between stations	4'00"	4'15"	4'30"	5'00"	5'30"	7'00"	
Scheduled number of trains	3	16	28	18	43	3	116
Ratio of train number	0.03	0.14	0.24	0.15	0.41	0.03	1.00

The number of high speed trains "v" is the ratio to the total number of trains, of the number of the trains of (1) to (4) excluding (5) low speed trains and (6) freight trains, according to the above train marks. And the number of low speed trains "v'" is the percentage of trains with the train mark (5). Therefore, according to Table 5-1.

$$v = 0.03 + 0.14 + 0.24 + 0.15 = 0.56$$

$$v' = 0.41$$

Then, the track capacity for one way "N" is as follows:

$$N = \frac{1,440}{hv'+(r+u+1)v} \times f = \frac{1,440 \times 0.6}{6 \times 0.41+(4+2.5+1) \times 0.56} = 129$$

When, h = 6[min.], r = 4[min.], u = 2.5[min.], f = 0.6[min.]

This formula is useful in analying the closed state of the double-track operation, as well as cases of single-track capacity.

Furthermore, collecting trains into the available time zone, or standardization of the train schedules, is required to cope with the increasing number of trains. Then the operating available number of trains in a period of time more often becomes the problem.

As measures for increasing transport to handle transport demands in double track operations, increasing hauling tonnage, improving the quasi-parallel diagram to the complete parallel diagram, expanding the parallel diagram time zone, and standardization the diagram in the daytime will be promoted.

In the case of the Tokaido-line of the JNR, the one way track capacity desired to perform the task of each train is 120; the practical limit which can be realized, even though the speed of trains is partially sacrificed by the diagram standardization, is 240; and the physical limit is 300.

5-2 Track Circuit

5-2-1 Track Circuit Systems

(1) Classification of track circuit systems

The track circuit systems which can be used in the AC electrified system are divided into three kinds: the DC track circuit, LF (low frequency) track circuit (generally up to several hundred Hz), and the AF (audio frequency) track circuit, when classified by frequency. These track circuits each have their features of performance and character, and it is recommended the decision as to which adopt to be made, considering economy and maintenance, utilizing their strong points. The features of the 3 systems are shown in Table 5-2. The characteristics of these are summarized below:

(a) DC Track Circuit (single-rail)

- o This system is simple, maintenance is easy, and it is economical.
- o The control distance is shorter than with other systems.
- o The system is easily affected by the rush current of an AC electric rolling stock or the DC stray current. Polarization trends to occur in a PC sleeper section.

When the single-rail track circuit is constructed in the station tracks, detecting breakages in the rail on the return circuit side is impossible, and the rail voltage in the case of the rail breakage will rise considerably as mentioned in Item 5.2.3 (1). Considering these points, the JNR has adopted double-rail track circuits for main tracks in the station tracks,

Table 5-2 Comparison of General Performance of the Three Track Circuit Systems

Item	System	DC Track Circuit (Single rail)	LF Track Circuit (25 ∿ 400 Hz)	AF Track Circuit (1,000 ∿ 3,000 Hz)
Function	1. Train detection (Shunting sensitivity)	It depends on Leakage, Control length, and action/release ratio of relay, etc.		
	2. Rail breakage detection	Impossible on the return circuit side	Possible	
	3. Transmission of multiple information	Impossible	Possible up to four pieces of information (although depends on type)	Possible up to about ten pieces of information (although depends on type)
	4. Approach detection	Impossible	Possible	
Characteristics	1. Anti-interference	Notice the rush current and the stray current	Notice the low frequency oscillation and higher harmonics	Notice the higher harmonics
Economy	1. Transmission distance (G $\leq$ 0.5[S/km])	Less than 1 km	2 ∿ 4 km	1 ∿ 2 km
	2. Non-insulation	Impossible	Difficult (Boundary is not sharp)	Possible (Boundary is sharp)
	3. Maintainability (Scope of concentration)	Simple	Generally, concentration of electronic devices is possible	Concerntration of electronic devices is possible
Applicability	1. Applicable range	Station tracks	Station tracks and between stations	

and has adopted, in part, single-rail DC track circuits for sidetracks. Therefore, when the single-rail DC track circuit is used for a main track in the station tracks, it is desirable to take the necessary measures.

(b) LF Track Circuit

- o The control distance of this system is generally the longest among the three systems, and it is economical.
- o It is difficult to make the non-insulated track circuit, or to make the multi-information system.
- o Much electric power is required, with this system.

Therefore, it is suitable for the track circuit between stations, because of the long control distance, if there no possibility of changing to the ATC in the future. And if the glued insulation rail which has the same life as the ordinary rail insulation is used, the difficulty of maintaining rail insulation can be solved.

In the JNR, in the station tracks, the divided and multiplied-frequency track circuit and large-scale divided frequency track circuits are used, and in the middle of the stations, the divided frequency track circuit is applied at present. Also types with lower power consumption are being developed. Concerning the 80 Hz AC code track circuit, the application to the electrification of the semi-main lines is in the process of being examined.

(c) AF Track Circuit

- o This makes a multi-information system easy, and it has a high possibility to develop to the ATC.
- o It is easy for making non-insulated track circuit, also for making the level crossing control.
- o It is easy to concentrate electronic devices, and as a result maintenance is easy.

Therefore, it is desired that the AF track circuit be used in the middle of stations where the above merits are utilized. The JNR uses the AF track circuit in the railway divisions where no signal high voltage power supply exists in the stations. The concentration of the devices to improve maintenance is under examination.

(2) Considerations about the Application

Signal transmission by the track circuit is different from general transmission systems, in that the distribution constants vary. Therefore, the track circuit applied must be the system which is sufficiently applicable for practical use concerning the shunting sensitivity, transmission distance, anti-disturbance, and rail breakage detection, etc., according to the change of these constants.

(a) Features of Track Circuit Transmission

1) The distribution constants are determined by the track circuit structure, and their values vary depending on the kinds of rail, track gauge, frequency, etc. Fig. 5-3 shows the distribution constants of the PC sleeper tracks.

2) Depending on the conditions of the weather and the ballast, the leakage conductance varies widely. Fig. 5-4 shows

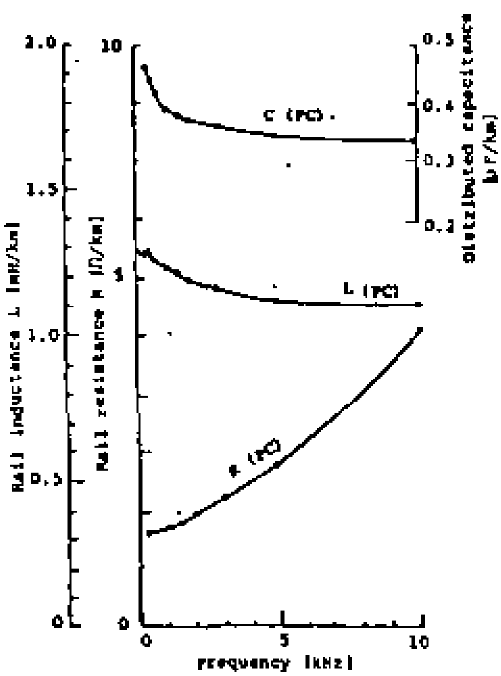


Fig. 5-3 Distribution Constants of PC Track Circuits

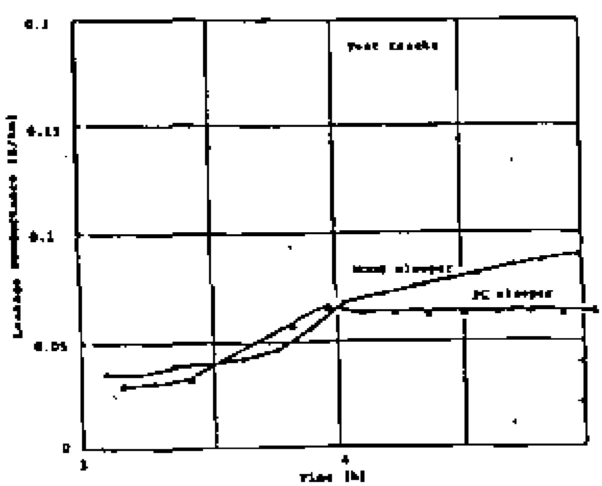


Fig. 5-4 Changes of Leakage Conductance during Rainy Weather

the changes of the leakage conductance of 2 kinds of test tracks during rainy weather, and we can see the tendencies of the wood sleeper and PC sleeper tracks in the rain. Because changes in the leakage conductance directly changes the receiving level of the track circuit, the shunting sensitivity and the rail breakage detection are affected.

3) The approximate of the characteristic impedance of the track circuit is $\sqrt{2\pi f\ L/G}$. And it increase in proportion to $\sqrt{f}$. Where, L = rail inductance (H/km) and G = leakage conductance (S/km).

   As in the cases of the distribution constants, the change of the characteristics impedance affects the transmission, and the shunting sensitivity and the rail breakage detection functions vary.

4) The transmission circuits are always unbalanced, and the large rolling stock current of more than two figures exists. Therefore, it is required to ensure the S/N necessary to the train detection.

(b) Train Detection

Train detection by the track circuit is made by utilizing the short-circuit from the train axle. Therefore, the shunting sensitivity varies due to the value of the circuit impedance. Figs. 5-5 and 5-6 show the receiving level change in the cases of 100 Hz and 2 kHz.

For example, in the case of 3 km control by 100 Hz, the variation of the receiving level of the track circuit due to the leakage variation is about 10 dB. Therefore, if the receiving level is compensated by 10 and several dB, a short-current sensitivity of more than 0.5Ω can be obtained.

Similarly, in the case of 2 km control by 2 kHz, the shunting sensitivity is about 0.2Ω. Thus, the short-circuit sensitivity also varies depending on the length of the track circuit.

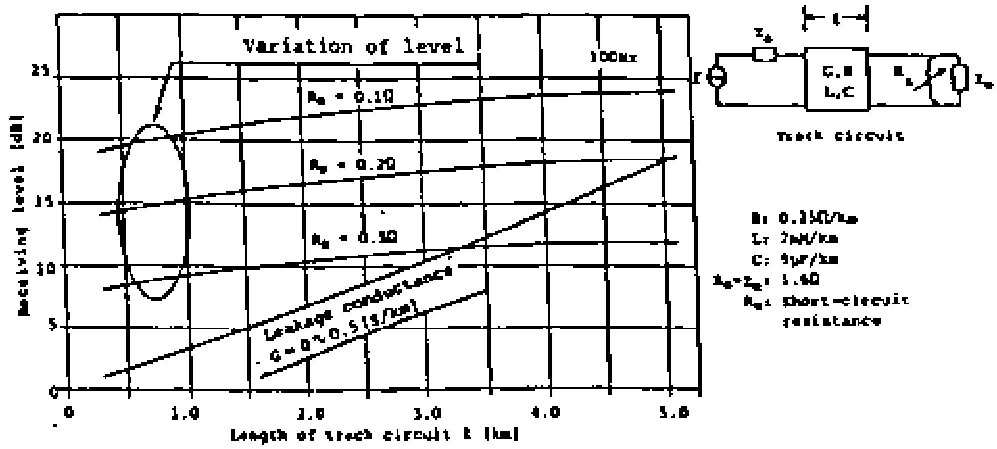


Fig. 5-5 Variation of Receiving Level
when Shunted at Receiving End

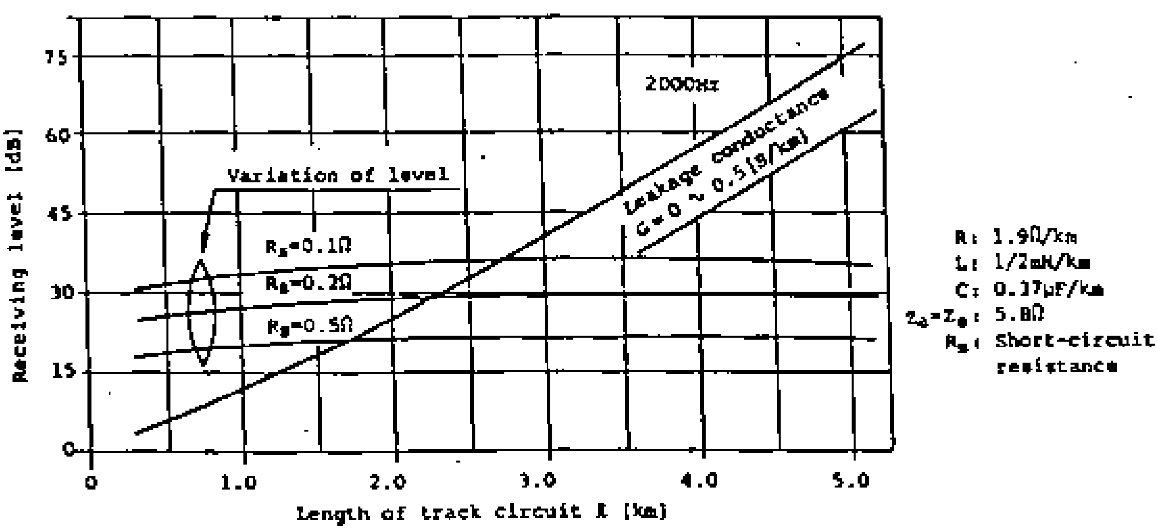


Fig. 5-6 Variation of Receiving Level
when Shunted at Receiving End

In the JNR, the shunting sensitivity of LF track circuits is determined at more than 0.06Ω. And for the AF track circuit, and DC track circuit (single rail), it is determined as more than 0.1Ω. However, some people are of the opinion that it should be about 0.3Ω, because of the resin brake shoe recently put into use.

(c) Rail Breakage Detection

The performance of rail breakage detection is very important in ensuring the safety operation and preventing dangerous failures, by detecting abnormalities in the track circuit system. Therefore, regardless of whether there is a train operating or not, it is necessary that the track relay "drop-away", when a rail breakage occurs. For this purpose, the next formula must be realized: $L_B \geq L_C$

Where L_B stands for the variation of minimum receiving level at the time of the rail breakage, and L_C represents the compensated receiving level.

Concerning the track circuit transmission at the time of the rail breakage, a complicated calculation is required as the multi-circuit to ground transmission which consists of the feeding current circuit and the adjacent track circuit. For reference, the calculation of 80 Hz AC code track circuit is shown in Fig. 5-7.

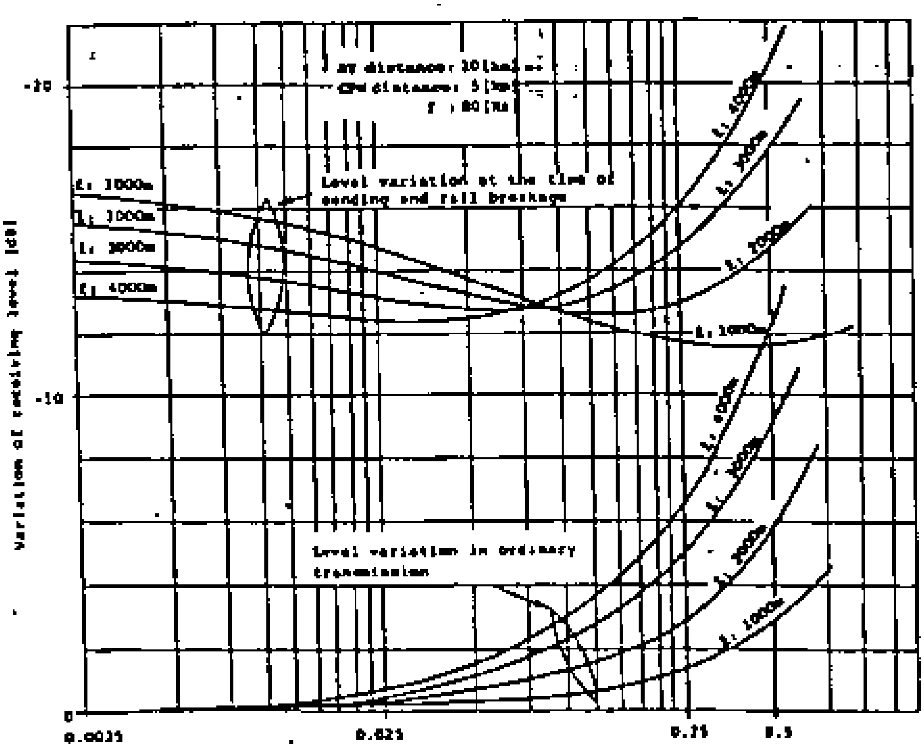


Fig. 5-7 Breakage Detection Features by Variation of the Track Circuit Length

In this figure, the leakage admittance is $G \leq 0.5$[S/m], and length of track circuit "ℓ" = 4,000[m], the minimum receiving level L_B at rail breakage time = 12.5(dB), and the maximum level variation in ordinary transmission L_C = 12.1 dB. Then the difference is 0.4 dB, and rail breakage detection is possible.

The shorter the length of the track circuit, the easier the detection of rail breakages. And the cases in which the AT distance is changed are shown in Table 5-3.

Table 5-3 Changes of Rail Breakage Detection by AT Distance

Detection of rail breakage	AT distance [km]	Length of track circuit [m]			
		1,000	2,000	3,000	4,000
Difference between the minimum receiving level variation at the time of rail breakage and the maximum receiving level variation at normal times $[L_B - L_C]$	10	8.5 dB	6.6 dB	3.6 dB	0.4 dB
	15	9.8 dB	7.0 dB	3.9 dB	1.1 dB

(d) Standards for Design

For the design of the track circuit applied in AC electrificated line, anti-interference (see Item 5-2-2.), train shunting sensitivity, and rail breakage detection performance must given special attention. These are the functions which must be ensured as a minimum for the safety operation system. Further, it is a basic condition of the design that each one is of the determined standard level. Table 5-4 is a summary of the possible cases when these standards are not satisfied.

Further, as design criteria, the control distance, reliability, economy and maintenance, etc. must be considered.

Table 5-4 Design Standards for Track Circuits

ℓ = Control length of track circuit G = Leakage conductance between rails
I_P = Electric rolling stock current U_B = Track circuit unbalance

Item	Standards for design	Possible phenomena when standards are not satisfied
1. Train shunting sensitivity	When ℓ = max, $0 < G \leq 0.5$ S/km, the following value is desired: more than 0.3Ω	Unstable action of the track relay when a train is operating ⇨ Fail-out Refer to 5.2.1 (2) (b)
2. Anti-disturbance	(1) DC single rail track circuit (in station tracks) (a) When ℓ = max, G = min (= 0), the following formula applies: $I_{RE} > I_R$ I_{RE} = release current of track relay I_R = DC disturbance current shunted to the track relay (However, the disturbance rush current mixed into the track circuit is the value considered the transient response at the receiving end.) (b) To prevent polarization, when ℓ = max, G = 0.5 S/km, it is desired that the ordinary current at the receiving end be increased	(a-1) When the interference current is the same phase, unstable action of the track relay when a train is operating ⇨ Fail-out Refer to 5.2.2 (3) (b) and (c) (a-2) When the interference current is inverse phase, the track relay becomes down-away when no train is operating ⇨ Fail-safe (b) Because the operating time and release time of the track relay becomes longer, returning to normal after the relay drop-away is delayed. Refer to 5.2.2 (2) (e) and (3) (c)
	(2) LF, AF track circuit When ℓ = max, G = 0.5[S/km], Ip = 400[A], U_B = 10[%], these conditions must be satisfied: (a) Stable operation against the electric rolling stock unbalance current of 40 A (including higher harmonics) In this case, $S/N \geq 6$ dB is desired (b) No failure against the disturbance current mixed into the signal frequency band	(a) When no train is operated, the track relay becomes down-away ⇨ Fail-safe Refer to 5.2.2 (3) (a) and (c) (b) Unstable action of the track relay when a train is operated ⇨ Fail-out Note: Especially in the track circuit of no-modulation type, when the large interference current is mixed into the signal frequency band, it causes the dangerous failure
3. Detection of rail breakage	When ℓ = max, $0 < G \leq 0.5$[S/km], the following conditions are satisfied: $L_B \geq L_C$ L_B = the variation of minimum receiving level at rail breakage L_C = the variation of maximum receiving level at normal transmission (Compensated voltage level)	o When no train is operated, the track relay does not down away ⇨ Fail-safe Refer to 5.2.1 (2) (c) o Even in the case where a train is operating, sometimes the track relay does not down away, depending on the position of the train, or the position of the rail breakage ⇨ Fail-out

(3) DC Track Circuit (single rail)

(a) Outline and Major Functions

The present DC track circuit (single rail), which is different from conventional ones, has stable train detection performance even against the disturbance, because the S/N is improved by increasing the normal current to increase the anti-disturbance ability against the DC disturbance. The control length of the track circuit, anti-disturbance ability, and shunting characteristics are shown in Figs. 5-8 ∿ 5-10. The major functions of the DC track circuit (single rail) are as follows:

1) Conditions of track circuit

a)	Kind of electrification	AC electrification
b)	Place used	Single rail in station yard (without main tracks)
c)	Variation of leakage conductance	0 ∿ 0.5 [S/km]
d)	Control length	20 ∿ 1,000 [m]
e)	Train shunting sensitivity	More than 0.8 [Ω]
f)	Multi-indication ability	2 position indication
g)	Rail breakage detection	Possible (only on the signal rail side)
h)	Maximum current of electric rolling stock	400 [A]
i)	Scope of device concentration	Power transmitting cable, less than 2 [Ω], 500 [m] Power receiving cable, less than 3.2 [Ω], 500 [m]

2) Conditions of environment

a)	Surrounding temperature	−30 ∿ +70 [°C]
b)	Humidity	Less than 95%
c)	Power source	DC 12 [V] ± 10%

3) Track relay

a)	Type	Polarized gravity-drop type
b)	Coil resistance	0.3[Ω]
c)	Rated current	2.0[A]
d)	Minimum operation current	1.3[A]
e)	Release current	0.8[A]
f)	Operation release ratio	More than 0.6
g)	Overcurrent	Continuous 2.8[A]
h)	Turning time	0.4[Sec]
i)	Contact arrangement	NR4

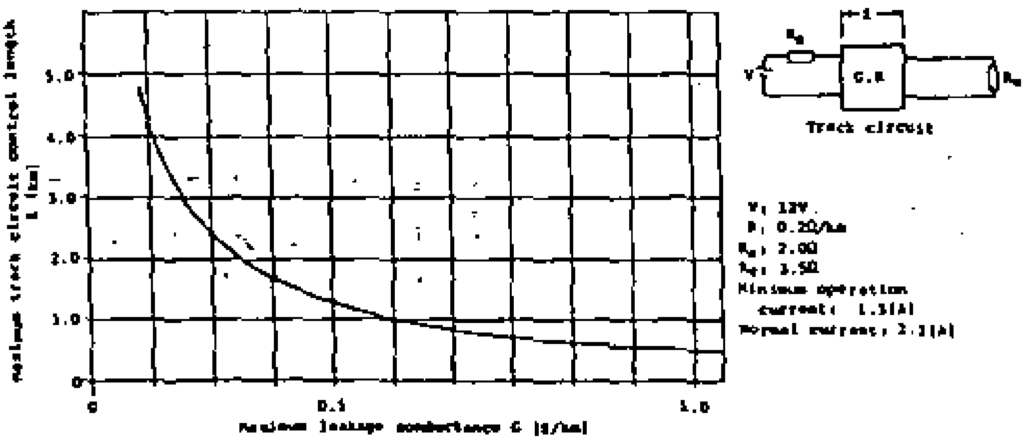


Fig. 5-8 Relationship between the Maximum Leakage Conductance and the Maximum Control Length of the Track Circuit

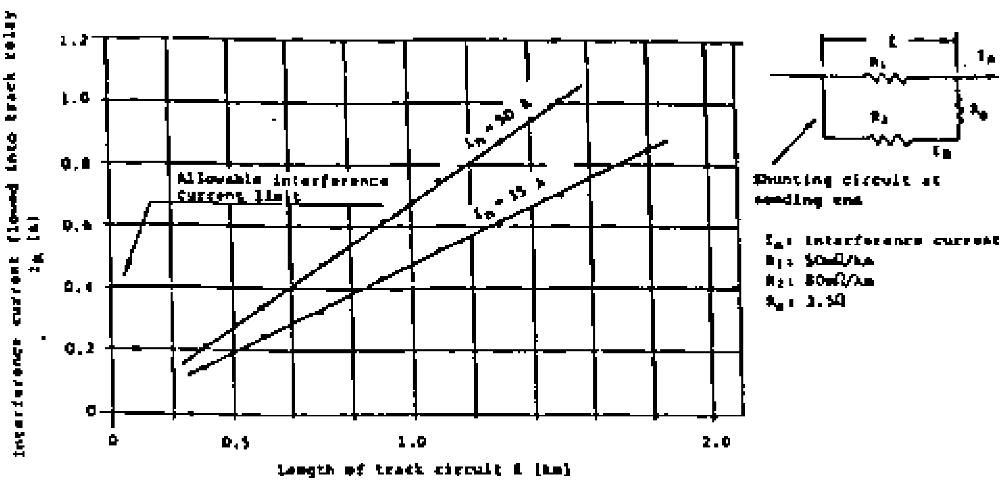


Fig. 5-9 Interference Current Characteristics

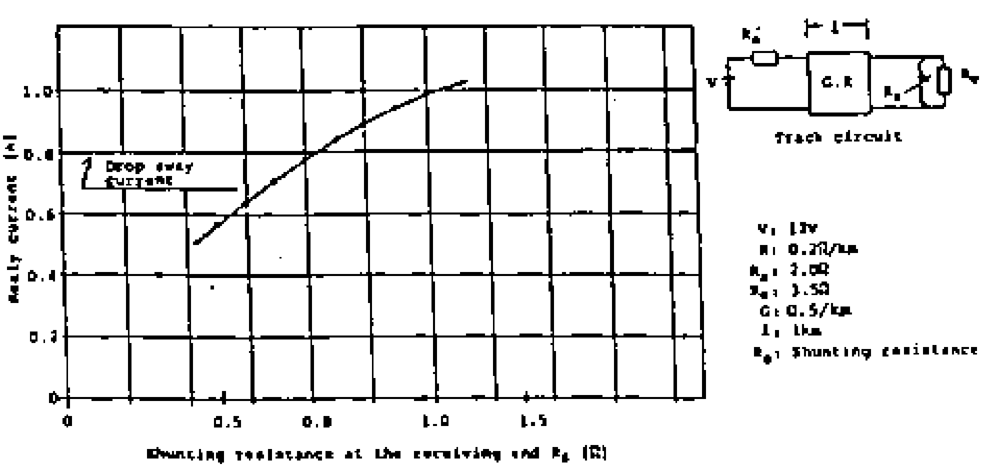
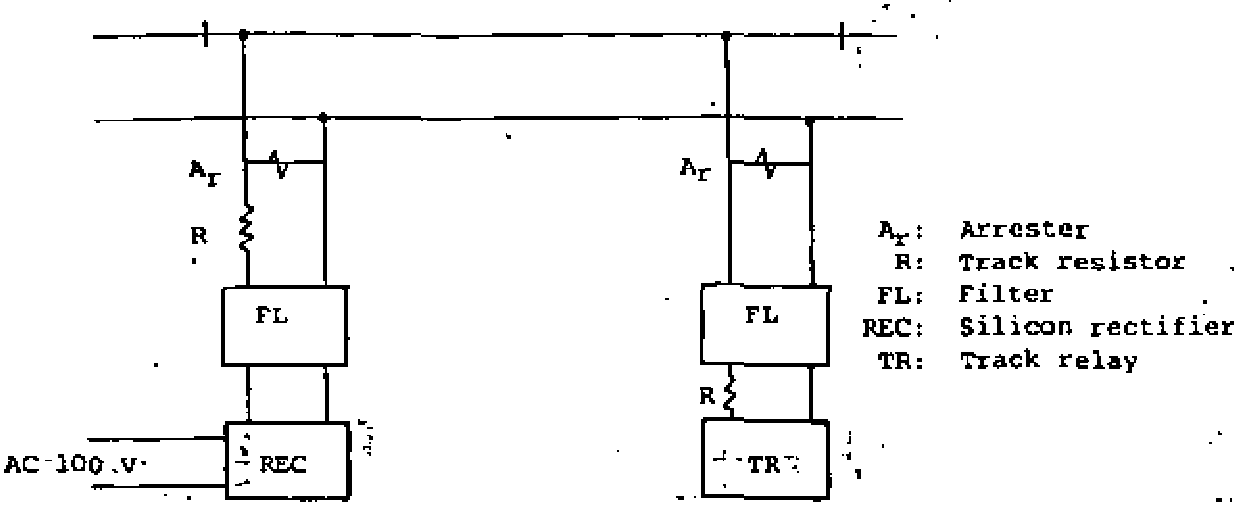


Fig. 5-10 Relay's Current Characteristics at Shunting of Power Receiving End

(b) Construction of Track Circuit

The DC track circuit construction is the single rail type as shown in Fig. 5-11.



Ar : Arrester REC : Silicon rectifier
R : Track resistor TR : Track relay
FL : Filter

Fig. 5-11 Construction of DC Track Circuit (single rail)

(4) Divided-and-Multiplied Frequency Track Circuit

(a) Outline and Major Functions

In the divided-and-multiplied frequency track circuit system, the frequency divider takes out 1/2 frequency of the power source frequency, the divided frequency current is sent to the track circuit, and the receiving side multiplies the frequency, then the 2-dimension 50 or 60 Hz track relay is driven. The construction of this system is simple, and the reliability is high. However, the beginning adjustment takes time and the power consumption is large.

This system is used when there are less than 10 track circuits in the station tracks of the JNR.

The major functions of the divided-and-multiplied frequency track circuit are shown below:

1) Conditions of track circuit

a)	Kind of electrification	AC, DC and non-electrification
b)	Place used	Between stations and station tracks (also single rail type is available)
c)	Variation of leakage conductance	0 ∿ 0.5[S/km]
d)	Control length	20 ∿ 2,000[m]
e)	Train shunting sensitivity	0.06 ∿ 0.2Ω
f)	Multi-indication ability	3 position indication
g)	Rail breakage detection	Possible
h)	Maximum current of electric rolling stock	400[A]
i)	Scope of device concentration	Less than 2[km] (less than 15[Ω] transmitting & receiving cable)
j)	Tolerance of disturbance current	50 or 60 Hz (40[A]), 25 or 30 Hz (1.8[A])

2) Conditions of environment

a)	Surrounding temperature	-30 ∿ +70[°C]
b)	Humidity	Less than 95%
c)	Power source	AC 110[V] $^{+10}_{-20}$%

3) Track circuit type

a)	Communication method	No-modulation phase discrimination
b)	Frequency	25 or 30 Hz

4) Transmitting system

a) Transmitting power 240[VA]

b) Apparent power 900[VA]

5) Receiving system

a) Receiving end level 1[V] 2.4[A]

b) Apparent power 220[VA]

c) Track relay (rated voltage or current)

Track side	AC 0.75[V] (0.90[V]) 1.25[A]
Local side	AC 110[V] 0.43[A] (0.36[A])
	With 50 Hz; inside ( ) is in the case of 60 Hz

(b) Construction of Track Circuit

The structure of the divided-and-multipled frequency track circuit is as shown in Fig. 5-12:

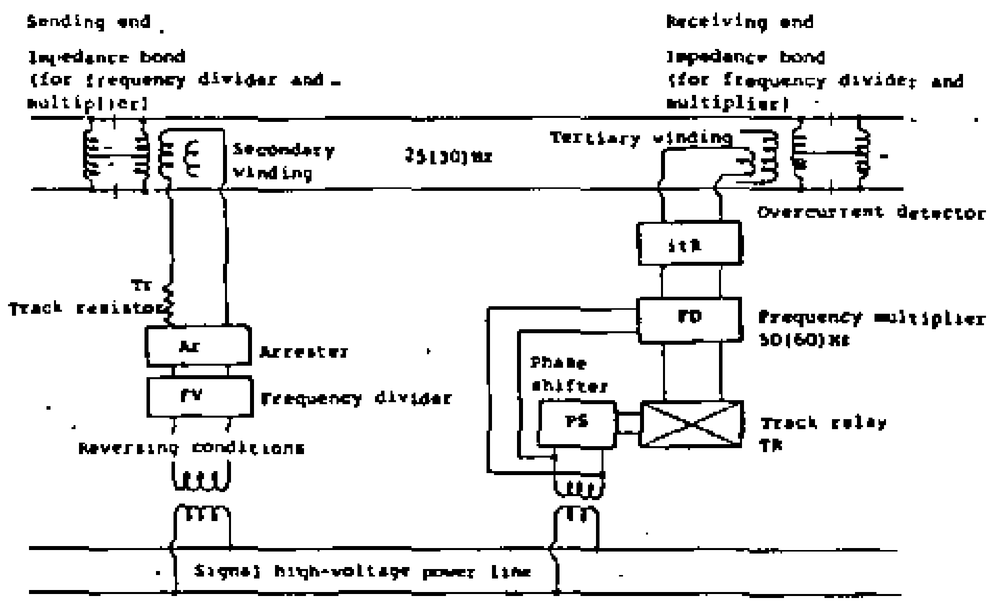


Fig. 5-12 Construction of Divided-and-Multiplied Frequency Track Circuit (double-rail)

Principle to Produce Divided Frequency

As shown in Fig. 5-13, two iron cores are wound separately around input coil N_1, and commonly with output coil N_2. The N_1

coils are wound in the inverse polarity to each other, and are connected in a series through the silicon diode.

The N_2 coil on the output side is connected to a resonance capacitor C_2, so that it may resonate to 1/2 or the input frequency.

When AC input of 50 Hz (or 60 Hz) is supplied to this circuit, it is a half-wave rectificated by the silicon diode, and given to N1 coils as the DC bias. Because the inductance varies periodically, due to the so-called parametric excitation, the oscillation of the divided frequency is produced.

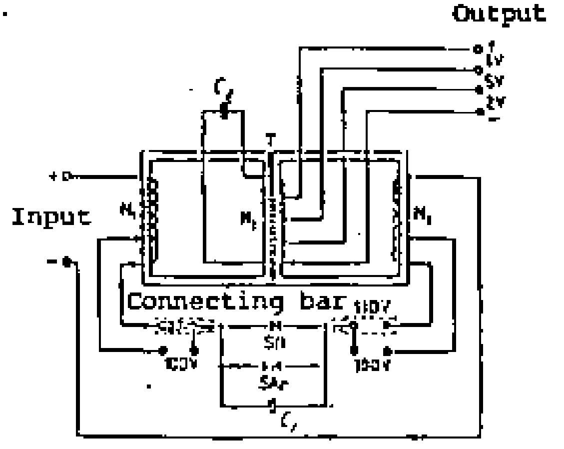


Fig. 5-13 Circuit Connection of Frequency Divider

(5) Divided Frequency Track Circuit

(a) Outline and Major Functions

The divided frequency track circuit has been developed to replace the conventional MG track circuit. This sytem contains frequency dividers for track use and local use, and drives the track relay of 25 or 30 Hz, with a 2 phase 4 line structure. In this system, there are few parts and it is highly reliability. The frequency divider for track and the frequency divider for local are used in inverse polarity, and the power source efficiency is good. This system has been used in the station tracks of JNR, in the case of more than 10 track circuits. The major characteristics of the divided frequency track circuit are as the following:

1) Conditions of track circuit

a) Kind of electrification	AC, DC and non-electrification

b) Place used	Station tracks (also single rail type is available)
c) Variation of leakage conductance	0 ∿ 0.5[S/km]
d) Control length	20 ∿ 1,000[m]
e) Train short shunting sensitivity	0.06 ∿ 0.2[Ω]
f) Multi-indication ability	2 position indication
g) Rail breakage detection	Possible
h) Maximum current of electric rolling stock	400[A]
i) Scope of device concentration	Less than 2[km] (less than 15[Ω] transmitting & receiving cable)
j) Disturbance current resistivity	50 or 60[Hz] (40[A]), 25 or 30[Hz] (1.8[A])

2) Conditions of environment

a) Surrounding temperature	-30 ∿ +70[°C]
b) Humidity	Less than 95%
c) Power source	AC 110[V] $^{+10}_{-20}$%

3) Track circuit type

a) Communication method	No-modulation phase discrimination
b) Frequency	25 or 30[Hz]

4) Transmitting system

	(Type 1)	(Type 2)	(Type 3)
a) Transmitting power (per yard)	1[kVA]	2[kVA]	3[kVA]
b) Apparent power (per yard)	3.3[kVA]	6.6[kVA]	9.9[kVA]

5) Receiving system

a) Receiving end level

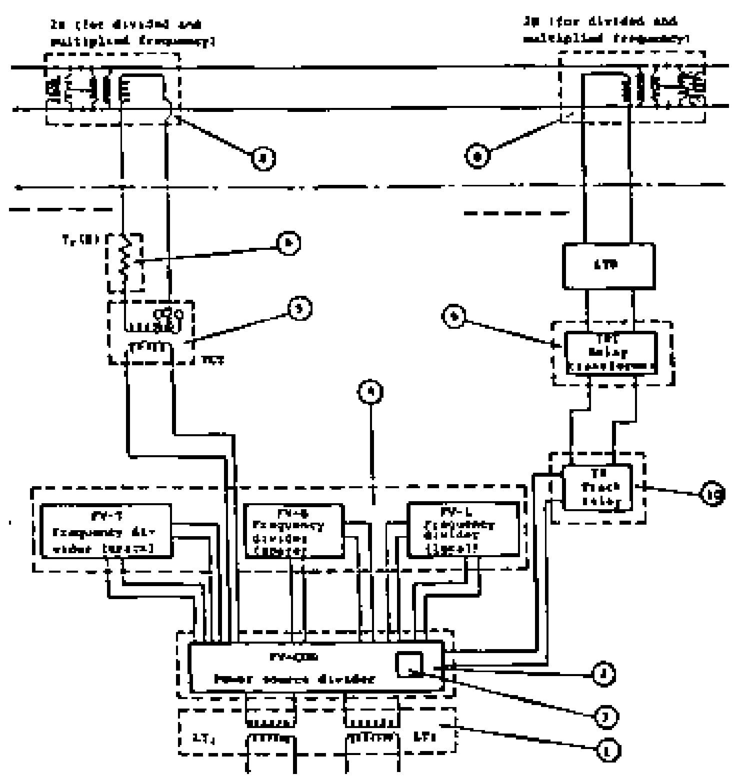
b) Apparent power — Same as the transmitting system

c) Track relay (rated voltage or current)

Track side	When 25[Hz], 20[V] 0.075[A]	
	When 30[Hz], 24[V] 0.075[A]	
Local side	25 or 30[Hz]: 110[V] 0.5[A]	

(b) Construction of Track Circuit

The construction of the divided frequency track circuit is as shown in Fig. 5-14.



① Line transformer
② Power source switch for divided frequency track circuit
③ Phase detection relay frequency divider
④ Frequency divider
⑤ Transformer for divided frequency track circuit
⑥ E-type track resistor
⑧ Impedance bond
⑨ Relay transformer (25-2 type, 30-2 type)
⑩ Track relay (25/30-2 type)

Fig. 5-14 Construction of Divided Frequency Track Circuit

As shown in Fig. 5-15, the power source switch for use with the divided frequency track circuit (FV-COD) consists of switches S_1 and S_2 for the normal and spare line transformers, switches S_3, S_4, S_5 and S_6 changing over the normal or spare frequency divider, the low voltage detector for input voltage (LVR), the phase detector for T and L phases of the frequency divider output, and the device for phase reversion.

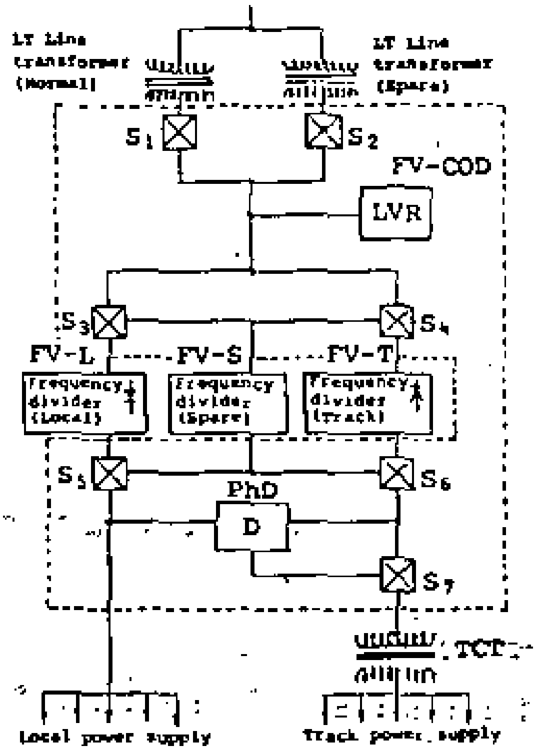


Fig. 5-15 Construction of Power Source Switch for Divided Frequency Track

(6) 80 Hz AC Code Track Circuit

(a) Outline and Functions

The 80 Hz AC code track circuit is a system in which 80 Hz frequency is adopted as the carrier in order to avoid the domain of low frequency oscillation from the thyristor control car to form a long track circuit and to avoid the electric rolling stock and its multiplied frequency, and in which low frequency modulation is made to increase the safety. The electric rolling stock current resistivity is the same as with other track circuit systems, and it can be used on 50/60 Hz electrification line. When the length of the track circuit is 4(km), it has a shunting sensitivity of more than 0.35(Ω); the device is small in size and conserves energy.

The major characteristics of the 80 Hz AC code track circuit are shown as below:

1) Conditions of track circuit

a) Kind of electrification AC, DC, and non-electrification

b)	Place used	Double-rail
c)	Variation of leakage conductance	0 ∿ 0.5 [S/km]
d)	Control length and shunting sensitivity	20 ∿ 2,000 [m], more than 0.8 [Ω] 2,000 ∿ 4,000 [m], more than 0.35 [Ω]
e)	Multi-indication ability	2 position indication
f)	Rail breakage detection	Possible
g)	Disturbance current resistivity	50 [Hz], 40 [A], 80 [Hz], 2 [A]
h)	Maximum current of electric rolling stock	AC 400 [A]
i)	Scope of device concentration	Control cable length 1 ∿ 3 [km], 40 [Ω]

2) Conditions of environment

a)	Surrounding temperature	-30 ∿ +70 [°C]
b)	Humidity	Less than 95%
c)	Power source	DC 24 [V] ± 10%

3) Impedance bond — 1 [mH], 200 [A/rail]

4) Transmitting system

a)	Modulation type	Square wave amplitude modulation
b)	Carrier frequency	80 [Hz]
c)	Modulation frequency	2.5 [Hz] (150 code/minute), 4.0 [Hz] (240 code/minute)
d)	Transmitting power	Maximum 40 [VA]
e)	Transmitter load impedance	600 [Ω]
f)	Power consumption	Normal state 50 [W]; shunting state less than 72 [W]

5) Receiving system

a) Demodulation type — Envelope detection

b) Receiver input impedance — 600 [Ω]

c) Minimum operation level — 15 [dBm] 0.6 [V]

d) Band-pass filter attenuation — 80 ± 4 [Hz], less than 6 [dB]; 80 ± 20 [Hz], less than 40 [dB]

e) Power consumption — Less than 3.5 [W]

f) Track relay — 7.5 [V], 600 [Ω], NR4

If the receiving level compensated is 12 ∿ 13 [dB], when the length of the track circuit is 4 [km], rail breakage detection is possible. Refer to Item 5-2-1(2)(c). In this case, 0.35 [Ω] can be ensured as the shunting sensitivity, as seen in Fig. 5-16.

To prevent the failure of the track circuit in the case of breakage in the insulation, the track circuits of 150 codes and 250 codes are used by placing them alternately. It is also possible to develop this to ATC by increasing it by several codes.

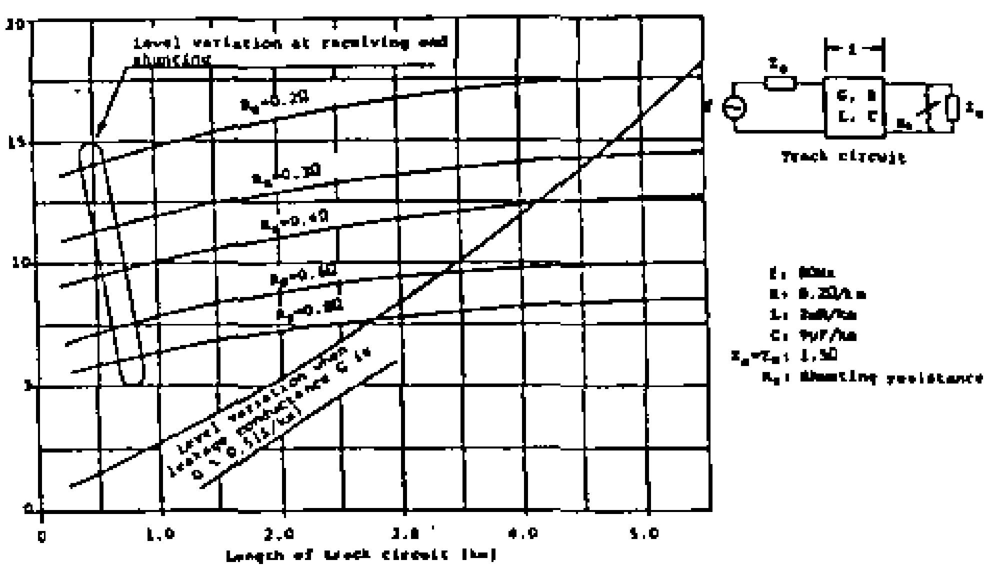


Fig. 5-16 Characteristics of Receiving Level Variation

(b) Construction of Track Circuit

The construction of the track circuit is shown in Fig. 5-17. The block diagram of the transmitter and receiver is Fig. 5-18. The signal level diagram is shown by Fig. 5-19.

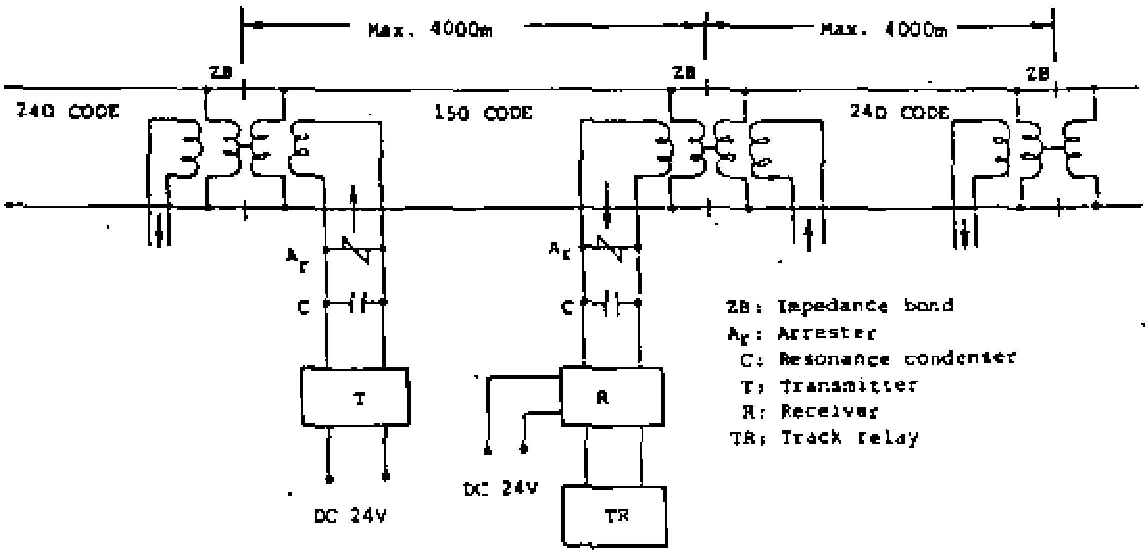


Fig. 5-17 Construction of 80 Hz AC Code Track Circuit

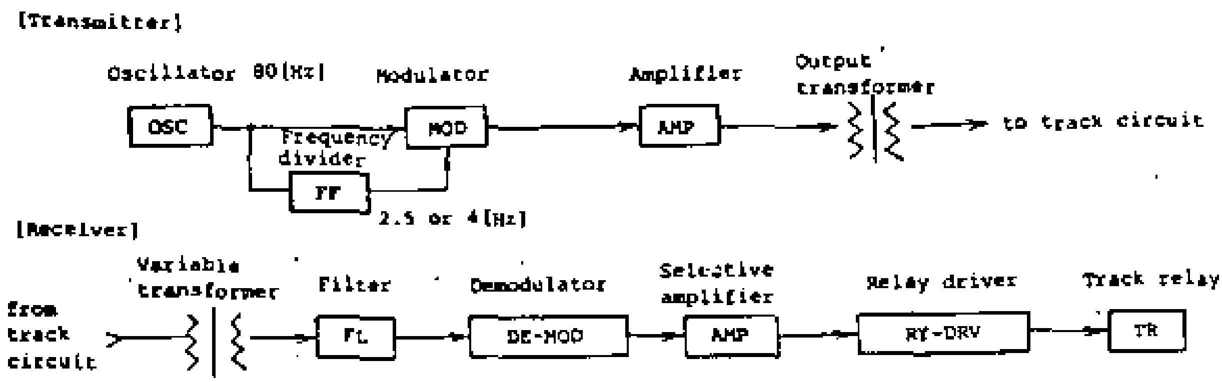


Fig. 5-18 Block Diagram of Transmitter and Receiver

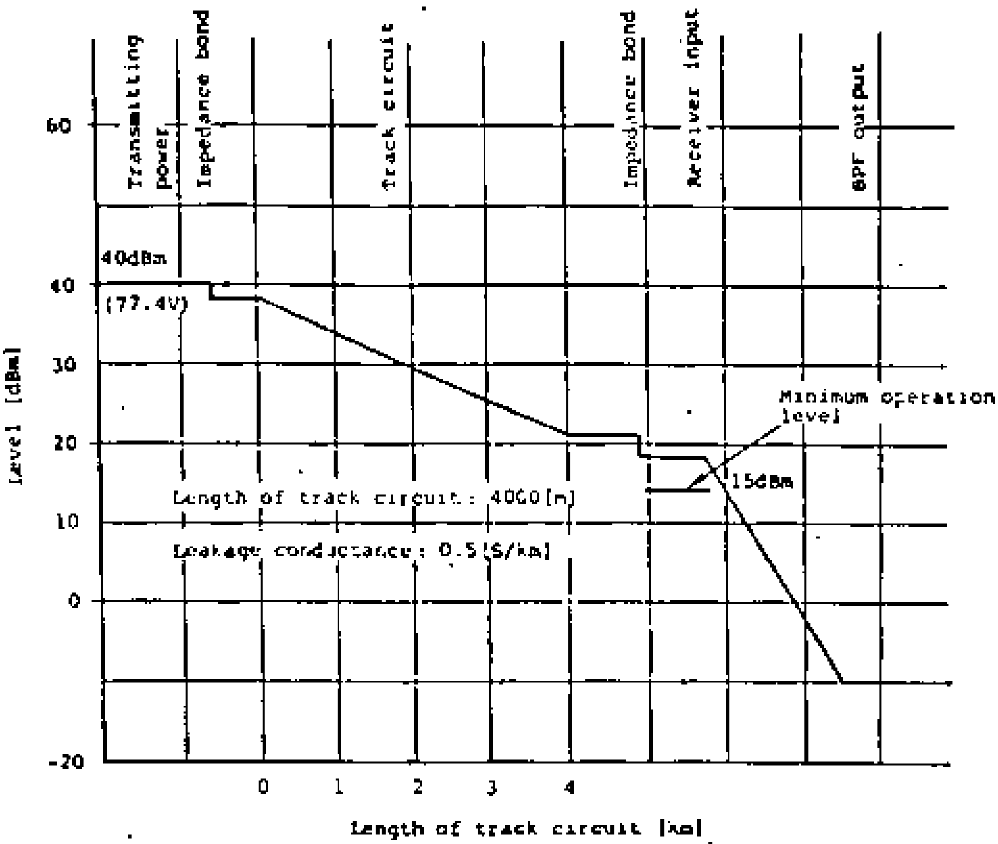


Fig. 5-19 Level Diagram of 80 Hz AC Code Track Circuit

(7) AF Track Circuit (concentrated device type)

(a) As the signal frequency of the AF track circuit (concentrated device type), the combined two waves of the single wave (sine wave), excluding the higher harmonics of the power source, are used. Thus train detection is done, and the devices are concentrated by cables. Because device concentration is available up to 10 km, the power source for the level crossing alarm between stations or the signal devices is supplied through buried low voltage power cables from the station, signal high voltage power lines are not required, and savings in the construction cost can be expected.

The major characteristics of the AF track circuit (concentrated device type) are below:

1) Conditions of the track circuit

a)	Kind of electrification	AC, DC, and non-electrification
b)	Place used	Between stations
c)	Variation of leakage conductance	0 ∿ 0.5[S/km]
d)	Control length	20 ∿ 2,000 m
e)	Train shunting sensitivity	0.2 ∿ 1[Ω]
f)	Multi-indication ability	2 position indication
g)	Rail breakage detection	Possible
h)	Maximum current of electric rolling stock	400[A]
i)	Scope of device concentration	10[km] (PE star-type cable 1.2ϕ)
j)	Disturbance current resistivity	50 or 60[Hz], 40[A] The higher harmonies component of the electric car current is signal wave +30 dB.

2) Conditions of environment

a)	Surrounding temperature	-10 ∿ +40[°C]
b)	Humidity	Less than 95%
c)	Power source	AC 100[V] ± 10%

3) Impedance bond — 1[mH] at 1[kHz]

4) Transmitting system

a)	Type	Combination of 2 frequency waves

b) Signal frequency

A line (up-track)	615, 630 Hz and 915, 930 Hz
B line (down-track)	565, 580 Hz and 865, 880 Hz (Refer to Fig. 5-20)

c) Transmitting power — +38 dBm (per single wave)

d) Transmitter load impedance — 600 [Ω]

e) Redundancy system — Stand-by reservation

f) Apparent power — Less than 150 [VA] (per track circuit)

5) Receiving system

a) Demodulation — 2 frequency amplification

b) Receiver input impedance — 600 [Ω]

c) Minimum operation level — -10 dBm (per single wave)

d) Band-pass filter attenuation

e) Redundancy system — Parallel double system

f) Apparent power — Less than 40 [VA] (per track circuit)

g) Track relay — 24 [V], 200 [Ω], NR4N4R4

The AF track circuit system is a system which concentrates devices at each station and which is equipped with the redundancy system. Therefore, it has the characteristics of high reliability, easy maintenance, easy detection of trains between stations, and can be easily removed to the ATC.

(b) Construction of the Track Circuit

The construction of the track circuit, the block diagram, and the level diagram are shown in Fig. 5-21, Fig. 5-22 and Fig. 5-23 respectively.

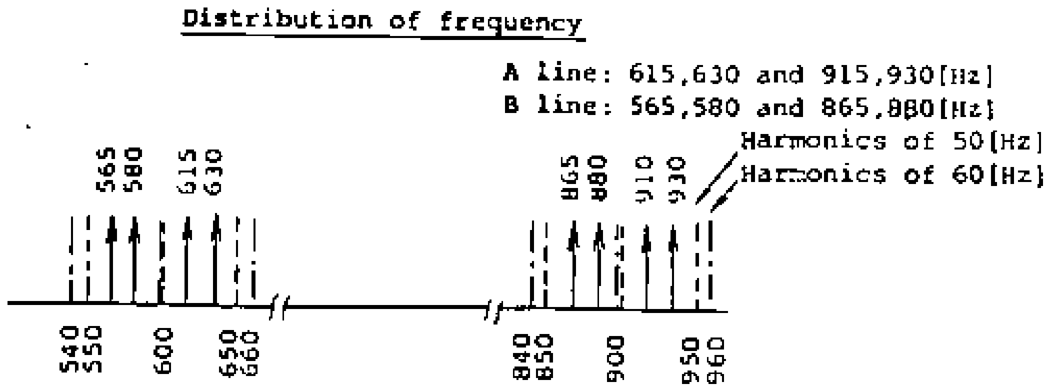


Fig. 5-20 Distribution of Signal Frequency

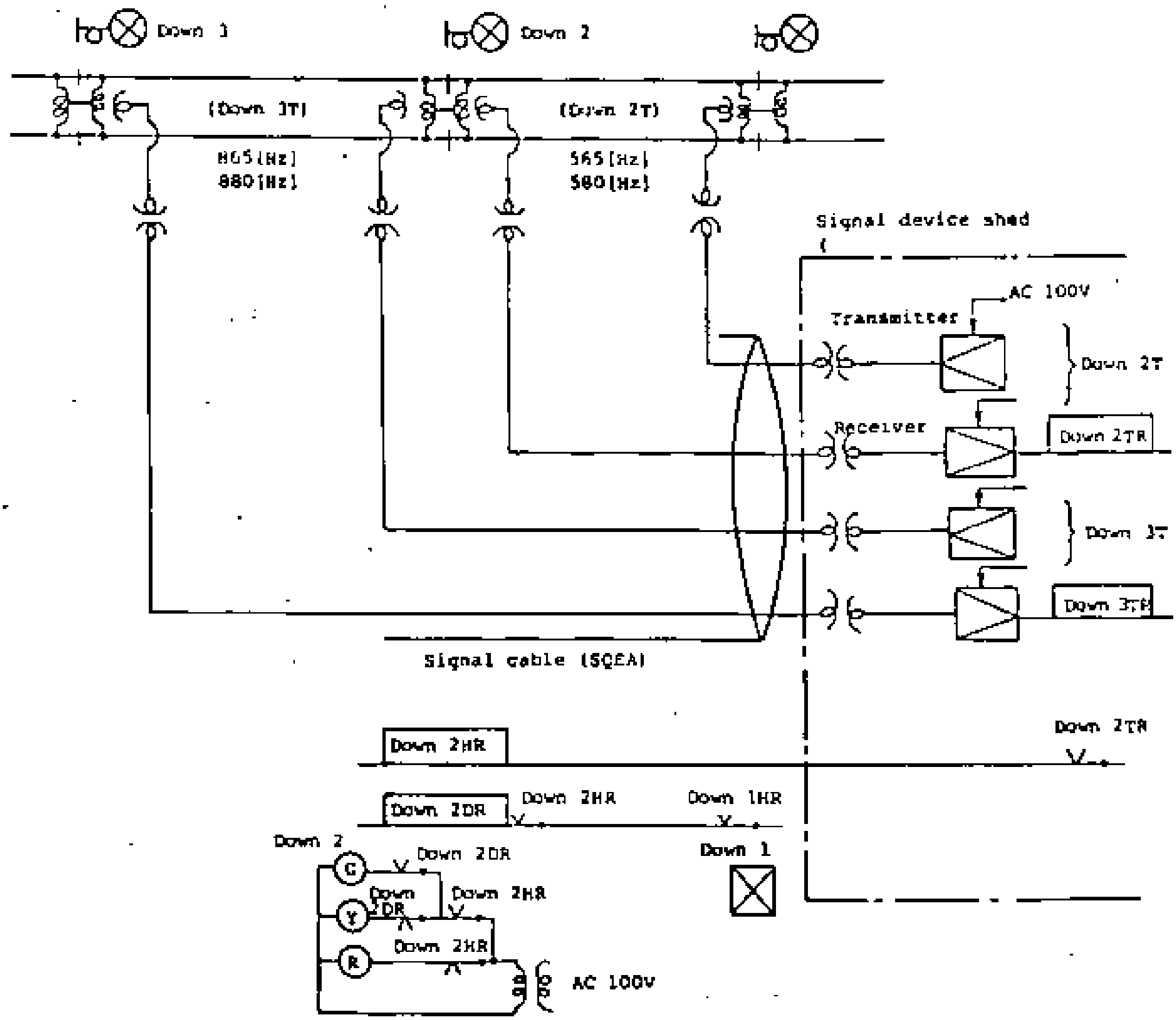


Fig. 5-21 Construction of the AF Track Circuit (concentrated device type)

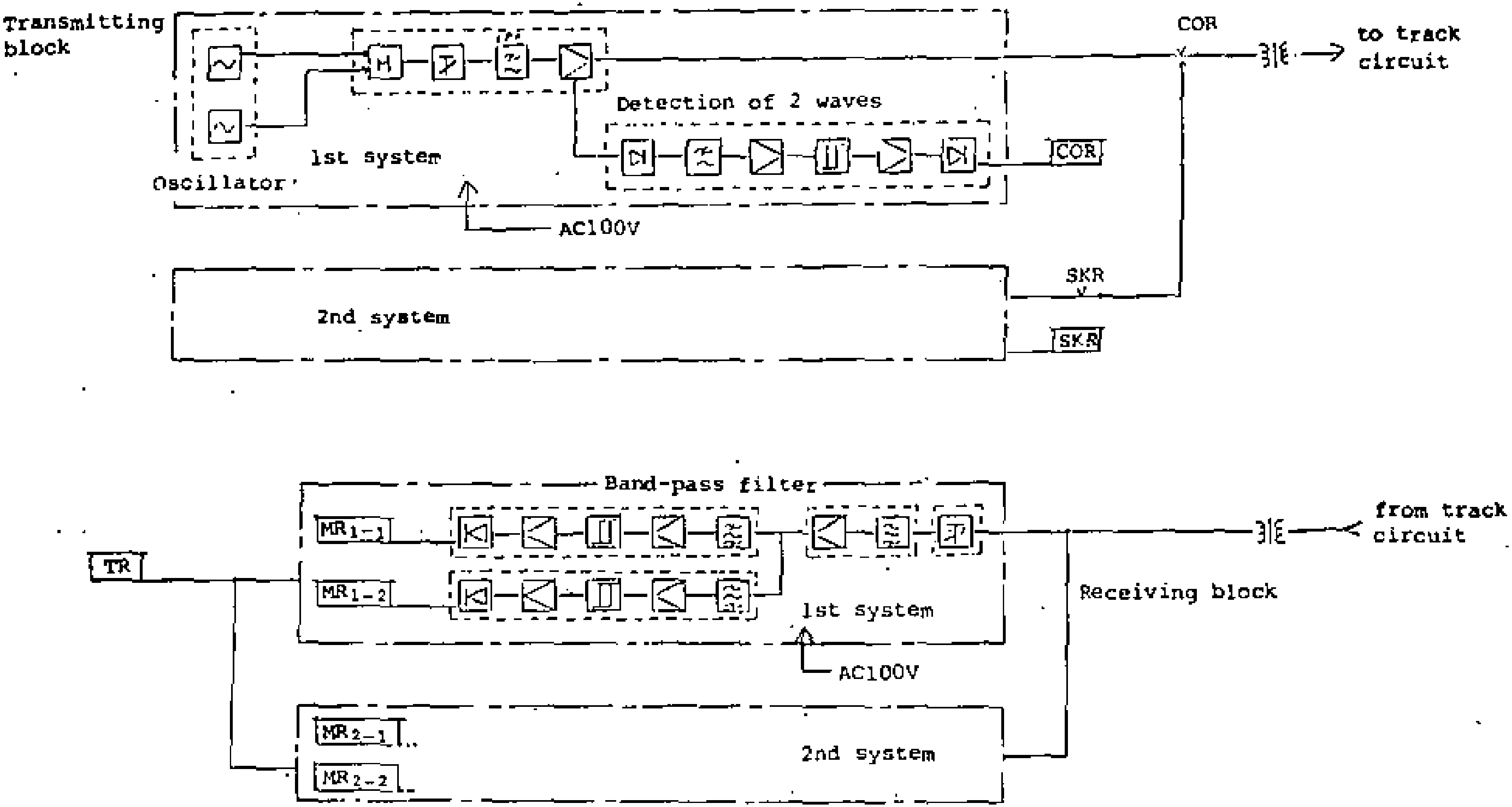


Fig. 5-22 Transmitting and Receiving Block Diagram

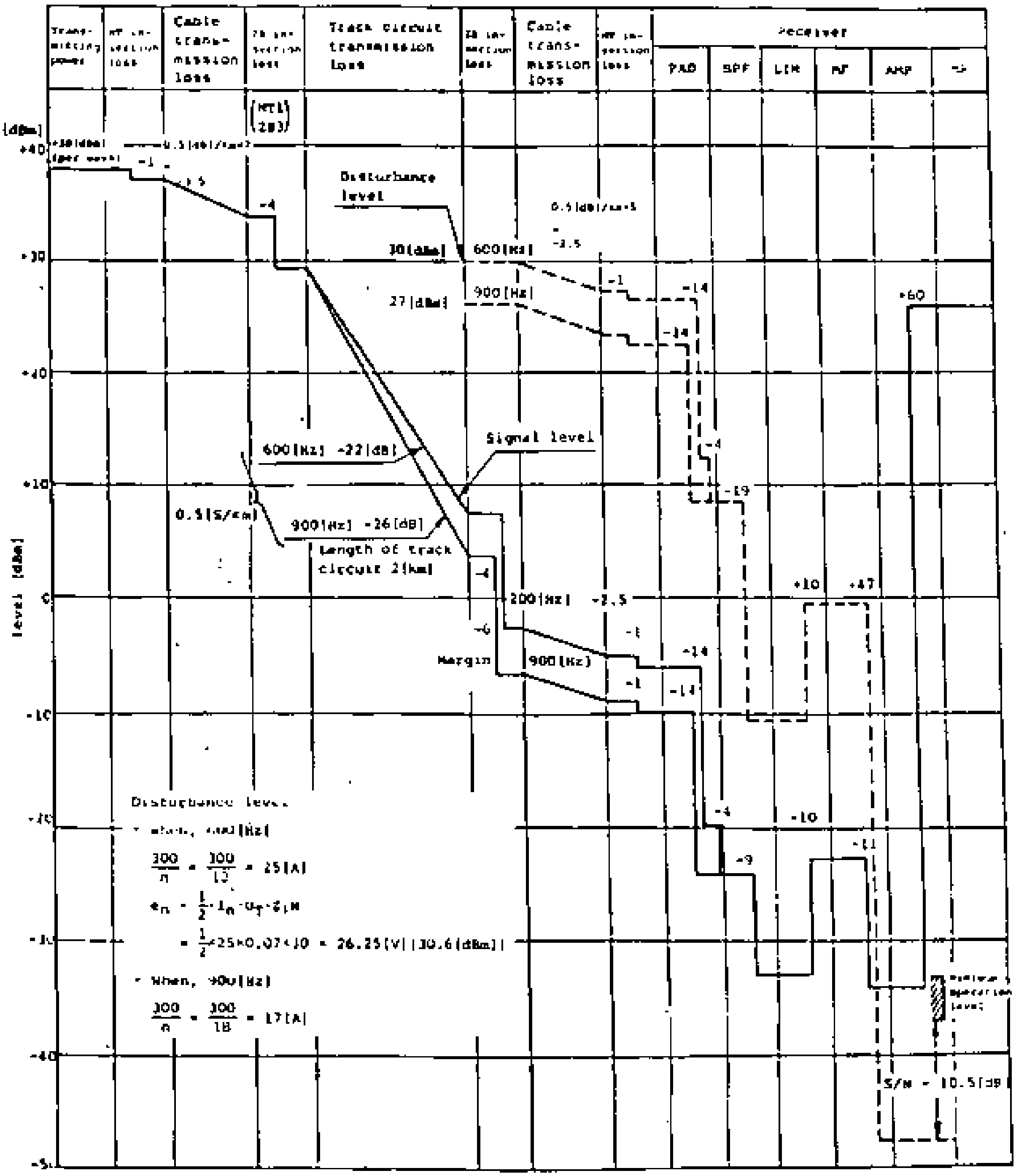


Fig. 5-23 Level Diagram of AF Track Circuit (concentrated device type)

(B) Non-insulated Track Circuit

In the non-insulated track circuit system, the track circuit itself exists, but there is no rail insulation of the track circuit boundary. Although the maintenance for the rail insulation is not required, train detection near the track circuit boundary does not exhibit sharp performance. Therefore, when signals exist, if the detection accuracy varies greatly, the signal is changed to red by the train itself, which must be looked out for. Moreover, the non-insulated track circuit generally has a short track circuit, and the shunting sensitivity is low.

The non-insulated track circuit is divided into 3 kinds, according to the receiving system: namely, the voltage receiving system, the current receiving system and the voltage current receiving system. In the case of the voltage receiving system, the accuracy of detection of the boundary is low. Therefore, to improve it, the use of a higher frequency is necessary. Although the detection accuracy with the current receiving system is good, there is much variation in the detection accuracy due to the shunting resistance of the wheel axle. As to the voltage current receiving system, although the field equipment is complex, the high detection accuracy can be obtained even with a low frequency.

The non-insulated track circuit is divided to two kinds by the place of transmission: the central transmitting type and the end transmitting type. In the central transmitting system, the receivers are installed at both ends, so its construction cost is cheap. Although the construction cost of the end transmitting type is high, it has the merit that it can be developed to ATC easily.

(a) Central Transmitting Type Voltage Receiving System

The major characteristics of this system are as follows:

Carrier frequency	5 waves, 6 ∿ 8[kHz]
Modulation frequency	21[Hz]
Track circuit length	500[m] (one side)

Shunting sensitivity	More than 0.8[Ω]
Transmitting power	+38[dBm]

An example of the track circuit construction of this system is shown in Fig. 5-24 below.

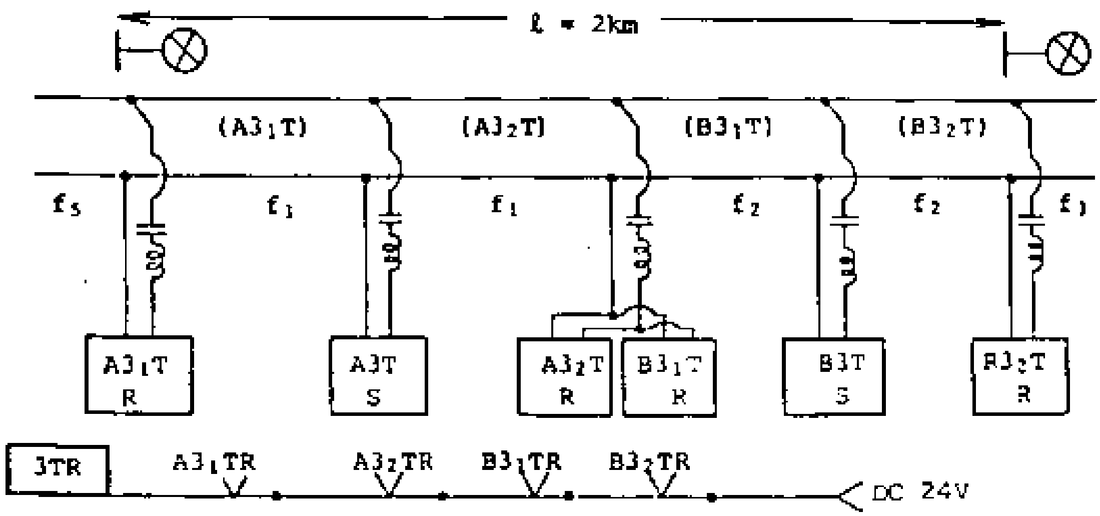


Fig. 5-24 Example of Central Transmitting Type Voltage Receiving System

(b) End Transmitting Type Current Receiving System

An example of the construction of this track circuit is shown in Fig. 5-25, and the major characteristics are listed below.

Major features:

Carrier frequency	6 waves, 2 ∿ 3[kHz]
Modulation frequency	16 ∿ 36[Hz]
	4 waves responding to G, YG, Y, YY
Track circuit length	1,000[m]
Shunting sensitivity	More than 0.2[Ω]
Transmitting power	+38[dBm]

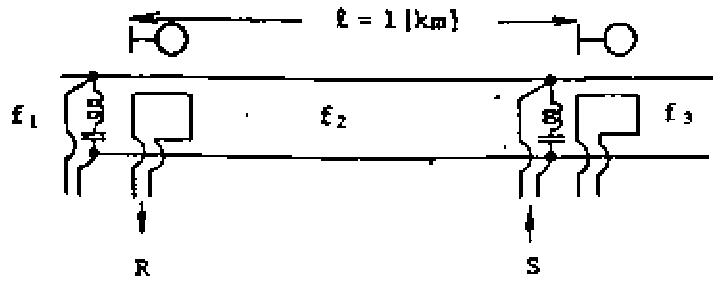


Fig. 5-25 Example of End Transmitting Type Current Receiving System

(c) Central Transmitting Type Voltage Current Receiving System

An example of this track circuit construction is shown in Fig. 5-26, and the major characteristics are listed below.

Major features:

Carrier frequency	6 waves, 320 ∿ 620 [Hz] or
	6 waves, 2 ∿ 6 [kHz]
Modulation frequency	6, 10 [Hz] or 16, 21 [Hz]
Track circuit length	1,000 [m] or 500 [m] (one side)
Shunting sensitivity	More than 0.3 [Ω]
Transmitting output	+38 [dBm]

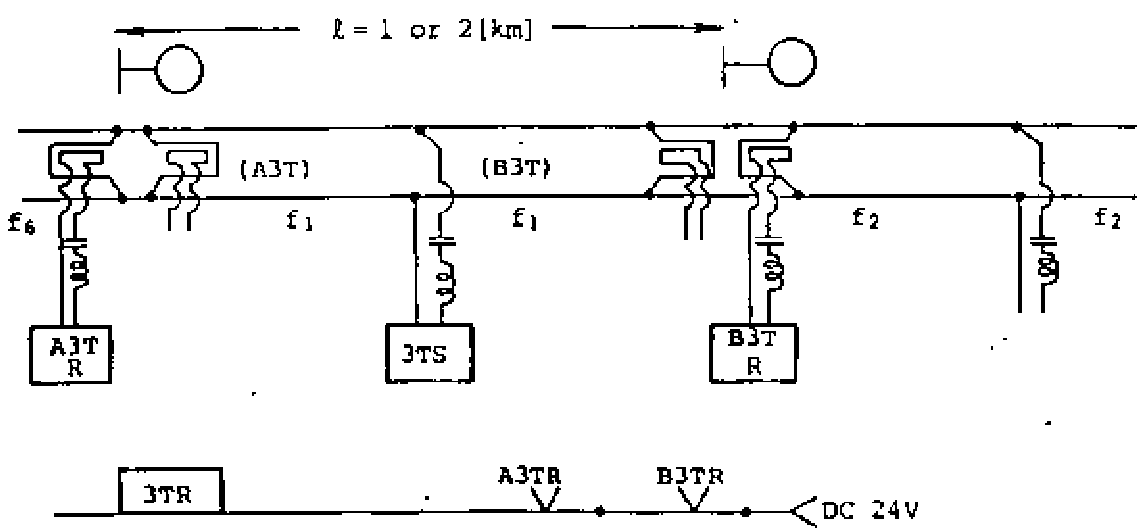


Fig. 5-26 Example of Central Transmitting Type Voltage Current Receiving System

5-2-2 Track Circuit and Rolling Stock Current

(1) Interference Current and Its Sources

Generally, in the AC electrified section, the electric rolling stock current flows unperiodically in the electric circuit, which consists of substation - trolley - electric rolling stock - rail - substation. This becomes the factor contributing various effects on the signal equipment.

Table 5-5 shows the sources of the interference current which chiefly affect the track circuit in the AC electrified section. As a major source affecting the track circuit, the higher harmonic current from the thyristor controlled car is shown in this table. It has been more than 10 years since the thyristor controlled car came about, and the interference has been reduced compared to the early days. However, even in the future, efforts should continue to be made to improve the interference, including the problems of the substation and signal system.

Needless to say, in the track circuit in the AC electrified section, the electric rolling stock current and the signal current coexist. Therefore, it is important to sufficiently resist the intrrference of the electric rolling stock current; that is anti-interference ability is required.

Further, it has been made clear by actual measurements in the past that the stray current from the DC electrified section extends to the scope of several 10 km. In applying track circuits, care must be given to this. Moreover, there are problems such as the effects of polarization on the DC track circuit in the PC sleeper section, the rush current and the low frequency oscillation due to the thyristor controlled car, etc.

In applying the track circuit, which is very important in ensuring safety operation, it is essential to sufficiently understand the various features and phenomena of these interference currents, so that the stability of the functions can be always expected under all environmental conditions.

Table 5-5 Sources of Interference Currents in AC Electrification

Electrification type	Division	Source		Track circuits affected
AC	Electric railway system	AC substation	Higher harmonic current	AF track circuit
		Thyristor controlled car Diode car	Higher harmonic current	
			Rush current	LF track circuit (70 ∿ 400 Hz)
		Thyristor controlled car	Low frequency oscillation	
		DC substation (AC/DC connected rail)	DC stray current	LF track circuit (20 ∿ 30 Hz)
		Others (PC sleeper section etc.)	Polarization	DC track circuit
	Other industrial systems	Current supply line	Induction	
		General plants	DC stray current	

(2) Effects on the Track Circuit

(a) Thyristor Phase Controlled Rolling Stock

The thyristor phase controlled rolling stock is different from the conventional rectified rolling stock, in that the size of the harmonic wave is not in proportion to the fundamental wave and varies according to the control phase angle, and that the maximum value of the higher harmonic wave does not occur simultaneously. Because the operation time of the train detective receiver is about one second, an interference current continuing longer than this may affect the detection, depending on the value. Therefore, the JNR performs frequency analysis by plotting the maximum value of each harmonic wave.

In past tests, there have been cases where low frequency oscillation due to the thyristor controlled rolling stock reached a maximum of 31 A in the range of several [Hz] ∿ 20[Hz], when the feeding circuit and the car control system were not sufficiently matched.

The thyristor phase controlled car of the JNR has reached the levels of performance described below:

o The high harmonic current varies according to the control phase angle, but the maximum.value generated is approximately $1/n^{1.6}$ at the powering time, and $2/n^{1.6}$ at the time of the regenerative braking. However, the regenerative current is generally less than 1/2 of the powering time. Therefore, as the absolute value of the higher harmonics, it is sufficient to use the value of the powering time. (See Figs. 5-27 ∿ 29)

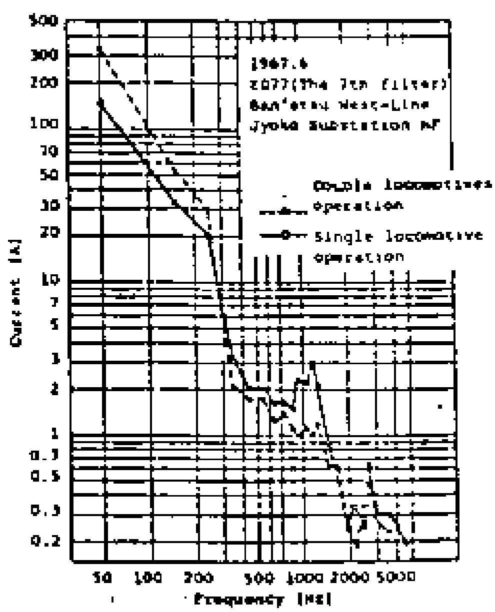


Fig. 5-27 Frequency Analysis of AC Thyristor Controlled Electric Locomotive

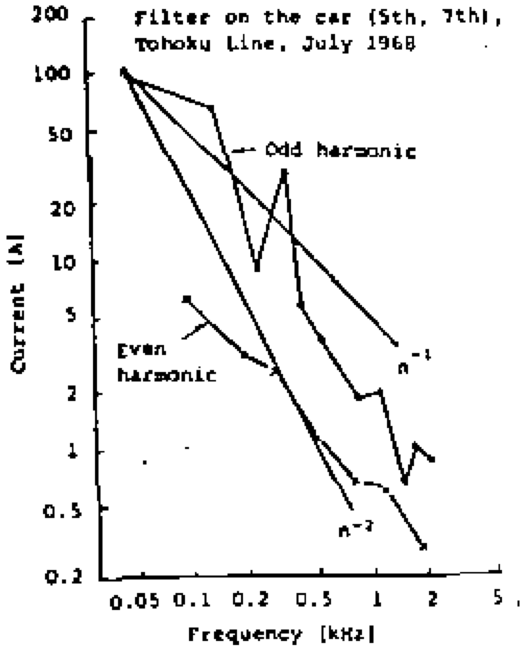
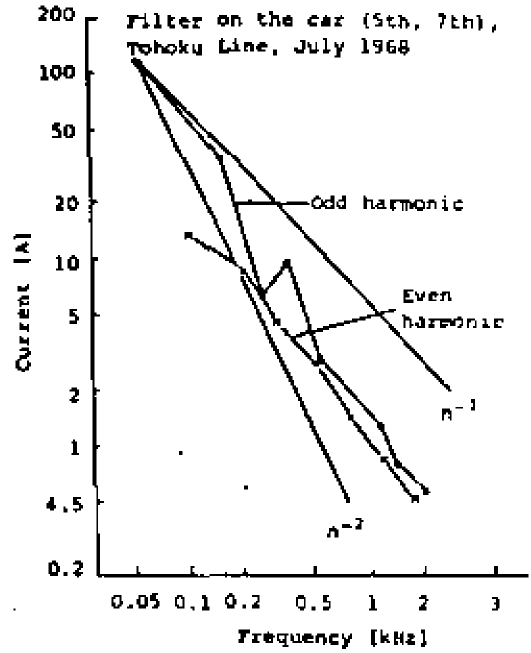


Fig. 5-28 Powering Current Frequency Analysis of AC Thyristor Phase Controlled Locomotive (EF71)



Fug. 5-29 Regenerative Current Frequency Analysis of AC Thyristor Phase Controlled Locomotive (EF71)

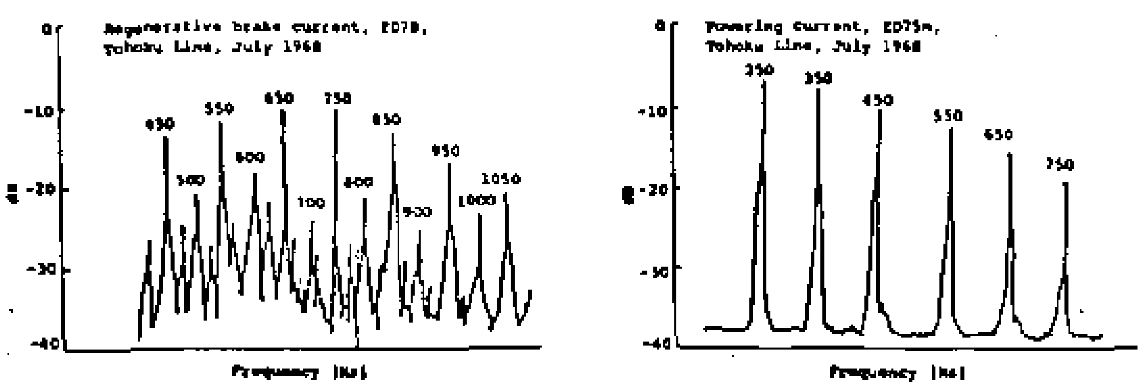


Fig. 5-30 Frequency Spectrum of Thyristor Controlled and Diode Locomotives

o With the advance of the control technique, the occurred current of the even harmonics is about 1/10 of the odd harmonics. (See Fig. 5-30)

o The generation of the low frequency oscillation tends to decrease remarkably in comparison with the 1970s, due to advanced analysis of the generation mechanism and car technology.

(b) Rush Current

When the AC electric locomotive or the AC electric car passes a dead section, or when its pantograph is raised, the air blast circuit breaker (ABB) is operated, and as the transient phenomenon of the main transformer on the car, a rush current from the excited current is generated. Because this current contains a large amount of DC component, it sometimes affects the DC track circuit. Therefore, when a DC track circuit is used, anti-interference planning must sufficiently take the rush current into consideration.

Fig. 5-31 shows the results of actual measurements by the JNR for the EF70 type AC electric locomotive. The rush current (DC component) which flowed along the rail when the ABB was operated was 30 ∿ 70 A. Although the attenuation during 0.3 ∿ 0.5 second is large, later the attenuation is small, and it takes 5 seconds until it becomes about 1 A. In the case of the new type electric locomotive, further improvement is expected by making the main transformer small.

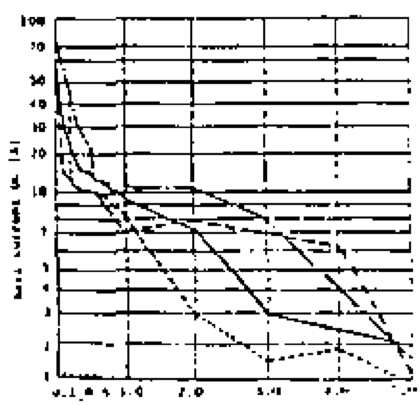


Fig. 5-31 DC Component of Rush Current by AC Electric Locomotive (EF70 type)

(c) DC Stray Current

Past actual measurements also clarify that if there is a DC substation near the AC-DC connecting point, the current of the DC electric rolling stock flows, even several tens of kilometers of rail into the AC electrified section. Fig. 5-32 shows the feeding circuit, in which the AC electrified section and the DC electrified section are directly connected and the return rail is used by both.

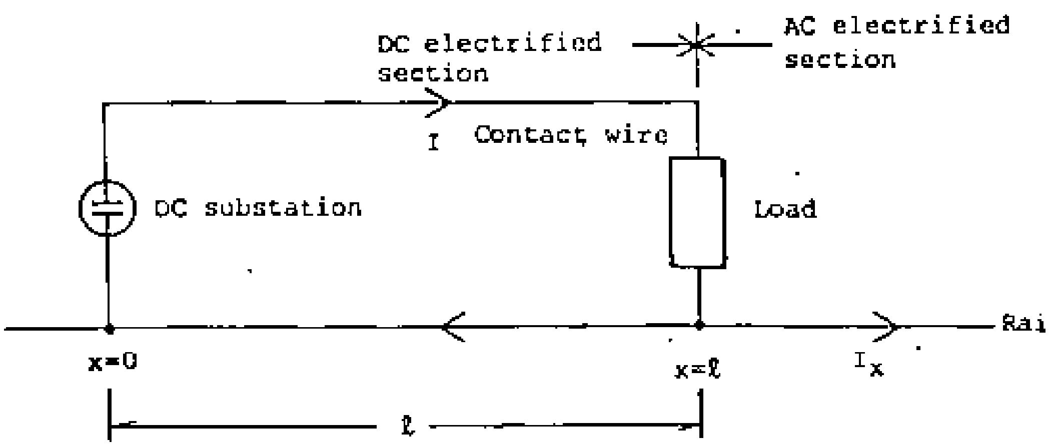


Fig. 5-32 Feeding Circuit at AC/DC Connecting Point

DC stray current I_x flowed to AC electrified section can be obtained approximately with the following formula from this figure.

$$I_x = -\frac{1}{2} I\epsilon^{-\alpha x} + \frac{1}{2} I\epsilon^{-\alpha(x-\ell)} \qquad [A]$$

Where, I = DC load current [A]

$\alpha = \sqrt{r \cdot g}$: Attenuation [1/km]

r = Rail to Ground DC resistance [Ω/km]

g = Rail to Ground leakage conductance [S/km]

Fig. 5-33 shows the calculations of the DC stray current which flowed along the rail in the AC electrified section, when the ground leakage conductance is changed to the conditions of a load current of 1,000 A and a load position of 10 or 20 km. From this figure, it is understood that the smaller the leakage conductance and the longer the distance from the DC substation to the AC/DC connecting point, the larger the DC stray current becomes.

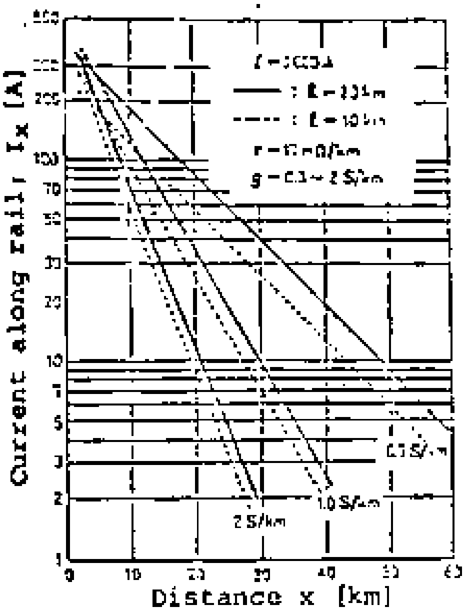


Fig. 5-33 Example of DC Stray Current Calculations

Because the leakage range of the DC stray current is wide when the DC electrified section and the non-electrified section are adjacent, it is a basic principle that the DC stray current should be completely cut off by the rail insulation.

(d) AC Stray Current

At the boundary between the AC electrified section and the non-electrified section, if the rail insulation is sufficient, the AC stray current to the non-electrified section theoretically does not occur. However, if the rail insulation at the boundary shorts, or is broken, the AC stray current is generated through the ground leakage resistance. Therefore, in propertion to the value of the stray current, the track circuit in the non-electrified section is affected. Although it depends on the type of track circuit in the non-electrified section, basically, one of the following countermeasures is required.

- o If the stray current is small and the transmitting device has sufficient power capacity, a series resistance is inserted at the receiving end to increase the transmitting output. (Improvement of S/N) o When the measure above is not effective, or if the stray current is large, the system must be changed to another type.

For reference, the AC stray current when the electrified section and the non-electrified section are not separated from the rail insulation is shown in Fig. 5-34. Variations of the AC stray current according to the train position are shown in Fig. 5-35.

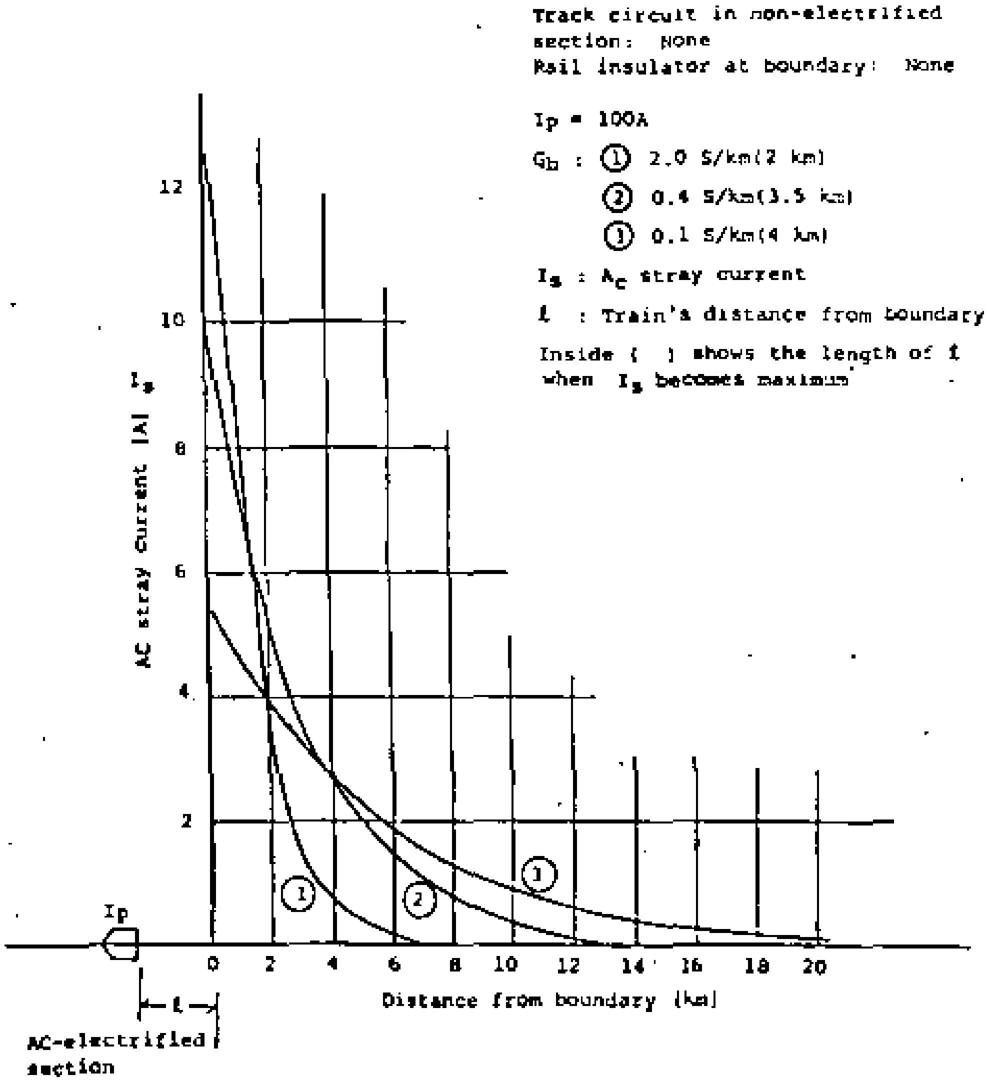


Fig. 5-34 AC Stray Current in Non-electrified Section

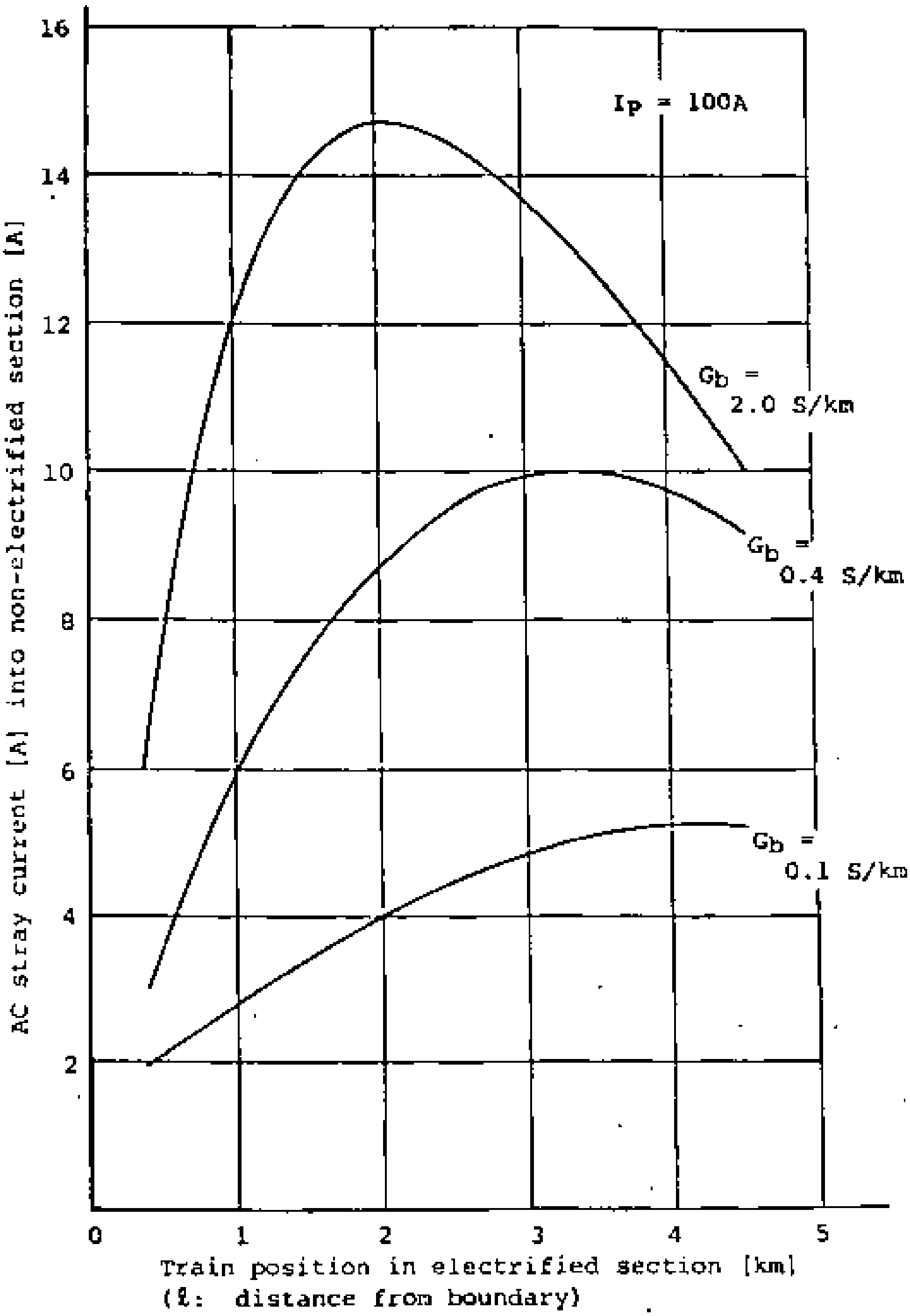


Fig. 5-35 Relationship between AC Stray Current and the Train Position

The relationship between the AT distance and the AC stray current varies greatly, depending on the location of the substation, the feeding current system, the ground leakage resistance, etc. When the AT distance is expanded from 10 km to 15 km, if the leakage resistance is small, the AC stray current hardly changes. However, if the leakage resistance increases, the AC stray current will increase by about 20% at 2.5Ω·km, and by 40 ∿ 50% at 10Ω·km.

The maximum AC stray current in the case of broken rail insulation is shown in the example calculations in Figs. 5-34 and 5-35. Therefore, if the track circuit can be improved so that it resists this AC stray current, it will be sufficient.

Although only the problem of the boundary between the AC electified section and the non-electrified section is described here, the case of the boundary between the AC electrified section and DC electrified section is the same.

(e) Polarization

In the case of the DC track circuit in the PC sleeper section, if the PC sleepers are wet, polarization of the rail occurs due to the DC voltage between the rails, because of the alkali ions of the concrete. Therefore, even if the transmitting power to the track circuit is cut off, the same polarity residual voltage exists between the rails.

Also, the JNR has experienced in the past polarization of the PC sleepers in the DC track circuit in tunnels. The changing time of the polarized relay took 40 ∿ 60 seconds, and several minutes were necessary for returning it to the former normal current after the track relay drop-away, due to the passage of a train.

For reference, the relationship between the residual voltage after cutting the sending power and the amount of time passed is shown in Fig. 5-36.

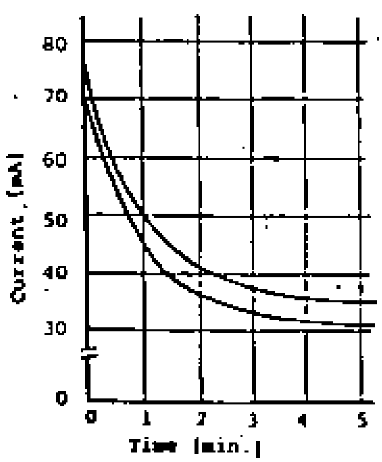


Fig. 5-36 Track Relay Current due to Residual Voltage

This can be regarded as a kind of battery. Therefore, by increasing the normal current in the track relay, the time of discharge can be reduced. Thus, the improvement of S/N of the DC track circuit can be achieved by increasing the normal current at the receiving end as much as possible, resulting in advanced anti-interference ability.

(3) Countermeasures against the Electric Car Current in the Track Circuit

(a) Track Circuit Unbalance and Anti-interference Ability

Generally, the unbalance ratio of the track circuit U_B is expressed by $U_B = U_r \pm U_z$

Where, Ur = unbalance ratio of the rail current, and U_z = unbalance ratio of impedance band.

U_r depends largely on the geometrical structure of the feeding circuit to the rail. Fig. 5-37 shows an example of actual measurements in a BT-system AC electrified section. The larger the frequency, the larger the unbalance ratio. And it also varies with the position of the train. This tendency is also appears in the case of the AT feeding current.

U_Z was 0.4 ∿ 2% in the case of a conventional rail. However, for a recent product, it was less than 0.1%, and U_Z was negligible.

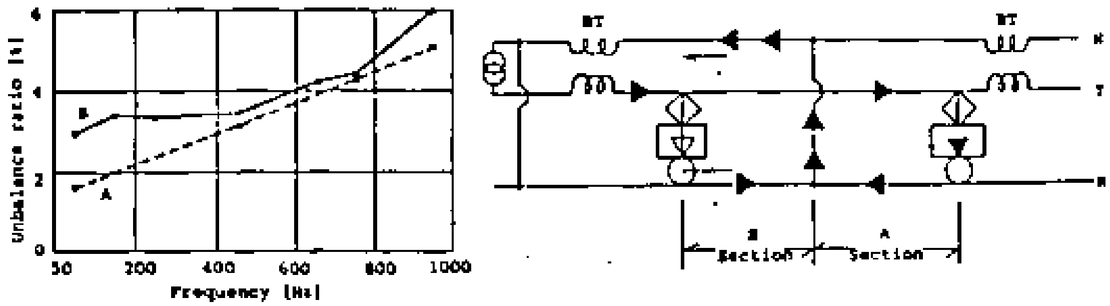


Fig. 5-37 Unbalance Ratio of Rail Current in BT-system AC Electrified Section

That is the track circuit unbalance in the DC electrified section mostly depends on the unbalance of the rail bond and the jumper bond. Further, in the AC electrifed section, as mentioned before, the track circuit unbalance is considered to be chiefly decided by the geometrical layout of the conductive parts in the feeding circuit.

When the equivalent interference current is mixed into the track circuit receiver "i_n" can be expressed by the following formula:

$$i_n = \frac{1}{2} \cdot I_n \cdot U_B \cdot K$$

Where, I_n = The "n" degree higher harmonic rolling stock current (A)

U_B = Unbalance ratio of track circuit

K = Coefficient determined by the communication system of the track circuit

That is, "i_n" is determined by the level of the high harmonic current mixed into the receiver in the frequency used, by the number of interference source, and by the unbalance ratio of the track circuit. Therefore, in the unbalance zone of the track circuit which requires stable performance (for example, U_B = less than 10%), the track circuit must be designed so that it is sufficiently resists the "i_n". Further, in the zone in which safety failures are permissible (for example, 10 ∿ 100%), it must be designed so that the track relay surely drops away.

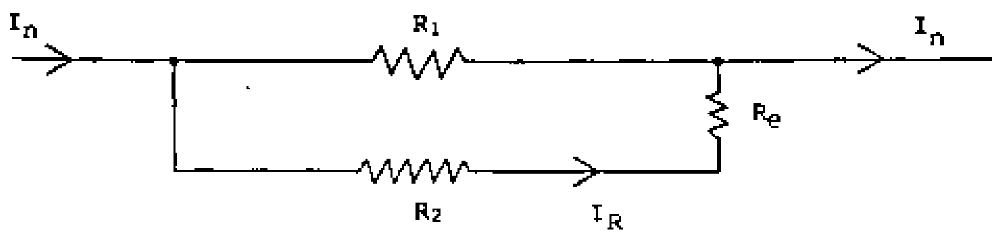
As the S/N of the receiver, the JNR ensures more than 6 dB in general, provided that rolling stock current is I_P = 400 A, the content of higher harmonics = $1/n^{1.6}$, and U_B = 10%.

(b) Anti-interference Ability of DC Track Circuit

As mentioned before, in the AC electrified section, DC components such as the rush current and the stray current exist. Therefore, when single-rail DC track circuits are constructed in the station tracks, these interference currents shunt into the track relay from the return rail, and dangerous failures may occur.

Let us calculate the relationship between the control distance of a single rail DC track circuit and the interference current shunted into the track relay, by taking a hypothetical value for the DC current flowing into the track circuit.

When the train shunt circuit at the power sending end occurs and no leakage of the track circuit exists, the current shunted into the track relay reaches the maximum. The equivalent circuit in this case is shown in Fig. 5-38



I_n = DC interference current flowing into the return rail side [A]

I_R = Interference current flowing into the track relay [A]

R_1 = Resistance of return rail [Ω]

R_2 = Resistance of signal rail [Ω]

R_e = Resistance of receiving end [Ω]

Fig. 5-38 Equivalent Circuit of Shunting at the Sending End in the Single-rail Track Circuit

With this equivalent circuit, $I_R = I_n \cdot R_1/(R_2 + R_e)$

Fig. 5-39 shows the relationship between the control distance "ℓ" and the interference current I_R when R_e is in the various conditions of I_n = 100 A, R_1 = 50 mΩ/km, and R_2 = 80 mΩ/km.

Because the rush current involves the attenuation factor, I_n varies according to the response time of the relay. As shown in Fig. 5-31, the longer the response time, the smaller I_n becomes. While, I_R also varies depending on the length of the track circuit, or the receiving end resistance.

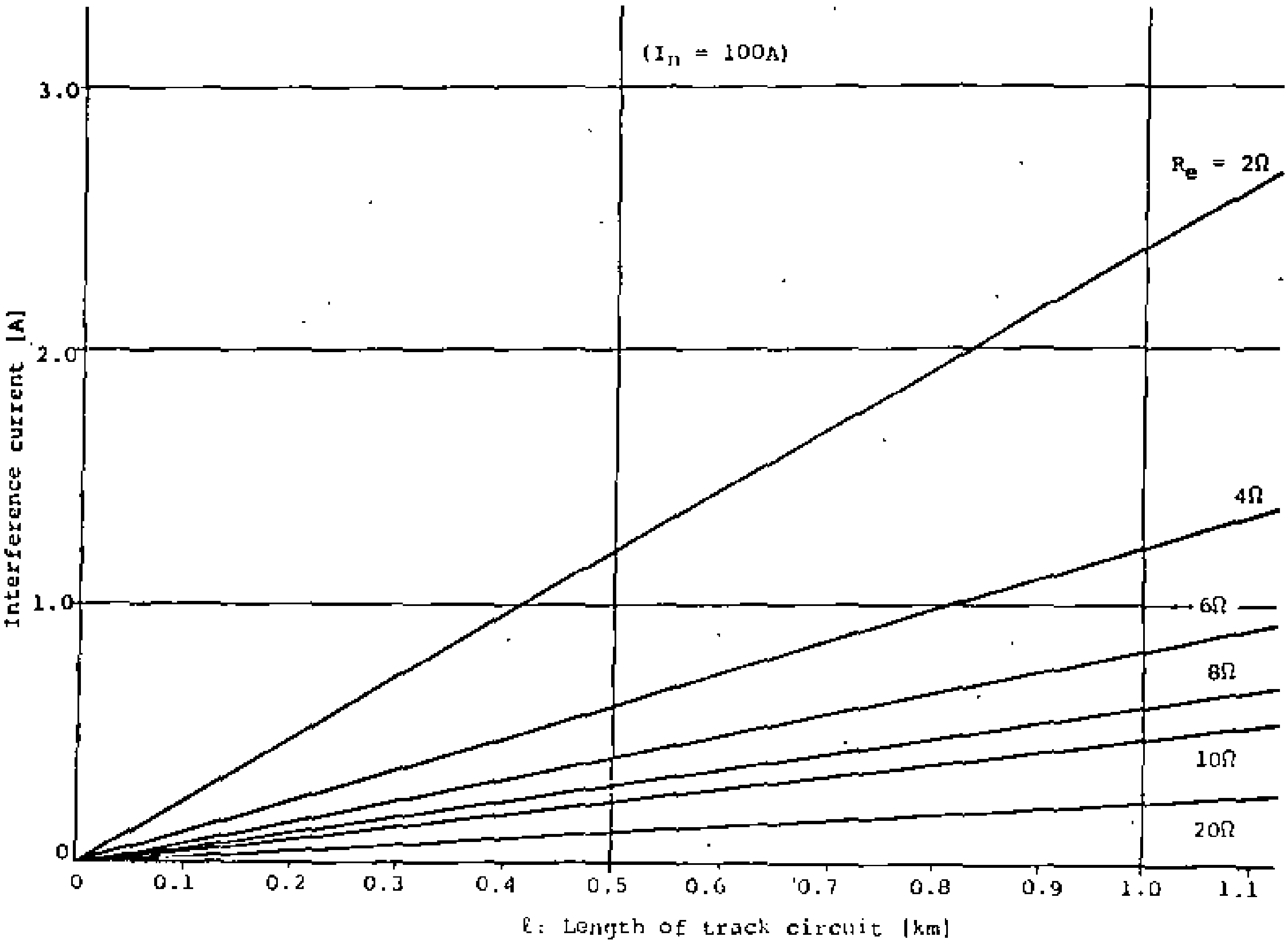


Fig. 5-39 Relationship between the Control Distance and Interference Current

Concerning the track relay, it is desirable that its release current be about two times the interference current. Also, the track relay must have sufficient anti-interference ability, including transient response of the relay (action/release time).

The control distance is also limited by the train shunting sensitivity, leakage conductance, and the resistance of the power sending and receiving ends. Therefore, it is necessary to decide the control distance taking the actual conditions of the yard and also the resistivity to the AC component interference into consideration.

(c) Basic Principles of Measures for S/N Improvement

As mentioned in Item 5-2-2(1), the scope of the phenomenon and effect of the interference current in the AC electrified section is not uniform. Therefore, countermeasures for this must be considered for each type of track circuit used. The phenomena produced by the interference current are divided to those resulting in safety failures and those resulting in dangerous failures. Especially, the DC track circuit causes dangerous failures, by turning into conditions for when no train is operating at times when trains exist, due to the interference by the rush current and the stray current.

The non-modulation type track circuit may directly cause dangerous failures when the interference currents mix into the signal. Further, it is recommended that this kind of track circuit not be used.

In any case, the basic principle of countermeasures for interference current is to improve the S/N. To S, the improvement of the track circuit type, increasing the transmitting output, improving the transmitter, increasing the receiving current, and reducing the track circuit length are considered. For the reduction of N, improvement of track circuit unbalance, adoption of a proper feeding system, and improvement of rolling stock are considered.

5-2-3 Effects of Feeding Current to Signal Equipment

(1) Increase of Rail Voltage

The voltage distribution of the rail voltage in a single track section of the AT feeding current system varies with the following conditions:

- o AT distance
- o Existence of CPW, and its distance from AT
- o Position of train

Provided that D = distance between AT, d = distance of CPW from AT, L = distance of train from AT, the increase of the rail voltage is as follows:

- o The rail voltage reaches maximum, when L ≒ 2/3 d
- o The rail voltage reaches minimum, when the train position is at AT.

This relationship does not change, in the single rail track circuit as well, unless the return circuit side rail is broken. However, when the return circuit side rail is broken, the rail voltage generally reaches maximum when a train exists near an AT and the rail breakage position is between the train and the AT.

Abnormal increases of rail voltage cause burned signal devices (power transmitting and receiving devices of DC track circuit, etc.), burned rail fastening devices (insulated joints, etc.), and electric shocks to maintenance workers or passangers, etc. Therefore, sometimes, countermeasures to control rail voltage are necessary.

The feeding current system and the structure of the track circuit in the station tracks are shown in Fig. 5-40. Concerning the rail voltage and the voltage loaded to the rail insulation, the calculations for the track circuit structure of Fig. 5-40 are shown in Table 5-6.

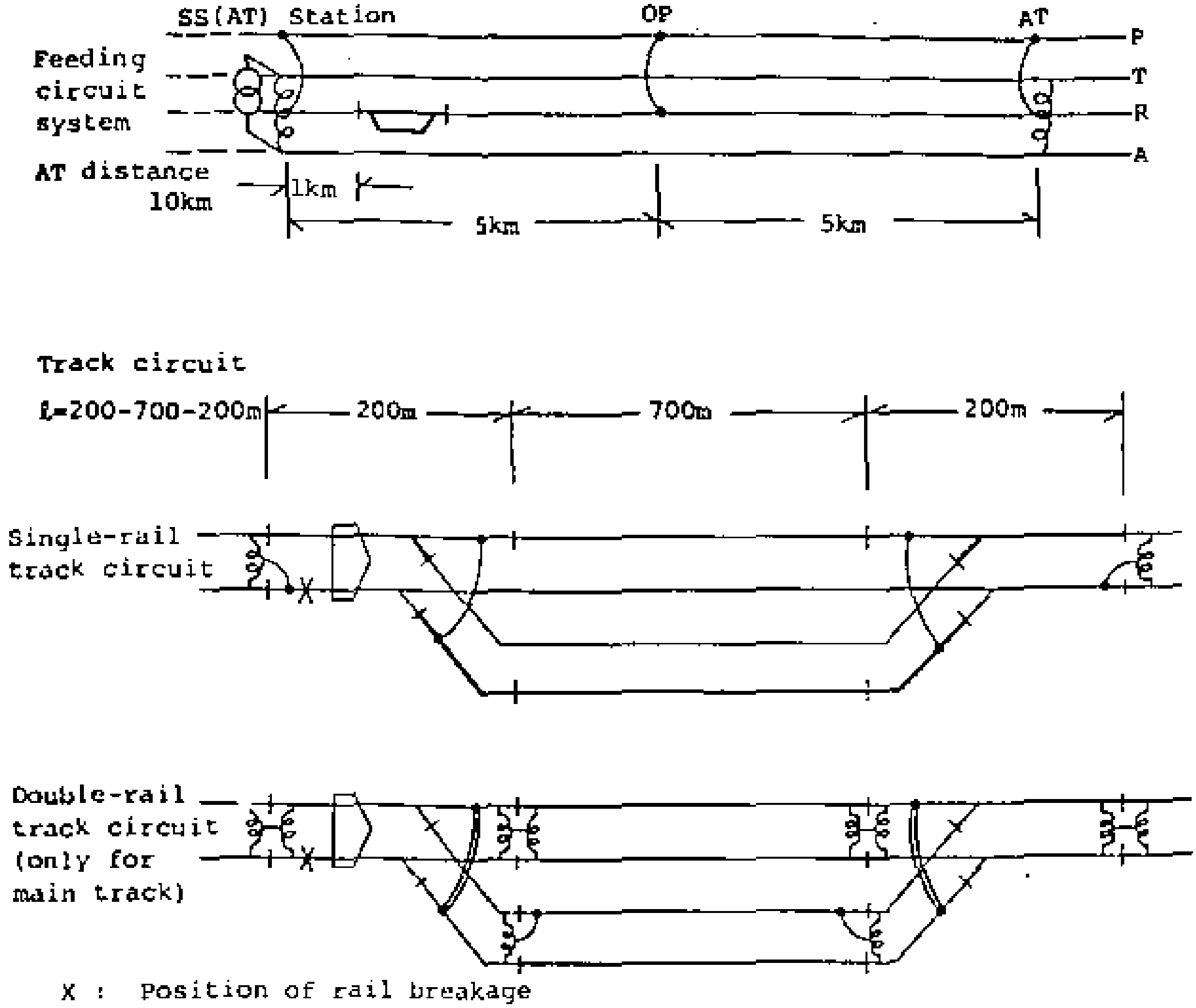


Fig. 5-40 Feeding Current System and Station Track Circuit Structure

Table 5-6 Increase of Rail Voltage at Time of Rail Breakage

Mode \ Lekage constant		Single-rail type in all station tracks	Single-rail type only for side track
Normal	0.1 S/km 0.2	20 V (20 V) 18 V (17 V)	18 V (20 V) 15 V (15 V)
During rail breakage	0.1 0.2	150 V (230 V) 120 V (180 V)	30 V (18 V) 25 V (14 V)

Inside ( ) shows the maximum voltage loaded to the rail insulation

I_p = 100 A, based on the conditions in Fig. 5-40.

As to Table 5-6, the values hardly change even if the length of the station track circuit is varied considerably. When the AT distance is extended from 10 km to 15 km, the rail voltage increases by about 25%.

During normal times, there is almost no difference between the double-rail type and the single-rail type as regards the rail voltage and the voltage loaded to the rail insulation. These voltage values are in the range of 15 ∿ 20 V for load current 100 A. However, if rail breakage occurs, when a single-rail track circuit is constructed for the entire station, the rail voltage reaches as much as 150 V, and the voltage loaded to the rail insulation reaches 230 V.

When a main track is constructed with the double-rail track circuit, large voltage does not occur, even if one side rail is broken. When the entire station is constructed with a single-rail track circuit, although large voltage does not occur during normal times, in the event that the return circuit side rail is broken in a section in which no more than 2 return circuits in parallel are constructed, the return circuit is limited. Thus we fear large voltage may occur.

(2) Countermeasures to Control Rail Voltage

Fig. 5-41 shows the variation of the rail voltage with the load.

Generally, the maximum leakage resistance in good weather is presumed as 5Ω·km for ordinary ballast. Therefore, the rail voltage during normal times is about 33 V. Further, the smaller the ground leakage resistance becomes, the lower the rail voltage becomes.

However, if the neutral point of the track circuit or the return rail is grounded artificially, the ground return current will increase and the induction voltage in the communication cable will increase.

In the case of the JNR Shinkansen bullet train, the rail voltage reaches about 300 V even during normal times. Therefore,

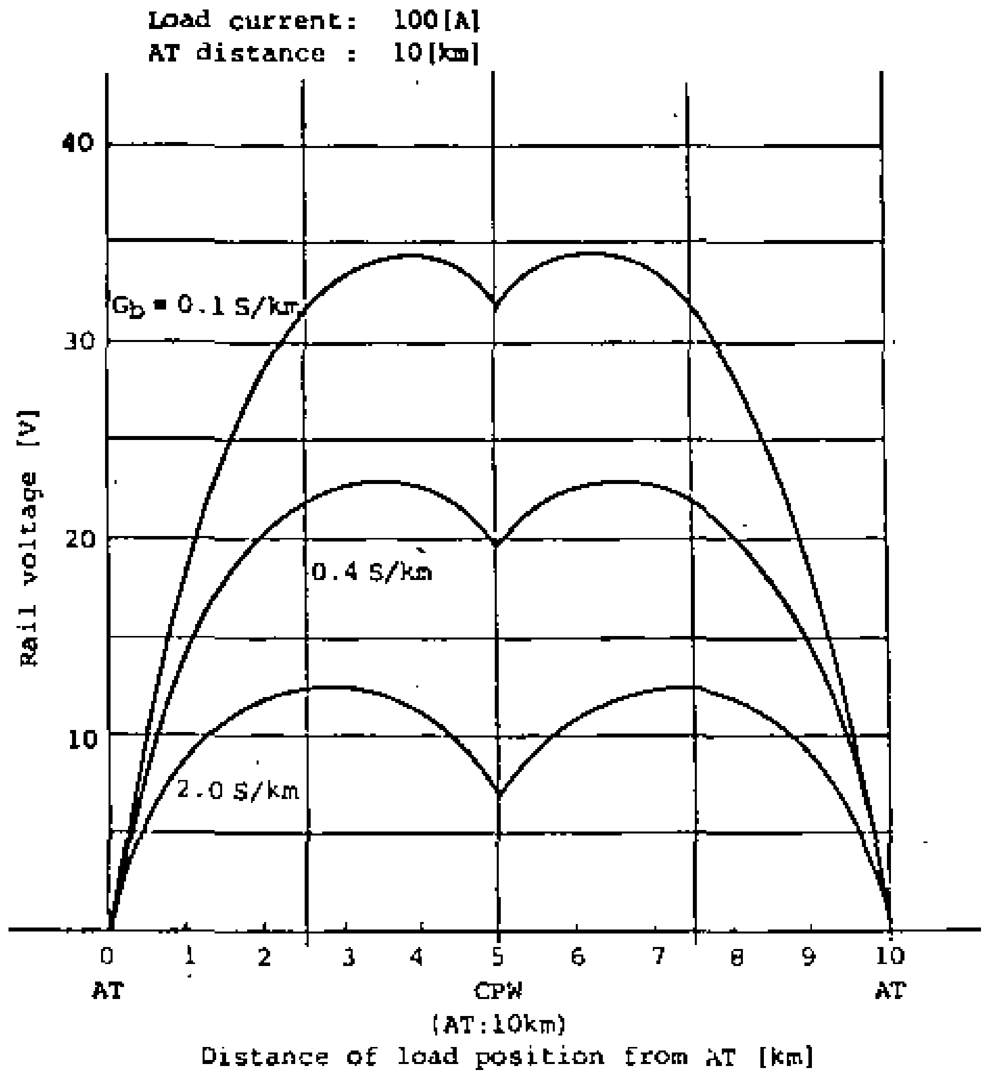
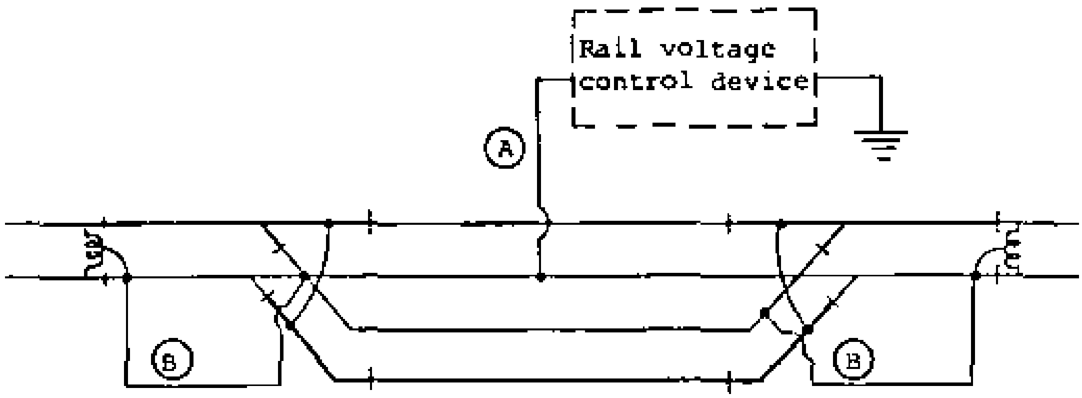


Fig. 5-41 Variation of Rail Voltage with Load Removal

the voltage control device is installed near the passenger platform, by which only the power source frequency is grounded through a low resistance.

Also, as the voltage increasing control method when there is a rail breakage in the single-rail track circuit, there is the method shown in Fig. 5-42 in which a bypass circuit in parallel is added to one return circuit section. However, the breakage detection function of the return rail is lost in the part where the circuit is composed in parallel.



(A): Countermeasure during normal times
(* Adopted in the Shinkansen of the JNR)
(B): Method when rail breakage occurs in single-rail track circuit

Fig. 5-42 Rail Voltage Control Measures

(3) Induction Interference to Signal Equipment

As the power source of the contact wire in the AC electrified section, a high voltage of 50 or 60 Hz is used. Therefore, induction voltage or induction current is generated in signal devices such as the block circuit, and signal control cable, which are parallel to or adjacent to the contact wire. Also there is the possibility that the track circuit installed nearby may suffer interference due to electromagnetic induction.

As types of induction interference, there is interference due to electrostatic induction generated in proportion to the contact wire voltage and interference due to the electromagnetic induction generated in proportion to the electric rolling stock current. These are summarized in Table 5-7. Induction interference to the signal and safety equipment is mostly due to electromagnetic induction, which can be reduced to some extent by screening. However, it is practically impossible to reduce it to zero.

Table 5-7 Induction Phenomena Affecting the Signal Devices in the AC Electrified Section

Kind of induction	Induced bodies	Interference	Permissible induction voltage
Electrostatic or Electromagnetic induction	(1) Cable (2) Bare conductor (3) Iron tube, etc.	Possibility that men may suffer electric shock (Dangerous voltage)	Normal times: 60 V Abnormal times: 430 V (Standards of CCITT)
Electromagnetic induction	Track circuit	Possibility that the relay may malfunction (Ground current)	

(a) Affects on the Human Body

When the distance from the feeding current conductor is small, due to the contact wire voltage, a high electrostatic voltage beyond the allowable range is induced in signal devices, iron tubes, steel cables, etc. Examples of electrostatic induction calculations for the AT feeding current system of the JNR are shown in Fig. 5-43.

In this figure, (c) means the position of the signal device and "h" is its height. Because of the effects of the screen grid of PW, GW, etc., the electrostatic induction voltage of actual equipment is presumed to be lower than the values in the figure.

Moreover, through ground faults of the contact wire, etc., the rail voltage increases rapidly instantly. If the human body contacts these devices, it is dangerous. Therefore, it is necessary grounding be performed that for all devices which can be grounded.

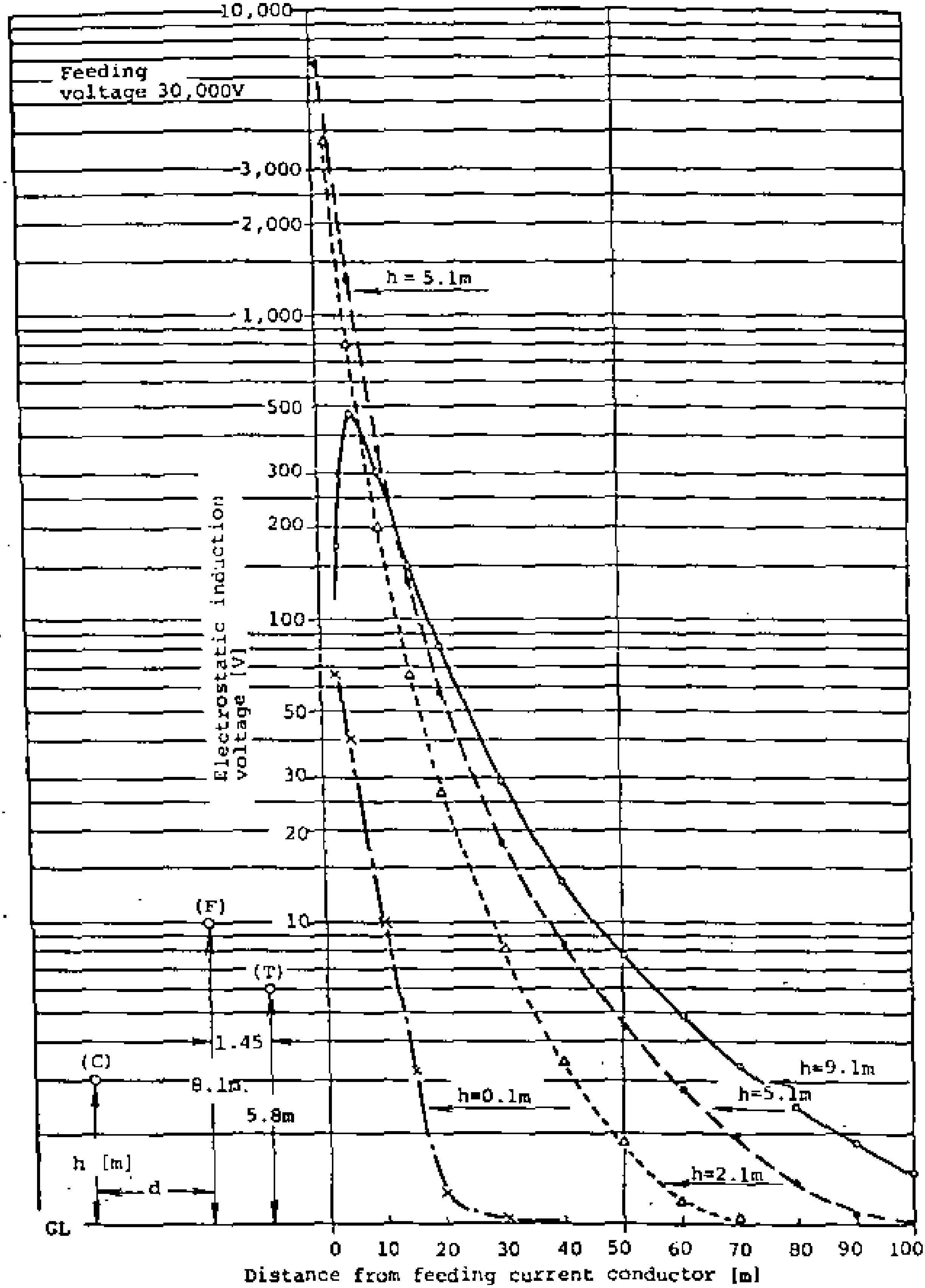


Fig. 5-43 Calculations of Electrostatic Induction

(b) Effects on Signal Equipment

1) Signal control circuit

According to past measurements, there are no special problems concerning the effects of electrostatic induction on the signal control circuit.

Also, concerning the effects of the electromagnetic induction, the balance ratio of the vinyl cable for signal use is 40 dB at the least, and that of the cable is 60 dB, in general.

Therefore, it is considered that no effects occur, not only in the case of short cables in the station, but also in the case of long distance circuits connected with the DC device load.

2) .Track circuit

Due to the AC electrification, sometimes the track circuits in the DC electrified section and non-electrified section, which are parallel to or across the AC feeder lines, are affected. Further, the range affected varies according to the level of the electric rolling stock current, and the geometrical relations of the positions.

The effects of the induction interference by the AC electrification differ depending on whether it occurs in the station tracks or between the stations. In the case of the station tracks, for the track circuit which performs the approach locking and the route locking of the relay interlocking device, a track circuit unbalance ratio of 100% is considered to allow safe operation even during abnormal times. While if it is between stations, a 20% track circuit unbalance ratio is considered sufficient.

Also, the allowable interference voltage loaded to the track relay at that time must be 1/2 of the relay drop-away voltage, because the value of the vane vibration in the 2 dimension type track relay is 1/2 of the relay drop-away voltage.

The allowable values of the interference currents in the track circuits commonly used are as follows:

DC track circuit (single rail);	The allowable interference current flowing into the track relay is 0.4 A. (Refer to Fig. 5-9)
Divided-and-multiplied frequency track circuit, and commercial frequency track circuit;	In the case of 100% track circuit unbalance, the limits of values of the interference currents flowing in the rail are shown in Fig. 5-44. The allowable values of the interference currents obtained from this figure are shown in Fig. 5-45.
80 Hz AC code track circuit;	50 Hz 40 A, 80 Hz 2 A Refer to Item 5-2-1 (6)
AF track circuit (concentrated device type);	600 CH 25 A, 900 CH 17 A Refer to Fig. 5-23

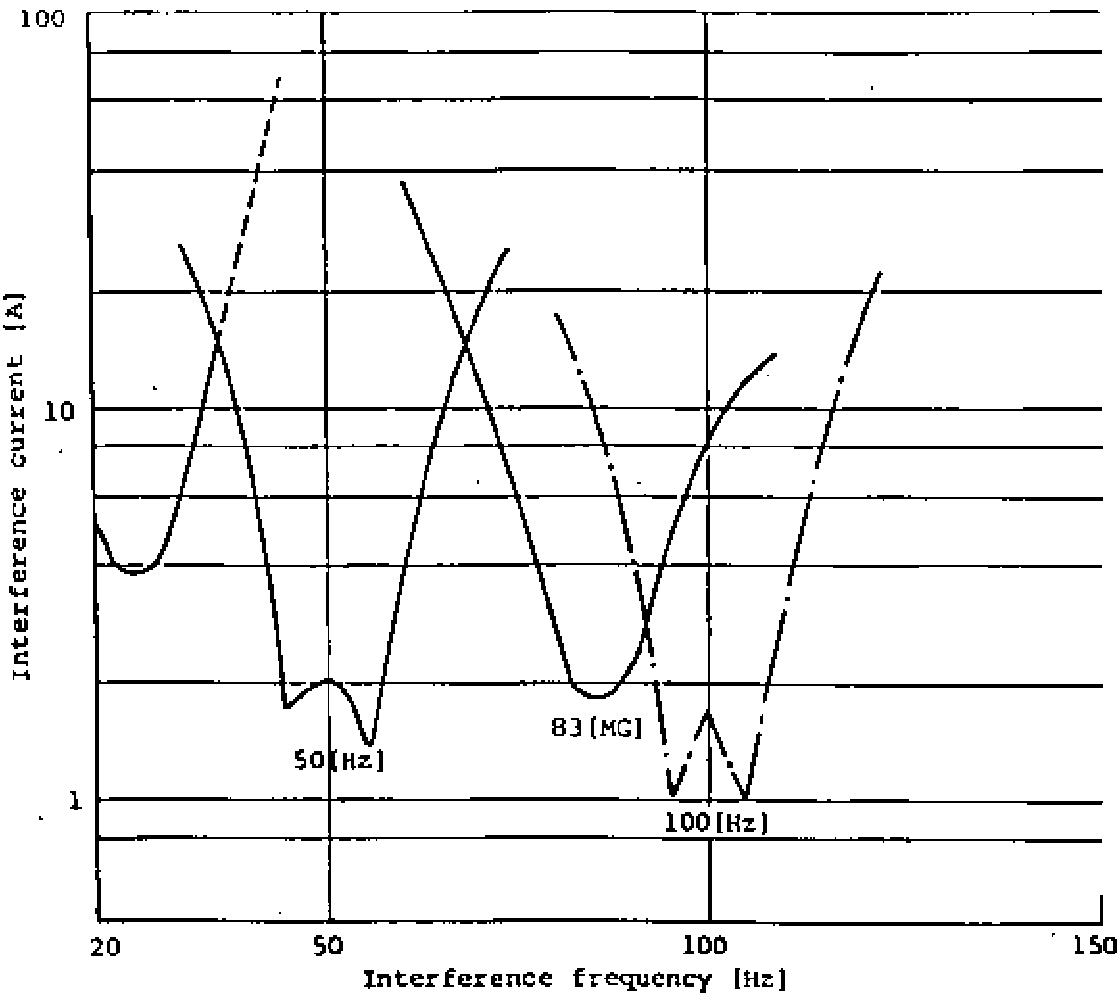


Fig. 5-44 Limit of Interference Currents of Various Track Circuits

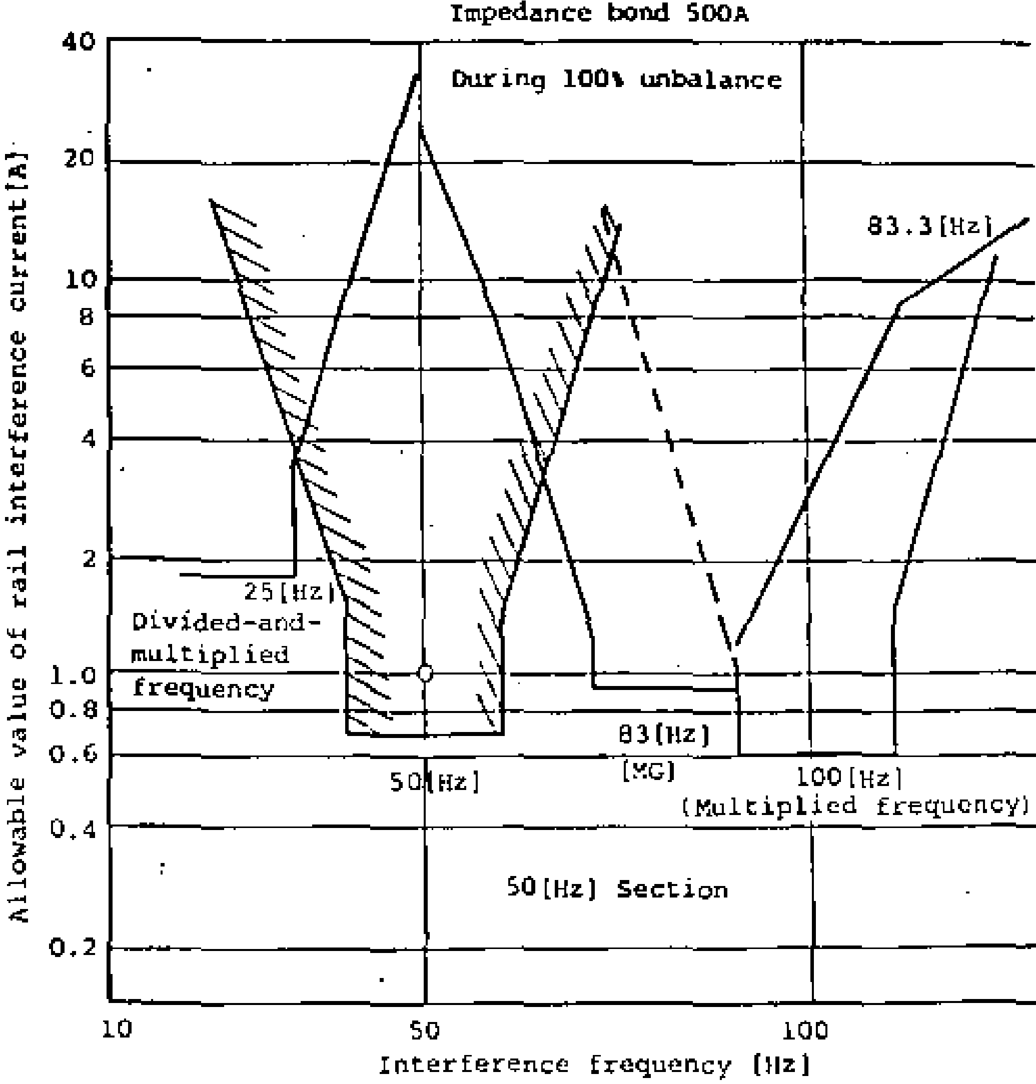


Fig. 5-45 Allowable Values of Interference Currents in Track Circuits

(c) Calculations of Induction Interference to Track Circuit

The electric railway forms the ground return circuit. In the case of the circuit shown in Fig. 5-46, the induction voltage as in the following formula occurs in the induced circuit.

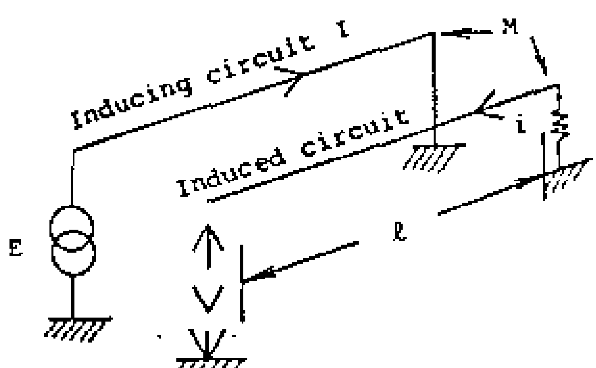


Fig. 5-46 Principle of the Electromagnetic Induction of the Electric Railway

$$V = -j\omega M \ell I \quad [V] \qquad \text{(Formula 1)}$$

When, V = To-ground induced voltage to the induced circuit [V]

ω = Angular frequency [rad/sec]

M = Mutual inductance [H/km]

ℓ = Length of parallel circuit section [km]

I = Induced current [A]

$$i = \frac{V}{Z_R}\left(e^{-\gamma \ell} - 1\right) \quad [A] \qquad \text{(Formula 2)}$$

Where, i = Ground return current flowing in the induced circuit [A]

Z_R = To-ground impedance of the induced circuit [Ω/km]

γ = To-ground transmission constant of the induced circuit [1/km]

$\gamma = \sqrt{Z_R\, Y}$

Y = Ground leakage admittance [S/km]

In the case that the induced circuit is a signal cable, besides the to-ground induced voltage "V" and the ground return current "i", there is the problem of noise voltage generated in the cable core due to the unbalance to ground of the cable core.

Further, when the induced circuit is a track circuit, the ground impedance "Z_R" is small, and the ground return current "i" becomes the problem.

The actual calculation of the induction is not simple as in Fig. 5-46. Because there are several electric conductors (T, PW, F, and rail, etc. in Fig. 5-47) concerning induction, the effect of the induction from the each electric conductor must be calculated respectively and the vector sum of these obtained.

Concerning the AT feeding current system, the current distribution of the feeding current circuit becomes complicated due to the AT distance, the distance between the PW and the impedance bond neutral point, the load position, the ground leakage admittance of the rail, etc.

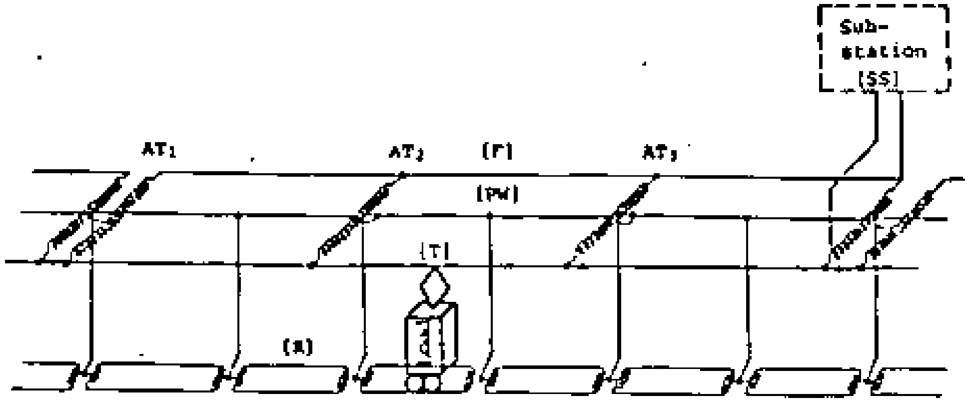


Fig. 5-47 AT Feeding Circuit System

Also concerning the track circuit on the induced side, the interference induction varies according to the distance from the electric railway (AC electrified), the length of the parallel circuits section, the relative position to the feeding current, whether or not there is screening, etc.

Although it is possible for these induction calculation to be obtained manually, the calculations becomes complex and it is difficult to obtain an accurate value.

The JNR has established a system which processes all the above calculations with a large-scale computer, including the mutual inductance M and the ground return current induced in the track circuit.

Concerning the JNR Shinkansen bullet train, part of the calculations are shown below. Fig. 5-48 shows the inducing current and the induced current in the track circuit of which the distance is 100 m when the train position varies. The distribution of the inducing current varies much according to the position of the train.

Fig. 5-49 shows the results of calculations in the most severe conditions to understand the scope of the induction interference from the Shinkansen. From the results, we know that the induced current in the track circuit which is parallel to the Shinkansen is as follows:

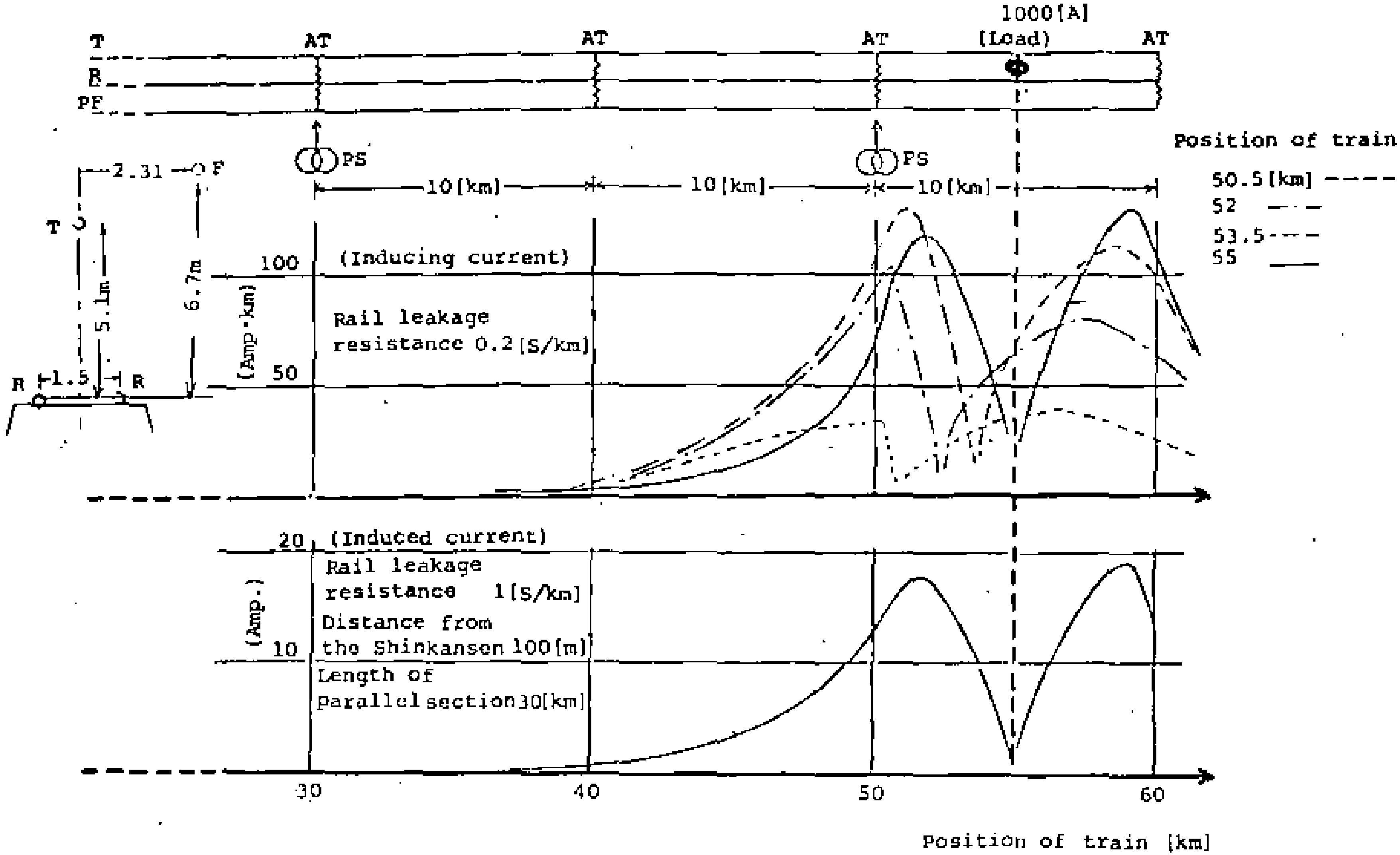
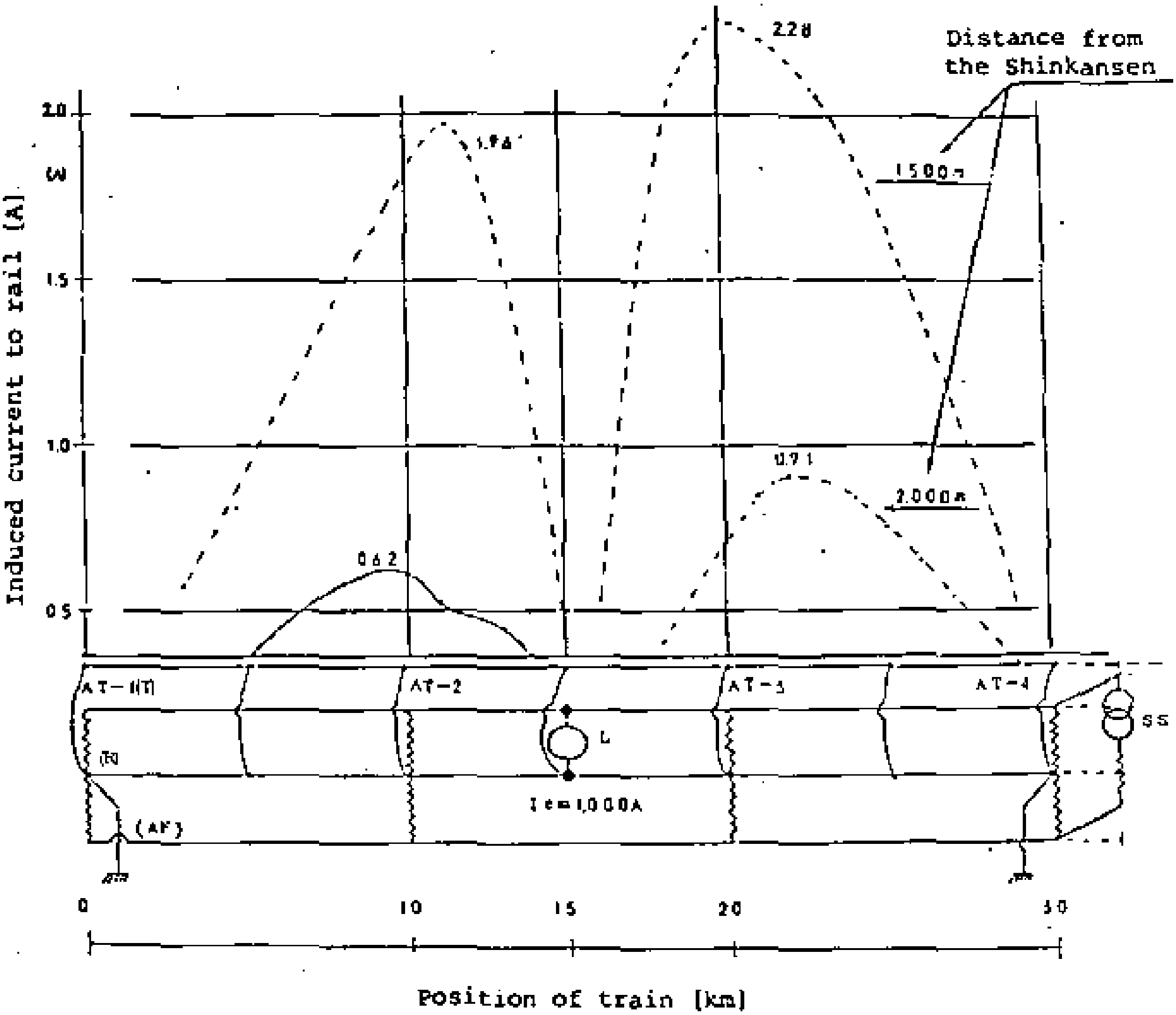


Fig. 5-48 Distribution of Induced Current when Train Position Varies



Rail ground leakage resistance

{ Shinkansen 0.2 S/km
 Conventional line 0.5 S/km

Ground conductivity 10^{-2} S/m

Both of the Sinkansen and conventional line are single track

Length of parallel section 30 km

Fig. 5-49 Relationship between the Distance from the Shinkansen and the Induced Current

When the distance of the track circuit from the Shinkansen is 2 km, the maximum induced current is 0.91 A, and when the distance is 1.5 km, the maximum is 2.28 A.

Generally, a commercial frequency track circuit is used for the conventional line, parallel to the JNR Shinkansen.

The scope and method of improving the induction interference in this case are shown in Table 5-8.

Table 5-8 Measures for Improving Induction Interference on the Commercial Frequency Track Circuit (when track circuit unbalance ratio is 100%).

Distance from Shinkansen	Disturbing current induced to rail	Measures for improving induction interference on commercial frequency track circuit
More than 2 km	Less than 1 A	Not necessary
1.5 ∿ 2 km	1 ∿ 2 A	Adjustment by resistance
Less than 1.5 km	More than 2 A	The system is changed to DC, divided-and-multiplied, divided, 80 Hz or AF track circuit.

Table 5-8 shows the case of station tracks in general. The track circuit unbalance ratio between stations is 20%. Therefore, the values can be obtained by multiplying the values of induced interference current in the table by fire.

Accurate induction calculations are not obtained from Table 5-8, and as was mentioned before, the conditions of screening and the length of section must be considered.

(d) Protection from Surge Voltage

As types of surge voltage to the signal devices, there are thunder surge which strikes through the line transformer from the high voltage distribution line, thunder surge from aerial cables, and abnormal voltage due to contact with wire ground-fault, etc. To protect the signal devices from these abnormal voltages or thunder surges, countermeasures using insulated transformers, protective devices, vaccum arresters, or Zener diodes are required.

5-3 ATS

5-3-1 Classification of ATS Systems

Although safety in train operation depends on the caution taken by the driver, with the advance of high speed and high density operations due to electrification, it is desirable that ATS (automatic train stop device) be installed for the improvement of safety.

The ATS is a system in which the brake is automatically operated when the train has run beyond the limited speed through control which operates with the signal indication. As shown in Table 5-9, there are various types of ATS. (ATS is sometimes called ATP)

(1) Control System

Information transmission systems to the cab are roughly divided into two types: the point control system and the continuous control system. The point control system is operated by wayside coils which are installed on the ground; and the continuous system is operated by utilizing the track circuit.

It is said that the point control sytstem is inferior to the continuous control system in its adaptability to indication changes of the signals and in reliability of the information transmission system. However, the construction of the point control system, including the ground devices, is simple, and it is superior in maintenance of the equipment and economy. Moreover, when there are various operation sections of cars, extensions to other sections is possible only by installing simple ground devices. Therefore, for cases such as transport between cities, the point control system is superior to the continuous control system.

(2) Information Form

The wayside coil system is a modulation system utilizing dropping LC oscillator installed on the car. If the resonance frequency of the wayside coil on the ground is set at "f_1", when the

Table 5-9 Classification of ATS Systems

Control system	Information transmission	Information forms	Speed checking system			Kind of brake	Name of type
Point control system	Wayside coil	Single information	On car	Point	No memory, Operation after confirmation-treatment	Emergency	A
		Multi-information		Continuous	With memory, step-pattern	Ditto	B
					With memory, brake-pattern	Ditto	C
				Point	No memory	Ditto	D
		Single information	Ground		No memory	Ditto	E
	50 Hz track circuit		On car		No memory, Operation after confirmation-treatment	Ditto	F
Continuous control system	AF track circuit	Multi-information	On car	Continuous	With memory, step-pattern	Nomral	G
					With memory, brake-pattern	Emergency	H

device on the car passes over the wayside coil it can receive the information of "f_1". Because about seven kinds of wayside coils on the ground can be installed, the car can receive seven kinds of information. When the number of bits of information is not sufficient, by combining two wayside coils, more information can be received. By locating the two wayside coils at a proper distance, the passing speed can be checked on the car. In the future, the train classification and train number device can be equipped on the car, without any wide reformation of the device on the car.

Concerning the track circuit system, by intermitting the transmission in the commercial frequency track circuit, 3 ∿ 5 kinds of codes are produced; and by combining frequencies in the AF track circuit, 5 ∿ 10 kinds of information are continuously produced.

(3) Speed Checking System

The speed checking of the ATS is classified as the following:

(a) Whether the speed checking is done or not.

(b) Whether the speed is checked on the car or on the ground. When the checking is done on the car, the wayside coil system is easy. Depending on the kind and distance of the wayside coils, the car receives the speed limit, which is compared with the train running speed. In the case of checking on the ground, the train running speed is calculated by the passing time of the loop coil installed on ground, and if the train speed exceeds the speed limit, the ATS is operated from the ground.

(c) Whether there is a memory on the car or not. In the case of speed checking on the car, there is the system in which the speed limit information received from the ground is put into the memory device and the speed is continuously checked, and the system in which there is no memory and the speed is checked only at that point.

(4) Confirmation Treatment or Not

With some types of point control systems, there are cases where adapting to changes in the signal can not be done sufficient. To prevent this problem, the driver, after switching to "confirmation treatment", operates the train with his caution. However, if the "confirmation treatment" is done, the ATS is cut off and is not operated. Therefore, a system which has the ATS function at the least even after the "confirmation treatment", or a system in which the "confirmation treatment" does not exist from the first is desired.

(5) Emergency Brake or Normal Brake

When a driver has made an error, if the ATS is used to support it, the emergency brake is suitable. However, when we want to make minor speed control by the ATS, the ATS will operate very often, and a normal brake is more suitable. Therefore, a high class ATS is one which functions approximately the same as the ATC (automatic train control device).

Thus, each type of ATS has its respective features, and selection of the appropriate type is generally decided by considering the train density, kinds of rolling stocks, the operation of the section, the duties of the driver, and the investment.

Concerning the conventional lines of the JNR, the cars utilized include a wide range, and the conditions of the sections used are very different. Therefore, as ground devices, a simple and unified sytstem is required. Accordingly, except in commuter traffic section in major cities, the simplest type of point control system (Type A of Table 5-9) has been generally used. However, systems in which there is a memory on the car and the speed is continuously checked, without the "confirmation treatment" (Type G of Table 5-9) has been developed and its application to main sections are being planned.

5-3-2 Various ATS Systems

As mentioned before, there are various types of ATS, and some of these are explained here.

(1) The Present ATS System of the JNR

The present ATS system is type A of Table 5-9. It was developed based on the cab alarm device which has been previously developed. Therefore, its structure requires "confirmation treatment" by the driver when the alarm is indicated.

To ensure safety in all trains, the alarm-points interlinked with the signal indication control of the signal device are made at the points of a set distance from the signal on the ground (Miximum emergency brake distance plus empty running distance, for the maximum speed of a train in the section).

Therefore, a train approaching the signal device indicating the stop signal will receive an alarm to the driver at this alarm point, in spite of the train speed.

In this case, unless the driver switches to "confirmation treatment" within 5 seconds after receiving the alarm, the train will be stopped with the emergency brake through the fucntion of the ATS. However, after the driver switches to the "confirmation treatment", the ATS will not operated the emergency brake. Namely, it is a system in which the transport efficiency is not be obstructed by unnecessary stopping of a normally running train by the ATS. Therefore, after the confirmation treatment has been made by the driver at the alarm point, the operation will be performed, depending on the driver's caution and skillfulness.

Fig. 5-50 shows the function of the present ATS, and Fig. 5-51 shows the construction of the ATS of the JNR.

(2) Point Control Type Continuous Speed Checking System

The point control type continuous speed checking system is Type B in Table 5-9. The car is equipped with a memory device for checking the speed and the continuous speed checking is done based

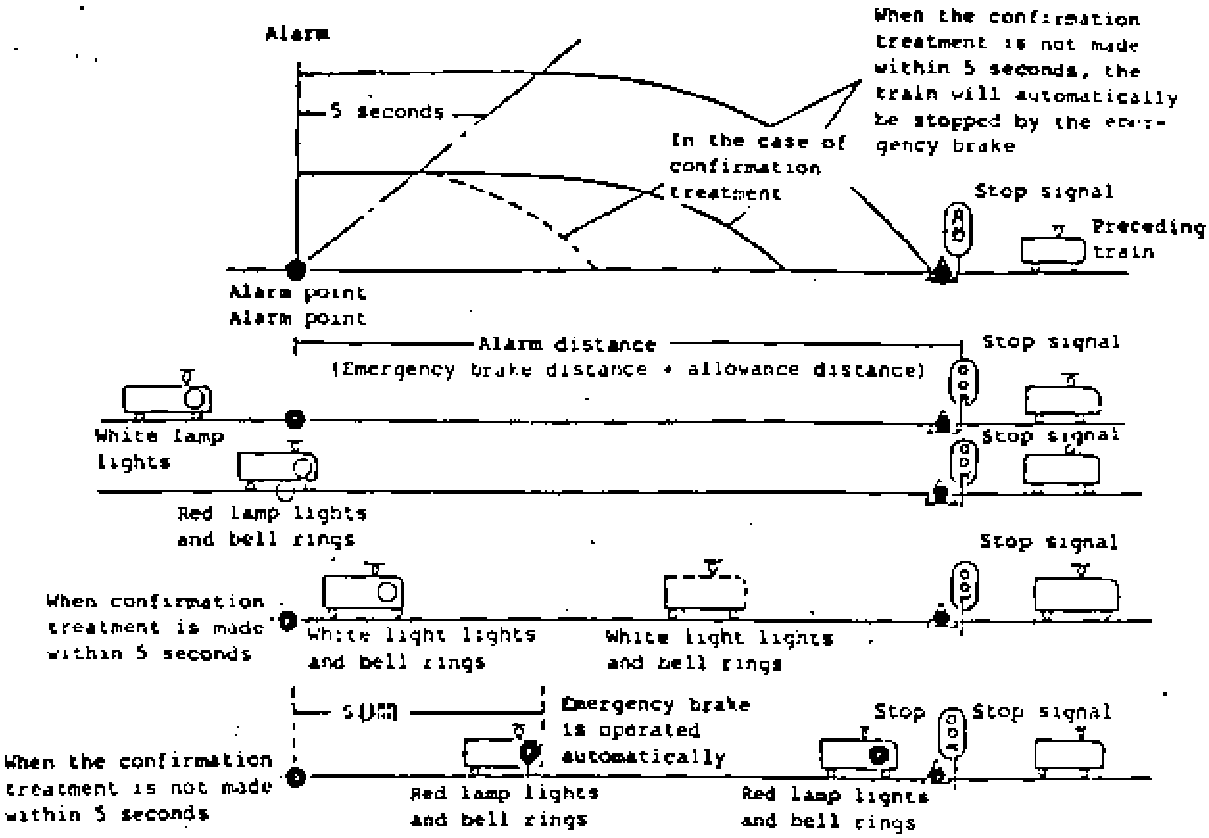


Fig. 5-50 Functions of the Present ATS

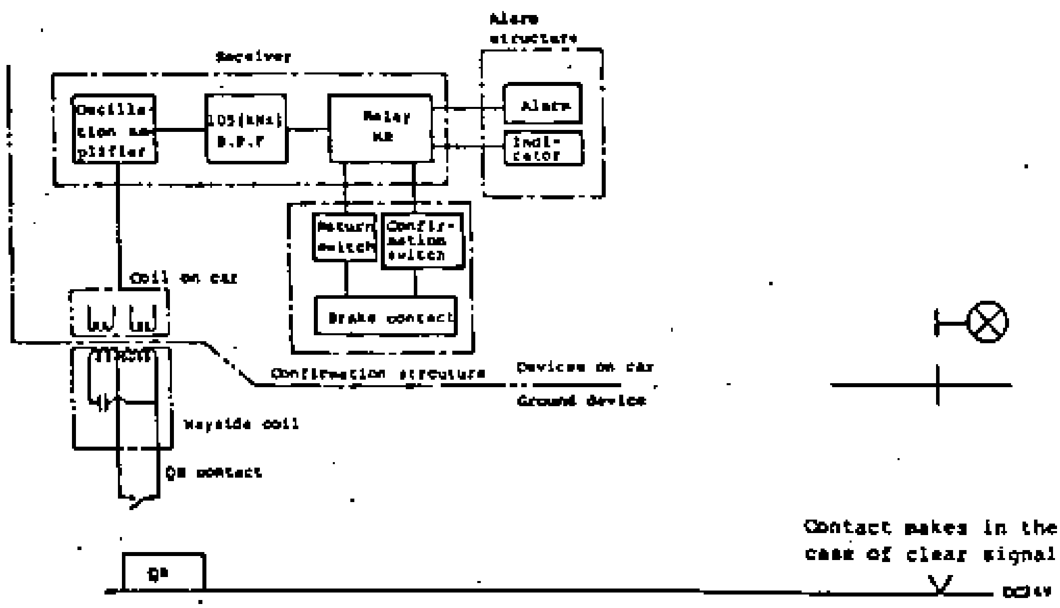


Fig. 5-51 Construction of ATS System of JNR

on the information from specified points on the ground. This type is used by some civil railways in Japan, Because detailed control can be done according to the signal indications, it is suitable for commuter traffic sections in large cities. However, much information is required for curve control, and the adaptability to changes in the signal indication is not sufficient.

An example of this system is shown below. The speed check point performs the speed checking in 4 steps (65 km/h for Y signal, 45, 30, 0 km/h for R signal). See Fig. 5-52.

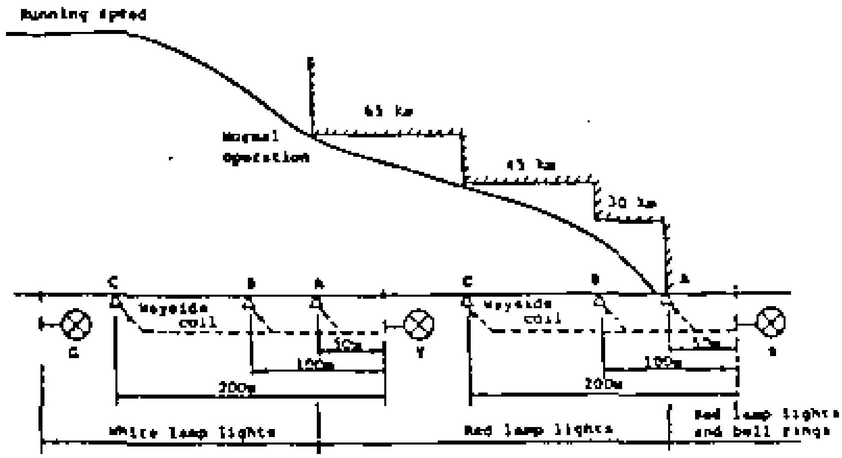


Fig. 5-52 Example of Point Control Type Continuous Speed Checking System

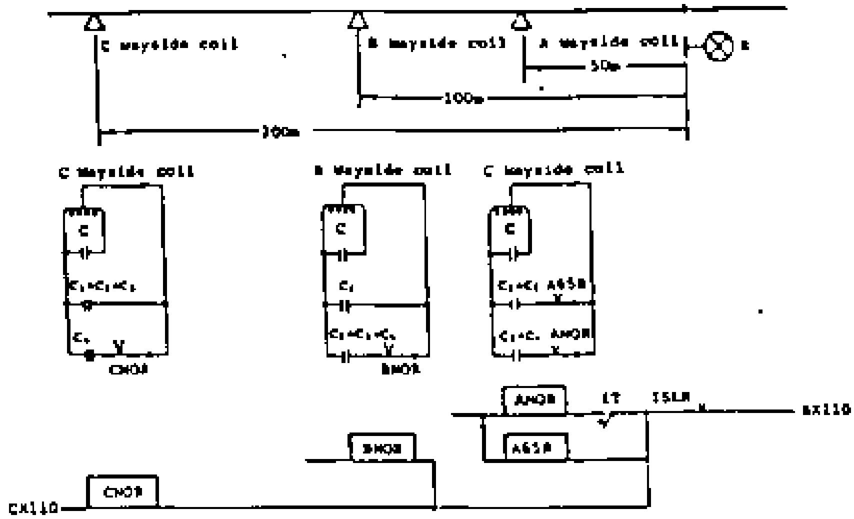
There are 3 kinds of wayside coils as follows:

- Wayside coil A: 3 pieces of information: "free", 65 km/h, and "stop"
- Wayside coil B: 2 pieces of information: "free".and 30 km/h
- Wayside coil C: 2 pieces of information: "free" and 45 km/h

The changeover of the information is made by the changeover of capacitor, $C_1 \sim C_4$.

When the signal device breaks down, the train can enter the area inside the signal by pushing the confirmation key when passing directly over the wayside coil.

The connecting diagram of the ground device and the device on the car are shown in Figs. 5-53 and 5-54, respectively.



Relations between the Capacitor and the Speed Limit and Resonance Frequency

The relation among speed limit, resonance frequency and condenser

Speed limit	Resonance frequency	Condenser	Speed limit	Resonance frequency	Condenser
0 km/h	132 kHz	C	65 km/h	116 kHz	C_1+C_2
30 "	124 "	C_1	Free	100 "	$C_1+C_2+C_3+C_4$
45 "	108 "	$C_1+C_2+C_3$			

Fig. 5-53 Standard Connection of Ground Device

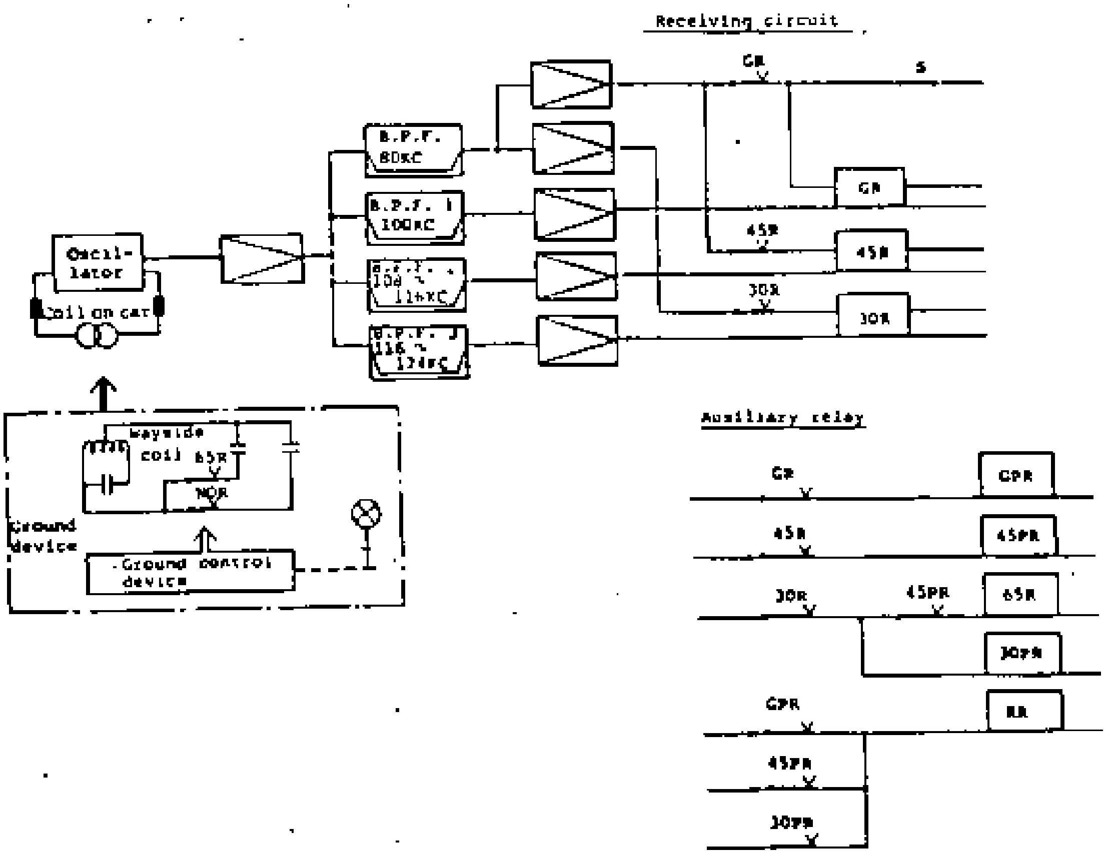


Fig. 5-54 Connecting Diagram of Devices on Cars (Summarized)

(3) Point Control Type On-car Speed Checking System

The point control type on-car speed checking system is Type D in Table 5-9. In this system, the emergency brake is operated when the actual speed exceeds the speed limit, by comparing the standard time (generally 0.5 or 1 second) which has been put in the memory on the car with the passing time of the distance of 2 wayside coils.

The system is used in some private railways in Japan. Because there is no memory for the checked speed, its construction is simple and the adaptability to changes of the signal indication is good. By locating the wayside coils at suitable intervals of distance, the desired speed checking is possible. Therefore, it is suitable for cases of future AC electrification, such as main lines between cities.

An example of this system is shown below. The speed checking point performs the speed checking in 3 steps (70, 30, 0 km/h for R signal). See Fig. 5-55.

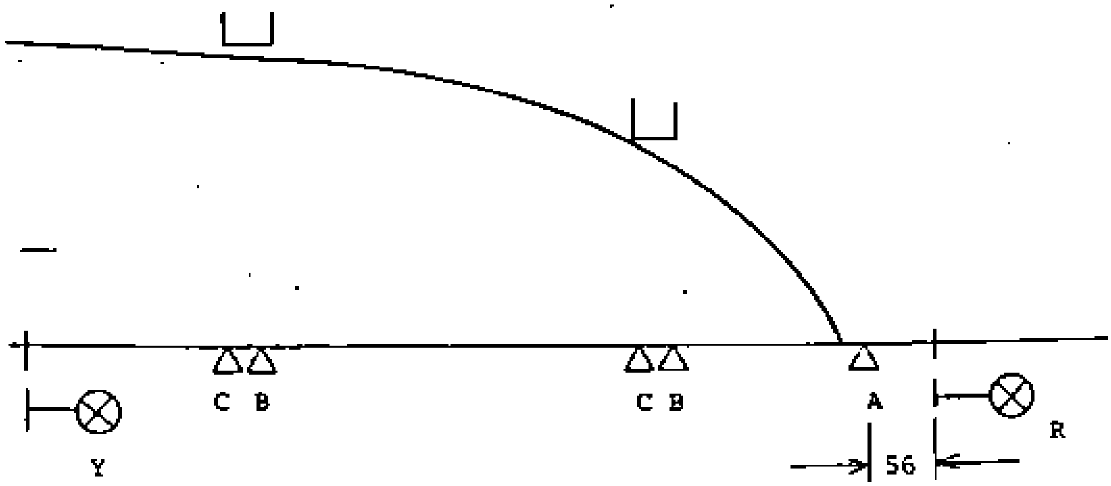


Fig. 5-55 Example of Point Control Type On-car Speed Checking System

The kinds of wayside coils are as follows:

Wayside coil A: Free and stop
Wayside coil B: Free and speed checking
Wayside coil C: Speed checking

Because wayside coils B and C are common for speed checking use, only the 2 kinds, A and B are sufficient. The changeover of each information is made by the changeover of the capacitor.

The distances for wayside coils B and C are as shown in Table 5-10, according to the checking speed for each 0.5 second.

Table 5-10 Distance between Wayside Coils at Speed Check Point

Checking speed (km/h)	Distance between wayside coils (m)
5	1.34
15	2.73
20	3.42
30	4.81
50	7.59
70	10.37

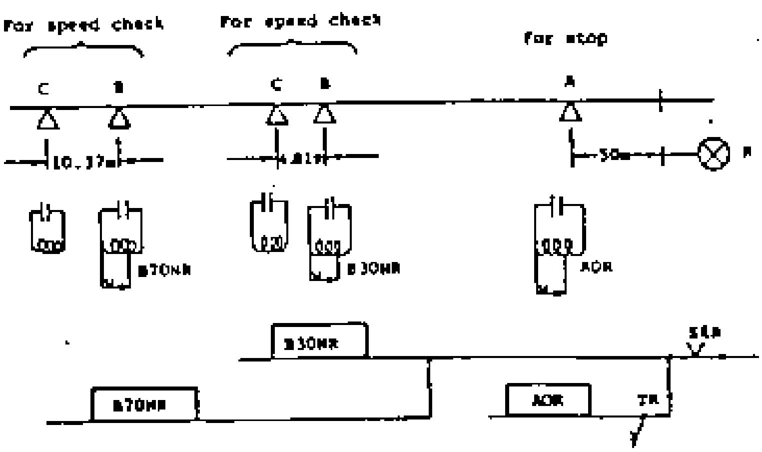


Fig. 5-56 Standard Connecting Diagram of Devices on Ground

The connecting diagram of devices on the ground is shown in Fig. 5-56.

This ATS system can also be used for checking the speed limit at a point or curve, for preventing over-running of the stub track, and interlocking of the crossing gate. Moreover, by adding the train number transmitter, the train number, etc., can be sent from the car to the ground, and the application to the train operation administration system is possible.

CHAPTER 6

ELECTRIFICATION AND COMMUNICATION

6-1 Induction of Communication in Conjunction with Electrification

6-1-1 Outline

One thing that cannot be disregarded in any attempt to electrify a railway is induction. The question of induction arises in regard to bare wires, cables and, as has been elucidated in the preceding chapter, track circuits.

Induction, as referred to here, is a phenomenon in which voltage of the kind that endangers communication circuits and noise hazards of the kind that hampers communication facilities are generated, as electric energy is transmitted to some of the communication lines when the communication lines are close to electric railways or power transmission lines.

Induction comes in two types -- electrostatic induction and electromagnetic induction. Their characteristics are shown in Table 6-1.

Table 6-1 Comparison of Characteristics of Electrostatic and Electromagnetic Induction

Type	Induction source	Communication lines affected
Electromagnetic induction	Electric current	Within 300 m from an A.C. railway Within 5 km from an overhead power transmission line Within 100 m from an underground power transmission line
Electrostatic induction	Voltage	Within several tens of meters from an overhead power transmission line

When rectification is made with mercury and silicone rectifiers in the D.C. electrification of a railway, noise hazards are produced on the nearest communication line primarily by the six-phase higher harmonic components which come out on the side of the direct current output. Such noise hazards are mitigated by inserting into the D.C. output side of the rectifier a wave filter which is composed of a reactor and a condenser and by improving the degree of balance of the communication line.

In the A.C. electrification of a railway, however, a commercial frequency (50 or 60 Hz) at a high voltage (20 or 25 KV) is used, with the consequence that the induction thus produced is quite strong, not only producing noise but endangering human lives as well. JNR sets the critical voltage at less than 60 V of the counterpoise voltage at normal times and less than 430 V at abnormal times. The tolerable limit of the noise voltage between lines is set at 1 mV for cables and 2.5 mV for bare wires (both are the values assessed with the auditory sensitivity taken into account).

In the case of an A.C. electrification, therefore, the high frequency waves are restrained with the insertion of filters into electric vehicles as a measure on the inducing side. In addition, an attempt is also made to lessen the induction by using an autotransformer (A.T. type) and installing a booster transformer and negative feeders (B.T. type) on the side of the feeder circuit.

In foreign countries, on the other hand, a feeder system (direct feeder system) in which neither B.T. nor A.T. is used is adopted. This simple system, which is equipped with simple feeder circuits, cannot necessarily be described as an effective system for urban areas from the standpoint of the induction of communication.

On the induced side, an attempt is made to lessen the induction by enclosing bare wires in cables, using shielded cables and inserting neutralizing coils and feeder draining coils. Moreover, a cumulation of the induction voltage is prevented by inserting insulating coils and sections.

6-1-2 Electrostatic Induction

In case an overhead contact system or an electric power line is suspended above the ground surface in parallel with a communication line and their heights above the ground are h_1 and h_2, respectively; the electrostatic capacity is C_{12} and the counterpoise electrostatic capacity is C_{22}, the voltage of the electrostatic current induced in the communication line is expressed in the equation of:

$$V_S = \frac{C_{12}}{C_{22} + C_{12}} V$$

where V is the counterpoise potential of the electric power line. This equation may be replaced by the following one.

$$V_S = \frac{\log \frac{b^2 + (h_1+h_2)^2}{b^2 + (h_1-h_2)^2}}{2 \log \frac{2h_1}{r_1}} V$$

where r_1 is the radius of the electric power line, b is the horizontal distance between the electric power line and the communication line, h_1 is the height of the electric power line and h_2 is the height of the communication line.

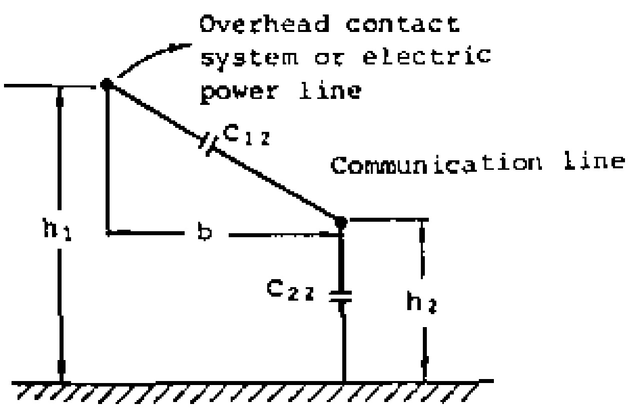


Fig. 6-1 Electrostatic Induction

As is discernible from this equation, the magnitude of the electrostatic voltage is determined by the voltage of the electric power line and the locational correlation between the electric power line and the communication line. The parallel length of the communication line has nothing to do with the magnitude.

6-1-3 Electromagnetic Induction

When the electric current flows an electric power line with the ground as its return route, a magnetic line is generated as indicated by the dotted line in Fig. 6-2. Here, if there is a communication in parallel with the electric power line, an induction voltage is generated in the communication line, depending on a change in the magnetic line. As the electric current of the electric power line on its return route to the ground is I(A), the angular frequency is ω, the mutual induction coefficient of the electric power line is M(μH/km), and the parallel length of both lines is ℓ(km), the induction voltage Vm is expressed in the equation of:

$$V_m = -j\omega M \ell I$$

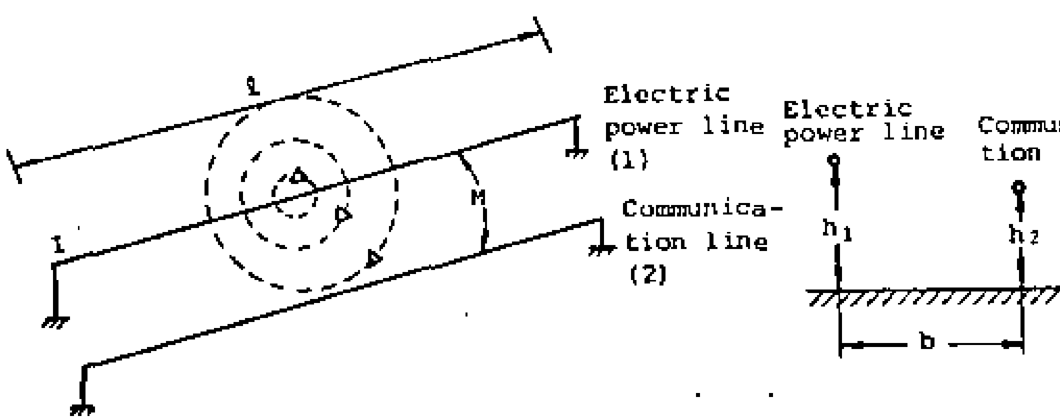


Fig. 6-2 Electromagnetic Induction

The relative induction coefficient M is determined by the distance between the electric power line and the communication line, ground conduction rate and frequency. The greater the aforementioned value, the smaller M.

This equation has been introduced separately by Carson of the United States and Pollaczek of Germany and is known as the Carson-Pollaczek formula. The equation is expressed as follows.

$$M = [2 \log \frac{2}{k\sqrt{h^2 + (h_1 - h_2)^2}} + \frac{4}{3\sqrt{2}} k\ (h_1 + h_2)$$

$$- 0.1544 - j\ \{\frac{\pi}{2} - \frac{4}{3\sqrt{2}} k\ (h_1 + h_2)\}]$$

where $k = 2\pi\sqrt{2\sigma f}$, σ is earth conductivity.

As is discernible from the earlier equation, the electromagnetic induction voltage greatly varies, depending on frequency, parallel length of communication lines, etc.

6-1-4 Earth Conductivity

The lines which serve as the basis for a prediction of the electromagnetic induction voltage are two parallel lines above the ground. The electric and communications are normally composed large numbers of parallel lines. Therefore, the electromagnetic induction which is generated between both systems is clarified in a complicated circuit equation with an application of the theory of multi-line transmission. The simplest basic circuit is the correlations between a single electric line and a single communication line. On this basis, various, complicated phenomena may also be progressively clarified.

Here, an important role is played by the earth. When induction is studied, the earth is an important parameter which cannot be disregarded at any moment.

This holds true in the case of electrostatic induction but the earth plays a more important role in the case of electromagnetic induction.

As a matter of fact, the earth features a big resistance and its value varies to a great extent, depending on the soil. This is known as the earth conductivity.

The earth conductivity is the reciprocal of the resistance ratio and expressed in siemens (S/m) on the basis of the S.I. unit.

For the computation of induction, there is a need to compute the earth conductivity. JNR makes it a practice to measure it at a standard distance of 4 km. The estimated values of the earth conductivity are shown in Table 6-2.

Table 6-2

Soil	σ[S/m]
Wet soil	0.05
Dry soil	0.005
Clay	0.1
Choke	0.03
Loam	0.01
Coarse sand	0.3×10^{-3}
Gravel	0.3×10^{-3}
Aqueous rock	$(1 \sim 10) \times 10^{-3}$
Igneous rock	$(0.3 \times 1) \times 10^{-3}$

Comparison

Underground water	: 0.05[S/m]
Iron	: 1×10^{7}[S/m]
Insulator	: Less than 10^{-8} [S/m]

6-1-5 Induction Characteristics of Various Feeder Systems

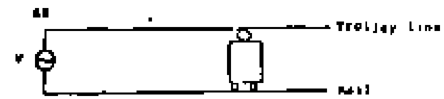
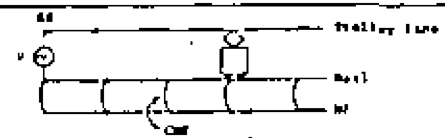
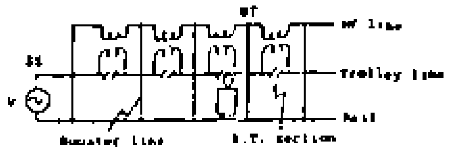
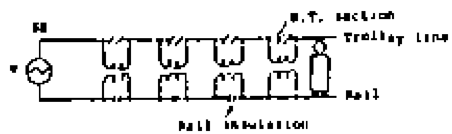
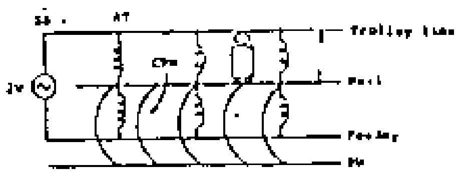
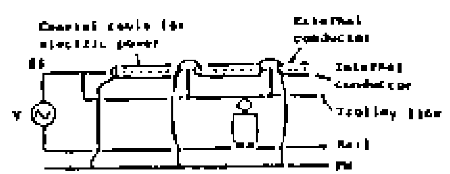
Programs for electrification under various feeder systems have been referred to in other chapters. In this chapter, an attempt will be made to introduce the characteristics of each feeder system with special reference to the induction characteristics.

(1) Direct Feeder System

The direct feeder system is the most basic of them all, composed of trolley lines (T) and rails (R). One variation is a system in which NFs are posted in parallel with the rails and the rails are connected with an NF at every several kilometers with NF connecting wires. Here NF serves as a protective wire (PW).

The advantage of the direct feeder system lies in the fact that as the composition of its circuit is simple, this system is cost-effective and easy to maintain, whereas the disadvantage is that as the rails in the entire section is charged with the return circuit current, the hazards of induction to the communication

Table 6-3 Induction Characteristics of Feeder Systems

Appellation		Distribution chart	Characteristics	Application	
				Japan	Foreign countries
Direct feeder system	① Basic type (T-R)		1. The hazards by induction are greatest. 2. The induction is several times greater than in the B.T. feeder system when the communication line is long. 3. The induction is as big as or a little bigger than in the B.T. feeder system when the communication line is short. 4. The induction increases with a plural load. 5. The screening effect is greater for "with NF" in ② than in the Basic Type in ①.	———	Put to wide use in such foreign nations as France, Britain and the Soviet Union
	② With NF (T-R-NF)				
B.T. (booster transformer) feeder system	③ With NF		1. The hazards by induction are small. 2. The induction increases due to a B.T. saturation at an accident. 3. The section exposed to induction is confined virtually to the section between B.T. and the booster line. 4. The effects of a reduction of communication induction are somewhat better for "with NF" in ③.	Conventional lines and Tokaido Shinkansen	Partly in Britain, France and Sweden
	④ Without NF			———	Norway and partly in Britain, France and Sweden
⑤ A.T. (autotransformer) feeder system			1. The hazards by induction are small. 2. The induction is somewhat large than in the B.T. system when the communication line is long. 3. The induction is somewhat smaller than in the B.T. system when the communication line is short. 4. The induction of the overall length is small when the self-impedance of the trolley and feeder is brought close.	Conventional lines, Sanyo Shinkansen and Tohoku-Joetsu Shinkansen	The United States (25 Hz) (Under development in the Soviet Union and France)
⑥ C.C. (coaxial cable) feeder system			1. The hazards by induction are small. 2. The induction characteristics are similar to those of the A.T. feeder system. 3. The induction a little smaller than in the A.T. system when the communication line is long. 4. The induction is a little larger than in the A.T. feeder system when the communication line is short. 5. The electrostatic capacity is great, so are the effects of harmonic resonance.	Some sections of Shinkansen	Nil

line are great and the rail potential is higher than in any other feeder system.

(2) B.T. Feeder System

In the B.T. feeder system, a boost transformer is installed at every four kilometers or so and the trolley wires are fitted with B.T. sections to contain and absorb the return current with which the rails are charged, so much so that the effects of a reduction of communication induction are of significance.

The B.T. feeder systems come in two types -- a simple B.T. feeder system in which boost transformers are placed between the trolley wires and the rails and a system in which NFs are installed to absorb the electric current. The former system is simple but far inferior to the latter in terms of the effects of a reduction of communication induction. But it goes without saying that the B.T. feeder systems are better than the direct feeder system. In the rail insulation, there appears a voltage at the secondary terminal of the boost transformer and short-circuiting and opening are repeated by the wheels when a train goes by, making the maintenance of the insulated section poor. A B.T. feeder system is therefore used in cases where the load current is not too big.

In any event, the B.T. feeder systems excel in the reduction of communication induction, on the one hand, and on the other, require B.T. sections, etc., so much so that the composition of their feeder circuit is more complicated than in the direct feeder system and that the impedance of the feeder circuit is great.

When the load is extremely great as is the case with JNR's Shinkansen, the arc which is generated in the booster section is large and it is necessary to come up with measures for its elimination. Here, the contact wires become complex in composition.

JNR makes exclusive use of a system in which NFs are in existence but B.T. systems without NFs are put to practical use in some countries.

(3) A.T. Feeder System

The A.T. system is one in which the feeder voltage from a transformer station is made higher than that of the contact wires and dropped to the necessary contact wire voltage with an autotransformer (AT) installed every 10 km or so along the rails.

In the A.T. feeder system adopted in Japan, the feeder voltage from transformer stations is twice as big as that of the contact wires. It would be possible as a matter of course to make it further higher by changing the number of AT's turns.

This system is fitted to the supply of massive electric power as the feeder voltage from transformer stations is high (two times). If the load capacity is left constant, the electric current is halved, thus setting the voltage reduction rate at 1/4 and enlarging the distance between transformer stations. For a single load, therefore, it would be theoretically possible to make the distance between transformer stations four times longer than in the B.T. feeder system and 2.5 times longer than in the direct feeder system. In actuality, an increase in the distance between transformer stations results in increasing the number of trains in between, so that the distance will be made 2.5∿3 times longer than in the B.T. feeder system and about two times longer than in the direct feeder system. An extension of the distance between transformer stations is of advantage particularly when the point where a power source is available is a long way off.

Moreover, as the load current is absorbed by autotransformers at right and left, the induction voltage on the long communication line is offset and the current with which the rails are charged is contained, with the result that the effects of a reduction of induction hazards is of significance. If the distance between autotransformers is about 10 km for a load which comes in the neighborhood of the load for the conventional railway lines in Japan, the characteristics of communication induction are practically the same as those of a B.T. feeder system in which BT's are installed at an interval of 4 km.

In order to install AT's with a considerable capacity at every 10 km, however, there would be a need to install trolley lines and feeder wires of one and the same insulation class. There would be no booster sections but the circuit would become complicated in composition.

(4) Coaxial Cable Feeder System

In the coaxial cable feeder system, a coaxial electric power cable is laid along a railway line in addition to a direct feeder circuit (with NFs), and at every several kilometers, the internal conductor of the coaxial cable is connected with the trolley line and the external conductor with the rails.

Distribution of the electric current in the coaxial cable feeder system is similar to that of the A.T. feeder system, so much so that the effects of a reduction of communication induction is of significance. As the mutual impedance between the internal and external conductors is great for a coaxial cable, the reciprocating impedance drops to a significant degree, and the distance at which feeding may be done is as long as, or longer than, that of the A.T. feeder system, depending on the specification (thickness) of the coaxial cable.

The coaxial cable feeder system is of disadvantage in the sense that coaxial cables are dear and it is difficult to restore to normalcy the coaxial cables which are out of order, but these factors must be taken into account as against the total cost of the system, mutual spare systems of the upper and lower coaxial cables and other operation methods.

The capacitance to the ground of the feeder wire (internal conductor of the coaxial cable) is about 10 times greater than in the aerial suspension type. Given this factor, it is necessary to solve problems, such as on an increase in the action burden of lightning arresters for the feeder circuit in the light of an expansion of the harmonic current caused by a significant drop in the resonance frequency of the feeder circuit as well as the coordination of insulation.

JNR installs coaxial cables for several kilometers in a section of Shinkansen's power transmission system, and the use has been favorable for several years. Nowadays, coaxial cables are adopted in the feeder system of tunnels on a full scale, albeit for several kilometers. The reason is because the total cost of this system is lower than the cost of engineering works for other systems for which much space must be set aside for the composition of aerial circuits.

6-1-6 Comparison of Induction Voltage between Feeder Systems

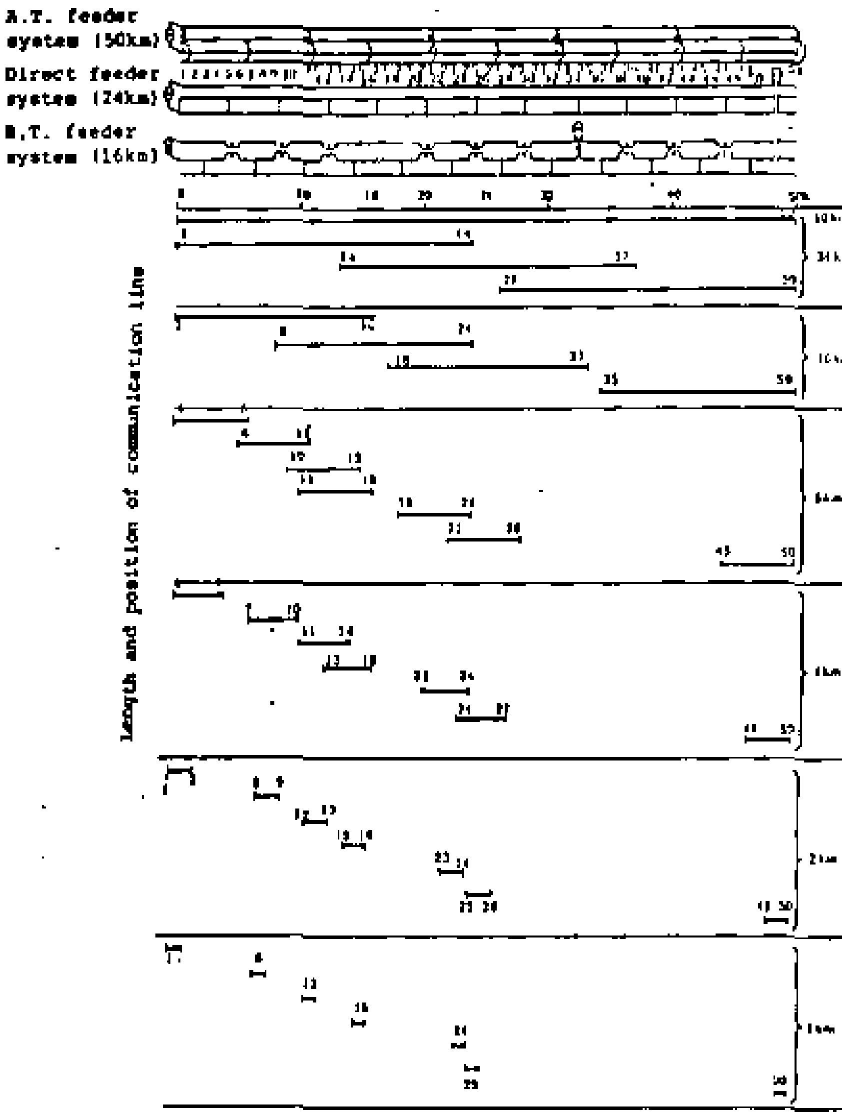
The simulated computation of induction voltage in various feeder systems is done below.

The condition for this computation is that an attempt is made to compute the induction voltage of the communication line which is generated when a single load moves along the feeder circuit of each model, and that the basic wave and an 800 Hz noise wave are taken up for a comparison that the direct feeder system, B.T. feeder system and A.T. feeder system are compared.

(1) Comparison of Induction Voltage of Basic Wave

Of the induction voltages which are generated in the communication lines (with route lengths of 1, 2, 4, 6, 16, 24 and 50 km) positioned at a point near the feeder point of each feeder circuit, a point close to its median point and a point close to its end, the greatest voltage is computed for separating distances of 50, 100 and 300 m, as indicated in Table 6-4. A study under JNR regulations shows that there is no influence in the B.T. feeder system as against the constant induction risk voltage critical value (60 V) in the case of communication lines (not shielded) with separating distance of 50 m and that in the case of 50 km, the voltage exceeds the critical value in the A.T. feeder system. In the direct feeder system, communication lines with lengths of more than 4 km are affected.

Table 6-4 Induction Voltage of Communication Lines in Feeder System



Single load, load current I=200A

f=60Hz, σ=0.01 ℧/m, Admittance of rail leakage 1 ℧/km

Communication line: not shielded

Length	Induction voltage (V) Separating distance 50 m			Induction voltage (V) Separating distance 100 m			Induction voltage (V) Separating distance 300 m		
	Direct system	A.T. system	B.T. system	Direct system	A.T. system	B.T. system	Direct system	A.T. system	B.T. system
50 km	369.1	69.1	49.0	266.4	51.6	37.2	161.1	30.3	20.9
34 km	369.3	57.6	48.0	286.4	44.7	37.2	161.1	25.1	20.9
	201.8	55.6	48.0	156.5	43.1	37.2	86.0	24.3	20.9
	315.0	41.0	48.0	267.5	33.4	37.2	150.5	18.6	20.9
16 km	219.7	50.0	48.0	193.8	36.8	37.2	104.9	21.8	20.9
	250.2	51.0	43.3	191.0	39.5	33.5	109.1	22.2	18.9
	137.0	40.2	45.7	106.4	37.4	35.4	59.9	21.0	19.9
	216.9	39.0	46.9	169.2	30.2	36.3	91.6	17.0	20.4
8 km	87.8	33.7	37.3	65.1	26.1	28.9	38.3	14.7	16.3
	98.6	32.6	40.0	76.4	25.3	31.0	43.0	14.2	17.4
	99.2	36.0	40.0	76.2	28.0	31.9	42.9	15.7	17.4
	98.3	35.2	41.3	76.2	27.3	32.0	42.9	15.4	18.0
	88.8	36.6	37.1	65.8	28.4	29.8	38.7	16.0	16.2
	56.3	23.4	37.1	43.6	18.1	29.8	21.5	10.2	16.2
	55.7	31.7	31.3	43.2	24.6	25.3	24.3	13.8	13.7
4 km	55.7	27.6	31.1	43.2	21.4	25.1	24.3	12.1	13.6
	65.6	27.9	32.3	50.9	21.6	25.1	28.4	12.2	14.1
	65.5	29.5	32.3	50.8	22.9	25.1	28.6	12.9	14.1
	65.9	23.9	31.3	51.1	18.4	24.3	25.8	10.4	13.7
	56.3	29.5	31.3	43.4	22.8	24.3	24.5	12.9	13.7
	40.1	19.1	32.7	31.2	14.8	25.4	17.5	8.33	14.3
	24.5	27.5	21.4	18.2	21.3	16.6	10.7	12.0	9.33
2 km	23.4	16.0	22.6	18.2	12.4	17.5	10.2	7.0	9.86
	32.8	16.5	18.1	25.5	12.8	14.0	14.3	7.19	7.89
	32.8	17.5	18.1	25.4	13.4	14.0	14.3	7.51	7.89
	33.2	11.4	21.4	25.7	8.81	16.6	14.5	4.97	9.33
	24.5	14.7	22.8	19.0	11.4	17.7	10.7	6.41	9.95
	24.5	11.4	21.4	19.0	8.84	16.6	10.7	4.97	9.33
	23.6	16.8	21.4	18.2	13.0	16.6	10.3	7.36	9.33
1 km	9.27	7.10	11.4	7.19	5.16	8.76	4.04	3.10	4.93
	16.6	7.86	10.8	12.9	6.10	8.35	7.26	3.43	4.70
	16.6	9.27	10.8	12.9	8.19	8.35	7.24	4.05	4.70
	16.6	5.82	10.8	12.9	4.51	8.35	7.24	2.54	4.70
	10.1	7.29	11.5	7.82	5.66	8.90	4.40	3.18	5.01
	10.1	6.34	10.8	7.82	4.91	8.35	4.40	2.76	4.70
	11.4	8.09	10.6	11.1	6.27	8.23	6.27	3.51	4.64

σ=0.01 ℧/m

f=60 Hz

Separating distance (m)	Mutual impedance $M \times 10^{-4}$ H/km	Ratio
25	7.403	1.303
50	5.682	1.0
100	4.561	0.775
200	3.291	0.560
330	2.566	0.436
500	1.731	0.295

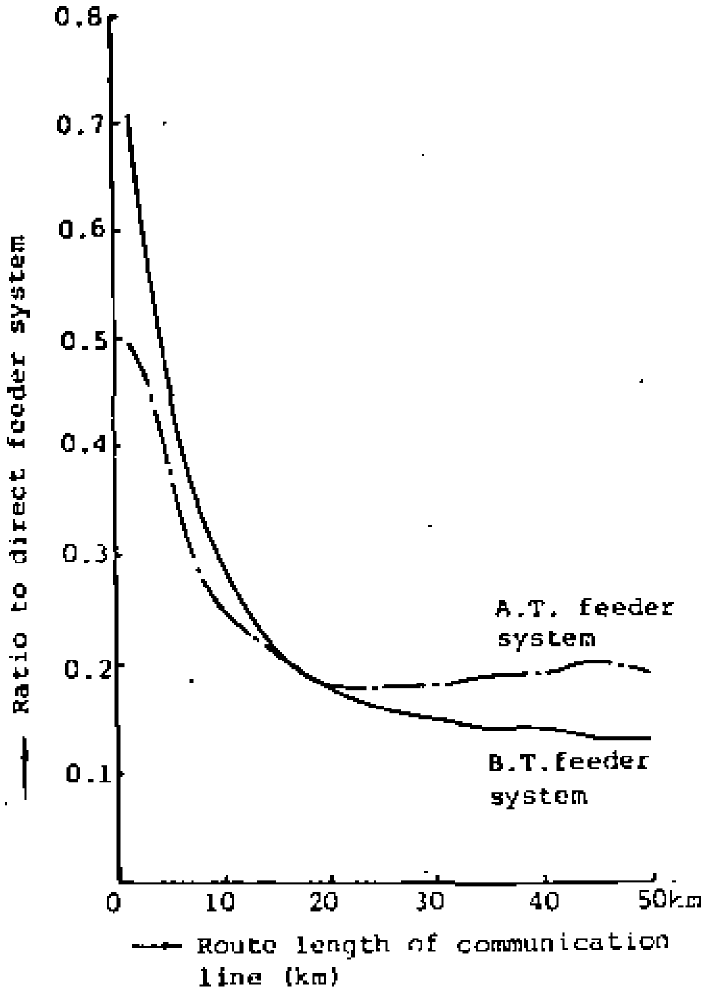


Fig. 6-3 Multiples to Direct Feeder System
Inductive voltage in the case of f = 60Hz

When the separating distance is 100 m in the A.T. feeder system, the voltage is lower than the critical value. In the direct feeder system, the voltage exceeds in the critical value when the communication lines are more than 16 km in route length even if the separating distance is 300 m.

From these results, the induction voltage increases virtually in the order of A.T. < B.T. < Direct when the communication lines are short, as indicated in Fig. 6-3. When the communication lines are long, the order is B.T. < A.T. < Direct. Particularly in the direct feeder system in which the communication lines are long, the induction voltage is about 7.7 times as big as in the B.T. feeder system.

When a communication line, 1 km long, is hypothesized in the position of each feeder circuit, the maximum induction voltage generated in each communication line with a length of 1 km by a movement of the load is computed as shown in Fig. 6-4.

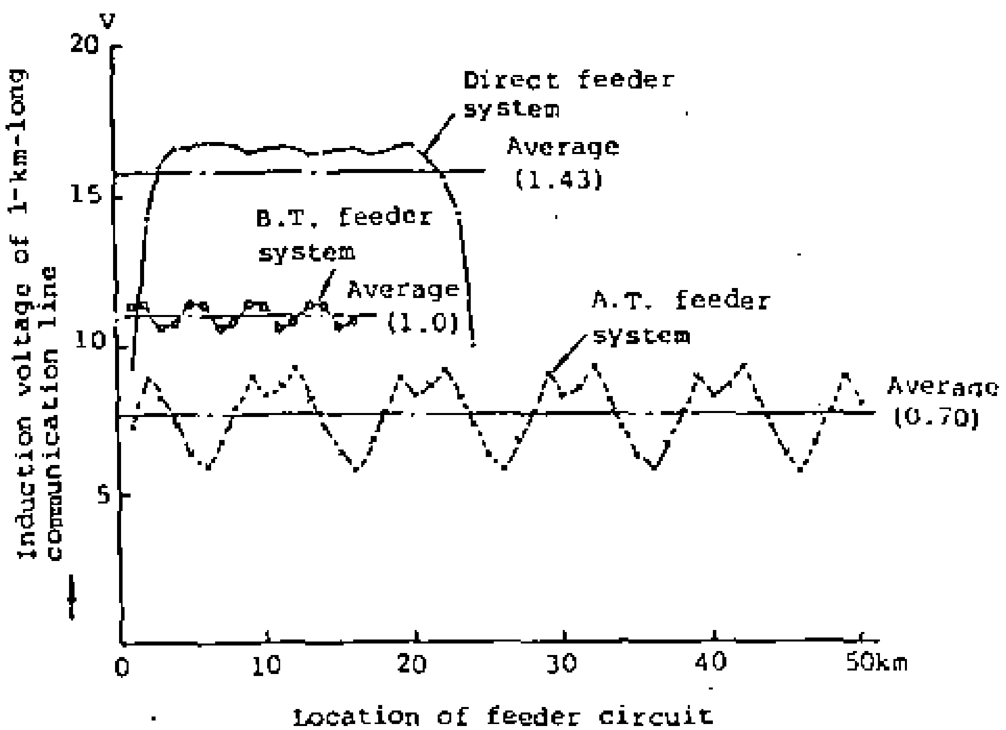


Fig. 6-4 Maximum Induction Voltage of 1-lm-long Communication Line at Every Kilometer in Feeder Systems (separating distance 50m)

When these induction voltages are averaged for each feeder circuit, the induction voltage stands at about 15.7 V in the direct feeder system, about 11 V in the B.T. feeder system and about 7.7 V in the A.T. feeder system. When these mean values are compared with that of the B.T. feeder system at 1.0, the mean value is about 0.7 times bigger for the A.T. feeder system and about 1.43 times bigger for the direct feeder system.

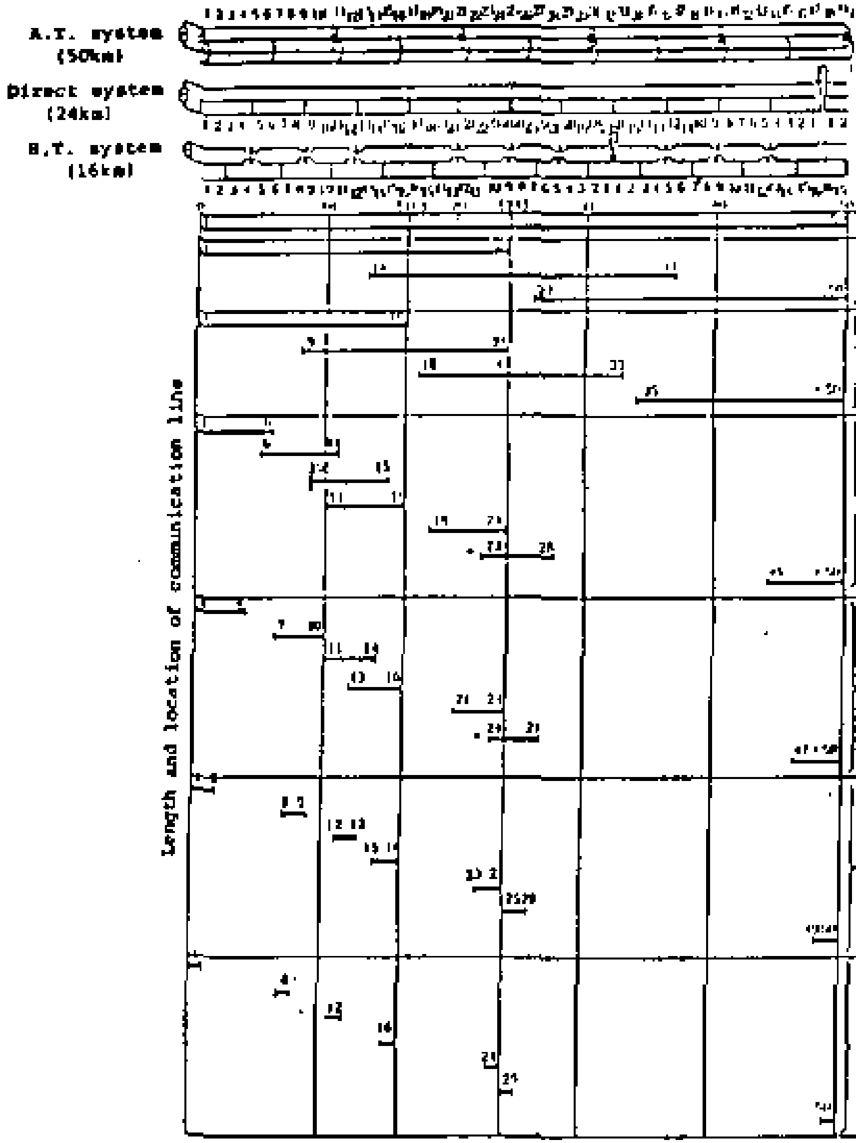
(2) Comparison of Voltages of 800 Hz Noise Level

Of the noise voltages (longitudinal electromotive voltages) which are generated by a movement of the load in the communication lines (with route lengths of 1, 2, 4, 6, 16, 24 and 50 km) installed at a point near the feeder point of each feeder circuit, a point near its median point and a point near its end, the maximum voltage is computed for the separating distances of 50, 100 and 300 m as indicated in Table 6-5.

In the table, the route length of the feeder is shorter in the direct and B.T. feeder systems than in the A.T. feeder system, so that the route length of 50 km in the A.T. system is added. Given this factor, the longitudinal electromotive voltage of the communication line is computed in the state or a matched feeder on the assumption that the next feeder circuit (with the same route length) stretches from the sectioning post. Therefore, the load is single when the communication line extends over both sides of the feeder circuit of the sectioning post, so that whichever large noise is adopted. Here, as the exposed length of the communication line becomes short, the noise voltage becomes small as indicated in Table 6-5.

From these findings, the longitudinal electromotive voltage becomes large in the order of A.T. < Direct < B. T. when the communication line is as short as 1 km, as indicated in Fig. 6-5. In proportion as the route length of the communication line increases, the voltage increases in the order of A.T. < B.T. < Direct. When the communication line has a route length of more than 13 km, the voltage increases in the order of B.T.< A.T.< Direct. When the communication line is longer than 24 km, the voltage is about 6.5 times bigger in the direct feeder system than in the B.T. feeder system.

Table 6-5 Induction Noise Voltage of Communication Lines of Communications in Feeder System (Vn)



Single load Jp=5A

f=800Hz σ=0.01 s/m Rail leakage admittance 1 s/km

Communication line: not shielded

	Induction noise voltage Vn (mV) Separating distance 50m			Induction noise voltage Vn (mV) Separating distance 100m			Induction noise voltage Vn (mV) Separating distance 300m		
	Direct system	A.T. system	B.T. system	Direct system	A.T. system	B.T. system	Direct system	A.T. system	B.T. system
50km	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24km	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
16km	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8km	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4km	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2km	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1km	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

σ=0.01 s/m
f=800 Hz

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
50	[illegible]	[illegible]
100	[illegible]	[illegible]
200	[illegible]	[illegible]
300	[illegible]	[illegible]
400	[illegible]	[illegible]

Note: The asterisk indicates the communication line which extends over two feeder sections.

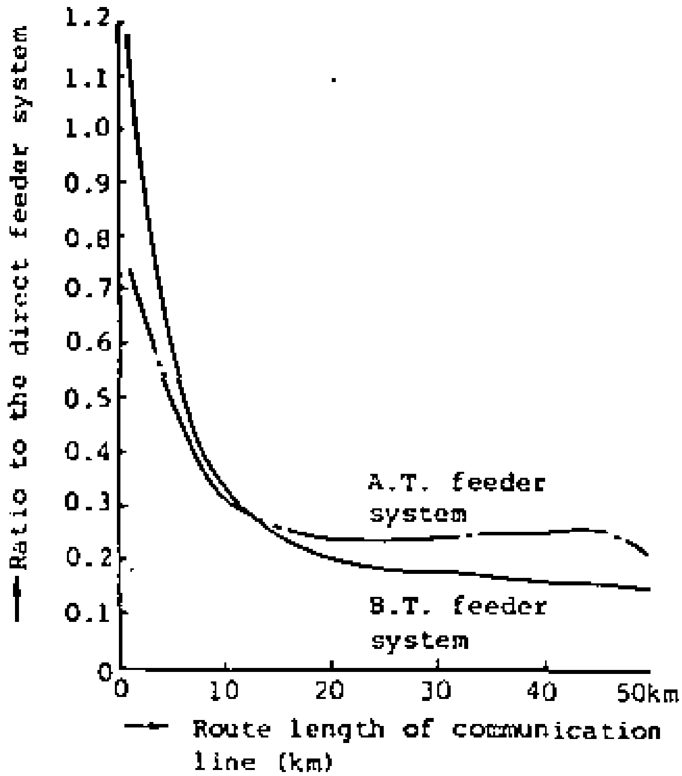


Fig. 6-5 Multiples to Direct Feeder System
Noise voltage in the case of f = 800Hz

When this is compared with the basic wave (60 Hz), the effects of the degrading current by the ground leakage admittance of the rail in the case of the noise voltage is smaller than in the case of the basic wave, so that when the route length of the.communication line is short, the noise voltage conservely becomes higher in the direct feeder system than in the B.T. feeder system. However, the ratio is smaller than in the case of the basic wave. When the communication line is more than 24 km, the ratio in the direct feeder system is about 6.5 times than in the B.T. feeder system, smaller than about 7.7 times for the basic wave.

When a communication line of 1 km in length is hypothesized for each feeder circuit, the biggest longitudinal electromotive voltage which is generated in each communication line of 1 km in length by a movement of the load may be computed as indicated in Fig. 6-6. The results indicate that the maximum and minimum

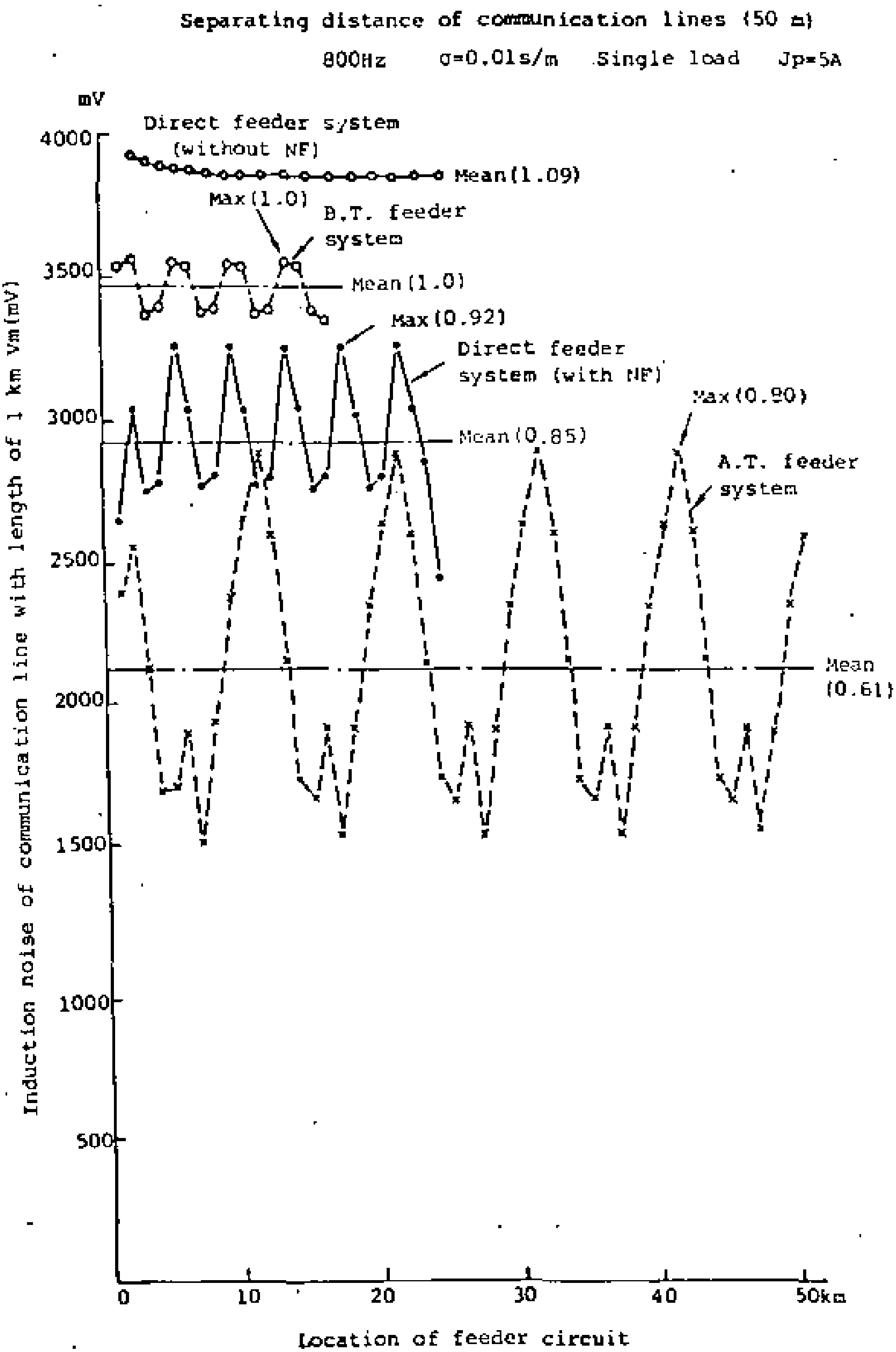


Fig. 6-6 Maximum Induction Noise Voltage of 1-km-long Communication Line at Every Kilometer in Each Feeder System

breadths of the noise vertical voltage in the entire section of the feeder circuit are greater than in the case of the induction voltage of the basic wave.

When the maximum noise voltage in each section of the 1-km-long communication line is averaged for the entire section of the feeder circuit, the noise voltage is about 2,920 [mV] in the direct feeder system, about 3,470 [mV] in the B.T. feeder system and about 2,120 [mV] in the A.T. feeder system when the separating distance is 50 [m]. From these results, the logitudinal electromotive voltage stands at about 0.61 time in the A.T. feeder system and about 0.85 time in the direct feeder system when the noise vertical voltage of the B.T. feeder system is set at 1.0. When they are compared with the induction voltage of the basic wave, there are converse signs that the noise vertical voltage is somewhat smaller for the A.T. feeder system (about 0.7 time as large as in the case of the basic wave) and that of the direct feeder system (about 1.43 times as big as in the case of the basic wave) is smaller than that of the B.T. feeder system.

6-1-7 Measures against Induction Hazards

When measures against induction hazards are to be taken, they must be studied from the diversified technological standpoint while returning to the original point of the electrification program.

For example, density of public communication lines by the economy and citizen's activity, critical values of induction voltage, etc., and legal restrictions in the country where electrification is to be stepped up must be studied in a comprehensive manner to work out induction measures. If an erroneous step was taken, what was done for an improvement of railway transportation with electrification would likely to result in generating induction hazards.

The flow of measures against induction hazards in normal circumustances is shown in Fig. 6-7.

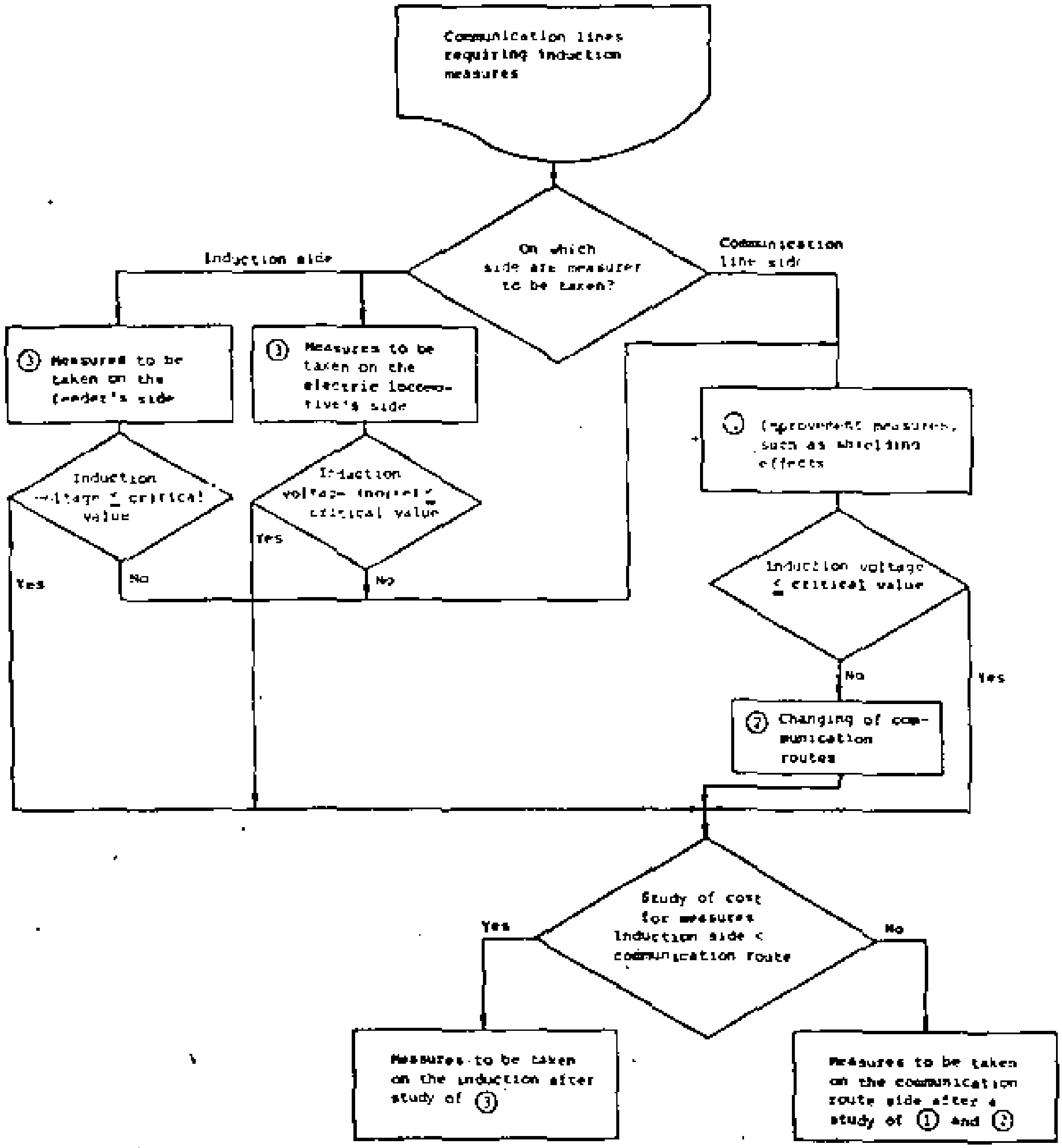


Fig. 6-7 Measures against Induction Hazards

As indicated in the figure, the induction measures for A.C. electrification may be divided into the following types.

Measures on the feeder's side Measures on the electric vehicle's side	Induction side
Measures on the communication route's side	Side of the induced

As far as induction measures are concerned, the induction hazards should be restrained as much on the induction side as possible, before steps are taken on the side of the induced. As measures on the side of the feeder, the B.T. and A.T. systems are widely in use. As regards electric vehicles, induction is generated by the thyristor of the phase control, so that it has become a practice to take harmonic wave measures.

Even if these measures are taken, the induction hazards on the side of the induced cannot be completely eliminated. Given this factor, it is necessary to take measures against induction hazards, such as for communication routes.

The induction hazards with A.C. electrification come in electrostatic and electromagnetic induction.

The electromagnetic induction voltage is generated by the added voltage of electric vehicles, giving rise to serious hazards, such as noise in the communication line, difficulty to listen to in telephone conversations and erroneous connection of exchangers. As for the countermeasures, scopes, methods, etc., are determined on the basis of a preliminary induction calculation, but they are complicated and difficult. Normally, the communication route is shielded with a cable and the track circuit is altered, such as with a change in system. As a matter of course, the track circuit for electrification itself uses a feeder circuit and rails, so that the insulated current of the contact wire is mixed, bringing about a direct impact. For this reason, it is necessary to change the system of the conventional track circuit.

In the following, an attempt will be made to introduce the basic matters related to contermeasures against electromagnetic induction.

(1) Measures on Feeder Side

In the B.T. feeder system, as is discernible from Fig. 6 - 8, the return current which has leaked to the ground is boosted by the boosting line due to the boosting effects of the booster transformer, and the volume of induction to the outside varies, depending on the locational relation between the electric vehicle and the boosting line. The volume of induction is greatest when the location of the electric vehicle coincides with that of the booster transformer. The interval for installation of booster transformer can be determined with the volume of induction to the exterior taken into consideration. In JNR, the distance is about 4 km in the suburban areas and 1.5 km in the built-up area.

In the A.T. feeder system, as is discernible from Fig. 6-9, the current which has leaked to the ground flows to the ATs at both ends of the load point, the direction is reversed, and the distance at which induction is given to the outside coincides with the distance between AT and AT, the electric current being less than half that of the B.T. system.

JNR standardizes the A.T. interval is set at 10 km, but in a comprehensive perspective, the induction degrading effects are practically the same as in the B.T. feeder system.

The distribution of the load current in the A.T. feeder system is not so simple as in the B.T. feeder system, and there is no simple way of knowing at what load point the volume of induction becomes greatest. Consequently, this computation is difficult to make, unless a computer is used, and the induction is computed after defining Amp · km.

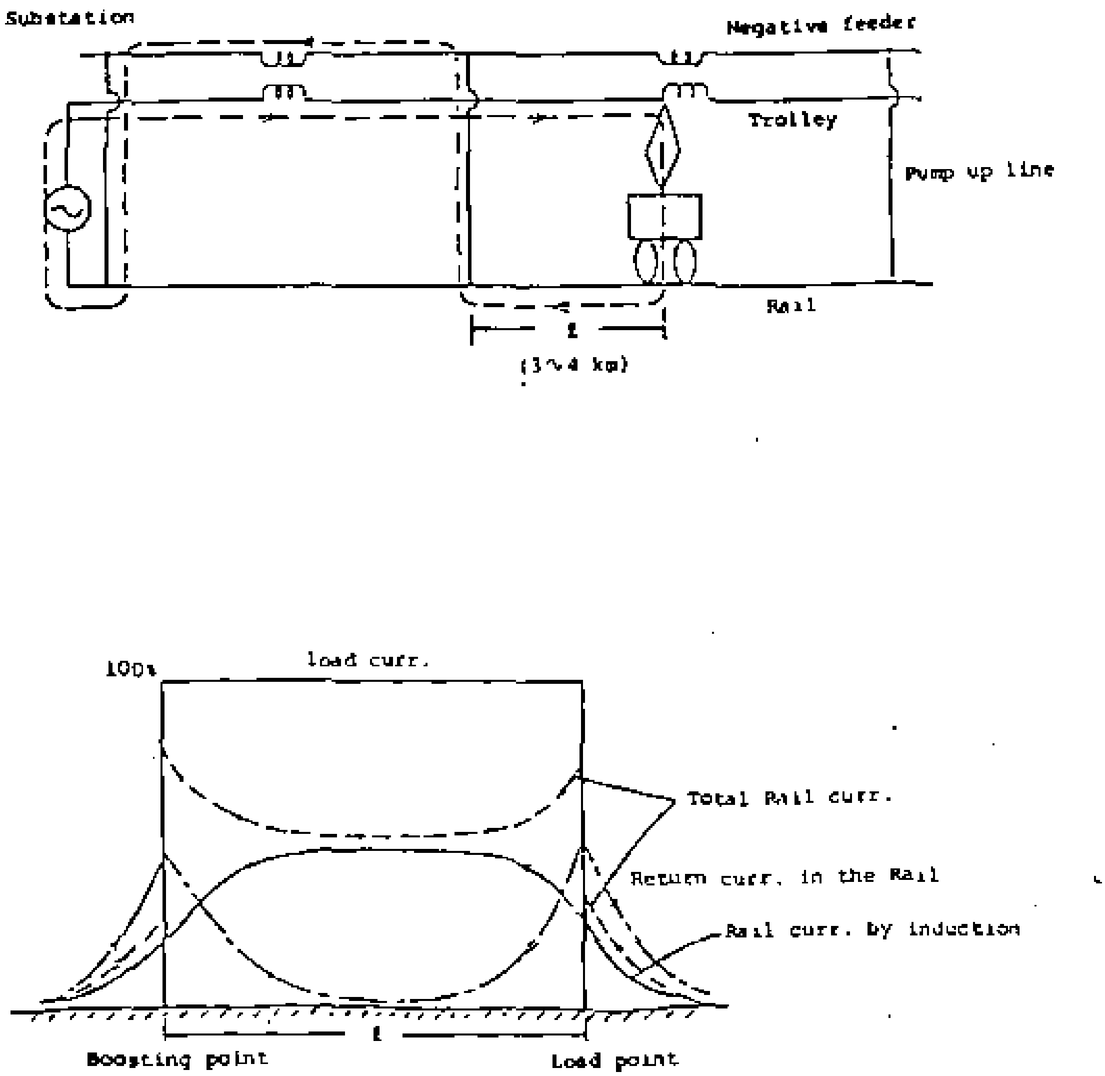


Fig. 6-8 B.T. Feeder System

Note: The distribution of the load current is virtually determined by the section between the load point and the boosting line, and even if the load moves, the induction voltage remains virtually constant.

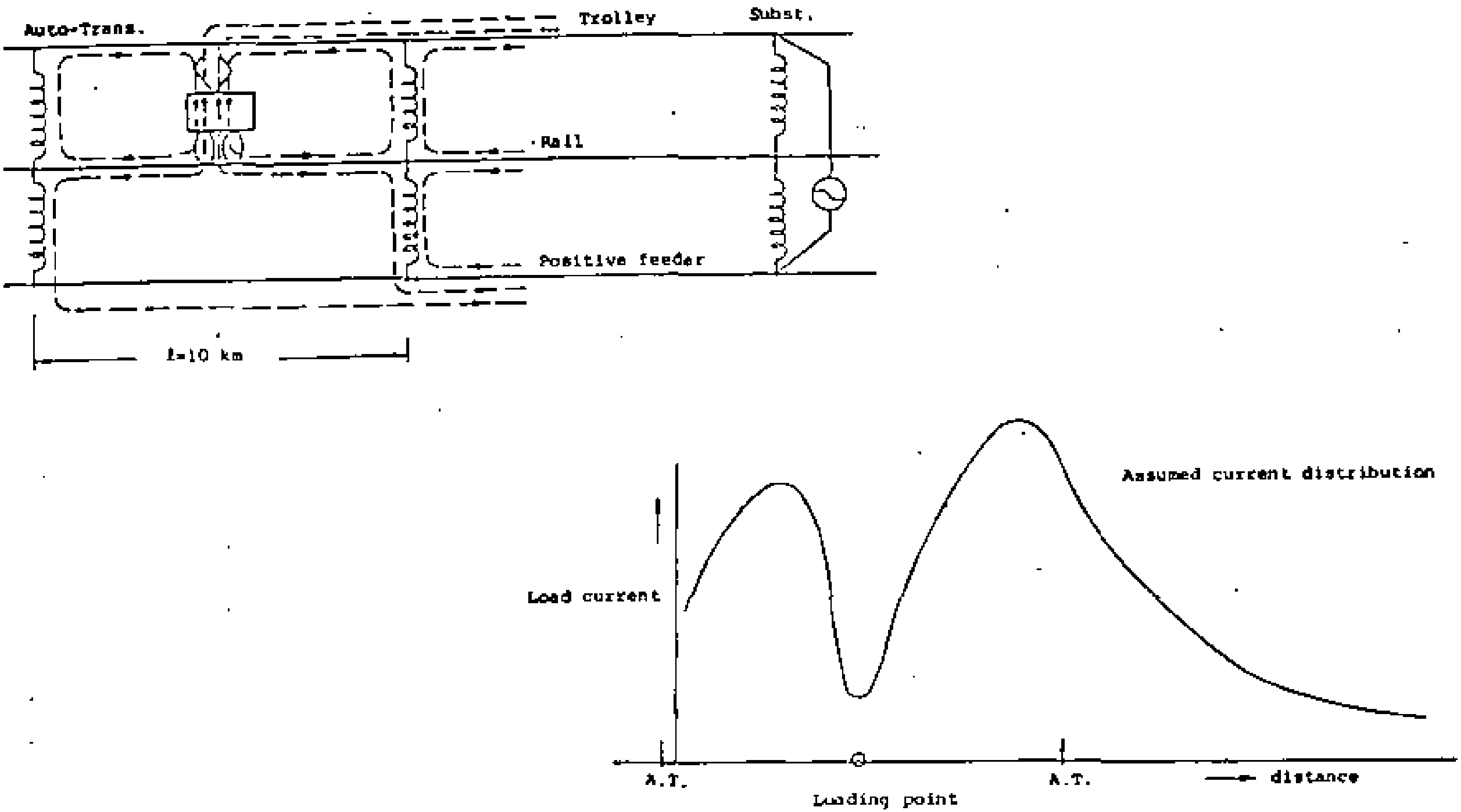


Fig. 6-9 A.T. Feeder System

In this equation, as indicated in Fig. 6-10, the electric currents with which the trolley line, feeder line and rail are charged are expressed as I_1, I_2, and I_3, respectively, and the mutual induction coefficients with the communication line are expressed as M_{1c}, M_{2C} and M_{3c}, respectively. The induction voltage V_m of the communication line is:

$$V_m = -j\omega(M_{1C} I_1 + M_{2C} I_2 + M_{3C} I_3)\,\ell$$

where ℓ is the length of the induced communication line.

Here, in case the contact wire and the communication wire are separated from each other to some extent, the distribution of the load current, extending over the feeder circuit, changes in a complicated manner in conjunction with a movement of the load. Consequently, the inducing current is computed in terms of Am·Km for each section, and the highest value is taken up for that section.

$$M_{1C} \doteq M_{2C} \doteq M_{3C} = M$$

so that

$$V_m \doteq -j\omega M(\dot{I}_1 + \dot{I}_2 + \dot{I}_3)\,\ell$$

Here, it is defined that

$$(\dot{I}_1 + \dot{I}_2 + \dot{I}_3)\,\ell = A_{mp}\cdot Km$$

$$V_m = -j\omega M\cdot A_{mp}\cdot Km$$

The induction voltage which is generated in a communication wire is computed is prospectively computed after the maximum Am·Km has been calculated. The Am·Km is the parameter with which the induction voltage is realized.

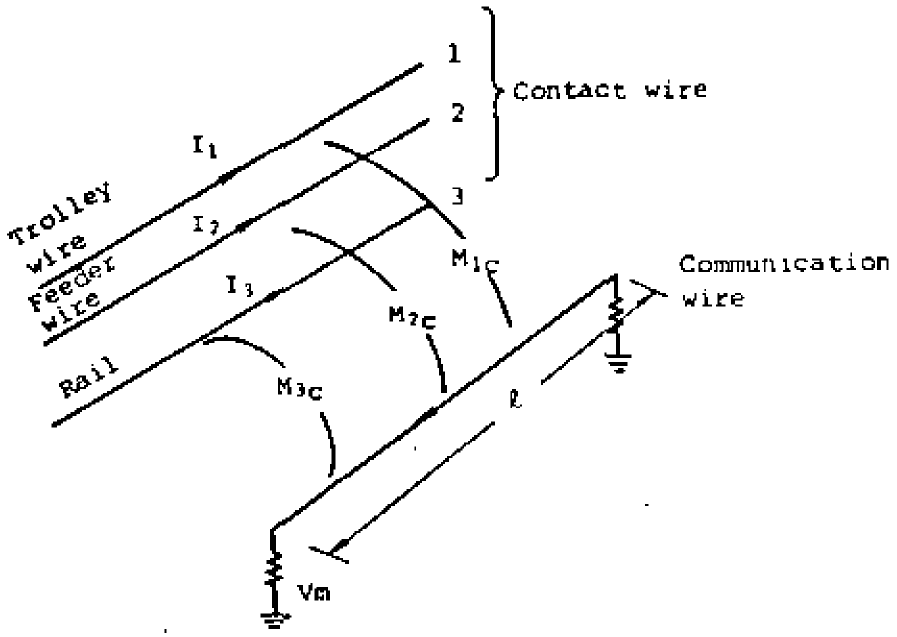


Fig. 6-10 Am·Km of Feeder Circuit

(2) Measures for Electric Locomotive

When an electric locomotive controlled with a thyristor chopper travels in a section electrified in A.C., a harmonic wave is generated in the feeder circuit, so that filters are installed in the electric locomotive, the number of divisions on the secondary side of the main transformer is increased, cumulative control and other measures are taken.

On the other hand, in the computation of the noise voltage, the equivalent disturbing current (Jp) for which the harmonic wave of the electric locomotive is assessed is used. The induction voltage is in proportion to the equivalent disturbing current. For any electric locomotive and car, it is necessary to minimize the equivalent disturbing current.

(3) Measures on Communication Side

According to the equation for the prediction of induction, the induction voltage may be reduced if the mutual induction coefficient, length of the communication route, shielding coefficient of communication cables, degree of equilibrium, etc., are reduced.

(a) Method of Reducing Mutual Induction Coefficient (M)

The mutual induction coefficient (M) is a constant which is determined by the separating distance between the feeder circuit and the communication wire, ground conduction ratio and frequency.

The earth conductivity is determined by the soil and the frequency cannot be changed. Consequently, the separating distance must be made longer to reduce M. Communication lines other those used for a railway line -- i.e., public and other communication lines in areas other than those in the raily site -- must be moved away as far from the raily line as possible, such as by changing their routes.

However, it is difficult for the sake of security and reasons to keep a railway communication route from the railway site in normal circumstances. Given this factor, it is impossible to reduce M.

Incidentally, the relationship between the earth conductivity and the separating distance and the mutual induction coefficient is shown in Figs. 6-11 and 6-12.

(b) Communication Circuit

The communication circuit is divided as it is put in with insulating coils at an appropriate interval as shown in Fig. 6-13.

Here, the distribution of the induction voltage in the communication wire is shown in the lower part of Fig. 6-13. However, this system is applicable to for a D.C. circuit and in case small sections are prepared with a large number of insulating coils, the loss in transmission cannot be ignored in the light of the loss resulting from a combination of insulating coils.

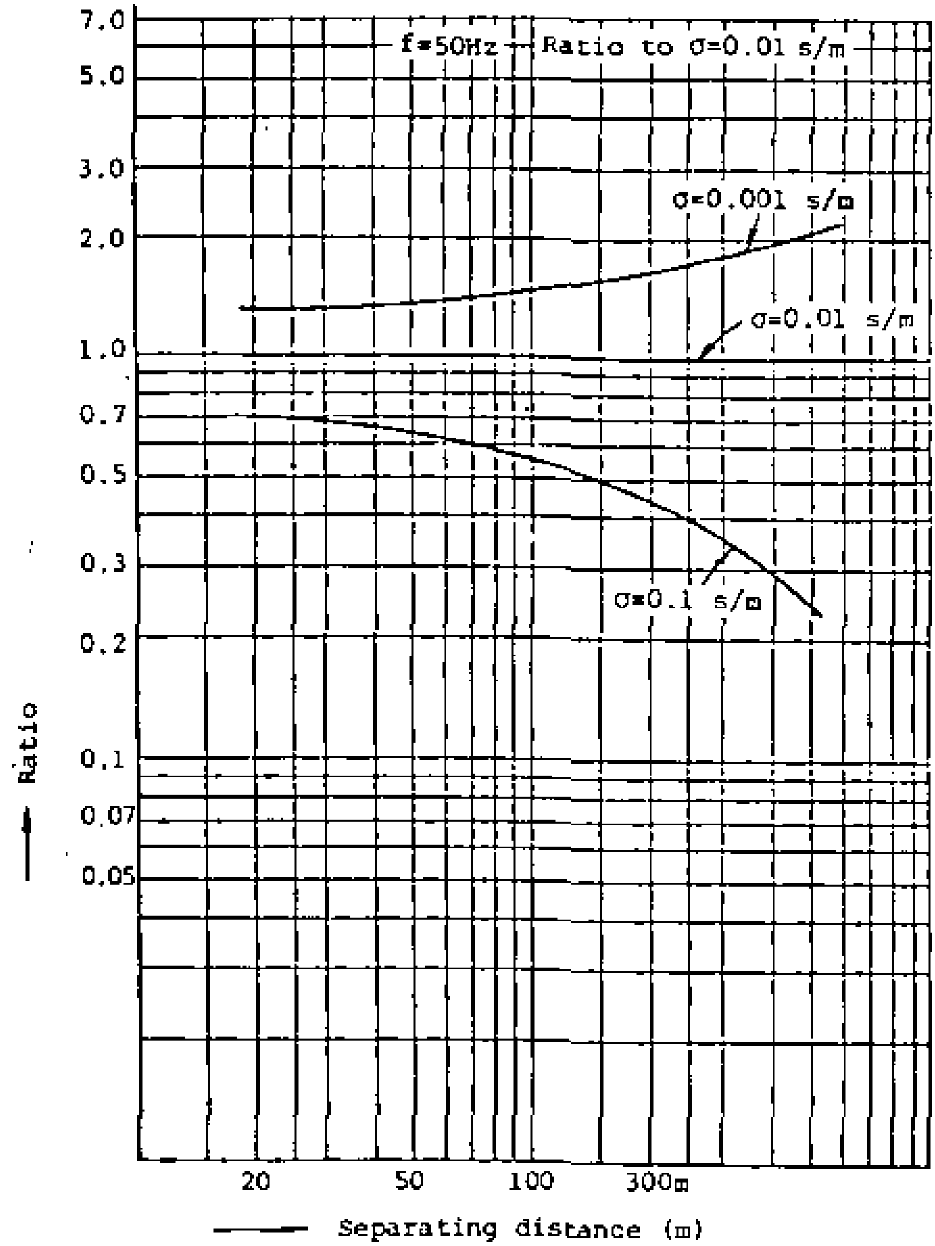


Fig. 6-11 Relationship between Separating Distance and Earth Conductivity to Induced Voltage

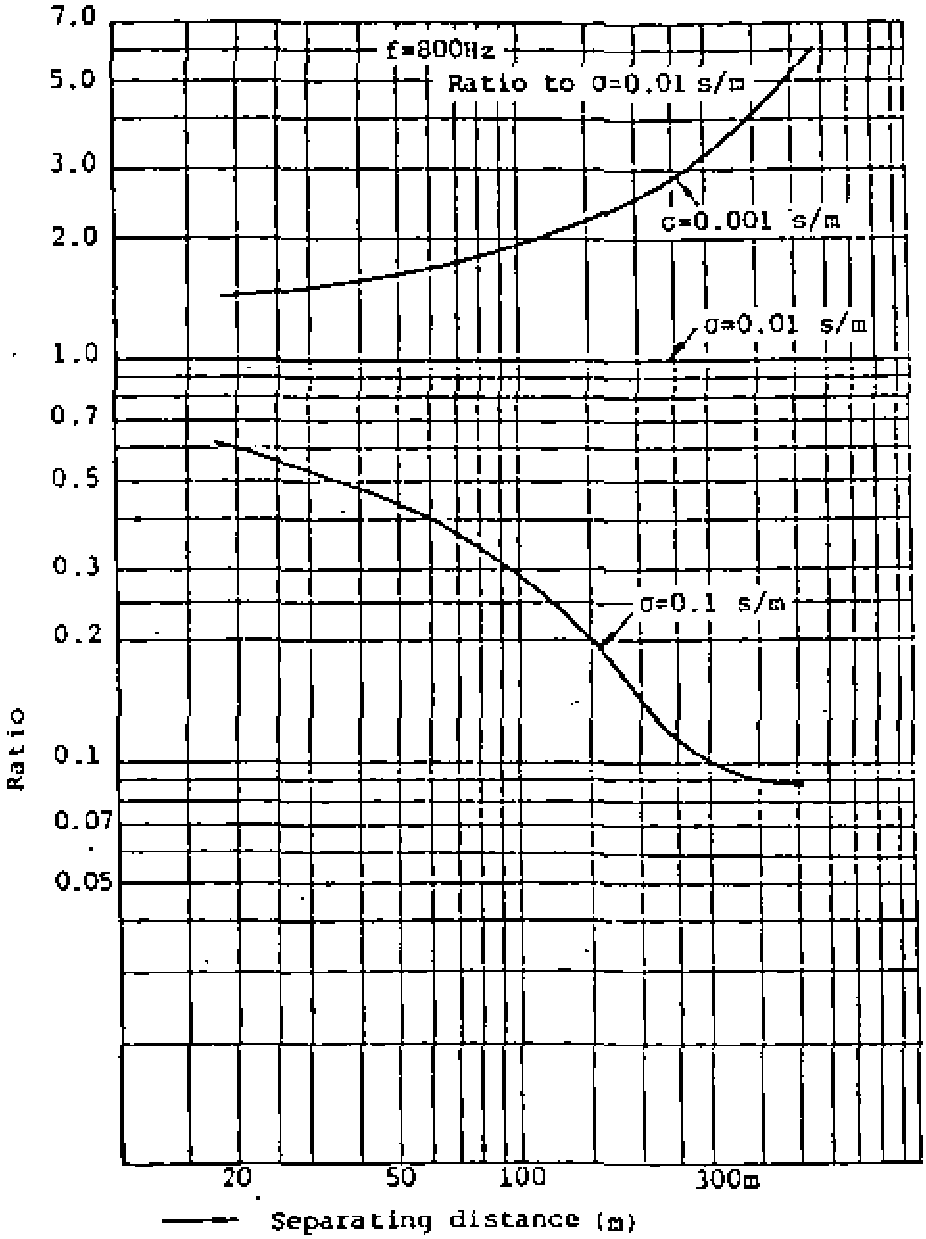


Fig. 6-12 Relationship between Separating Distance and Earth Conductivity to Induced Noise Voltage

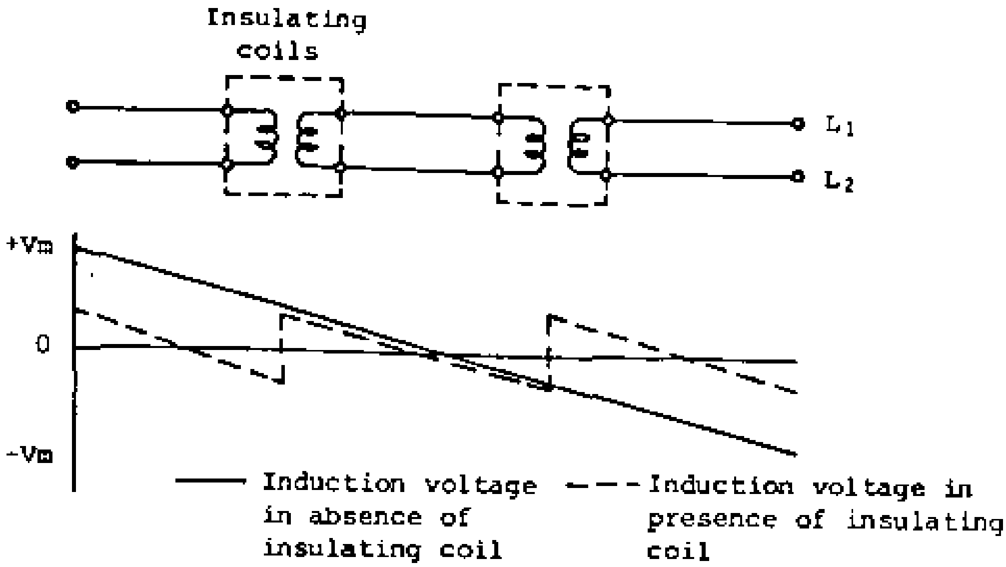


Fig. 6-13 Insertion of Insulating Coils

(c) Method of Using Shielded Cables

As regards the shielding coefficient of a shielded cable, the larger the inductance of the cable sheath, the better the shielding effect. Consequently, sheathing with steel belts which raises the permeability is of much effect. The smaller the value of the earth resistance for the earthing of the sheath and that of the sheath, the greater the effect.

$$K = (R_o + R_e)/(R_o + R_e + j\omega L)$$

where K is the screening factor, R_o is the resistance of the sheath (Ω/km), R_e is the earth resistance of the sheath (Ω/km) and ωL is the reactance of the sheath (Ω/km).

As is discernible from this quation, the screening factor against noise is smaller than that for the commercial frequency. The specifications of aluminum-sheathed steel belts for out-of-town communication cables, as indicated in Table 6-6, are that the screening factor is set at less than 0.6 with the electric current at 50 or 60 [Hz], the electric field at [V/km] and the earth resistance at 1 [Ω/km]. For Shinkansen, however, the screening factor is set at 0.4 with the electric field at 100 [V/km] and the earth resistance at 1 [Ω/1m], as the inducing current is big.

Table 6-6 Specifications of Screening Factor of Cables in Sections Electrified in A.C. (JNR)

Type of cable	Screening factor	Induction electric field
Cables for conventional railway lines	Less than 0.6	50V/km
Cables for Shinkansen	Less than 0.4	100 V/km

Of late, cables with electromagnetic steel belts which are designed to raise the permeability in order to set the screening factor at less than 0.1 have been developed. In principle, an underground burying method is used for aluminum sheaths. In order to reduce the construction cost, the cables the aerial suspension of which is made possible by corrugating aluminum have also been developed.

As regards the earthing of long shielding cables to be installed near a railway, JNR makes it a practice to set the resistance at less than 5 [Ω], while taking account of actual construction, and carry it out at places at an interval of several kilometers where earthing resistance may be readily secured. According to a trial computation in which a variety of conditions is hypothesized, the shielding effect may be improved if earthing is done halfway in addition to both ends. However, it would not be of effect if the earthing resistance at a halfway point is greater than that of both ends.

(d) Method to Minimize Balancing Degree of Circuit

In normal circumstances, a communication route is composed of two lines. If the ground electric potential of each line is equal, no induction voltage will be generated between two lines. In actuality, however, the lines will be out of balance due to the electrostatic capacity and line impedance. Cables normally have a balance of 60 ∿ 80 dB but the balance of the equipment with which the cables are connected is lower in many cases, so that the balance of the lines as a whole is reduced. To make up for an imbalance of the lines, it is advisable to insert lines of the kind which may assure a high impedance for the ground and a low impedance between the lines. The N-shaped repeating coil shown in Fig. 6-14 has such functions.

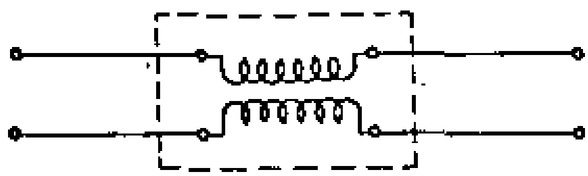


Fig. 6-14 N-shaped Repeating Coil

(e) Other Methods

Carrying is done with the use of a frequency which is not affected by induction noise. The abnormal voltage is chased to the ground with the installation of arresters, draining coils, etc. The methods employed by JNR are shown below.

The induction measures of the exchange telephone and dispatching circuits for which shielding cables are used are indicated in Figs. 6-15 and 6-16. Arresters are used for the arresting of lightning and other induction measures and other measures are taken. Wherever necessary, insulation coils, N-shaped repeating coils, etc., are also used.

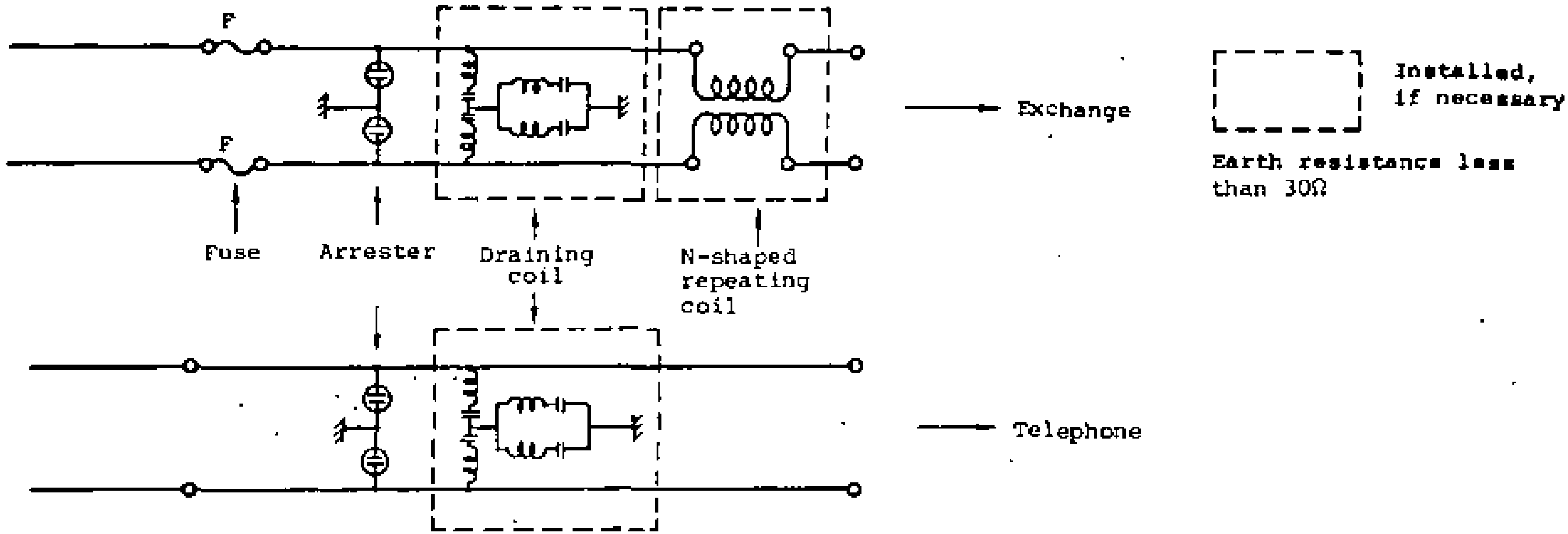


Fig. 6-15 Example of Induction Prevention Measures for Exchange Telephone Lines

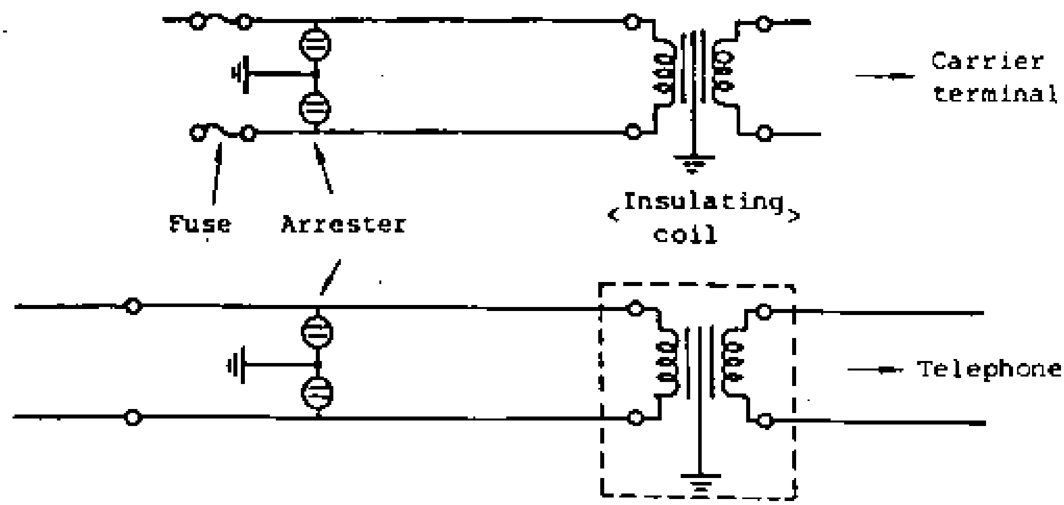


Fig. 6-16 Example of Induction Measures of Dispatching Circuit

6-2 Composition of Transmission Routes

6-2-1 Outline

The gravity of telecommunications in the railway transport system increases in the information-oriented society.

Telecommunications take charge of transmission routes. The transmission routes may roughly be divided into two systems -- wire and wireless systems. Both systems are linked to each other and integrated to form a network of communication routes. The networks of transmission routes vary, depending on the substance, reliability, distance, number of routes, etc. For the composition of a network of transmission routes, the most economical and effective method fitted to the characteristics of each network of transmission routes is formulated.

In the days when telegraph and telephone lines played the leading role, aerial bare wires constituted most of the transmission routes for railway communication. In recent years, however, it has become indispensable to transmit, process and control information in order to assure the smooth management and increased safety of railway enterprises. Given this factor, there has been a sharp rise in the demand of transmission routes and there have arisen strong calls for an improvement of their quality and for a retaining of their credibility. Against this background, the bare wires which have intrinstic defects in the form of limited route capacities, induction hazards to communication by A.C. electrification and instability caused by disasters, meteorological conditions, etc., have been replaced by SHF radio system and coaxial cable carrier for long-distance transmission routes between the head and regional supervisory bureaus or central provincial institutions. For medium-range transmission routes between a regional supervisory bureau and work sites and between work sites, the use of cables has been stepped up. Due an improvement of the quality of transmission, data communication, centralized transffic control (CTC) and centralized substation control (CSC) systems which are not directly linked to various computers have been developed for the sophisticated transmission, processing and control of information.

Table 6-7 provides an outline of the frequency belts used by JNR's transmission facilities.

Table 6-7 Frequency Belts Used by Transmission Facilities

Type of electric wave	Frequency	Facilities used
SHF	3,000 MHz ∿ 30 GHz	Microwave route (7,500 MHz)
UHF	300 MHz ∿ 3,000 MHz	Train telephone, train crew's radio telephone (400 MHz)
VHF	30 MHz ∿ 300 MHz	Various types of liaison (150 MHz)
HF	3 MHz ∿ 30 MHz	Snow-plows (30 MHz)
MF	300 KHz ∿ 3 MHz	For maintenance of power transmission lines and for ships (2 MHz)
LF	30 KHz ∿ 300 KHz	Induction radio, cable transmission routes
VLF	3 KHz ∿ 30 KHz	Carrier circuit (bare wires and telegraph)
LF	300 Hz ∿ 3 KHz	Telephone wires, carrier telegraph (vocal)

6-2-2 Cable

The railway transport system is based on rails, along which a variety of facilities are installed, and there arises a need to assure a flow of information and liaison along them. For this, it is necessary to install wire routes along the rails. In the old days, bare wires were used primarily for this purpose. The bare communication wires are of such a structure that their electric characteristics tend to change greatly under the influence of meteorological conditions and to be affected by storms, snowfalls, lightning and other natural disasters and man-made happenings, such as robbery. Moreover, as their capacity is limited, virtually every bare wire has been replaced by a cable for modern railways, thus turning out to be museum pieces.

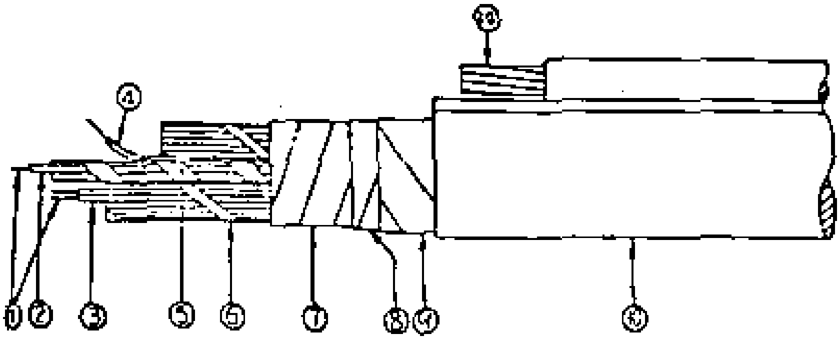
(1) What is the Cable?

Normally, the cable is a bundle in the shape of a rope in which a large number of thin cocentric wires, known as core wires, are insulated, twisted together and sheathed. For the communication cables, the core wires are standardized at 0.4, 0.65 and 0.9 mm in diameter. Other diameters include 0.32 mm, 1.2 mm, etc. For the signal cables, some are twisted with seven soft copper wires; some use soft copper wires as their core wires.

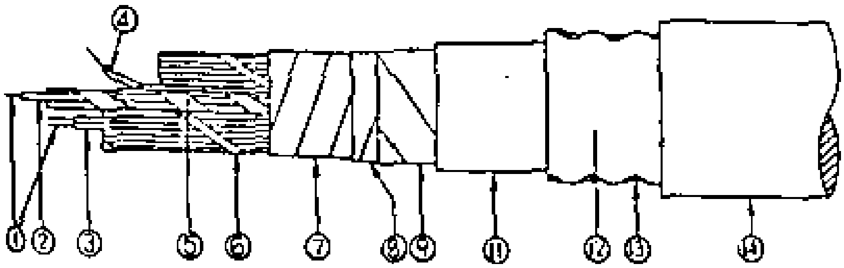
For the insulation of the core wire, it used to be a practice to use dry paper or vinyl, but at present, polyethylene (PE) or foaming polyethylene (PEF) is used. For PEF, fine air bubbles are contained in the inner part of PE and the characteristics of its transmission are improved. PEF is used as truck line cables, such as for carrier circuits.

For the protective sheathing of the consolidated core wires, it used to be a practice to use lead, but since 1955, it has become a practice to use polyethylene in most cases and vinyl in some cases. Nowadays, aluminum and Alpeth shearths are also used. When a cable is to be buried in the ground, it is sheathed with

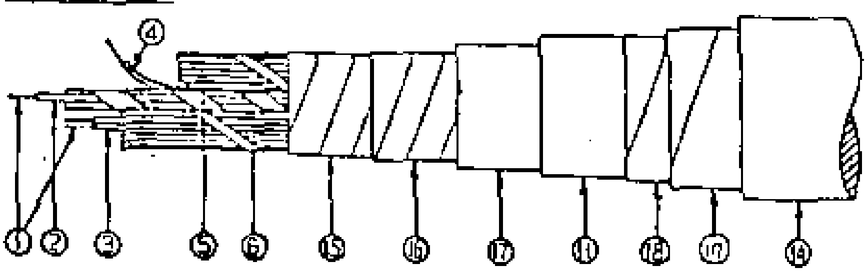
5S-type cable



Corrugated sheath cable



Aluminum sheath cable



No.	Appellation	No.		Appellation	
1	Conductor	12	Corrugated sheath cables	Corrugated sheath	
2	Insulator	13		Anticorrosion mixture	
3	Insulator	14		External sheath	
4	Pilot line	15	Aluminum sheath cables	Adiabatic layer	Insulating paper
5	Coarse binding tape	16			Metalled paper
6	Coarse binding tape	17		Aluminum sheath	
7	Wrapping tape	11		Internal sheath	
8	Shielding tape	18		Cloth tape	
9	Marker tape	19		Steel belt	
10	PE sheath	14		External sheath	
11	Corrugated internal sheath	20	Galvanized steel wire		

Fig. 6-17 Example of Cables Used by JNR

a steel belt, vinyl, PE or some other material for anti-corrosion and the prevention of external damage. For communication cables, two core wires are equally twisted at an appropriate pitch, or four core wires are equally twisted in the shape of stars and they are assembled in layers. Or unsheathed cables are suspended from catenary cables with hangers.

In sections electrified with A.C., an aerial suspension method is not used as aluminum-sheathed cables are used. In recent years, aluminum-corrugated cables have been developed, making it possible to use an aerial suspension method and strive to reduce the cost.

6-2-3 Carrier Communication

A communication cable is the most basic route of transmission but in general terms, the cable is composed only of a pair of core wires for a single circuit. Consequently, in case there is an increase in the volume of telephone communication, there is a need to increase the logarithm to a point where the demand may be satisfied, but it would cost an enormous amount of money to increase the number of medium- and long-distance routes. It would be extremely economical if a method with which a plurality of communication could be simultaneously with a single circuit. To satisfy this call, carrier communication and multiplex transmission techniques have been developed, and what has been perfected by such techniques is carrier technology.

(1) Carrier and Multiplex Transmission

In radio broadcast, sound waves are converted into storng and weak electric waves by means of microphones in the studios of each broadcasting station, but they cannot be broadcast as electric waves as they are. Given this factor, each broadcasting station carries (transmits) electric waves at a specific frequency to a receiver at each family. With the receiver, a necessary channel is selected and voices are reproduced.

In carrier communication, therefore, the high-frequency electromagnetic wave (carrier wave) which takes charge of the carrying is converted into a voice signal or other wave (or modulated) and transmitted, the signal components provided to the carrier wave are taken out on the side of a receiver (or recovered) and reproduced in voices and others.

As indicated in Fig. 6-18, A represents the frequency range (audio band) and is put to common use for cables. The ranges other than A are normally open. If they are used -- e.g., the signal wave which is the component of each unit of communication is put in the B, C and P frequency ranges in an orderly manner without being mixed with adjacent signal waves -- a plurality of signal waves may be transmitted by a single route.

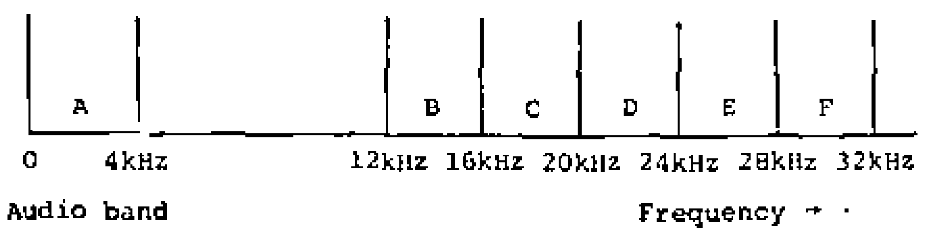


Fig. 6-18 Principles of Frequency Division Multiplex Transmission

The system in which such a plurality of independent signal waves are accumulated in a carrier route and at the same time a large number of signals are transmitted is called a multiple communication system. Of the multiple communication systems, the system in which independent signals are arrayed in terms of frequency and many signals are transmitted is called a frequency division system.

In order to use many circuits in a single carrier system, efforts are made to efficiently transmit signals in carrier routes in high frequency ranges. As a result, carrier cables, coaxial cables and microwave communication have been developed. On the basis of these developments, short-distance cable carrier telephony systems, coaxial carrier telephony systems, SHF systems, etc., have been developed.

(a) Carrier Telephony

The multiplex carrier telephone the installation of which is most popular at present is of the aforementioned system. This system uses cables, more than 0.9 mm in diameter, and is composed of 12 channels in a frequency range of 12 to 120 kHz. This system is also entirely solidified (transistorized). With a cable core wire of 0.9 mm in diameter, there is much decrement for such frequencies, so that a repeater is installed at every 12 km or so. When the distance exceeds 100 km, the distortion of the wave pattern becomes great and the S/N ratio worsens, so that the standard is confined with this distance. In Fig. 6-19, the composition of the system and the arrangement of frequencies are indicated.

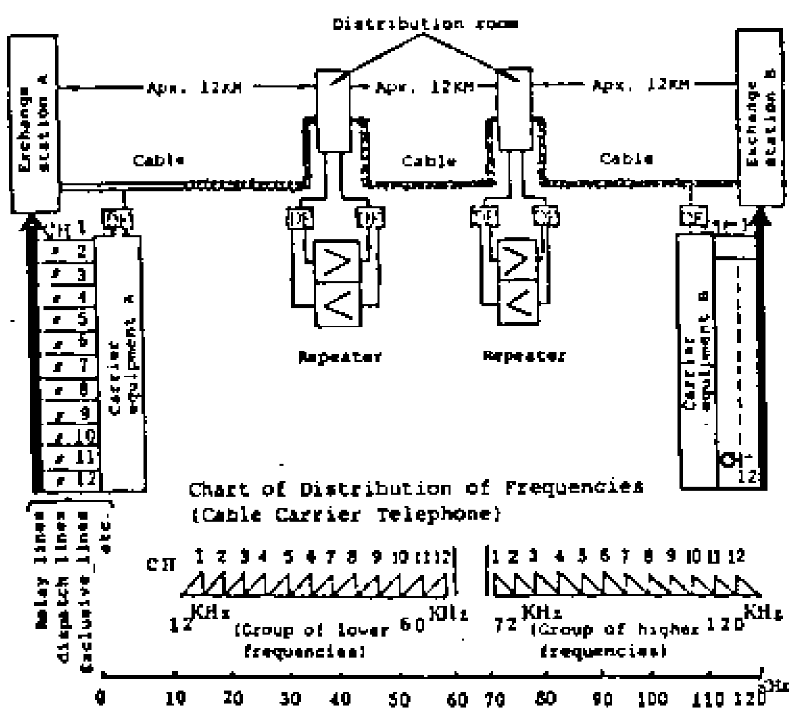


Fig. 6-19 Composition of Carrier System (FD) and Arrangement of Frequencies

In addition, there is a coaxial carrier system with large-capacity carrier circuits, making it possible to compose 960 channels in a carrier range of 60 ~ 4,000 kHz and setting the relay distance at about 3.8 km. For JNR's Shinkansen, CTC, CSC and various other information and control channels are accommodated in preparing a basic carrier route.

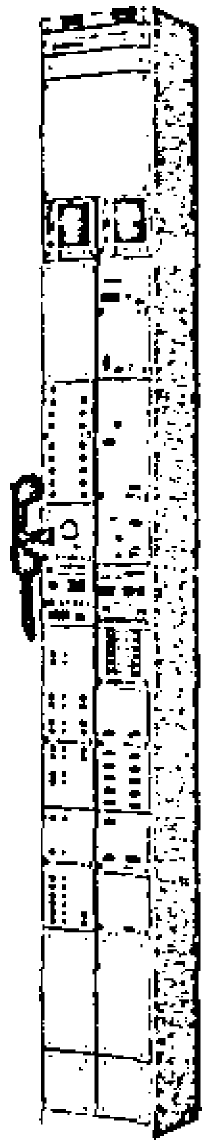


Fig. 6-20 Cable Carrier Terminal Equipment

(2) Carrier Telegraphy

As a means to transmit telegraphic signals, a cable is directly charged with the direct current for transmission at close distances. As the signal pattern is distorted in the case of long-distance transmission, a carrier wave with an appropriate frequency is modulated with telegraphic signals and sent out. The receiving side recovers it and reproduced telegraphic signals. This carrier telegraphy system is in use.

There are a variety of carrier telegraphy systems, but the principal ones include an amplitude modulation system (AM) in which the carrier wave is made intermittent with telegraphic signals and a frequency shift system (FS) in the carrier wave frequency is shift by the mark space of the telegraphic signal. The AM system is of the single-current type in which the carrier wave is made intermittent, whereas the FS system is of the metallic return-current type in which the carrier wave current with varied frequencies is used.

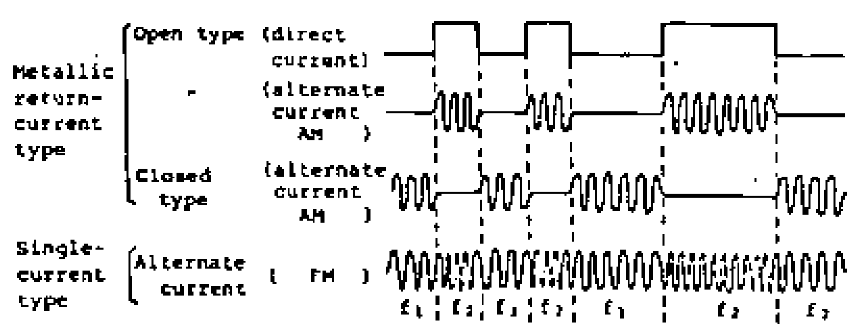


Fig. 6-21 Code Current Transmission System

For JNR, the FS system is mainly used for low-speed transmission in that no distortion is caused either by noise or level vibration. For the data transmission of more than 2,400 bits/sec, a phase modulation system is adopted.

JNR's FS systems come in two types -- a system for audio frequencies in which frequencies within the audio range (300 ∿ 3,400 Hz) are used as carrier waves and a system for super-audible frequency are used as carrier frequencies. For the former, a carrier or SHF telephone circuit is used and 6 or 12 telegraphic channels with a speed of 200 bits/sec are used. In the latter, up to six channels may be accumulated in a pair of cables but there are difficulties about the quality of the channels. In practically every case, the former system of audio frequencies is used.

6-2-4 SHF

As the modernization of transportation is in progress, it has become indispensable that transmission routes should be developed to cope with massive information and respond to calls for instant deliveries of information.

SHF is the highly reliable and stable transmission routes by which an adequate number of channels may be offered and which are high in transmission quality, proof against disasters and high stable. In JNR, the distance of about 2,000 km between Hokkaido (northern island) and Kyushu (southern island) is placed under this SHF systems. The SHF systems total about 6,500 km in aggregate length, forming part of the basis for a modernized railway today.

(1) Characteristics of SHF Communication

(a) Wide Transmission Band -- Multiplex Communication

The SHF system uses high frequencies of 3,000 ∿ 30,000 MHz. For transmission with 1,200 channels placed in this system, a frequency width of about 5 MHz is required. As this is 1/1,000 that of the basic frequency and therefore comparable to a frequency width of 0.001 MHz in terms of a 1 MHz belt of radio waves. The greater the basic frequency, the easier the broadening of the frequency width, thus making it possible to transmit much information. SHF for JNR's truck systems use a 7,500 MHz band and the section with the greatest capacity is 1,200 channels.

(b) Good Directivity of Antenna -- No Jamming

When the frequency is high, it is possible to come out with an antenna with a sharp directivity (travel of electric waves in a specific direction). JNR's parabolic antennas transmit parallel electric waves like a searchlight. This suggests that even if the same frequency is used at one and the same time, there will be no jamming as long as different routes are used for the electric waves. In JNR's SHF relay system, two frequencies are normally used on an alternate basis with a view to economizing electric waves.

(c) High Gains of Antenna -- with Small Transmission Output

The electric waves which are projected from a parabolic antenna beams in a narrow space, so that the gains are higher than those of the standard antenna. Therefore, the transmitter's output may be relatively small even for communication at long distances.

(d) Straight Projection of Electric Waves -- Transmission with High Reliability and Stability

In the SHF band, electric waves beam straight, so that they are restricted by the distance of an obstructed view. As the transmission is stable and highly reliable, it is possible to transmit them at long and medium distances with reflectors and repeated.

(e) Little Noise -- Excellent Channel Quality

In the SHF band, electric waves are little affected by natural and artificial noise and the good quality of circuits is assured.

(f) Invulnerable to Disasters

For a wire route, wires are stretched at long distance but the travel route is space for the SHF system. In addition, measures are taken against fires, storms, earthquakes, snow disasters, floods, etc., for the relay substations and reflectors under the SHF system.

(g) Low Construction and Maintenance Costs

An SHF system is composed of an extremely large number of channels, so that the cost per circuit is low, making this system economical. The only construction required for this system is that during which its relay stations are constructed. The construction period is shorter than that of a wire circuit.

(2) Outline of JNR SHF Communication

(a) Communication System

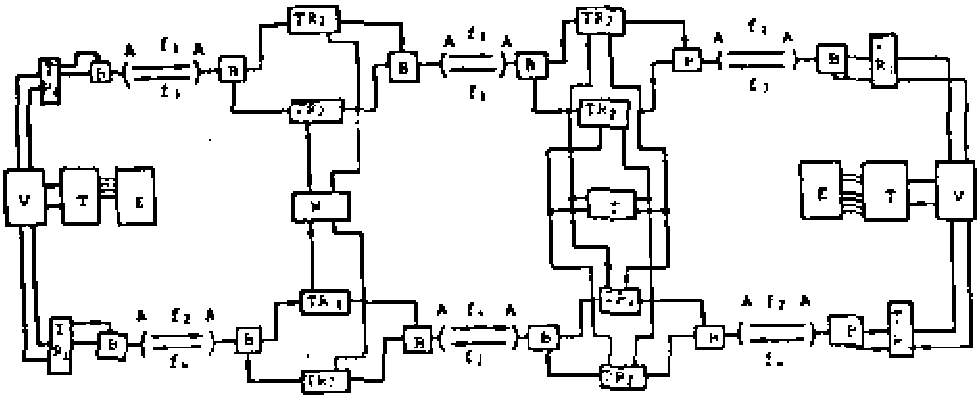
The SHF communication system for JNR's truck lines is known as an SS-FM system. In order to multiply many calls, the amplitude is modulated with different frequencies for each circuit. The group of frequencies thus produced is frequency-modulated with a radio transmitter and beamed as electric waves.

Then there is another frequency modulation system in which a number of circuits are arrayed in time under a puls code modulation system and then frequency-modulated. This is known as PCM-FM system and used for some sections.

(b) Spare Route and Set Systems

For the SHF route for a trunk line, a spare route system which may assure a high credibility is adopted. In the spare route system, indicated in Fig. 6-22, two sets of radio facilities with two different frequencies are installed -- one for one route and the other for two routes -- and the transmitters of both routes are in operation at all times. Here, either of the two routes is used by the receiving side. For this reason, two radio routes are in operation at all times and even when one route is put out of order due to some reason, the normal route may be automatically and instantaneously switched on the receiving side to assure the continuity of communication. This system therefore is highly credible.

A spare set system is installed in SHF sections other than those where the spare route system is in use. In the spare set system, as indicated in Fig. 6-23, only one route is installed but two radios are installed. If one radio has broken down, the other one is automatically switched on.



T : Terminal station equipment

V : Video combiner equipment

B : Branching device

W : Supervision rack

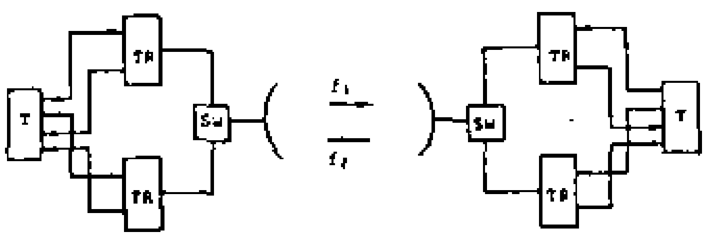
E : Relay and exchange system

TR_1 : Transmitter-receiver for detection and relay

TR_2 : Transmitter-receiver for Heterodyne relay

A : Antenna

Fig. 6-22 Comprehensive Systems Chart of Spare Route System



T : Terminal station's equipment

TR : Transmitter-receiver

SW : Wave guide switch

Fig. 6-23 Spare Set System

Nowadays, there are many cases in which the spare set system is preferred to the spare route system in the light of the improved reliability of the equipment and the allocation of electric wave frequencies. JNR makes it a practice to use the spare set system for new installations.

(c) Relay System

SHF features a long electric wavelength and is close in wavelength to light so that it takes on the character of straight propagation like electric waves. In order to establish a long-distance circuit, therefore, a relay station will be set up within a visible distance (30∿80 km) and the electric waves will be relayed from one such relay station to another to connect a place at a faraway place. At relay stations, such as supervisory and control stations, where many circuits have to be branched and places where circuits have to be branched to raise the coefficiency of use of the circuits, a video relay system is used. For other stations, a heterodyne relay system is employed. In case the visibility is obstructed by mountains, etc., as relay systems do not have to be introduced as the distance between relay stations is not long, a reflector plate is placed at a place from which both relay stations are visible for a non-feeding relay.

6-2-5 Digitalization

(1) What is the Digital?

The modernization of railway transportation is getting all the more brisk in conjunction with the sophistication of social activity. In this environment, there has appeared a phenomenon of reversal by circuit in which the conventional telephone system sustained by analogs is replaced by non-telephone communication, such as facsimile communication, data communication and control communication. There are signs of a further advance in the appearance of this phenomenon with the development of on-line computers.

On the other hand, the advance of semiconductor technology and digital signal processing technology, to say the least of LSIs, is remarkable, and it may be predicted that there will be rapid progress in the digitalization of transmission routes. Such signs are not confined to transmission routes and the digitalization of exchange and terminal equipment will make progress, shifting to the formation of a comprehensive digital network.

(2) Merits of Digital Communication

The merits of digital communication are as follows:

(a) Strong against induction noise and little effect from a level change.

(b) The costs for terminal equipment and repeaters are greatly reduced due to the introduction of LSIs.

(c) Stable and high quality of transmission. This particularly holds true in the quality of the transmission of data.

The PCM system is compared with the FDM system in Table 6-8.

Table 6-8 Comparison of PCM and FDM

Item of comparison	PCM system	FDM system
① Noise resistance	(1) As the pulse is reproduced and relayed, there is no multiplication of noise, distortion and leakage in the transmission route. (2) The S/N ratio of random noise in one relay section is good enough with 20 dB.	(1) The noise which interferes and mixes in the whole of a transmission route is all accumulated and appears as circuit noise at the final receiving end. (2) An S/N ratio of 65∿75 dB is required for one relay section.
② Cable used	City PE cable usable	Out-of-town PEF cable
③ Level modulation	As electric waves are reproduced, relayed and transmitted after they have been converted into pulse codes, the changes in the loss of the transmission route do not appear as level changes in the circuit. There are slight level changes in the terminal station's equipment (about 0.3 dB).	As level changes by the AGC function and those of the compressor and the terminal station's equipment are taken into account, it is necessary to set the S/N ratio at 2 dB.
④ Band of transmission frequency	(1) Maximum frequency: 1,544 MHz (2) Relay distance: Required at every 2∿3km for ϕ0.9 mm cables.	(1) Frequency band: 12∿120 kHz (2) Relay distance: Required at every 10∿13 km for ϕ0.9 mm cables.
⑤ Cost-effectiveness	Expensive wave filters are not used. Digital IC is fitted to mass-production.	Expensive wave filters are used both at terminal stations and for repeaters, limiting the reduction of the cost.
⑥ Flexibility of channel panel	There is one kind of channel panel. Interchangeable for all call channels.	Not interchangeable because filters with different frequencies are used for call channels.
⑦ Superiority in date transmission	As the transmission signals are pulses in terms of the quantity of digitals, massive information may be transmitted efficiently and highly qualitatively, depending on the data signal processing system.	In general, the transmission coefficient (capacity of transmission of data signals), albeit different depending on the speed and processing of the data signal, is less than 1/4 that of the PCM system.

(3) Digitalization at JNR

In JNR, there appeared a phenomenon of reversal in 1980 from telephones to data channels, control channels, etc., by type of channels. At present, practically every transmission route is of the FDM system which uses analogs and the circuit coefficiency cannot necessarily be described as favorable.

Given this factor, JNR, attaching improtance to the merits which are to be gained from digitalization, acts in concert with the trend of CCITT and NTT (Nippon Telegraph and Telephone Public Corporation) and intends to digitalize transmission routes, exchange equipment, etc.

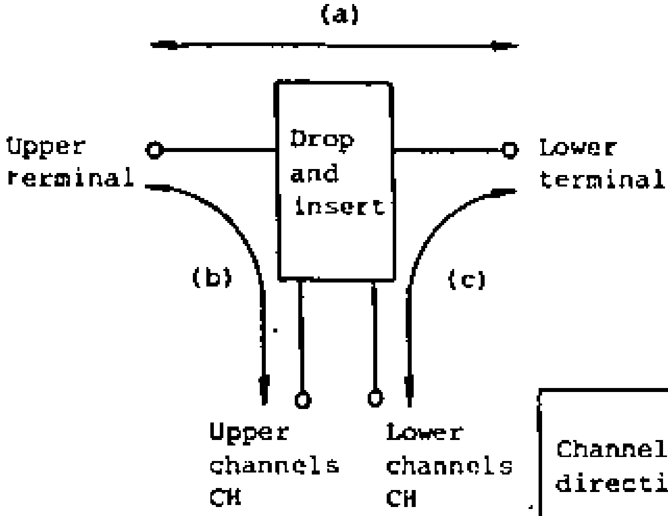
As regards the present digital PCM system, specifications are set for:

Wire system: PCM-24 (1.5 Mb/s, 24 CH)

Wireless system: 2 GHz PCM (1.5 Mb/s, 24 CH)
(1.5 Mb/s × 2, 48 CH)

The various problems posed for a shift from FDM to PCM are under study at present.

One characteristic feature of the PCM system for which specifications are set by JNR is that as transmission routes are prepared in parallel with railway tracks in railway communication, the drop and insert of transmission route is of merit. Drop insert, as indicated in Fig. 6-24, is a system in which only the necessary channels are branched and the electric waves are converted into voice signals and other channels are relayed in the form of digitals. In this system, Stations B and C adopt the drop and insert system as indicated in Fig. 6-25, and the transmission route may be constructed at low cost.



Channel direction	Max usable channels	
	$b_{max} = 18$ $c_{max} = 6$	$b_{max} = 12$ $c_{max} = 12$
(a)	24 - b	24-b(b or c)
(b)	$b < 18$	$b < 12$
(c)	$c < 6$	$c < 12$ $c < b$

Fig. 6-24 Combination of Drop and Insert Channels

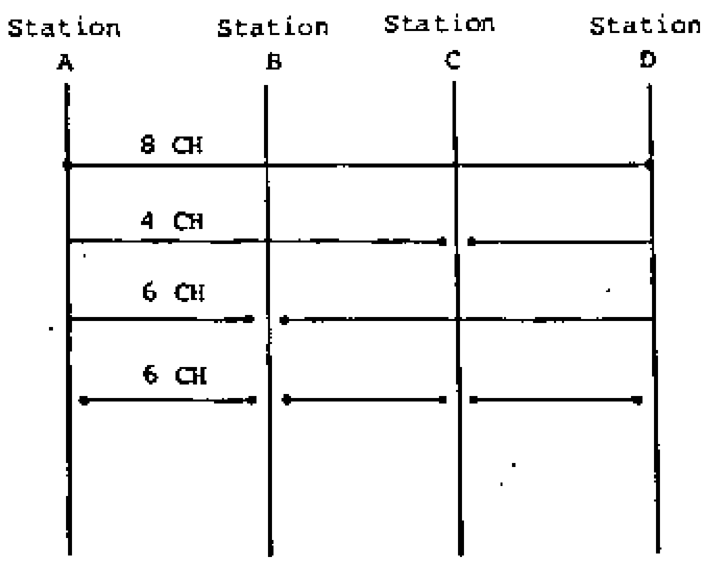


Fig. 6-25 Composition of Circuit in Drop and Insert System

6-3 Optical Fiber Communication

6-3-1 Optical Fiber Communication

Ten years or so have elapsed since the full-fledged research and development of optical communication with light as the medium was started.

In this system it is feasible to compose favorable communication circuits by taking advantage of the characteristics of optical fibers, such as broad band, low loss, non-induction, small diameter and light weight. For this reason, optical fiber communication has been developed to a point where it may be put to practical use not only in public telecommunications but in railway communication as well.

The use of the optical fiber communication system makes it possible to transmit picture images broad in band and data the quality of which must be high. Multiplex communication, be it large or small in quantity, is also possible in a flexible manner and transmission may be done at low cost.

Optical communication is expected to play a major role in the composition of cost-effective digital communication networks in future.

6-3-2 Development Laser and Optical Fiber

(1) Development of Laser

Light is a kind of electromagnetic wave. The light which is available in nature is a combination of electromagnetic waves the band of which is very broad and which does damped oscillation (Fig. 6-26). In 1960, however, Mainman of the United States succeeded in experimenting the oscillation of ruby laster. This laser, quite different from light available in nature, is coherent light in terms of space and time with a narrow frequency band like electromagnetic waves, such as microwave used in radio communication. In 1962, Nathan et al. succeeded in developing semiconductor laser which oscillated infrared pulses at 77[K]. Many improvements have since been made and semiconductor laser which continuously oscillates at room temperature with a life span of more than 10^5 hours has been developed. Semiconductor laser has many features. Compact and lightweight, it may be oscillated by small electric current and if this electric current is modulated by signals, the output light may be directly modulated. Semiconductor laser has become the principal optical source for optical fiber communication.

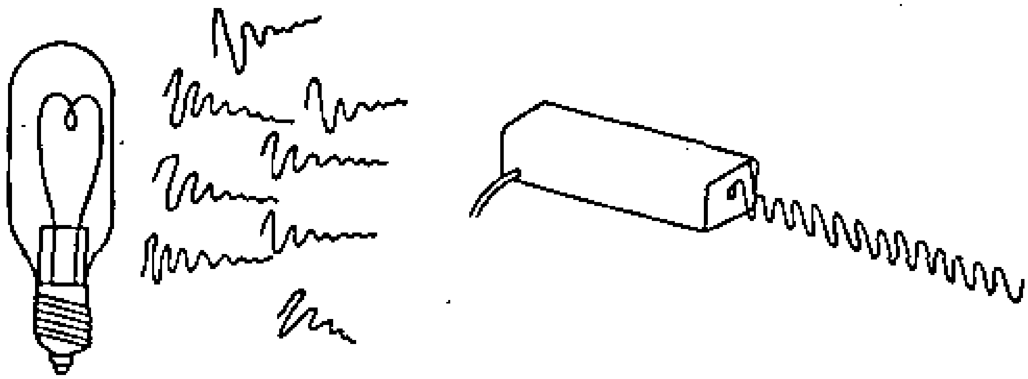


Fig. 6-26 Difference between Incoherent Light, Such as Natural Light, and Laser Light

Laser light has a frequency of several hundreds of thousands of GHz, that is, more than 10^4 times as big as the maximum frequency of several tens of GHz (milliwave band) of the electric wave used in communication at present, and has the potential of carrying information more than 10^4 times as much as that which is carried by the electric wave.

(2) Development of Light Fiber

Even laser light which has the above features is subject to dispersion and degradation in the atmosphere and cannot be transmitted as long in distance as the electric wave. Photoconductive wave routes with lenses had been under study but were not put to practical use as there are many difficulties.

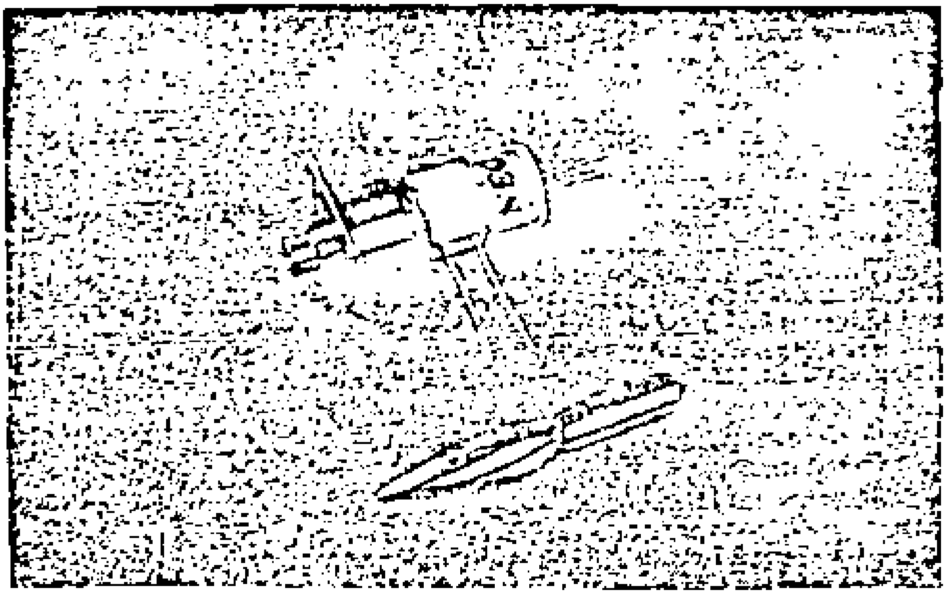


Fig. 6-27 Semiconductor Laser Element (Integrated with Optical Fiber Connector)

In 1970, Coning Company of the United States developed a low-loss quartz optical fiber with 20 dB/km, and there has been rapid progress in making optical fibers low in Loss. In Japan, a low-loss optical fiber with 0.22 dB/km, close to the theoretical limit, at a wavelength of 1.55 μm has been developed in Japan, becoming an assured transmission route for optical communication.

The optical fiber which has simplest construction is optical fiber of the step index (SI) type with a core of an evenly high refraction rate n_1 at the center and a clad of a low refraction rateing. In this, light is transmitted with a repetition of total reflection at the boundary between the core and the clad. One problem posed for optical fiber of the SI type is that the transmitted waves fall apart during the course of their transmission, as the light transmission speed varies between rays of light with different projection angles to the boundary surface or those in different transmission modes (mode dispersion).

In contrast optical fiber of the graded index (GI) type is such that by providing the refraction rate of the core with square distribution, the transmission speed is equalized for each mode to reduce the mode dispersion (Fig. 6-28 (b)). At present, optical fiber of the GI type is primarily used for optical communication.

In addition, optical fiber of the single mode type the core diameter of which is smaller (several μm) and which can be transmitted only in one mode has also been developed.

The low-loss optical fibers are primarily made of quartz. In addition, multi-component glass, plastic and their compounds are used.

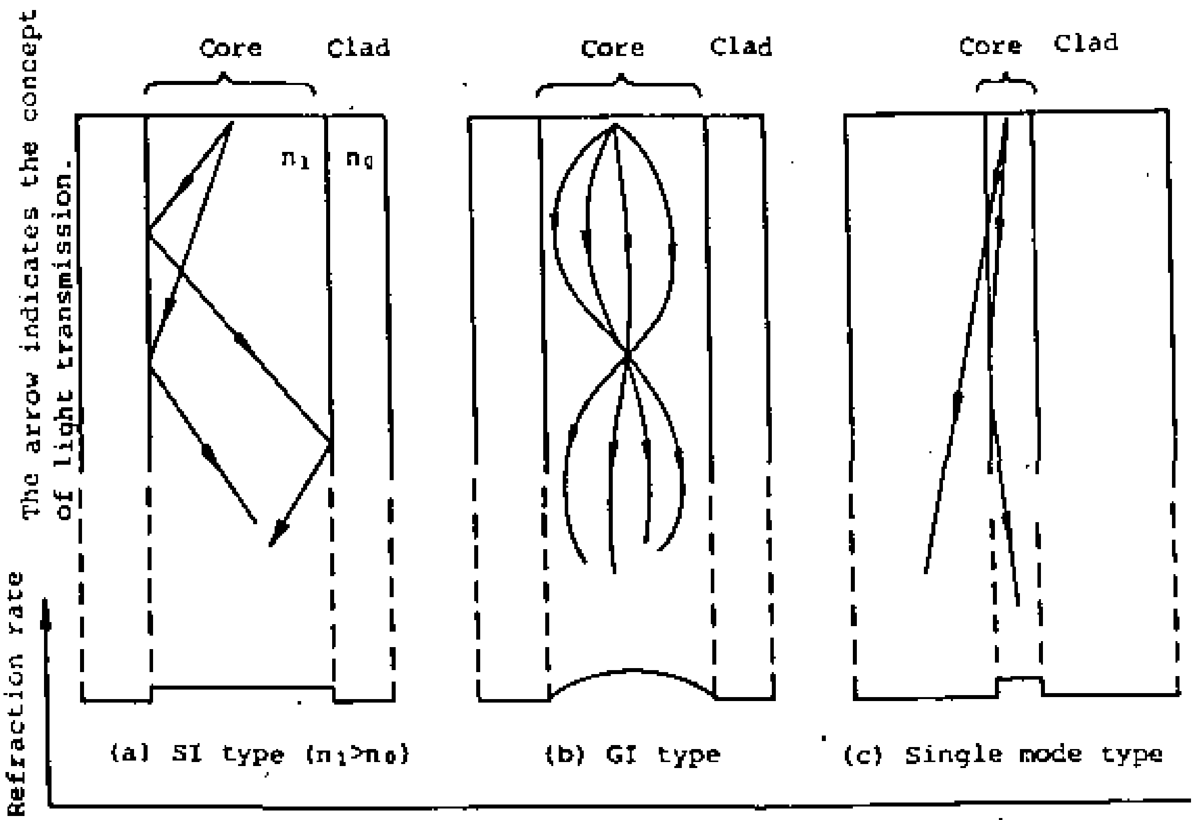


Fig. 6-28 Optical Fiber of Each Type

The clad diameter is 100 ∿ 200 μm.

The core diameter is 50 ∿ 100 μm for the SI and GI type and several μm for the single mode type.

A photograph of an optical fiber cable is given in Fig. 6-29 and a cross-sectional picture of optical fiber of the GI type is shown in Fig. 6-30.

Fig. 6-29 36-core Optical Fiber Cable

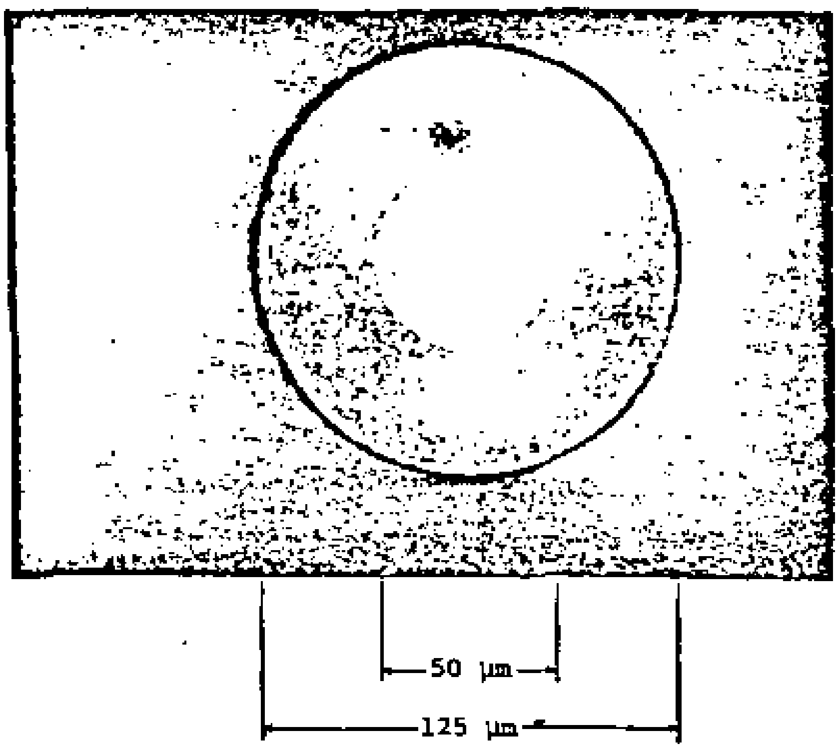


Fig. 6-30 Cross Section of GI-type Optical Fiber

6-3-3 Merits and Applicability of Optical Fiber Communication

(1) One Merit of Optical Fiber Communication is That Transmission Large in Capacity is Possible

Optical fiber communication features lower loses and larger capacities than the conventional coaxial cable communication. This is still under study, but if an optical multiple system is used at the same time, it will be possible to further enlarge the capacity. The specification of conventional coaxial cable communication and optical fiber communication are compared in Table 6-9.

Table 6-9 Comparison of Coaxial Cable Communication and Optical Fiber Communication

	Relay distance	Band width
Coaxial cable	5 km	12 MHz
Single-mode fiber + 1.55 μm LD	100 km	32 Mbit/S
GI-type fiber +0.8 ∿ 0.9 μm LD	10 km	100 Mbit/S

* Under study

This feature might be described as the primary reason why high hopes should be pinned on the future of optical fiber communication. Optical fiber communication is used for large-capacity communication at short and medium distances, such as public telephone circuits, TV signals and picture-image information, and for long-distance communication, such as seabed cable communication.

(2) The Optical Fiber Cables are Small in Diameter and Lightweight

The optical fibers are extremely thin or 100 ∿ 200 μm. That is why they are thinner and more lightweight than the coaxial cables. This feature makes it possible to do construction work with ease and in an economical manner and optical fibers are usable for the internal wiring of the machinery which have to be lightweight and for which the saving of space is mandatory, such as aircraft and ships.

(3) There is No Electromagnetic Induction Noise

For wiring along electric power transmission lines and electric railway lines and inside industrial plants, optical fibers are of advantage as they are not affected by induction. Particularly for railway communication, drops in the cost of the optical system would make it possible to make it non-metallic, as there is no need to come out with induction measures.

(4) There is No Cross-talk

With light used as the transmission medium, there is no electric cross-talk as is the case with metallic communication lines.

(5) Resource-saving

The materials are inexhaustively available and there is no danger that they will dry up, making it possible to produce low-cost optical fibers in the future.

(6) Proof against Water, Moisture and Heat

Optical fiber cables may be used in such an unfavoable environment which cannot be put up with by conventional copper wires.

Optical fiber communication with such a variety of features has also a variety of applications. To form economical and optimum systems in each field, there is a need to choose appropriate luminaries, light transmitting and receiving devices.

As luminous elements, light emitting diodes (LED) are used in addition to semiconductor laser (LD) to which reference has been made earlier. LED is a semiconductor which emits incoherent light but low in cost and long in life, being full usable for small- and medium-capacity communication at short and medium distances. As the linearity to the exciting current is favorable, optical fiber cables are fitted to the transmission of analogs, such as ITV, and also local communication of several kilometers, such as the terminal circuit of data communication.

Structurally, the optical fibers come in the SI, GI and single modes. The cost rises in this order. The single-mode fibers excel in bands and the GI-type fibers in non-relay transmission. The components include quartz, which features a low loss but is expensive, plastic the features of which are to the contrary, and multi-component glass which comes in between quartz and plastic. Then there are quartz core plastic-clad, multi-component glass core plastic-clad and other compound fibers, and each has its own features.

Low-cost Si-pin photodiodes and Si-APD which is somewhat costly but excels in senstivity and response speed are used as light intake elements in the 0.8 μm band. In the 1.3-1.6 μm band, the only light intake element which is usable at present is Ge-APD, which has such demerits as high cost, much dark current and poor moisture characteristics. At present, the development of devices with new materials is being briskly carrier out.

6-3-4 Optical Fiber Communication in JNR

The greatest merits which are gained from the use of optical fiber communication -- in which the characteristics of optical fibers are put to effective use and which are made up of routes higher in quality and efficiency than ever -- as railway comunication are: ① the loss is low and transmission may be made among several stations without a relay, ② its broad band may be put to effective use in forming systems for the transmission of surveillance picture images and for multiplex transmission, and ③ the routes which are not affected by electrification noise and impulse noise may be formed, as the optical fibers are not affected by induction noise.

JNR has the following concept for the sectors in which optical fiber communication systems may be used in the future while making full use of the above features.

(1) Extension of circuit for trunk transmission routes.

(2) Replacement of FDM carrier.

(3) Transmission of ITV and terminal circuit of data communication (local system)

(4) Long-distance transmission of TV (band compressing system)

The secondary PCM group (96 CH vocalized at 6.3 Mb/s) and the tertiary group (480 CH vocalized at 32 Mb/s) constitute the main part.

The secondary group (6.3 Mb/s) using the optical system is structurally shown in Fig. 6-31.

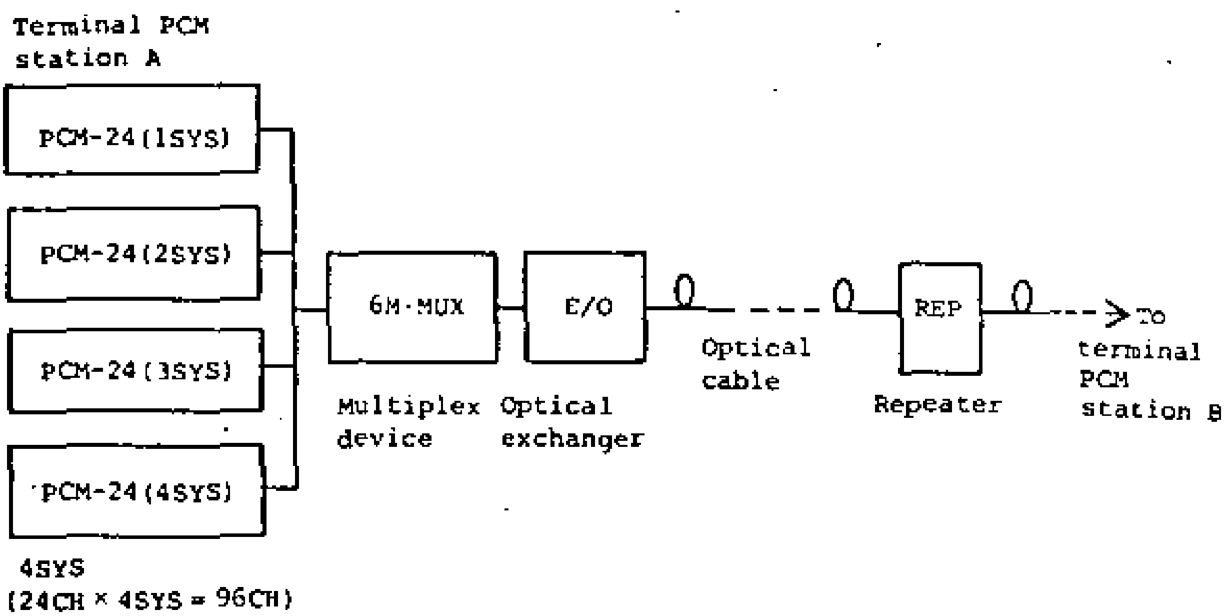


Fig. 6-31 Secondary Optical Group System

SEMINAR ON ELECTRIFICATION

June, 1982

JAPANESE NATIONAL RAILWAYS

JAPAN INTERNATIONAL COOPERATION AGENCY

CONTENTS

CHAPTER 7

PERFORMANCE OF AC ELECTRIC ROLLING STOCK AND RATING OF MAJOR EQUIPMENT

CHAPTER 7. PERFORMANCE OF AC ELECTRIC ROLLING STOCK AND RATING OF MAJOR EQUIPMENT

7-1 Basic Performance

7-1-1 Introduction

The overall performance of electric rolling stock is the synthesized result of various performances which are the bases of the operation of trains, such as traction performance, running performance (running safety), braking performance, and current collecting performance. In this section, the traction performance of electric rolling stock is described.

7-1-2 Traction Characteristics of Electric Rolling Stock

Force required for traction of trains is called tractive effort. The tractive effort usually varies with speed. The value of the tractive effort is determined by the speed-tractive-effort characteristics which depend on the prime mover of the rolling stock (traction motor) and by adhesive characteristics which depend on the friction between rails and wheels. The adhesive characteristics will be described in section 7-2. In this section, the traction performance will be explained.

In general, the traction motors and the wheels are directly linked by the gears in the electric rolling stock. Therefore the traction characteristics are determined by the characteristics of the traction motor. DC series motors are primarily used for the traction motors of the electric rolling stock, and the DC series motors will be described in this section. The same concept will be applied to other DC or AC motors.

(1) Characteristics of Traction Motors

The general equation of the characteristics of DC motors is

$$E=E_t - I\cdot R=\frac{P}{a}\cdot Z\cdot \phi\cdot \frac{n}{60}= K\cdot \phi\cdot n \qquad (1)$$

where E: Induced voltage (V)

E_t: Terminal voltage (V)

I: Armature current (A)

R: Internal resistance of motor (Ω)

P: Number of poles

a: Number of armature circuits

Z: Number of armature conductors

ϕ: Effective magnetic flux for each pole (Wb)

n: Number of revolutions per minute (rpm)

From the equation (1), the speed characteristic becomes

$$n=\frac{E}{K\cdot\phi} \quad (2)$$

Since the output of the motor is E·I (W), torque T (kg·m) becomes

$$T=0.976\cdot\frac{E\cdot I}{n}=0.976\cdot K_1\cdot\phi\cdot I=K_2\cdot\phi\cdot I \quad (3)$$

In the series motors, the armature current is equal to the field current, or there is a constant relationship between both currents. Therefore, there is a definite relationship between ϕ and I in above equation. The relationship is referred to as the so-called saturation characteristic and varies with such structures of the motors as the number of turns of field windings, field cores, and armature cores, and the like. In the range where the current value is small, ϕ is approximately proportional to I. If I is increased, ϕ is also increased but tends to saturate. For simplicity, it is supposed here that ϕ is proportional to I, and the equations (2) and (3) are transformed as follows

$$n=\frac{E}{K_1'\cdot I} \quad (4)$$

$$T=K_2'\cdot I^2 \quad (5)$$

The number of revolutions is proportional to the voltage and inversely proportional to the current. The torque T is proportional to the square of the current.

(2) Characteristics of Rolling Stock

Now let us consider the characteristics of the electric rolling stock on which this traction motor is mounted. The relationship of the rolling-stock speed V (km/h) and the tractive effort F (kg) on driving wheels with respect to the number of revolutions n of the traction motor and torque T are

$$V = \frac{60 \cdot \pi \cdot D \cdot n}{G} \times 10^{-3} \qquad (6)$$

$$F = \frac{2 \cdot G \cdot T \cdot N \cdot \eta}{D} \qquad (7)$$

where D: Diameter of driving wheel

G: Gear ratio in reduction gears

N: Number of motors

η: Transmission efficiency of gears

In this case, the gear ratio has a very large characteristic factor. With the same traction motor, if the gear ratio is large, low speed but a large tractive effort are obtained. On the contrary, if the gear ratio is small, high speed and a small tractive effort are obtained. The former is suitable for commuter trains and suburban trains in the case of electric cars, and for freight trains in the case of locomotives. The latter is suitable for express or limited-express trains or locomotives for passenger trains. However, on recent traction motors, wider weak field control is used. The weak field control correspond in principle to the change of gear ratio. Therefore some electric locomotives can be used both for passenger trains and freight trains without discrimination.

The output P (kW) of the rolling stock can be obtained by the following equation from the speed V (km/h) and the tractive effort F (kg) on the driving wheels:

$$P = \frac{V \cdot F}{0.367} \times 10^{-3} \qquad (8)$$

There are rated output, rated tractive force, and rated speed in the rolling stock. The rated output is the maximum output when the traction motor is operated at a specified (rated) voltage under a specified cooling condition (ventilation) for a specified number of hours (continuous or 1 hour; continuous in general) and the temperature does not exceed the specified temperature rising limit. The operations of electric rolling stock are not limited within this rated output, and the electric rolling stock can be used in a region exceeding the rated value for less than a specified number of hours.

An example of the speed-tractive effort characteristics in the actual operation of electric rolling stock is shown in Fig. 7-1.

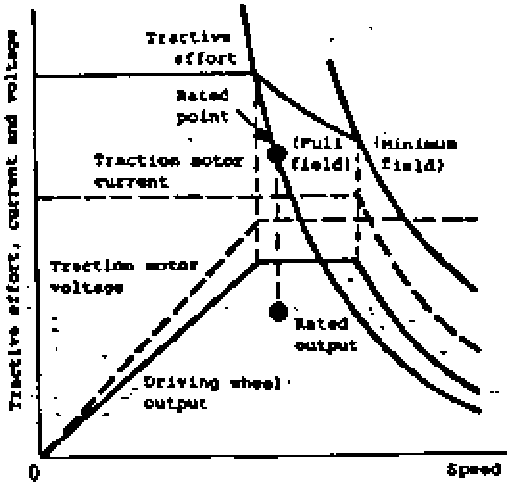


Fig. 7-1 An Example of Output Characteristics of Rolling Stock

At the start, acceleration is achieved at an approximately constant current within the limit of adhesive performance (therefore at an approximately constant tractive effort). At this time, the terminal voltage is increased in proportion to its speed. When the terminal voltage reaches its maximum level, it is usual to perform the weak-field control (in some rolling stocks the control apparatuses are not provided), with the voltage being kept constant. In general, since the field is weakened so that the armature current becomes constant, the input becomes constant, and the output region is also constant. That is, the tractive effort decreases in inverse proportion to the speed. There is a limitation in the weak field depending on the conditions of the commutation and the like in the traction motor, and the field ratio (ratio between the field current and the armature current) cannot be decreased below a specified value (minimum field). If the speed exceeds this value, the tractive effort rapidly decreases, and the output of the rolling stock also decreases.

Therefore, there is no direct relationship between the actual output and the rated output, and sometimes the former becomes nearly twice the latter. The limit of the output is determined by the adhesive performance, the overcurrent and overvoltage resistance of the traction motor, overspeed resistance, and the like.

Therefore, the excellence of rolling stock performance is dependent not only on the rated output but also on how broad the output characteristics are. Rolling stock which is provided with a large maximum output, a broad weak field region, and a high allowable maximum speed can be regarded as rolling stock having excellent performance. If the temperature rise of the traction motor is considered, it is advantageous to have rated tractive effort.

The traction performance of rolling stock is described above. As for trains, train resistance is added to the traction performance, and the accelerative force is then obtained. The train resistance comprises running resistance, grade resistance, and curve resistance. The difference between the tractive effort and the train resistance is the accelerative force. The accelerative force is sometimes called acceleration resistance.

The running resistance is resistance caused when the train runs on flat, straight rail track. The running resistance is mainly composed of rolling friction resistance between the wheels and the rails, friction resistance of bearings at various portions, and air resistance. The values of these resistances are different depending on the type of rolling stock, and experimental equations have been obtained through running tests. When the rolling stock is about to move, an especially large value is indicated. This is called starting resistance.

When the train runs on a gradient rail track, the train receives grade resistance which is the component of the weight of the train. This value is proportional to the value of the sine of the angle of gradient. The curve resistance varies with the radius of the curvature and the rail gauges, and its magnitude is inversely proportional to the radius of the curvature. In general, the curve resistance is small and does not pose a serious problem. However, it should be considered when the train has to start on a gradient rail track with continuous sharp curves.

The relationship between train resistance and speed is shown in Fig. 7-2. Tractive effort and train resistance are shown in Fig. 7-3. The portion wherein the tractive force exceeds the train resistance expresses the accelerative force.

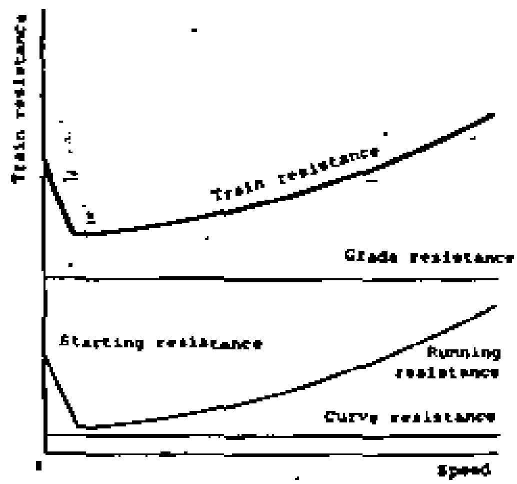


Fig. 7-2 Train Resistance Curves

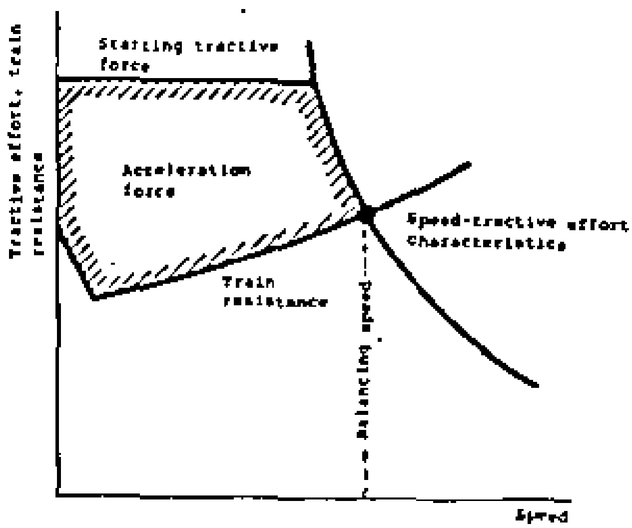


Fig. 7-3 Acceleration Force Curves

If the tractive effort is lower than the train resistance, deceleration occurs. As a matter of course, the tractive effort when the train starts should overcome the train resistance (varies with the weight of the trains and the gradient). It should be determined in due consideration of the conditions of the train district where used and the trains. The tractive effort at the start depends largely on the factor of adhesive performance which will be discussed below. The rolling stock performance is greatly affected by whether the adhesive performance is good or not.

7-2 Adhesion

The problems of adhesion can be divided into three; the problem of the coefficient of friction (coefficient of adhesion) between the rails and wheels, the problem of effective utilization of the coefficient of adhesion, and the problem of readhesion.

(1) Coefficient of Adhesion

The ratio between the maximum limit of the force of the driving wheels which can transmit power without slipping on the rails and the weight on the wheels is called the coefficient of adhesion (μ). An example of the coefficient of the friction measured on dry rails is shown in Fig. 7-4. The average value is 0.41 and standard deviation is about 0.048. When the rail

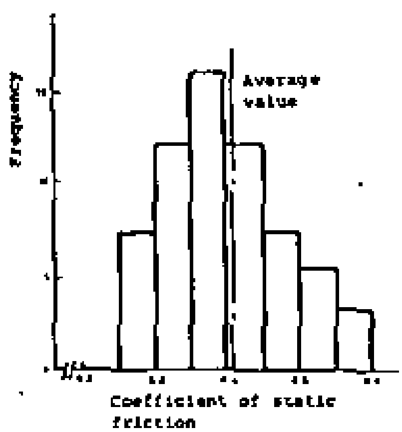


Fig. 7-4 Distribution of Coefficient of Static Friction

surface is wet, the value drop slightly. If oil is applied, the value drastically decreases. For actual rolling stock, since the boundary between the adhesive state and the slipping state is not clear and the weight of each axle varies, the coefficient of the adhesion as the rolling stock becomes apparent value. Furthermore, the coefficient of adhesion decreases with the speed. The cause is considered to be the effects of the variation in axle weight due to the up and down movement of the wheel and axle. The coefficient is considerably reduced by rain, frost, snow, corrosion, dirt, oil, etc. on rail surfaces. The coefficient of adhesion is increased by scattering sand on the rails. Measured examples of the speed characteristics of the coefficient of adhesion in Japan are shown in Fig. 7-5.

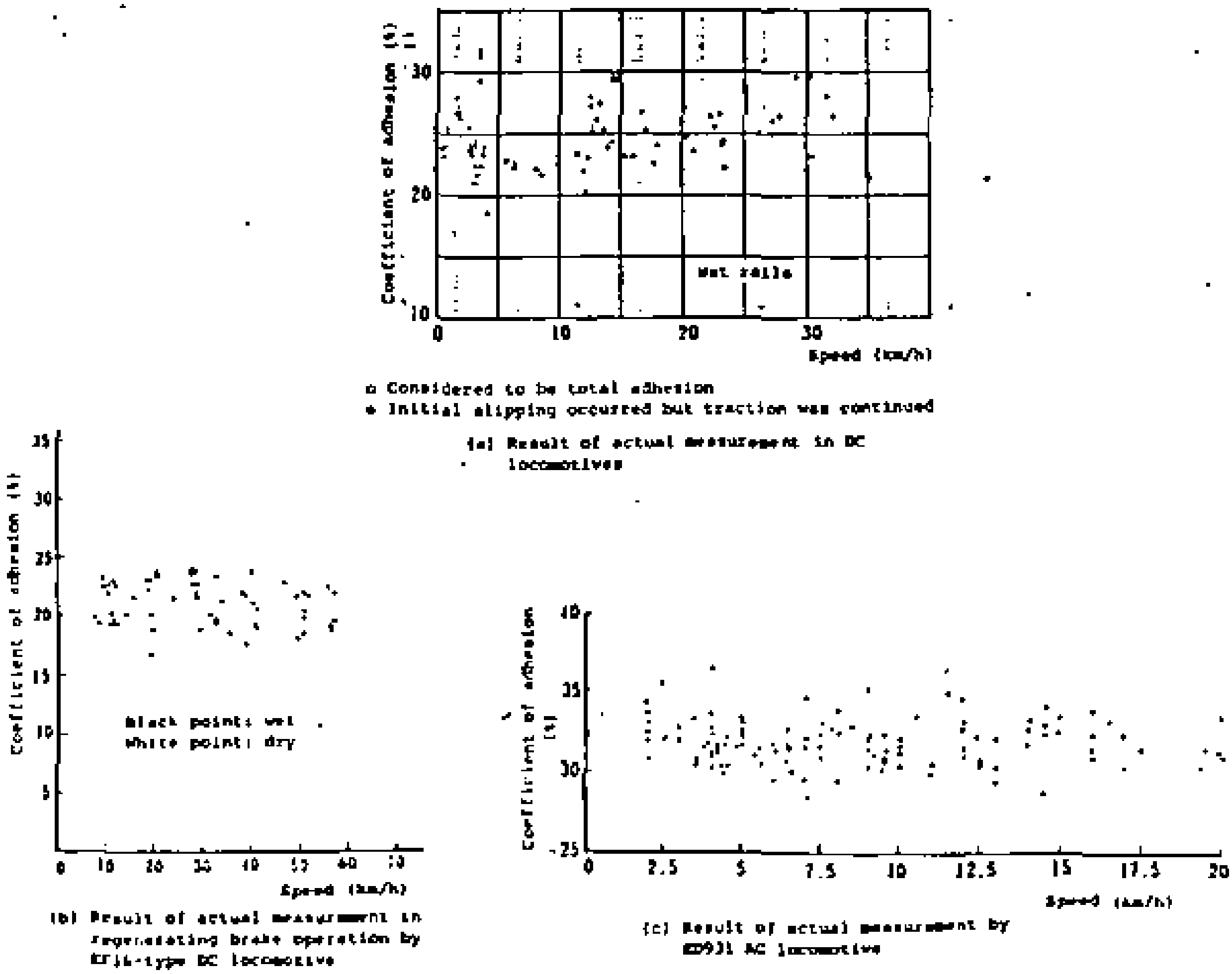


Fig. 7-5 Distribution of Coefficient of Adhesion and Speed Characteristics

When slipping occurs, sliding friction is caused, and the coefficient of friction rapidly decreases in opposition to the slipping speed. The coefficient of adhesion itself on the wet rails does not decrease very much. However, since the difference between the coefficient of adhesion and the coefficient of rolling friction is small, slipping is considered likely to occur. Measured examples of the coefficient of the rolling friction of AC electric locomotives in Japan are shown in Fig. 7-6.

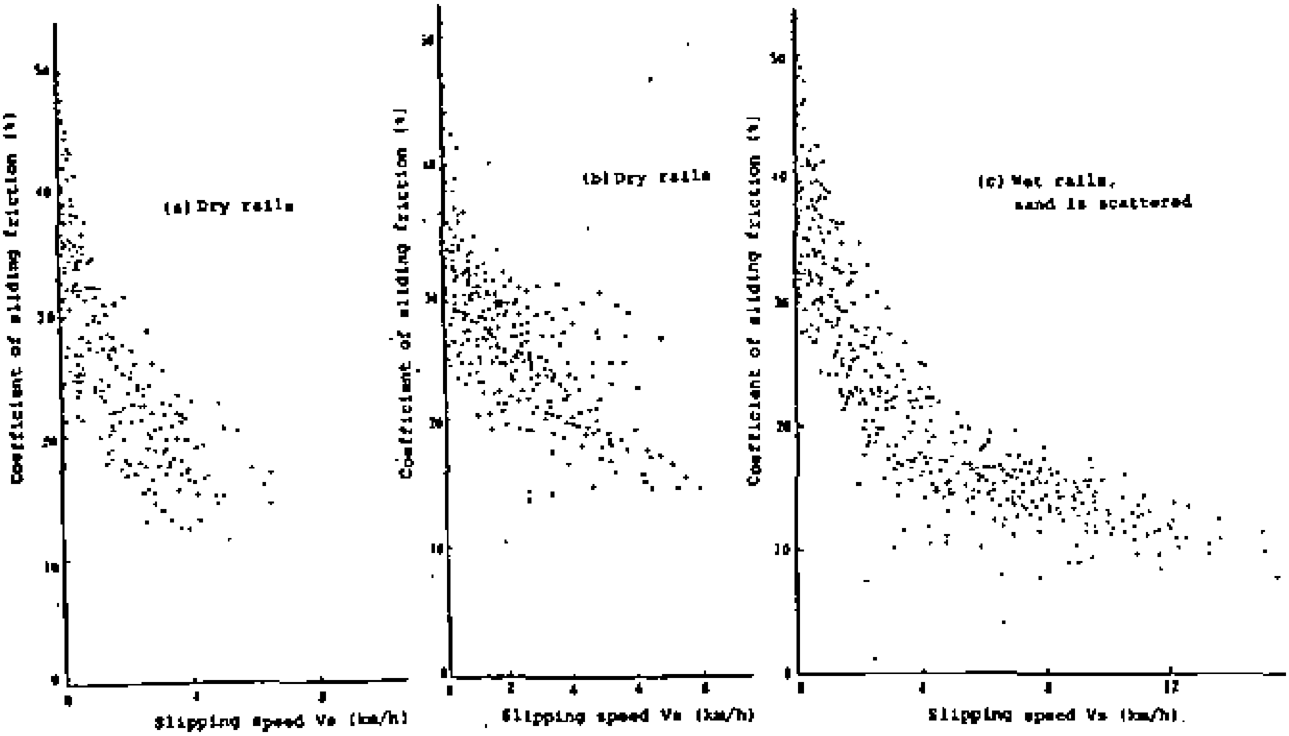


Fig. 7-6 Example of Actual Measurement of Coefficient of Sliding Friction (ED75)

(2) Effective Utilization of Coefficient of Adhesion

In order to obtain as large a tractive effort as possible, the following matters should be considered:

(a) Increase Axle Weight

Axle weight cannot be increased too much. Heavy axle weight would break the tracks. Axle weight is limited by the structure of rail tracks and bridges.

(b) Reduce Axle Weight Shift

At the time of starting, movement is caused by the traction force on the rail surface and the difference in the height of application points. Therefore the pressure of one axle applied on the rails, that is, the axle weight, is shifted. The shift of axle weight is reduced to a minimum by lowering the transmission surface of the traction force as low as possible or by improving the transmission mechanism. Or the amount of the shift of axle weight is compensated by changing the individual forces of the motors (changing the field ratio or the voltage) and the like.

(c) Scatter Sand on the Rail Surfaces

(d) Increase the Number of Control Stages of the Motors (or Provide Continuous Control)

The average tractive effort is brought near the limit of adhesion by increasing the number of the control stages.

(e) Increase the Readhesion Characteristic

As for slipping (sliding), once the wheel begins to slip, so-called sliding friction is caused, the slipping can not generally stop, and tractive effort disappears. When slipping occurs, it is important to have the wheels readhere as quickly as possible and to prevent the loss of tractive effort. Readhesion performance determines the value expected in the distribution of the coefficient of adhesion having broad dispersion. In the case of good readhesion performance, a high adhesion coefficient can be obtained. In DC electric cars which do not have readhesive function, a 0.15 adhesion coefficient is the limit which can be expected in the accelerating region. On the other hand, in AC locomotives wherein readhesion can be performed, a coefficient of 0.3 can be easily obtained.

As for the methods of readhesion, one method is to detect the slipping with a slipping sensor and forcibly accomplish readhesion by the use of sand scattering, notch returning, armature shunting, air brakes, and the like. The other method is natural readhesion by the use of circuit structure and selection of circuit constants. The AC locomotives have excellent readhesion characteristics because of the latter.

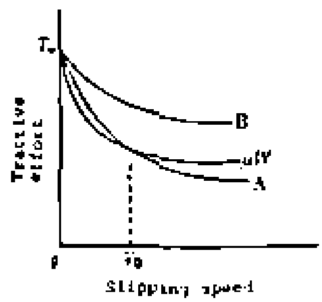


Fig. 7-7

In Fig. 7-7, the traction force becomes larger than the adhesion traction force μW, and the slipping is supposed to start at To in the figure. As the slipping speed increases, traction force decreases in accordance with the characteristics of tho motor as shown by curve A or curve B. While μW becomes the rolling friction with the slipping speed, the value of μ becomes small and changes as shown by a curve μW. If the characteristic of the motor is as shown in the curve B, the slipping is not stopped and dispersion occurs. In the case of the curve A, the balance is obtained at the slipping speed V_0, and the readhesion is accomplished. As shown in the Figure, however it is not best for the tractive effort to be in this lowered state, and it is expected that V_0 will become zero at the next chance. In the case of rheostatic control, or when the traction motors are connected in series, curve B is obtained, and the readhesion characteristics are not good. When the traction motors are all connected in parallel, and the voltage regulation at the terminals of the motor is small, the readhesion is readily performed as in curve A.

In AC locomotives and rectifier-type locomotives have better readhesive performance. They are provided with main smoothing reactors, and as a result the readhesive characteristics are improved. Fig. 7-8 shows the state of the readhesion. When a reactor is not provided, the curve is

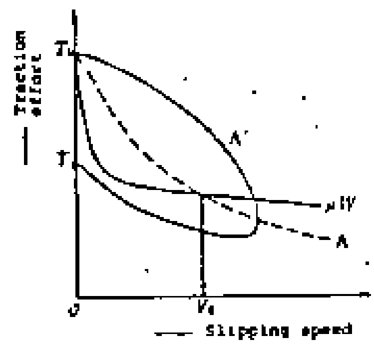


Fig. 7-8 Readhesion of AC Locomotives

described as broken line A. When a reactor is provided, the reduction in the current of the motor delays is as shown by curve A', and the slipping speed becomes larger than V_0, a loop is described in the direction of T_0 to A' to T_1, and the readhesion is completely accomplished. In this phenomenon, if the value of the reactor is small, the loop is small and convergence occurs at V_0. If the reactor is too large, the decrease in the current is delayed, and dispersion is caused. Therefore it is necessary to select a suitable reactor inductance.

7-3 Method of Determining the Rating of Important Equipment

7-3-1 Method of Determining Performance of Rolling Stock

The characteristics of electric rolling stock are described in section 7-1. Even though the weight of a train is given, the load of the electric rolling stock varies with the conditions of the railway tracks (gradient, speed limit, and the like) and the operational conditions. This load is peculiar and different from general industrial machines. Load conditions are intermittent, vary from time to time, and temporarily exceed the rating. If overload conditions exceeding the rating continue for a long time, the temperature in the windings and the like of main-circuit equipment such as traction motors and main transformers rise too much, the life of the equipment (especially insulators) will be drastically shortened, and the equipment will break. This means that the determination of the ratings of the important equipment of the electric rolling stock should not be made by the maximum load but by understanding the overall operating conditions.

The basis of the determination of the ratings is the temperature rise. The estimating calculation of the temperature rise can be best performed by a simulated run in the actual train district. However, the calculation is tremendously complicated and takes a lot of time. Therefore, the manual calculations have until recently been performed on a simple and short railway track which imitates the actual train district. However, since a method of simulating operations in the actual district by computer has been developed recently, it is usual for this method to be exclusively used.

A considerably accurate estimated calculation of the temperature rise in equipment can be performed through simulation. The root mean square (RMS) current serves as a yardstick in determining the temperature rise or rating of the apparatus and is convenient. The RMS current is a root mean square current expressed by

$$\text{RMS current} = \sqrt{\frac{1}{T} \int_0^T i^2 dt}$$

where T: time i: current

The temperature rise of the winding of the electrical equipment is proportional to the square of the current (in cases where the temperature rise of the equipment is supposed to be based on the copper loss), and the current that gives the equivalent temperature rise is the RMS current.

On the other hand, in determining the rating of the equipment, the thermal time constant of the temperature rise is an important factor together with RMS current. The thermal time constant is required in estimating the temperature rise at the overload in a short time. Especially, it is required in calculations for determining whether the rolling stock can be used in short-time overload when the rolling stock stops on a gradient and restarts. The thermal time constants of important electrical apparatuses are shown in Table 7-1.

Table 7-1 Thermal Time Constant of Main Electric Apparatuses

Apparatuses	Parts	Cooling method	Thermal time constant
Traction motor	Armature	Self-ventilation	20~40 min.
		Forced ventilation	15~20 min.
	Field	Self-ventilation	30~40 min.
		Forced ventilation	20~40 min.
Main transformer	Coil	Oil-circulating, air-cooled	3~6 min.
		Dry type, Air-cooled	10~20 min.
	Insulating oil	Oil-circulating, air-cooled	60~90 min.
Silicon rectifier	Between junction and base	Air-cooled	Several cycles
	Between base and the air	Air-cooled	Several seconds
Smoothing reactor	Coil	Forced ventilation	15~30 min.
		Self cooling	Several hours

In determining the actual rating, as shown in Fig. 7-9, the weight of the train and the railway-track conditions (gradient, speed limits, interval of stations, etc.) are given, the performance of electric rolling stock (rated speed, rated tractive effort, starting current, deceleration performance, etc.) is assumed, and the running simulation is programmed. In this way, the RMS current of the traction motor, the temperature rise in the major apparatuses, operating time, energy consumption, and the like are calculated. A sort of estimation can be made on the value of the rating for each apparatus. However, the values of the rated speed and the rated tractive effort of the rolling stock are not always the optimum values. Therefore, in general, the rated speed is changed (corresponding to the change in gear

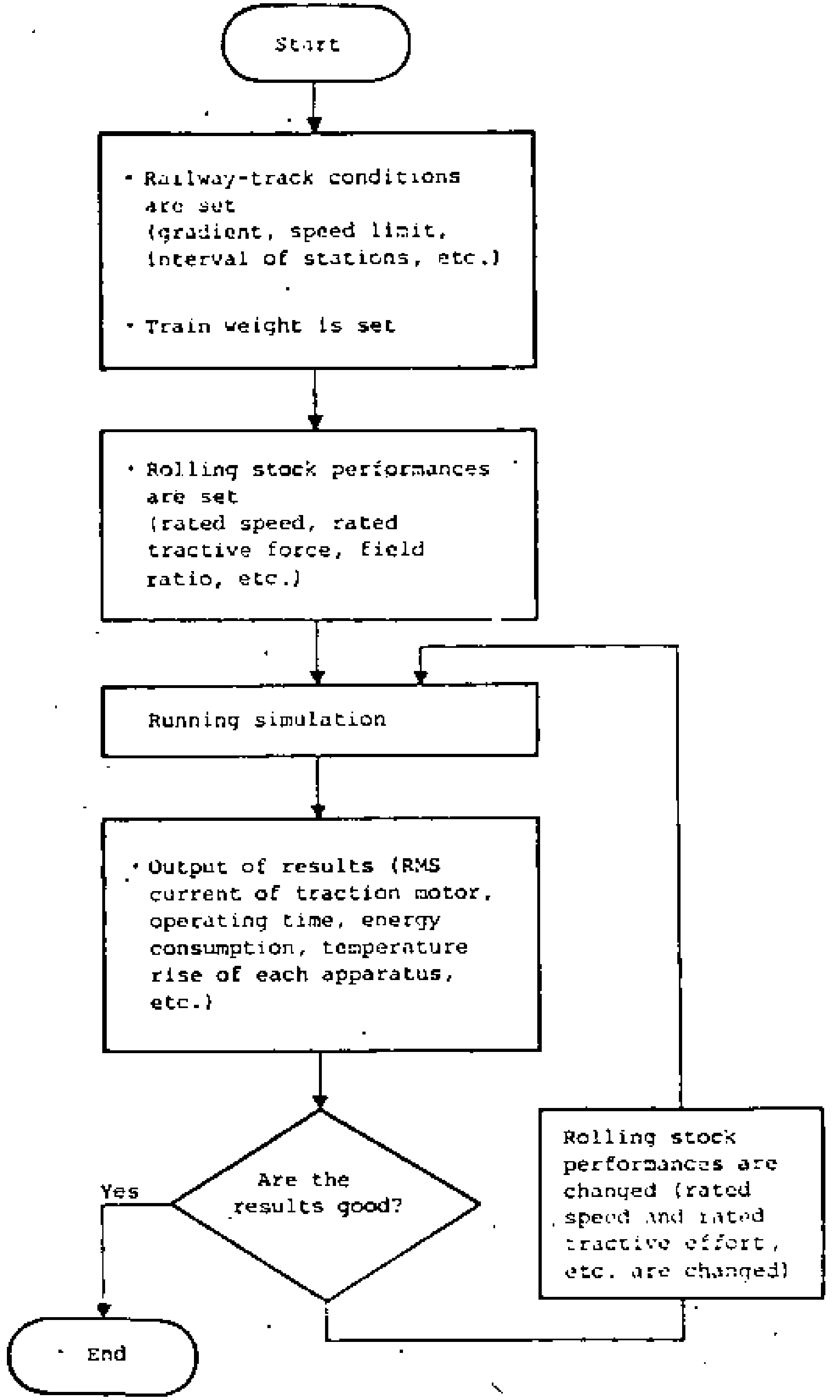


Fig. 7-9 Flow Chart on Determining the Rating

ratio of the driving gear), the simulation is further repeated, and the optimum performance of the rolling stock is determined. In Fig. 7-10, an example of the relationship between the RMS current (corresponding to output), the operating time and the rated speed when the rated speed is changed is plotted and illustrated. In this case, if the rated speed is increased, the operating time is shortened to some extent but is not shortened when the rated speed exceeds that point. Beyond that point, only the RMS current increases (the large-output apparatus is required). Therefore, it is understood that the there is a suitable rated speed.

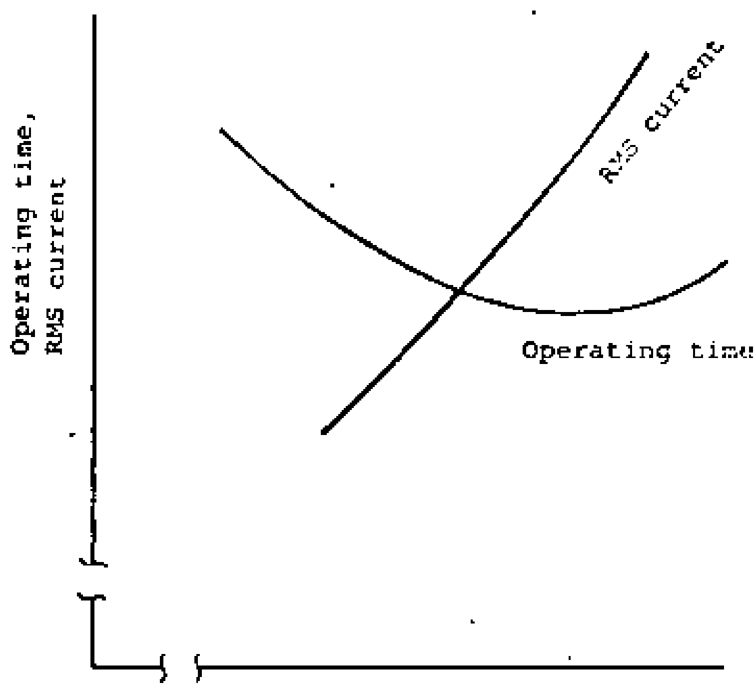


Fig. 7-10 Characteristic between RMS Current, Operating Time and Rated Speed

The rating is determined as described above. However, further consideration is required at the steepest gradient in the district, where the restarting should be made. In this case the temperature rise in equipment in a short time should be considered. A number of traction motors are provided in electric cars and locomotives, and one or several of them may be cut out. Therefore, it is necessary to consider the cut-out-operations of the motors.

7-3-2 Traction Motors

The characteristics of rolling stock depend on the characteristics of the traction motors. Even though the same traction motor is used, the characteristics of the rolling stock can be changed by changing the gear ratio of the driving gear. In general, if the gear ratio is increased, the traction force at low speeds is increased (in electric cars, the acceleration performance is improved), acceleration at high speed is reduced conversely, and the maximum speed is suppressed to a low level (due to the limitation in the maximum number of revolutions of the traction motor). If the gear ratio is made small, the high speed performance is improved but the traction force (rated traction force) at a low speed becomes small. The gear ratio, especially, when a one-stage reduction gear is used (depending on the module and the diameters), has limitations and cannot be increased infinitely. In ordinary locomotives, the gear ratio is 4 to 5.

The rating of the main motor is determined by the method described in 7-3-1 in the previous section. However, in the actual traction motor, the allowance wherein selection is made becomes broad depending on the diameter of the wheels employed and the gear ratio. It is important to determine the rating in consideration of the balance between the mechanical problems of the traction motor and the driving gear and the rectifying performance of the motor.

Furthermore, the thermal capacity in the armature of the series motor is generally different from that of the field of the motor. And if the rated current of the field is reduced (weak field rated motor), the motor becomes compact and light weight.

The limit of the temperature rise in the traction motor is determined by the life of the insulator. Even though an insulator of the same insulating class is used, the limit of the armature is different from that of the field. Since the armature is rotated, its temperature rise limit is smaller than that of the field winding. The limit of the temperature rise in accordance with the insulation class of the traction motor is shown in Table 7-2.

Table 7-2 Temperature Rise Limit of Traction Motors for Rolling Stock

(Unit: deg)

Class of Insulation / Components	Class B	Class F	Class H
Stator winding (resistance method)	130	155	180
Armature winding (resistance method)	120	140	160
Commutator (electrical thermometer method)	105		
Bearing (thermometer method)	55 (Bearing wherein grease with good heat-resistance is used) 40 (Other than above)		

7-3-3 Main Transformers

The rating of the main transformer is calculated by the method as shown in 7-3-1. At present, most of the main transformers are of an oil-circulating air-cooled type, and the thermal time constant is very large. It is necessary to determine the rating by further adding the loads of auxiliary machines to the RMS current of the traction motor.

The winding rating of the main transformer does not always coincide with that of the traction motor. In general, the rating of the main transformer is smaller. In the case of tap control, all secondary windings are not used at all times. In the case of phase control, the secondary-winding's current is changeable according to the control angle α. The rating can be reduced by the amount corresponding to the total thermal amount.

In the main transformers for the rolling stock, the rated current density of the winding is usually larger than that of general transformers. They are usually made of copper rather than iron. The temporary overload is included in the load of the rolling stock during the operation, and the difference in temperature between the winding and the cooling oil is large. Therefore, care should be taken in the partial temperature rise in each winding, and the temperature of the winding at the time of restarting should be considered. In addition to the rating especially with regard to the main transformer in locomotives, it is necessary to reduce the voltage regulation of the DC voltage on the traction motor side in order to improve the self-readhesion performance, and also it is necessary to reduce the leakage reactance and to improve the power factor characteristics. In order to reduce the inductive disturbance to the communication line, a large reactance is adopted. The problem of inductive disturbance is especially considerable in thyristor-type rolling stock. It is understood that inductive disturbance can be reduced by providing the multiple stages on the secondary side and selecting appropriate mutual reactance characteristics. Shell-type transformers are advantageous because reactance characteristics can be selected at will, and the many opposing surfaces between the high and low voltages can be provided.

Table 7-3 Temperature-Rise Limit of Control Apparatuses for Rolling Stock

Components		Temperature-rise limit (deg)	
		Resistance method	Thermometer method
Windings	Class A insulation	85	65 (85)
	Class E insulation	100	80 (100)
	Class B insulation	110	90 (110)
	Class F insulation	135	115 (135)
	Class H insulation	160	140 (160)
Point of contact	Main contactor	-	75
	Knife-edge contactor (automatic)	-	35
	Knife-edge contactor (externally controlled)	-	40
Terminal		-	60
Flexible conductor		90 (The adjacent portion should not be affected in a harmful way)	
Bare conductor and bare winding		The adjacent portion should not be affected in a harmful way	

Note: The temperature-rise limits for winding in parenthesis are applied to the large-current windings having a small number of turns such as blow-out windings and current windings.

7-3-4 Main Rectifiers

In recent rectifiers in rolling stock, silicon diodes and/or thyristors are used. Since the thermal capacities of these elements are very small, it is required in the rating design that the elements withstand maximum load current and that no fault occurs from the overcurrent at the time of short circuit (at the time of flashover of the traction motor). A load pattern under the severest conditions, which will actually occur corresponding to the adhesion limit or the maximum acceleration current, is established, and the rating is determined. An example is shown in Fig. 7-11. The actual rated current is ordinarily nominated in a simpler pattern in the form of continuous operations plus a 10-minute overload.

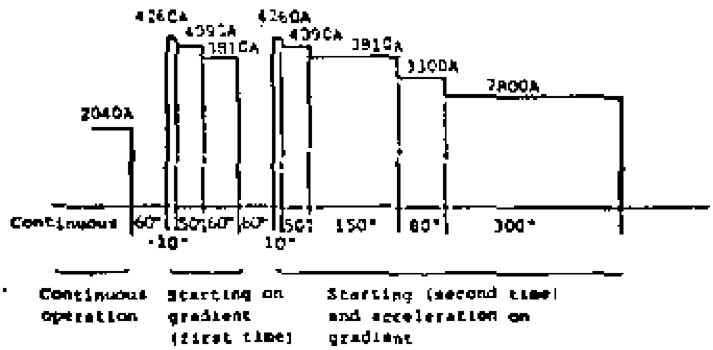


Fig. 7-11 Examples of Load Patterns of Rectifiers (ED75 series)

7-3-5 Rating of Main Smoothing Reactors

Here characteristics are similar to those of the traction motor. The temperature rise has the same tendency to change, but the thermal time constant of the open-core, forced-ventilation type reactor is smaller than that of traction motors. In order to improve reliability and maintenance, it is usual to add some allowance. As for the inductance characteristics, it is necessary to determine the characteristics from the pulsating current characteristics of the traction motor and the permissible limits of turning current on and off. In general, so as to get the hyperbolic inductive characteristics and constant ripple factor against the current, various air gaps are provided and/or magnetic paths are joined together in iron cores. Furthermore, it is necessary to consider the value of the inductance in order to improve the readhesion characteristics.

7-3-6 Others

With respect to other electrical equipment, for example, convertors in main circuits and switches, the current rating and the size of the electric wire are determined in the similar way as described in the determination of the above-mentioned apparatuses. It is especially important in determining the rating to know the thermal time constant of the equipment.

CHAPTER 8

MAIN CIRCUIT SYSTEM OF AC ELECTRIC ROLLING STOCK, ITS CONTROL AND CHARACTERISTICS

CHAPTER 8. MAIN CIRCUIT SYSTEM OF AC ELECTRIC ROLLING STOCK, ITS CONTROL AND CHARACTERISTICS

8-1 Main Circuit System, Control Method and Features

8-1-1 Main Circuit System

The control system of AC electric rolling stock is changing from the system of directly driving AC commutator motors with special frequency (16-2/3 Hz) (direct system) which was employed in Switzerland, Germany, etc. to the system of driving DC motors using rectifiers with a commercial frequency system (rectifier system). For the 16-2/3 Hz system, a rectifier system is mostly being used. This is mostly because a rectifier system can use DC motors of excellent performance and easy maintenance while the direct system requires substations to convert to special frequency, because there were disadvantages in the maintenance of commutator motors and because the rectifier system has better re-adhesion performance compared with the direct system and is more suitable for larger output capacity. Moreover, mercury arc rectifiers have now been replaced by silicon diodes and thyristors and their performance has been greatly improved.

For voltage control systems, there is a tap changing system which changes the tap of the main transformer and a system of controlling the phase with thyristors, etc. Also, systems are now being tested in which the commutator motor is driven by once converting to DC with a rectifier and then reversing to three phase alternating current with a thyristor invertor. Some of the representative systems are introduced below.

8-1-2 High Voltage Tap Control

The tap changing system has the advantages of no power loss, all parallel connection of traction motor and better re-adhesion performance. The system of taking out this tap from the primary winding side (high voltage side) of the main transformer is called the 'high voltage tap changing system'.

At the early stage of AC electrification of the Japanese National Railways, a high voltage tap changing system was mainly adopted for the following reasons:

(1) Although high voltage, the tap can be changed by breaking small current and there is little wear in the changeover switch due to arc.

(2) There is a greater number of windings on the high voltage side and more taps can be taken.

On the other hand, the primary high voltage tap changing system has the following weak points:

(3) For insulation, the changeover mechanism will become larger and it requires more time for changeover.

(4) The main transformer requires tap transformer and step-down transformer and it will be heavier and bulkier.

Although it has advantages and disadvantages as described above, in the case of the low voltage tap changing system, great wear of changeover switch due to large current occurs and it is unfit for large output. Therefore the high voltage tap changing system was adopted. The high voltage tap changing system is, for the reason of its construction as mentioned above, normally equipped with tap transformers and step-down transformers. As shown in Fig. 8-1, a tap is drawn from around the zone near input voltage of winding on the primary side to low voltage zone and it is stepped down to required voltage with a step-down transformer. Required voltage on the secondary side is determined by traction motor voltage and then because the locomotive'as parallel connection of all traction motors is generally selected to improve adhesion performance, voltage on the secondary side will be near the rated DC voltage of the traction motors.

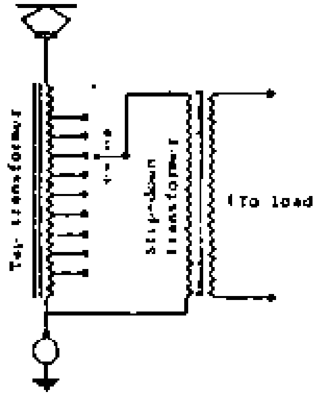


Fig. 8-1 , General System of High Voltage Tap Control

There are many ways to change taps without interrupting current but in the case of high voltage tap control, as line high voltage is impressed on the tap changer, insulation of control circuits and operating mechanisms, etc. becomes important.

For this reason, the changer becomes bulky and its operation slower. On the other hand, however, as the number of taps increases, a simpler changing system is used:

Fig. 8-2 shows an 'inchworm' advance system and fig. 8-3 an alternating advance stage system, both showing a figure of principle of mechanism. Both change taps by moving sliding elements (brushes or rollers) on a series of conductive segments connected to the taps. Closing/breaking of current is done with a changeover switch interlocked with shifting of the sliding element and a control sequence which does not generate arc is required between the segment and the sliding element. Only 2 changeover switches are required for the inchworm advance stage and its construction is simple. But high accuracy is required for installing the switches between the segment and the sliding element and there is the disadvantage that sufficient clearance cannot be provided between the segments for insulation. In order to eliminate this disadvantage, there are methods such as shifting the sliding element independently like an inchworm only when passing over the segments.

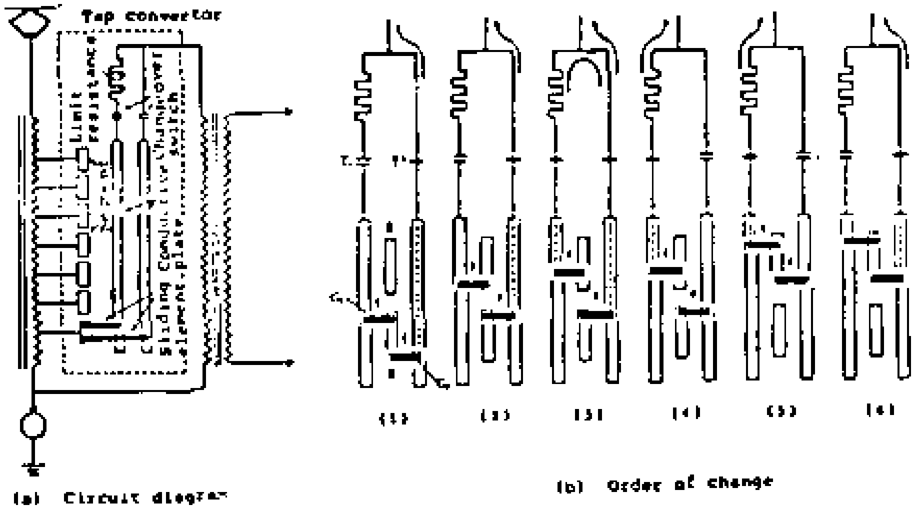


Fig. 8-2 Principle of High Tap Changing (Inchworm Progression)

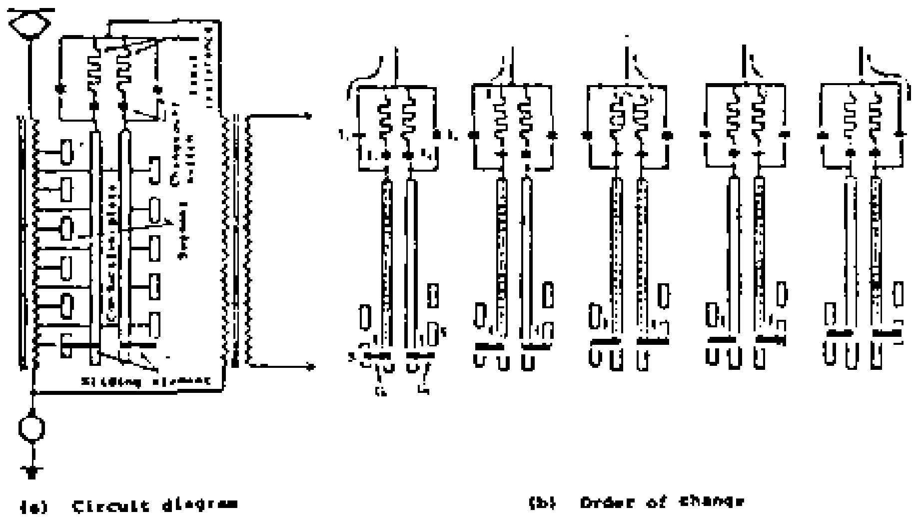


Fig. 8-3 Theory of High Voltage Tap Changing (alternating progression)

For the alternating advance stage system, a series of segments is arranged separately for odd stages and even stages and the sliding segment is shifted, so not much accuracy is required for installation and there is a sufficient clearance between segments for insulation. Four changeover switches become necessary, however, which makes the system heavier and bulkier.

For either of the above systems, current limit resistance is required to control the short circuit current, because the current between taps is temporarily short-circuited. If its performance is not adequate, a current limiting reactor may be used. Since the system using the current limiting reactor has disadvantages in weight, size and price and the breaking load of the changeover switch becomes severe, however, there is little merit in using the system except for such special purposes as obtaining intermediate voltage between taps.

For simplifying the maintenance of changeover switches, there are methods such as using vacuum switches with high breaking performance and thyristors, etc. Before resorting to these methods, arcless tap changing of low voltage tap changing system has been put into practical use and the low voltage tap changing system with higher re-adhesion performance has been adopted.

8-1-3 Low Voltage Tap Control

The low voltage tap changing system has the following advantages:

(1) Main transformer is compact and light weight.

(2) The tap changer may comprise a cam/shaft control unit and unit switch, etc.,

while it has the following disadvantages:

(3) It has large control current. In the case of arc breaking, as the maximum current is limited by the breaking performance of changeover switch, it is not suitable for large output.

(4) There is a limit to taking out a great number of taps of low-voltage large current from the winding on the secondary side and a small number of taps can be taken out.

When using the system for electric cars, it does not require much overall output and the traction motor can be used in series connection, so practical application is made possible when an insufficient number of taps is supplemented by some measures.

Fig. 8-4 shows so called cumulative/differential movement system. The secondary winding of main transformer consists of tap winding and base winding and by changing to negative polarity (differential) or positive polarity (cumulative) with combination switches K_1, K_2, the apparent number of taps can be doubled. Moreover, as the intermediate voltage between taps can be obtained with a limiting current reactor with intermediate taps, the number of tap stages are redoubled. Thus a 25 stage notch curve is obtained by voltage differentials between the 6-stage taps and both windings. This system is used for the old-type of Shinkansen electric cars of the Japanese National Railways.

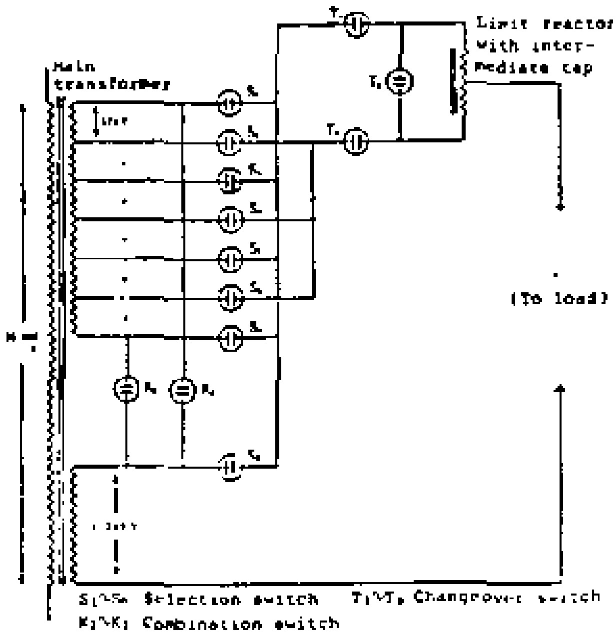


Fig. 8-4 Low Voltage Tap Control (Cumulative/Differential Type)

The cumulative/differential movement system when used for locomotives is disadvantageous with regard to re-adhesion performance. The cumulative/differential movement system is a low voltage tap used for pulling out trains and most of the secondary windings are arranged in series and then reactance of the main transformer becomes largest and the regulation of DC voltage becomes large. When the voltage regulation is large, DC current greatly increases when slipping and this adds to further slipping which is not desirable for practical application.

To improve re-adhesion performance when pulling out trains, it is necessary to reduce voltage regulation at low speeds or reactance of main transformer at low voltage tap. For this, a system such as that shown in Fig. 8-5 which simply takes out taps from the secondary winding side is desirable. However, as mentioned before, such a low voltage changing system has an insufficient number of taps. Fig. 8-6 shows a system where the tap changing system is replaced by thyristors and the changeover switch is turned to arcless changing and where continued control between the taps is made possible by adopting phase control between the taps of the thyristors. This system consecutively turns on and off S switches on an even series and odd series just as alternating advance stage of high voltage tap changing, and intermediate voltage is obtained by dividing voltage between taps as required and giving phase angle order to thyristors.

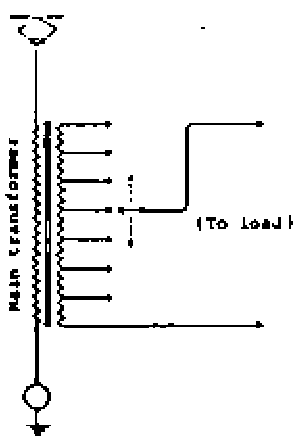
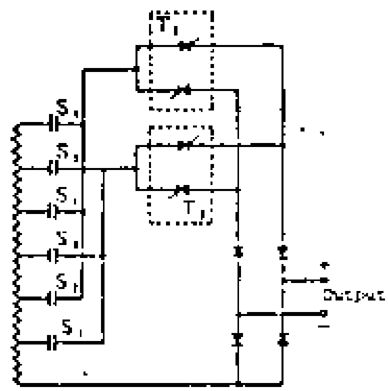


Fig. 8-5 General System of Low Voltage Tap Control



Sequence	S1	S2	S3	T1	T2	Output voltage
1 (Control)	O			180°→0°	off	
2 (Changeover)	O	O		0°	off	
3 (Control)	O	O		0°	180°→0°	
4 (Changeover)		O	O	off	0°	
5 (Control)		O	O	180°→0°	0°	

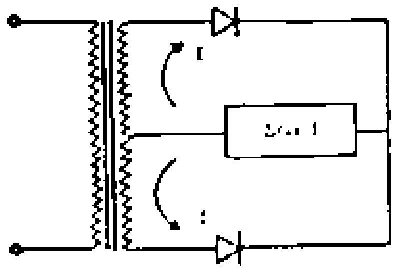
Fig. 8-6 Arcless Tap Changing for Both Continuous Voltage Control

The advantages of this system are that arcless tap changing can be done, the reactance of the main transformer is small at low speeds and has good re-adhesion performance, and the price is cheap because the thyristor has good voltage resistance between the taps. It also has a better power factor and few harmonics compared with all stage thyristor phase controls system which will be discussed below. The system was made possible by the development of a thyristor and the thyristor part could be substituted for the magnetic amplifier. The Japanese National Railways first used magnetic amplifier system before the advent of thyristors and then changed to the thyristor system. This system can be called a completed form as control system of taps and is used in representative AC electric locomotives, ED75 and 76 model, of the Japanese National Railways.

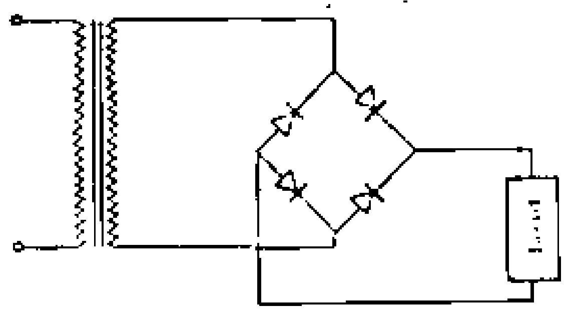
8-1-4 Phase Control with Thyristors

When a thyristor for electrical power was developed for practical application, 'the thyristor phase control system' which controls the total DC voltage with thyristor convertor was put into practical use.

In the case of mercury arc rectifiers, the rectifier system used was single-way system (push-pull connection), but when diodes and thyristors come to be used, the double-way system (bridge connection) was adopted. The rectifier bridge comprising thyristor and diode is called 'Hybrid bridge' and the one comprising only thyristor is called 'thyristor bridge'. The hybrid bridge is used for AC electric rolling stock requiring only voltage control when powering and thyristor bridge is used for electric rolling stock using AC regenerative brakes which is also capable of invertor operation of convertor. The thyristor control system has the following characteristics.



(a) Single way



(b) Double way

Fig. 8-7 Single Way and Double Way

(1) There is no contactor such as tap changer and maintenance and inspection will be easier.

(2) Full notchless control will bring about smooth acceleration performance and high adhesion characteristic.

(3) The thyristor phase control system can reduce reactance of the main transformer and improve re-adhesion performance of the locomotive. When automatic fixed voltage restriction (AVR) is used.to maintain fixed DC voltage against current, re-adhesion performance is further improved.

(4) The equipment can be made compact and light weight.
When phase control is made, there arise the following problems with voltage and current waveform compared with the case of simple diode convertor:

(5) Power factor will decrease.

(6) Deflection of AC current and voltage waveform becomes greater and impediment by high harmonics will increase.

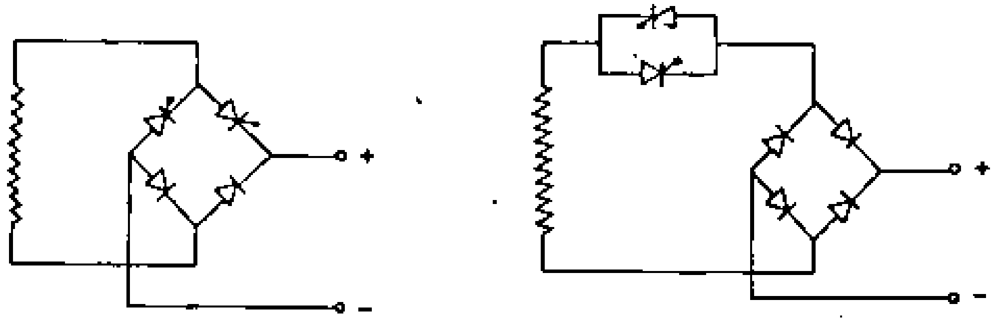
These problems will be corrected by the following methods.

(7) Divide the windings on the secondary side of the main transformer into several sections and connect in series. (cascade connection)

(8) Improve overall voltage and current waveform and phase relations by devising control systems such as asymmetrical control, phase stop control and fixed width control, etc.

(9) Connect resonant filter to high harmonics and absorb certain higher harmonics.

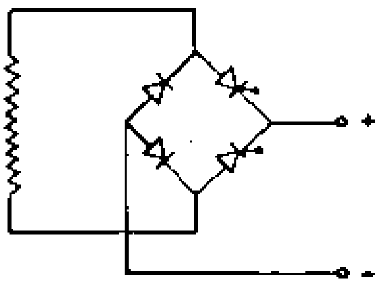
The aforementioned 'arcless tap changing system' is similar to multi-stage connection in series corresponding to several steps of taps and improves problems of the aforementioned thyristor control rolling stock. Fig. 8-8 a) ∿ d) show representative main circuit system which controls thyristor phase.

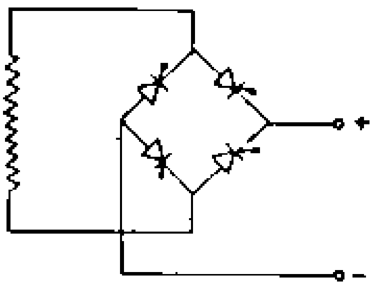


(a) Hybrid bridge (Symmetrical on AC side)

(b) Hybrid bridge (Inverted parallel thyristor on AC side)

Fig. 8-8 Various Systems of Thyristor Phase Control (1)





(c) Hybrid bridge
(Symmetrical on DC side)

(d) Thyristor bridge

Fig. 8-8 Various Systems of Thyristor Phase Control (2)

Symmetrical connection of AC side of a) is a most representative mixed bridge and has the possibility of decreasing the number of diode series compared with the system of b) but it requires a protective fuse since the AC side is short-circuited when the thyristor breaks down.

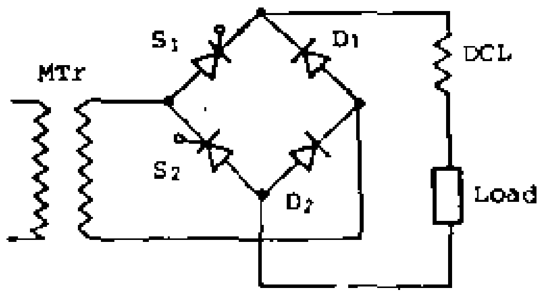
Reverse parallel connection of thyristor on AC side of b) may increase the number of diodes compared with the system of a) but when thyristor breaks down, short-circuti current does not flow and a protective fuse is not required.

Symmetrical connection on the DC side of c) shows the commutation failure phenomenon when a thyristor to be ignited misfires, so it is necessary to install a bypass diode separately or install limit which will not choke the phase angle too much.

The system of c) requires only half the number of diodes compared with systems a) and b) but because of the aforementioned problems, it is not used for rolling stock.

Fig. 8-9 shows the form of current carriage on the hybrid bridge.

Fig. 8-8 d) shows a thyristor bridge. Fig. 8-10 shows the form of current carriage on the thyristor bridge. The figure shows a system which simultaneously ignites thyristors on opposite sides and is called 'symmetrical control', while a system which ignites each thyristor separately is called 'asymmetrical control'. Fig. 8-11 shows the form of current carriage of asymmetrical control.



(a)

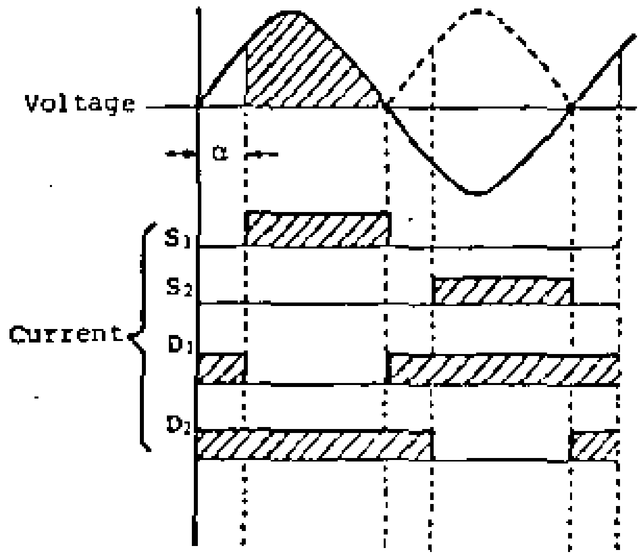
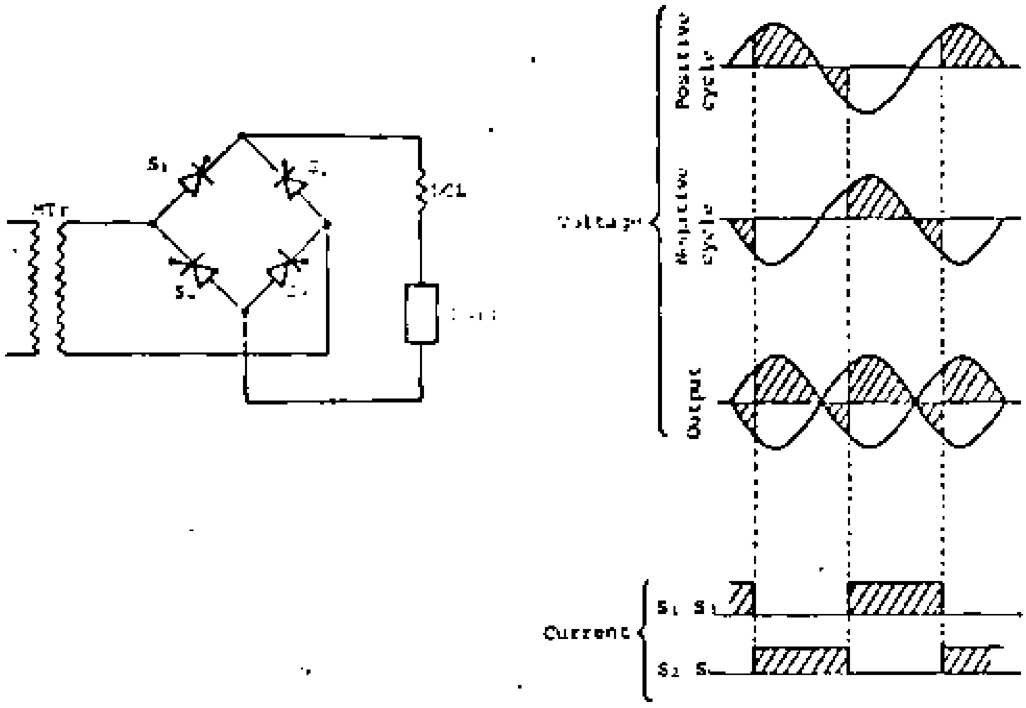
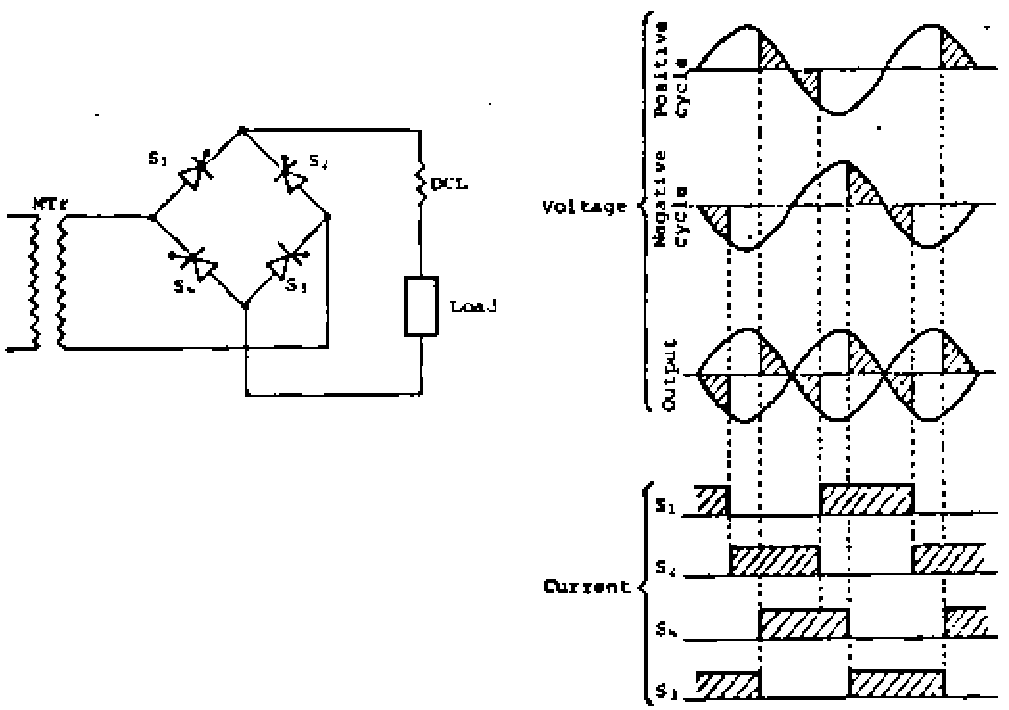


Fig. 8-9 Form of Carrying Current on Hybrid Bridge



(a) Main circuit (b) Form of carrying current

Fig. 8-10 Form of Carrying Current on Thyristor Bridge (Symmetrical control)



(a) Main circuit (b) Form of carrying current

Fig. 8-11 Form of Carrying Current on Thyristor Bridge (Asymmetrical control)

As shown in the figure, in the case of asymmetrical control, voltage change corresponding to same thyristor control phase angle is about one half that of symmetrical control and it is more advantageous for high frequency control. But twice as many phase control devices are required compared with symmetrical control. By adopting thyristor control, automatic fixed voltage restriction (AVR), and automatic fixed current restriction (ACR), etc. as well as continuous voltage control can be easily undertaken. Therefore, it can be said to be the most suitable control system as well as chopper control, etc., for fixed speed operation control by speed directive type and automatic operation (ATO), etc.

8-1-5 Other Control Systems

The first of these is a combination of the main transformer, main rectifier and resistance control as shown in Fig. 8-12.

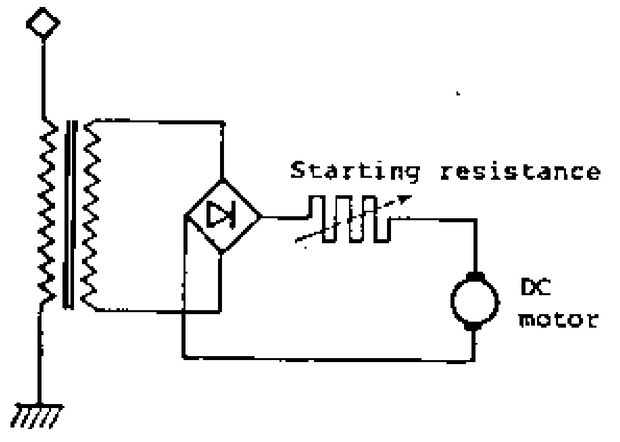


Fig. 8-12 Rheostatic Control System

This system is a simple addition of an AC-DC convertor to the DC electric rolling stock. It is heavy and no improvement can be made in performance but it is easy to apply to the rolling stock which is directly operated through different power supply systems (AC and DC).

The rectifier plus chopper system shown in Fig. 8-13 is used to control AD/DC electric rolling stock as well as the resistance control system. As a control system of the exclusive AC electric rolling stock, improvements in performance and elimination of contactors for main circuits are made possible unlike the resistance control. It is an improvement over the resistance control but compared with a simple thyristor control system, it is at disadvantage in weight and price. But power factor is better compared with the phase control system.

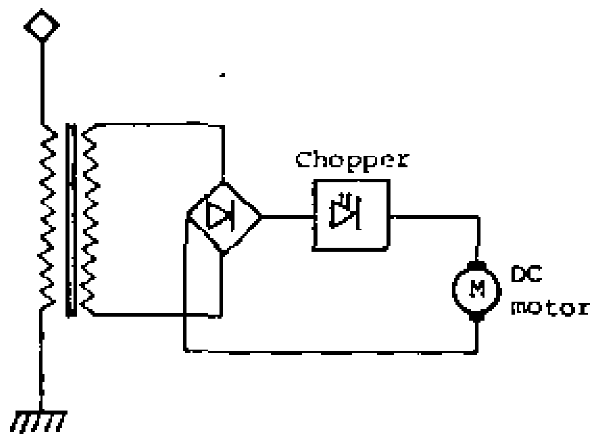


Fig. 8-13 Chopper Control System

Fig. 8-14 shows a driving system of commutatorless motor by the combination of AC/DC convertor and three phase invertor, and induction motor is mostly used for traction motors. Induction motors are generally lighter compared with DC motors of the same output and the weight of a truck can be reduced but the total weight including the convertor will be greater. Regenerative braking will become possible when an AC/DC convertor is added with inversion function. Also for improving the power factor of an AC/DC convertor, a system equipped with forced commutation device is tried for 16-2/3 Hz, etc. (ex. Quadrantal convertor of DB, 3C-LUB for ET420, etc.). The circuit shown in Fig. 8-15 (a) is

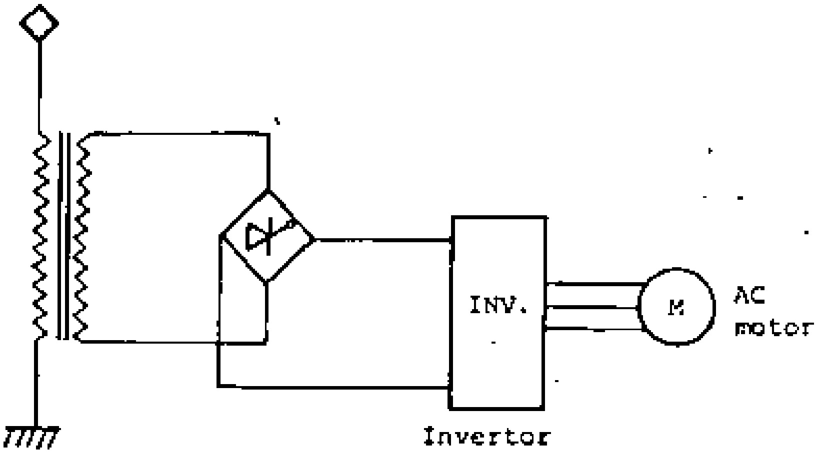
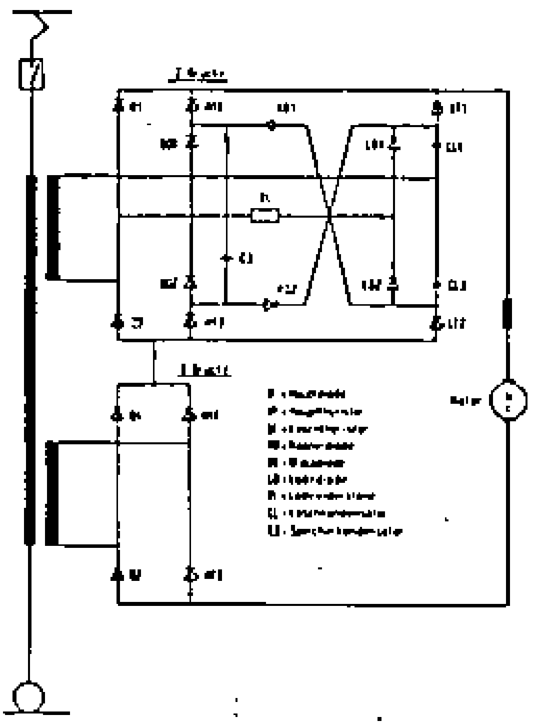
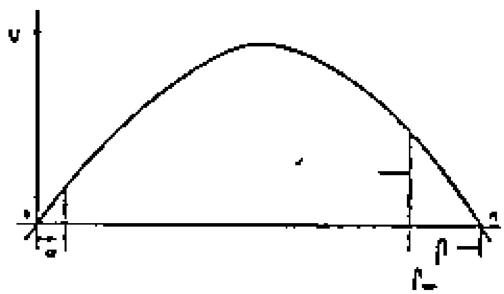


Fig. 8-14 AC Motor Traction System



(a) Main circuit with forced commutation circuit (3C-LUB)



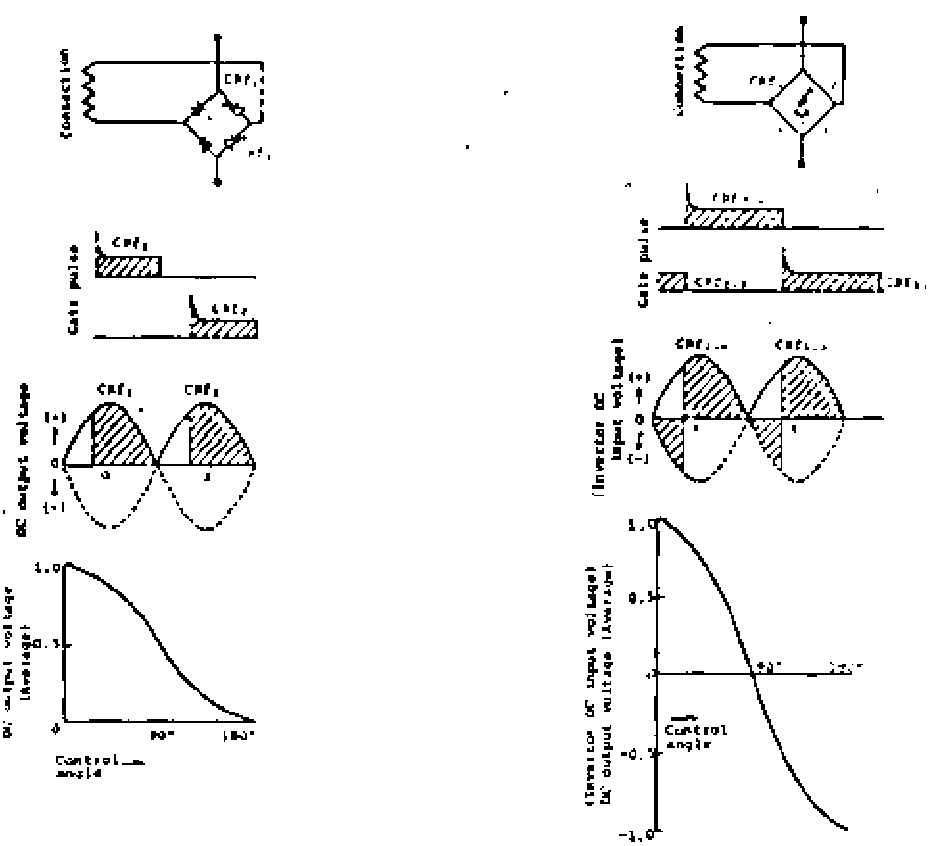
(b) Method of phase control
(α, firing angle
β, extinction angle)

Fig. 8-15 Circuit Equipped with Forced Commutation Circuit and Method of Control a 3C-LUB circuit and it has the function of controlling firing angle α and extinction angle β as shown in (b). It is a system which carries the same width of current at both front and back sides of 90° as the center. But equipment increases to carry out commutation and its weight and price increase, so a careful study must be made for its appropriateness except in areas where 16-2/3 Hz electrification is carried out for improving power factor.

8-2 Theory, Control and Effects of AC Regenerative Brake

8-2-1 Theory

Fig. 8-16 (a) and (b) shows connection of hybrid bridge and that of thyristor bridge respectively.



(a) Hybrid bridge (b) All thyristor bridge

Fig. 8-16

Since the hybrid bridge system's DC output voltage can not turn to negative voltage, it cannot make invertor operation. On the other hand, the all thyristor bridge system has all arms comprising thyristors and opposite arms are fired with gate pulses of the same phase. (This is called symmetrical control.) In this case, the current carrying angle of each arm is about 180° regardless of control angles so far as DC current is not interrupted, and a negative period appears on the DC output voltage waveform. In case of a control angle of $0° < \alpha < 90°$, the average value of the waveform is positive but in the case of a control angle of $90° < \alpha < 180°$, it becomes negative and invertor operation becomes possible. In case of operating invertor, when the control angle α is made too large, commutation fails. In the practical circuit, as shown in Fig. 8-17, as there is always reactance on the AC side, AC current is not instantly inverted when the thyristor is fired and overlapping angle u is created. Therefore, the current carried through thyristor arms 2, 4 will not turn to 0 at α, and it will only turn to 0 at $\alpha + u$ $(= \beta - u)$. Thyristor arms 2, 4 start to extinguish at this point. When angle of lead

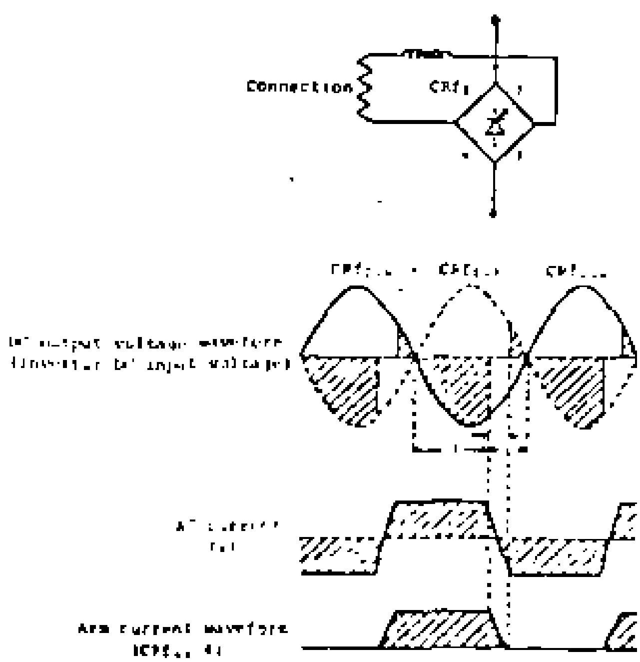


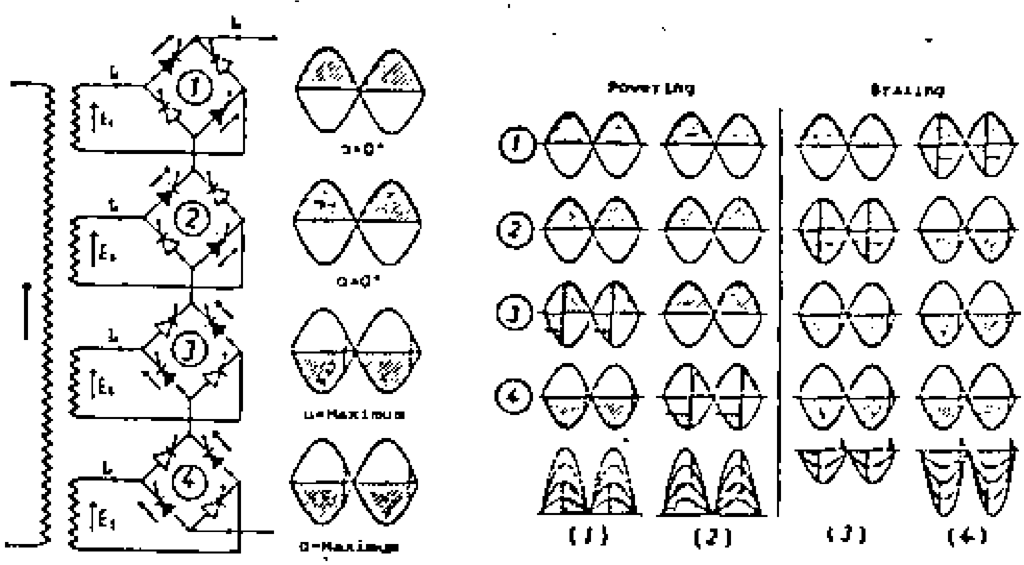
Fig. 8-17 Waveform of Each Part during Operation of Invertor

of control β is small, current on the thyristor arms 2, 4 cannot be commutated to thyristor arms 3, 4 and motor voltage on the DC side and AC voltage overlap during the next half cycle and overcurrent is produced. This is called commutation failure. The angle of lead of control requires minimum value of β min. which will not cause commutation failure. This value must be made larger, the larger the reactance on AC side.

8-2-2 Symmetrical Control

The symmetrical control is the same control system theoretically explained in 8-2-1. It is a system of controlling voltage by having some producing positive voltage with α at less than 90° (powering area) and others producing negative voltage with α at more than 90° (regenerating area) and making their total any positive voltage (during powering) or any negative voltage (during being regenerative).

Fig. 8-18 (a) shows a case where the secondary side of the main transformer is divided into four parts and 4 thyristor bridges are connected in series. As shown in the figure, when (1) and (2) are controlled with α=0° and (3) and (4) with α = maximum (= β min.), the total output voltage becomes almost zero. The passage of current is formed with each arm and the secondary winding. By bringing the control angle (3) from this position close to zero, up to 1/2 the positive voltage is obtained as shown in the same figure (b)-(1) and by further bringing the control angle (4) close to zero, up to the total positive voltage is obtained as shown in (2). This shows during powering, but during regeneration, the control angle (2) is gradually increased from the condition as shown in the same figure (a) to β min., then up to 1/2 of negative voltage is obtained as shown in (b)-(3) and when (1) is controlled to β min., the total negative voltage is obtained as shown in (4).



(a) Control of each unit (b) Control angle and output voltage

Fig. 8-18 Symmetrical Control

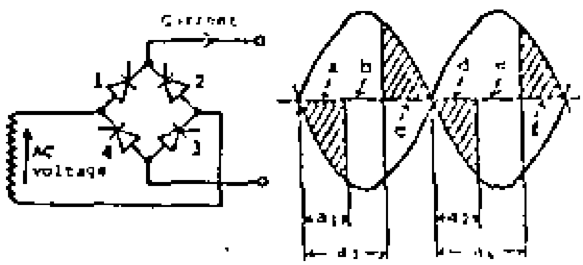
8-2-3 Asymmetrical Control

When symmetrically controlled, each unit bridge naturally generates either positive or negative voltage and in effect it is same as the number of stages of series connections being reduced to one half. Therefore, it is better to control both sides of the AC terminal of the bridge separately (asymmetrically) and make the passage of current without producing unnecessary voltage. This is called asymmetrical control.

In Fig. 8-19, Arms 1 and 2 fire every half wave at the same phase angles of α_1 and α_2 and completely apart from this, Arms 3 and 4 fire every half wave at the same phase angles α_3 and α_4.

This will make two combinations of current carrying arm (eg. 1-3 and 1-4) and produce a period of producing voltage (when the opposite arm is carrying current, eg. condition a. c.) and period of not producing voltage (when the arm adjacent to AC terminal is carrying current, eg. condition b). Therefore, with α_1, $\alpha_2 \rightarrow 0$ when α_3 and α_4 are controlled, only the positive voltage zone can be controlled and conversely with α_3 and α_4

close to the maximum value of 180° (at 180° commutation becomes impossible, therefore to α min.) when α_1 and α_2 are controlled, only the negative voltage zone can be controlled.



Conditions	Current carrying arm	Conditions	Current carrying arm
a	2, 4	d	1, 3
b	1, 4	e	2, 3
c	1, 3	f	2, 4

Fig. 8-19 Conditions of Control and Output Voltage under Asymmetrical Control

In other words, in the basic circuit shown in Fig. 8-16, while in the case of symmetrical control, 0° ∿ 90° are positive voltage and 90° ∿ 180° are negative voltage, in the case of asymmetrical control for the same circuit, there are 2 sets of gate control systems with positive and negative control ranges from 0° to 180° respectively. (Fig. 8-20)

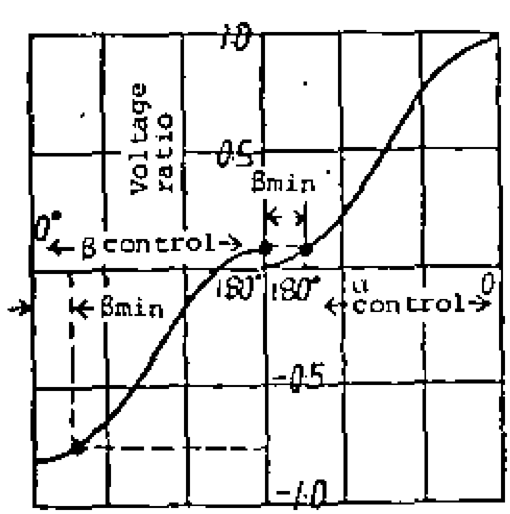


Fig. 8-20 Control Characteristics during Asymmetrical Control

The same applies to series connection and an example of division in half is given in Fig. 8-21. While powering, a group of α_{11} · α_{12} and α_{21}·α_{22} is fixed at 0° and a group of α_{13}·α_{14} and α_{23}·α_{24} is controlled. Likewise while regenerating, a group of α_{13}·α_{14} and α_{23}·α_{24} is fixed at minimum β and a group of α_{11}·α_{12} and α_{21}·α_{22} is controlled. As observed, while asymmetrical control has advantages in ripple factor, power factor and higher harmonics, a phase control system requires twice as many number of series connection bridges.

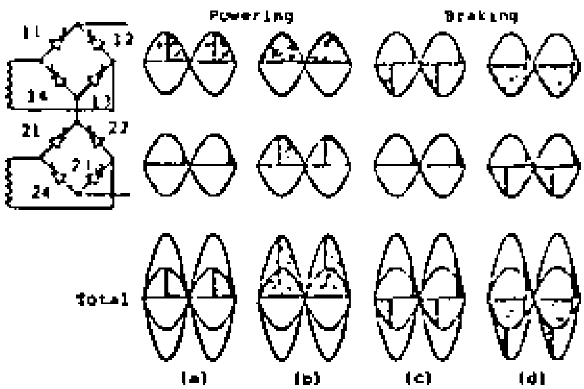


Fig. 8-21 Asymmetrical Control during Series Connection

8-2-4 Reduction of Third Harmonic and Improvement of Power Factor

In the case of single-phase rectifier type rolling stock, harmonics as many as power source frequency multiplied by odd number, are generated on AC side. Many countermeasures are undertaken but the third harmonic becomes a problem with respect to the power network.

In Fig. 8-16 Thyristor Bridge Circuit, and Symmetrical Control, theoretically the 3rd harmonic current contains 1/3 or 33% of the basic wave. Under asymmetrical control, just as in the case of the hybrid bridge, there is no difference in the absolute value of 3rd harmonic portion but the basic wave portion decreases in proportion to the better power factor and the percentage of the content will be greater.

The same trend appears when power factor is improved by series connection.

Therefore, certain countermeasures will have to be taken, when it is necessary to control the percentage of content of 3rd harmonic below certain level.

One of the methods considered is to make the waveform of AC current one which contains a small amount of 3rd harmonic. When waveform of AC current is made rectangular, the absolute value of the 3rd harmonic will be greatest when current is carried at a full 180° width of the half wave and at 60° width and it will be zero when current is carried at 120° width.

Therefore, it will be possible devise a method of control and decrease the 3rd harmonic. When regenerative brakes are used, the thyristor bridge will be operated as a separately excited invertor and the effect by the control angle will become great. To reduce the effect, it is necessary to further enlarge reactance on the AC side and to enlarge the angle of β min., but the power factor will go down. Various measures to be undertaken at the rolling stock end for reducing harmonics will be discussed in detail in 8-4.

Another method considered is to install an LC resonance power filter for absorbing the 3rd harmonic at feeder transformer on the ground. (It is nearly impossible to mount the equipment on the rolling stock because of its weight.) At the same time, this filter works as a phase advancing capacitor and improves the power factor. JNR has substations installed with 3rd harmonic filters which also improves the power factor.

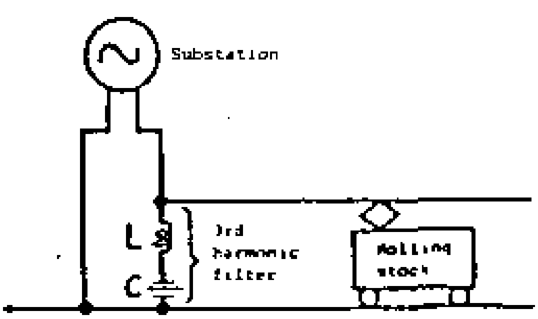


Fig. 8-22 Example of Installing LC Resonant Power Filter

8-2-5 Effects

The effect of power saving with AC regenerative brakes in the Japanese National Railways is discussed below. In October, 1968, JNR changed electrification system of continuous 33‰ grade section which had heretofore been DC powered to single phase 50 Hz AC and started to use regenerative brakes for balancing braking by the locomotive.

The topography of the district is as shown in Fig. 8-23 and electric locomotives of B-2-B and B-B-B type are used to pull passenger trains and freight trains. Electric cars which do not have regenerative brake are also used. Regenerative brake efficiency (regenerative energy divided by energy consumed during powering) estimated from the actual measured value between FUKUSHIMA and YONEZAWA is 35 ∿ 37% for passing trains and about 30% for local trains and overall power saving is estimated at a little over 30%.

As an example of saving purchased power, after AC electrification in October, 1968 power consumption after electrification decreased to about 84% of that of DC electrification. The value includes the amount of power consumption in other than graded sections, as well as by electric cars without regenerative brakes and increased number of trains after AC electrification, which will also show great effect of AC regenerative brakes.

AC regenerative brakes are not only more advantageous in power saving but also in weight and performance of electric locomotives compared with rheostatic brakes.

8-3 AC Motor Drive System and Its Problems

8-3-1 Background

The system of driving AC rolling stock with an AC commutator motor is generally used in West Germany and Switzerland where a special 16-2/3 Hz frequency is used. Also in Japan in the beginning of AC electrification by commercial frequency, several

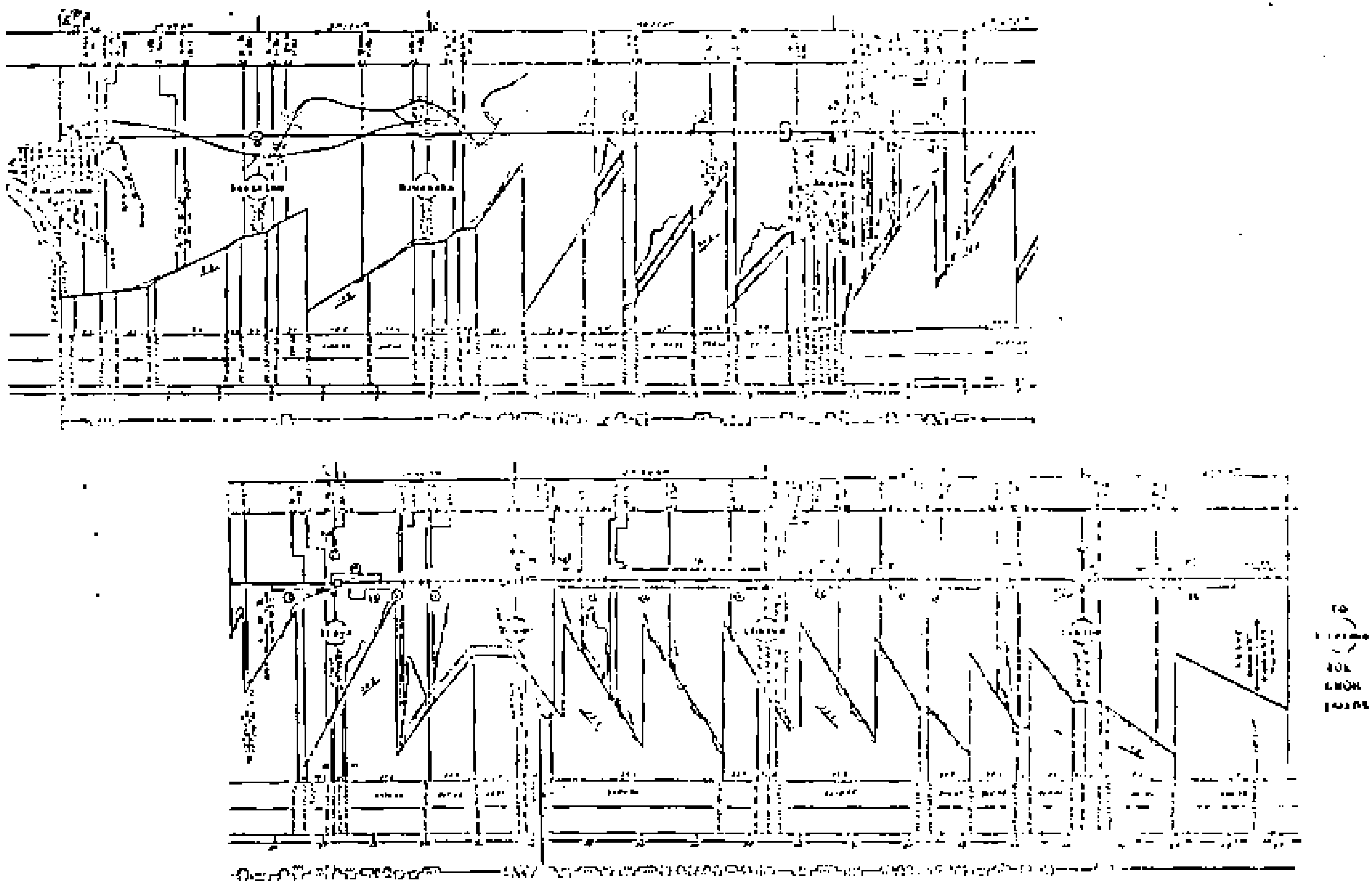


Fig. 8-23 Topographic Map of District where Balancing Regenerative Brakes are Used (OHU Main Line between YONEZAWA and FUKUSHIMA)

models of motors were manufactured and compared with the system using DC motors. According to the results of various tests, the DC motor system using the rectifiers on the car has since been adopted domestically in Japan.

On the other hand, the AC motor traction discussed here is a traction system using the so called AC non-commutator motors such as induction motors or synchronous motors, etc. Outside Japan, a method of direct control by changing poles using 3 phase induction motors and collecting power from multiple AC trolley wire or such methods as driving 3-phase induction motors by changing single-phase AC to 3-phase with a motor generator have long been put into practical application. Although these methods have the advantage of simplifying the construction of the motor, they have disadvantages in their equipment and control methods, so they are not widely used. Therefore, a serious study of AC motor traction system has only been started since static invertors with a large power thyristor could be put into practical use.

According to the published literature, the earliest type of rolling stock using a three phase invertor traction system is a diesel electric locomotive which was remodelled by Brush Co. in England in 1965. It had a synchronous generator driven by a diesel engine and the AC output was commutated to DC by a diode bridge. Four AC traction motors of 168 kW were controlled to 0 ∿ 100 Hz with 4 invertors installed separately. In those days, the rating of thyristor elements was small and required many series and parallel units, making the invertor became large, so only one model was manufactured. This locomotive was a diesel electric locomotive and it was not an AC line system. In 1968, AC input type VL80K, VL80B model locomotives were manufactured in USSR.

VL80K is induction motor type and VL83B is a synchronous motor type, both of which are 4-driving axles type locomotives and permanent connection types. They were later remodelled to synchronous motor type with 8 driving axles.

JNR conducted KUMOYA 791 type electric car equipped the synchronous motor in 1972 and a test run was achieved on the NIPPO main line.

Also a test of an induction motor system was conducted in France and AC electric locomotives such as E120 type of DB and Ee 6/6 II Model of SBB were introduced.

In 1980, JNR made a trial production of a 650 kW induction motor and AC/DC convertor, DC/3φAC invertor, etc. and various tests are being undertaken on the test rack for practical use in the future.

8-3-2 Characteristics of AC Motor Traction System

Comparing the AC motor traction system with the DC motor traction system, the following points are noted on the motor.

(1) As there is no commutator, maintenance is not required.

(2) Squirrel-cage induction motor and synchronous motor using a non-contact exciter have no brushes and if the motor is excited with a slip ring for synchronous motor, as there is little brush wear, maintenance and inspection will be easier.

(3) As there is no commutator, the highest number of revolutions can be enlarged and the motor can be made compact. Therefore, the weight of the truck including the traction motor can be reduced.

(4) Especially in the case of an induction machine, axial direction will be shorter for the size of rotor and it can be made compact.

(5) A squirrel-cage induction motor is of simple construction and easier to build.

(6) There are no accidents caused by flashover. Also its performance has the following characteristics.

(7) By the speed-torque characteristics of the traction motor and quick brake response, adhesion performance between the rail track and the wheel is improved.

(8) There is no limit to the field factor unlike DC motors, so high speed performance can be increased.

(9) There is greater possibility for regenerative brake.

While they have these advantages, converting systems such as invertors, cyclo convertors, etc. are required and many technical problems as complex circuits and commutation limit and physical and economic problems restricting the outer shape, weight, price, etc. of the whole vehicle must be solved. In addition, if multiple AC motors are run with one convertor, control of different wheel diameters will also become a problem..

8-3-3 Types of AC Motor Traction Systems

When AC motor traction systems are classified, they are grouped by motor into induction motor systems and synchronous motor systems, and by power convertor they are grouped into cyclo convertor systems which directly covert AC input of a certain frequency into AC output of variable frequency and a system using invertor which once commutates AC input into DC and further converts it to AC of variable frequency output.

The cyclo convertor system, the former, is only limited to the current type but the latter or the system using rectifier and invertor is further classified into the voltage type and the current type.

(1) Induction Motors and Synchronous Motors

When using a synchronous motor, as it is impossible to control torque with an invertor of separate control type which gives frequency from outside and as there is a possibility of dissynchronization, an automatically controlled invertor is used in combination to determine the number of its own revolution by input power. Also the current type is used for invertor or cyclo convertor and commutation is done by rotating machine's counter electromotive force and timing of commutation is matched with appropriate phase of counter electromotive force, so the position detector to transmit the position of rotor to the invertor side becomes indispensable. As observed, the commutation of invertor or cyclo convertor is carried out through the counter electromotive force of the motor and complex commutation circuit becomes unnecessary, which has the advantage of eliminating the use of a high speed thyristor. On the other hand, it is impossible to operate multiple motors with single invertor, and each motor must be equipped with an individual invertor, with respective rotor position detection signals given to the invertor.

Generally, the revolving field type is of simpler construction, but slip rings, or a non-contact exciter or other means become necessary to excite the field magnet.

For these reasons, as the construction of the rotor is not as simple as that of a squirrel-cage induction motor, it is a little inferior to the induction motor in achieving a higher number of revolutions. Therefore, the induction motor is more likely to have advantages in terms of size and weight.

Judging from the relations of commutating voltage as described above, input voltage and input current become nearly same phase and operation at a high power rate becomes possible.

However, with motors with a rating of several hundreds to 1MW, as its size is determined by other factors, the advantage of making it compact can hardly be achieved.

On the other hand, in the use of induction motors detection of the number of revolutions is required for controlling torque but detection of rotor phase is not necessary and an invertor in a separate exciting system which determines frequency with an outside oscillator can be used.

However, as commutation of the invertor is not coordinated to induced voltage, it is necessary either to use a forced commutation circuit using oscillating current or to use semiconductor elements with self extinction ability such as a gate turn-off thyristor (GTO) or transistor for large power, etc.

Also when the difference in the diameter of the wheel which is driven by respective motors is controlled under a small value, multiple motors can be run in parallel with a single invertor. In the case of squirrel-cage induction motors, it can be run at a high number of revolutions, so it can be made compact and lightweight.

From the foregoing, if commutation of the invertor can be done with a simple circuit by using GTO, etc., there are many merits in using the induction motor and the record shows that more induction motor systems have been produced to date. Trial production using synchronous motors has been undertaken as mentioned before, in cases such as the VL80B of the USSR and the KUMOYA 791 type electric car of JNR. In about 1981, the French National Railways (SNCF) ran tests with a current type invertor system. Those using induction motors include E120 type of West Germany and Ex 6/6 II type of SBB for areas of input frequency of 16 2/3 Hz for trial use. With input of commercial frequency of 50 Hz or 60 Hz, trial production is being carried out in Japan and West Germany.

(2) Voltage Type Invertor and Current Type Invertor

In case induction motor is used for AC motors as mentioned before, 2 types of invertor, i.e. Voltage type and Current type can be considered.

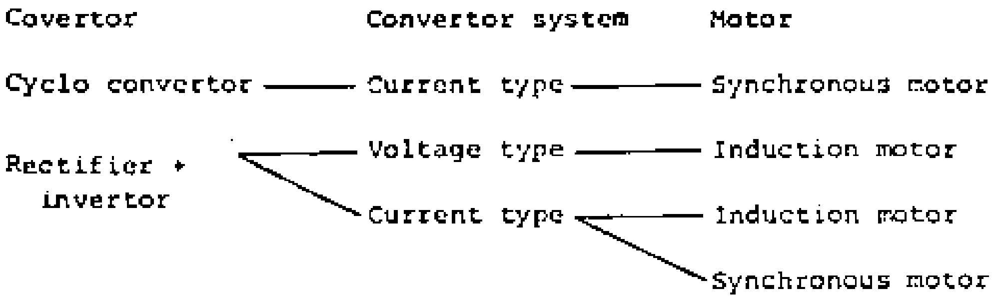


Fig. 8-24

Fig. 8-25 shows a comparison of voltage invertor system and current invertor system with electric rolling stock of AC trolley line.

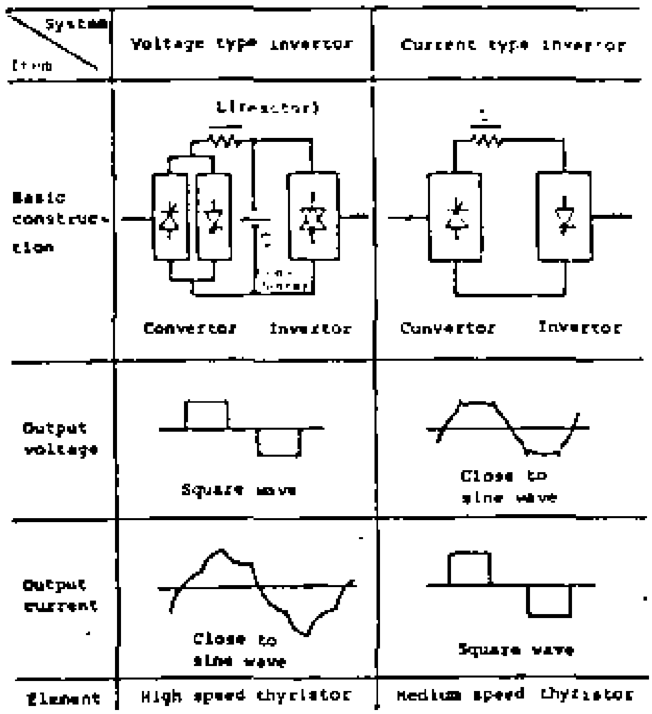


Fig. 8-25

With a voltage type invertor system, DC voltage is maintained at a certain value with an input rectifier. Motor voltage and frequency are controlled with a voltage type invertor. On the other hand, with current type invertor system, input voltage form the invertor is controlled with a rectifier on the input side, and only frequency control is carried out to simplify the circuit. With regard to the main circuit, a large capacitor is required for a voltage type invertor systems to maintain a certain voltage on the DC portion and a large current smoothing reactor is required for current type invertors to maintain certain DC current. When a regenerative brake is used, a current type invertor can construct the brake circuit by reversing the rectifier on the side, reversing the direction of voltage and without making any additional circuits.

With voltage type invertor systems, it is necessary to add a set of reverse series circuits to the rectifier on the input side or to use a rectifier on the input side or to use a mechanical convertor to reverse the voltage of the DC portion increasing the number of pieces of equipment used.

From the voltage and current waveform of the motor, a voltage type invertor system has a square waveform for voltage waveform and current waveform becomes nearly sine wave. This relation is reversed in the current type invertor system.

Generally the current type invertor system is simpler in overall construction from the standpoint of the composition of commutation circuits, etc.

When semi-conductor elements with self extinction ability, such as GTO, etc. are used, the voltage type invertor system will become similar. The selection is made according to the output of electric rolling stock and conditions of input voltage, etc.

8-3-4 Evaluation Based on the Actual Structure of Rolling Stock

The application of AC motors to AC electric rolling stock, has been tried and tested, as mentioned before, in Japan, the USSR, West Germany, Switzerland, etc. West Germany and Switzerland have already taken steps toward practical application ahead of others.

In particular, the E120 model locomotive manufactured by German Federal Railways for its main lines in 1979 has received worldwide attention as a full-scale large output induction motor system locomotive.

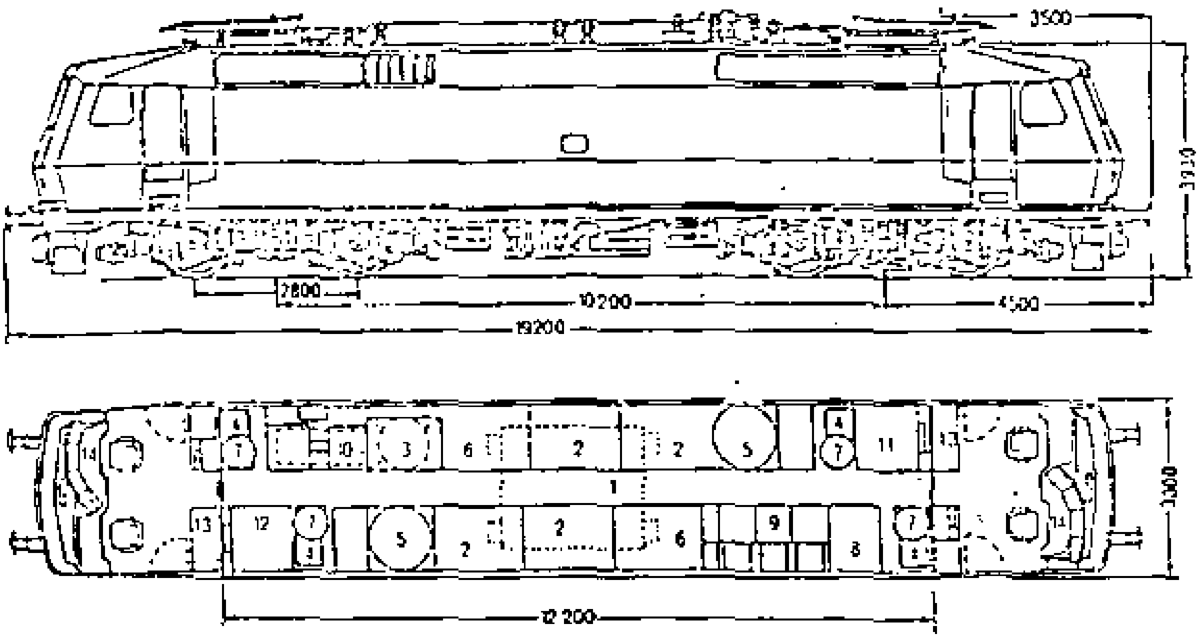
The German Federal Railway specially required compact size and light weight as well as large output, and much effort has been paid to make the whole equipment in compact size.

The E120 model is B_0-B_0 axial arrangement type and weighs 84 tons. The weight of the axle is 21 tons, and comparing with the AC commutator motor which was generally used by the German Federal Railway, the relative weight of the motor is lighter and the decreased truck weight including the traction motor gives less load on the rail track.

Table 8-1 Comparison of Elements of Main Locomotives

Item \ Type	E120	1044	BB 15000
Railway	DB	OBB	S.N.C.F
Maintenance weight	84t	84t	88t
Axle weight	21t	21t	22t
Axle arrangement	B-B	B-B	B-B
Maximum length	19200mm	16060mm	17470mm
Maximum width	3000mm	3117mm	3066mm
Motor type	3 Phase induction motor	Direct current motor	Direct current mono motor
Locomotive output (continuous)	4400kW	5148kW	4360kW
Traction motor output (continuous)	1400kW	1287kW	2180kW
Traction motor weight	2380kg	3750kg	7000kg
Electric system	A.C.15kV 16-2/3Hz	A.C. 15kV 16-2/3Hz	A.C. 25kV 50Hz
Control system	4 Quadrant convertor and PWM invertor drive	Thyristor phase control	Thyristor phase control
Track width	1435mm	1435mm	1435mm
Maximum speed	160km/h	160km/h	180km/h
First manufactured year	1979	1974	1971

From the standpoint of overall construction, the main transformer is suspended below the floor as in electric cars, producing more space above the floor. The center passage is installed on the floor with equipment arranged on both sides, which shows that much effort has been made to utilize space (Fig. 8-26).



1 Main transformer
2 Traction power convertors
3 Braking resistances
4 Traction motor chokes
5 Transformer oil cooler
6 Switchgear and capacitors
7 Traction motor blowers
8 Switchgear for auxiliaries
9 Convertor for three-phase auxiliaries
10 Compressor
11 Compressed air and braking equipment
12 Control equipment
13 Electronics module
14 Control desk

Fig. 8-26 E120 Type (DB)

The E120 was originally built as a common locomotive which did not require a change in gear ratio between high speed passenger trains and heavy freight trains. For this reason, the required output of the locomotive is large but use of an induction motor greatly contributes to the increased output of the traction motor and to reducing the truck weight.

Further, the induction motor system has greater pulling strength for axle to improve the adhesion performance of the rolling stock (Fig. 8-27).

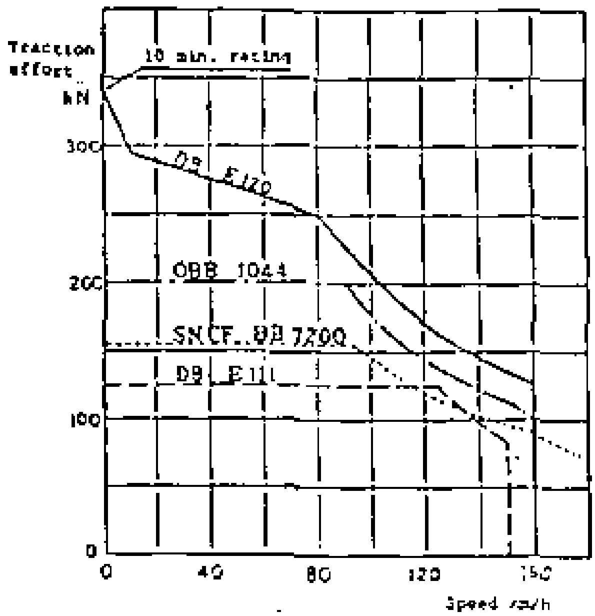


Fig. 8-27 Comparison of Pulling Strength of Main Locomotives

However, the induction motor drive system of AC electric rolling stock has a larger and heavier overall convertor compared with the DC motor drive system and it will become larger for making larger output, so in the district where axle weight restriction is severe, the structure of the rolling stock may become a problem.

In the case of the E120, a 16-2/3 Hz system is used and the main transformer in particular becomes larger in the 16-2/3 Hz system.

By using 4-quadrant convertor, the power factor is improved. By using the main transformer, increasing efficiency and making each piece of equipment smaller and lighter and by mounting other devices on the equipment as described before, problems are being solved.

The maintenance of brushes on AC commutator motor takes more time compared with DC motors and the fact that the volume of maintenance work is reduced by using an induction motor cannot be neglected.

From the standpoint of the circuit system, the control circuit, such as the invortor, becomes more complicated compared with the electric rolling stock.

While reliability and ease of maintenance of the traction motor are improved, there are certain disadvantages. Also initial cost at the time of manufacture of the rolling stock tends to be higher.

It is thought that this will improve in the future as reliability is enhanced and prices lowered by mass production.

The evaluation of induction motor traction system will likely change in the future when the reduction of the volume of maintenance work for the rail track and rolling stock is also considered.

8-4 The Problem of Harmonics

8-4-1 Analysis of Characteristics of Rectifier Circuits

The main circuit of AC electric rolling stock is generally a rectifier type with substantial reactance on the AC side, and load current on the DC side is not fully smoothed DC but so called pulsating current with large ripples.

Therefore, when planning is made without considering the fact that the main circuit is a pulsating current circuit and ripple current, voltage may not be obtained as planned and increased temperature caused by the pulsating current of the equipment and increase of commutation flash will make the equipment unusable.

Also steps must be taken against the problem of harmonic fault caused by the flow of harmonic current through the trolley line and the rail track.

(1) Setting of Basic Single Phase Rectifier Circuit

There are many rectifier circuits used for AC electric rolling stock, and here a single phase bridge circuit is taken up as shown in Fig. 8-28.

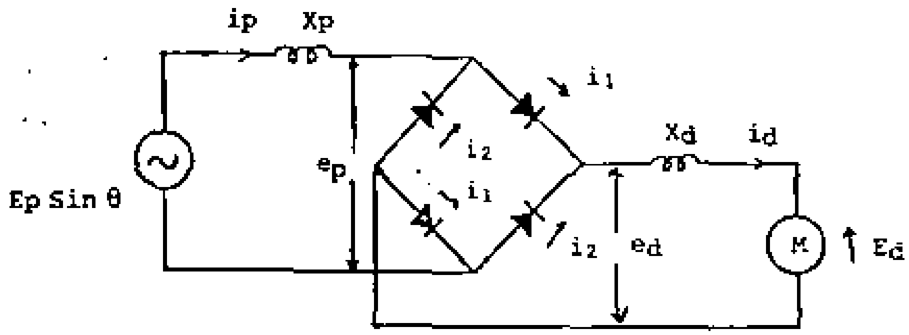


Fig. 8-28 Basic Single Phase Rectifier Circuit

For a fixed number of circuits, there are impedance of electric trolley line and impedance of the main transformer on the car as impedance (Xp) of the AC side, and after the rectifier, there are inductance possessed by the main smoothing reactor and traction motor and impedance (Xd) on the DC side.

Also the traction motor generally has counter electromotive force (Ed) which is generated by revolution.

(2) Commutation and Phenomenon of Overlap

Like a diode bridge, the operation of a rectifier not controlling phase immediately make commutator when power source voltage is reversed as shown in Fig. 8-29, when there is no reactance on the AC side.

But when there is reactance on the AC side, current cannot shift instantly as shown in Fig. 8-30 and for a certain period both the arm changing current and the other starting to carry current flow simultaneously and current 1 and current 2 overlap. This is called overlap. The period is called overlap angle. During the overlap angle, the circuit is short-circuited on the arm of the rectifier and part of the DC voltage will be missed. The lowering of average DC voltage due to the missing DC voltage is called 'commutation reactance voltage drop.

This will greatly affect the characteristic of the rolling stock.

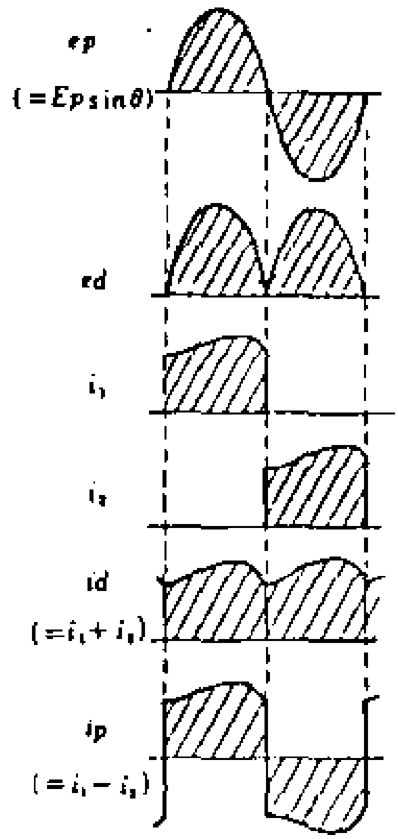


Fig. 8-29 Current Voltage Waveform
(In case of no commutation reactance)

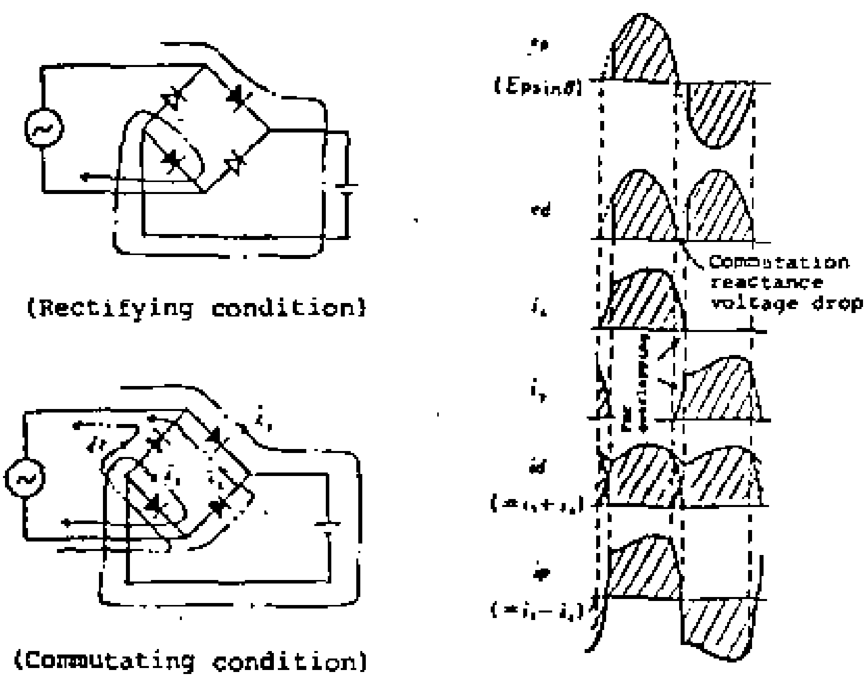


Fig. 8-30 Phenomenon of Overlap

(3) The Characteristics of Basic Rectifier Circuits Making DC Current Full Smoothing Current

Table 8-2 shows the characteristics of a single phase rectifier circuit analyzed by the Perfect Smoothing Theory.

(4) The Characteristics of Single Phase Bridge Circuits in Consideration of Pulsating of DC Current

Equivalent circuit of single phase bridge circuit (uniform convertor) is shown in Fig. 8-31 and waveform of each part is shown in Fig. 8-32.

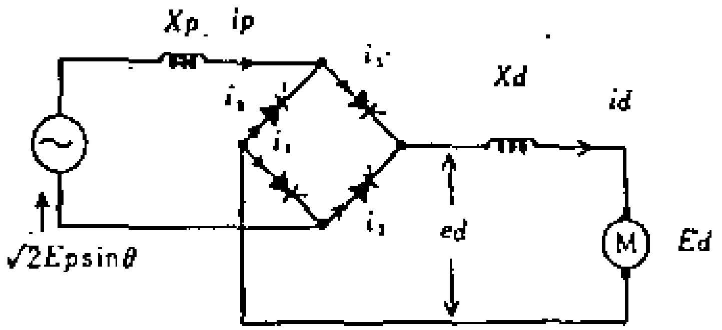


Fig. 8-31 Equivalent Circuit of Single Phase Rectifier

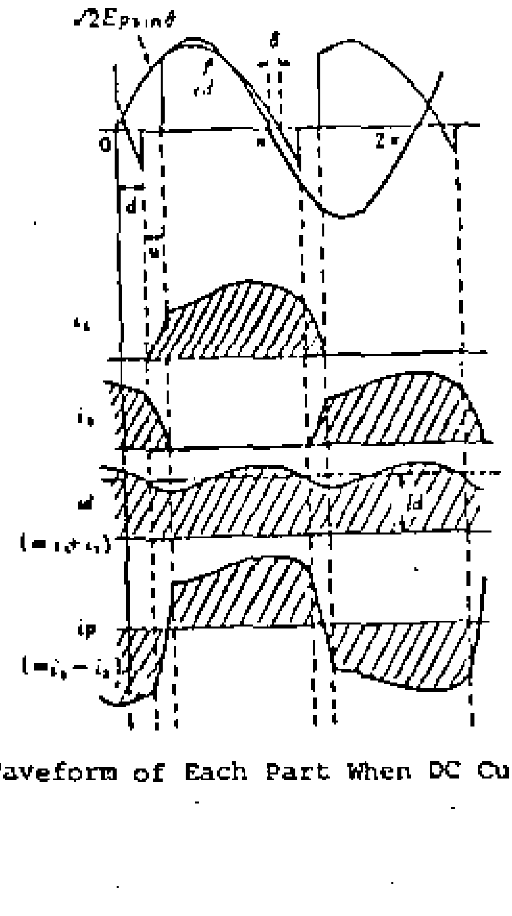
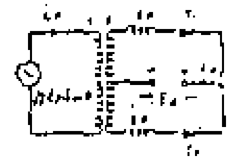


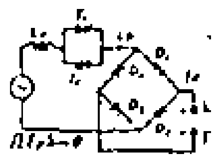
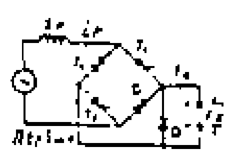
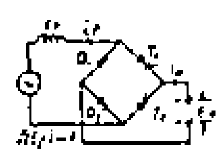
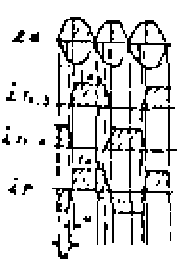
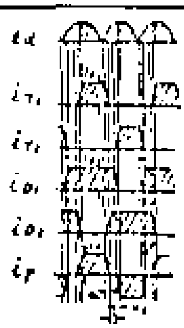
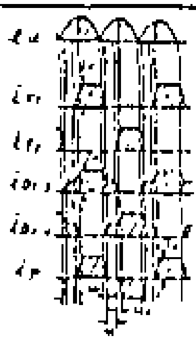
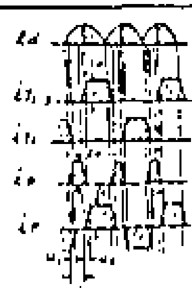
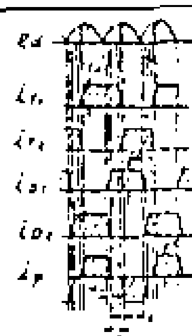
Fig. 8-32 Waveform of Each Part When DC Current Pulsates

Table 8-2

Characteristics of Basic Rectifier Circuit for the Rolling Stock

(In the case of DC current full smoothing)

		Single phase all wave (2-phase)
Name of connection		
Connection (assuming infinite reactance on DC side)		Winding ratio 
Non-load DC voltage (average value)	When not controlled: $Edo = \frac{\sqrt{2}Ep}{\kappa} \int_0^{\kappa} \sin\theta\, d\theta$	$\frac{2\sqrt{2}}{\pi} Ep = 0.9Ep$
	When controlled (inductive load): Edo'	$\frac{\sqrt{2}Ep}{\kappa} \int_{\alpha}^{\pi+\alpha} \sin\theta\, d\theta$ $= Edo \cdot \cos\alpha$
Commutation reactance voltage drop (average value of missing voltage during overlapping): Ex		$\frac{Xp}{\pi} Id = 0.319\, X Id$
Lap angle (Rectifier arm short circuited, and phase angle required for changes -Id → 0 → + Id — see waveform)		$u = \cos^{-1}\{\cos\alpha - \frac{Xp}{\sqrt{2}Ep} Id\} - \alpha$
AC input current (effective value) (effective value is calculated from instant value during rectifying and commutating): Ip		[illegible] $Id \cdot Ks\,(u, \alpha)$
Track rail power factor: $P.f. = \frac{(Edo' - Ex) \cdot Id}{Ep \cdot Ip}$		$0.9 \frac{\cos\frac{u}{2} \cos(\alpha + \frac{u}{2})}{K_1 (u, \alpha)}$
Waveform of each part ed: DC voltage iT: Thyristor current iD: Diode current ip: AC input current		
Main losses		(1) Rating of secondary winding of transformer is $\sqrt{2}$ times of others. (2) Regenerative braking is possible.

	Single phase bridge	Hybrid bridge (symmetrical on AC side)	Hybrid bridge (reverse parallel thyristor)	Hybrid bridge (With bypass diode)	Hybrid bridge (symmetrical on DC side)
					
		$\frac{2\sqrt{2}}{\pi} Ep = 0.9Ep$			
		$\frac{\sqrt{2}Ep}{\pi}\int_{\alpha}^{\pi}\sin\theta\, d\theta = Edo\frac{1+\cos\alpha}{2}$			
	$\frac{2Xp}{\pi}$ Id = 0.638xcId	0.319 · pId ...... $\alpha > u_1$ 0.638 · pId ...... $\alpha \leq u_1$			
	$u = \cos^{-1}(\cos\alpha - \frac{\sqrt{2}Xp}{Ep} Id) - \alpha$	$u_1 = \cos^{-1}(1 - \frac{Xp}{\sqrt{2}Ep} Id)$ $u_2 = \cos^{-1}(\cos\alpha - \frac{Xp}{\sqrt{2}Ep} Id) - \alpha$			
	+ Cos(2α + u)} −2 [illegible] Cos(α + u)] [illegible] + Cos(α + u))²	$Id\sqrt{\frac{\pi-(\alpha+u_2)}{\pi} + \frac{\alpha}{\pi(1-\cos u_1)^2}\{u_1(1+\frac{1}{2}\cos 2u_1) + u_2(1+\frac{1}{2}\cos 2\alpha) + \frac{3}{4}(\sin 2\alpha - \sin 2u_1)}$ $+ \frac{1}{2}\sin(\alpha+u_2)(\cos u_1 - 3\cos) \doteqdot Id \cdot K_R(u_1, \alpha)$ Where, $u_3 = \cos^{-1}\{\cos\alpha + \cos u_1 - 1\} - \alpha$			
	+ 1/2)	$0.9\frac{\cos^2\frac{\alpha+u_1}{2}}{K^2(u_1-\alpha)}$ ...... $\alpha > u_1$			
					
ng r r	(1) Regenerative braking is possible.	(1) Good power factor during control. (2) Regenerative braking is impossible.	(1) Accident current is small when thyristor puncture (Others are basically the same as those given on the right).	(Basically the same as AC side symmetrical hybrid bridge)	(1) Number of diodes is 1/2 of others. (2) Commutation failure is possible. (3) Regenerative braking is impossible.

In this case, as circuit resistance is not generally large, analysis is made without regard to this.

A circuit equation is prepared from current and voltage of each part and from this equation, DC voltage, DC current, overlap angle, AC current, power factor, and the harmonic content rate are obtained.

These characteristics drawn as a model are given in IEC Pub. 411-2 (Power Convertors for Electric Traction) which was offered mostly from Japan. An example (Uniform Convertor) is given in Fig. 8-33 ~ Fig. 8-38.

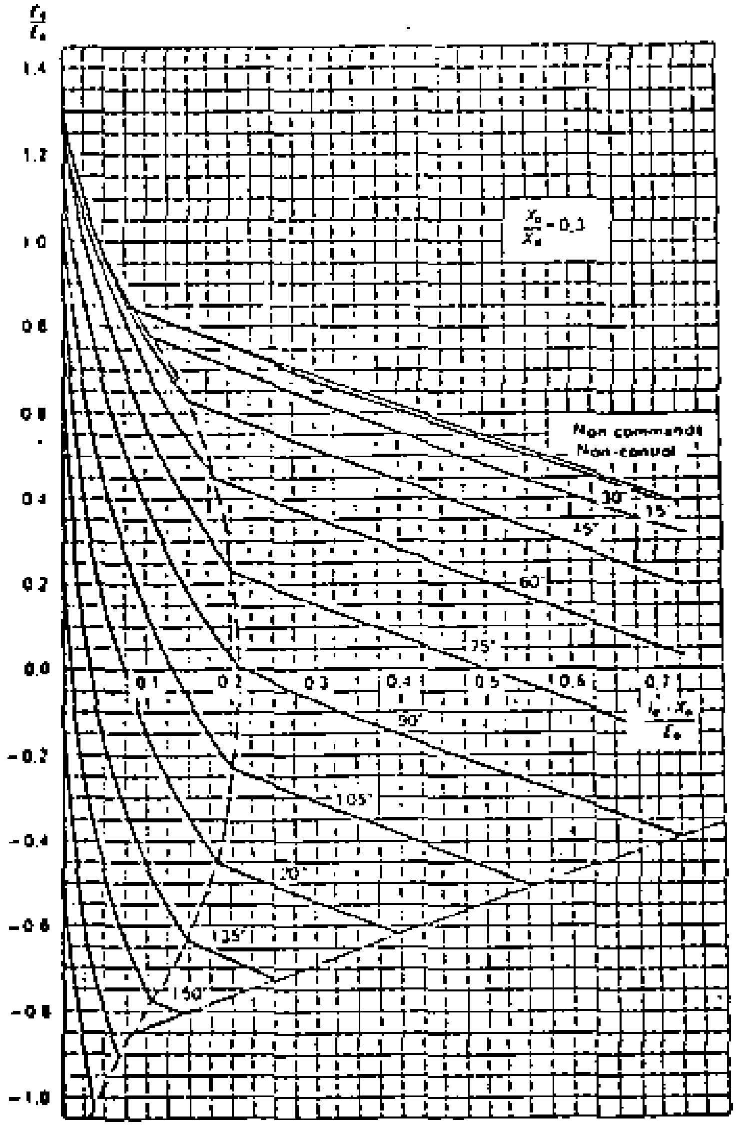


Fig. 8-33 DC Voltage Regulation

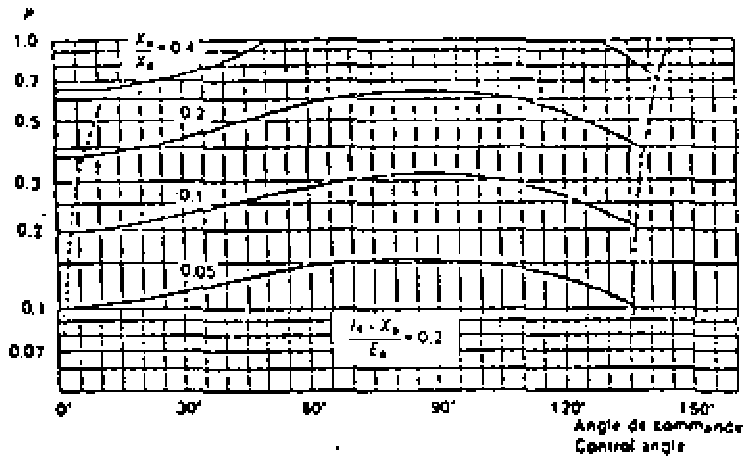


Fig. 8-34 Ripple Factor μ

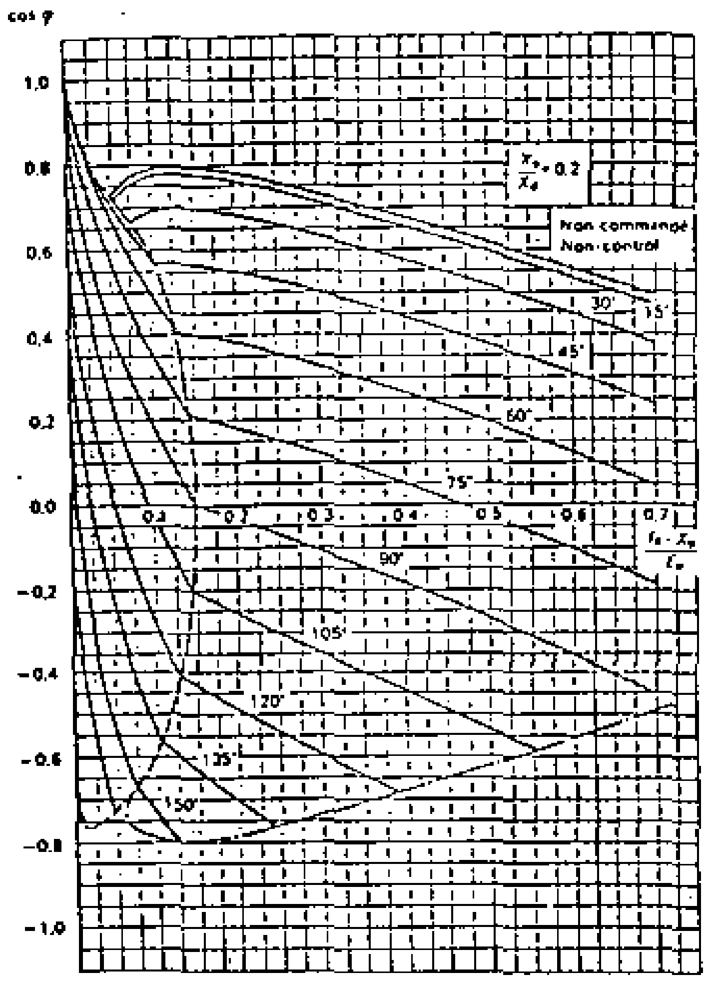


Fig. 8-35 Displacement Factor cos ψ

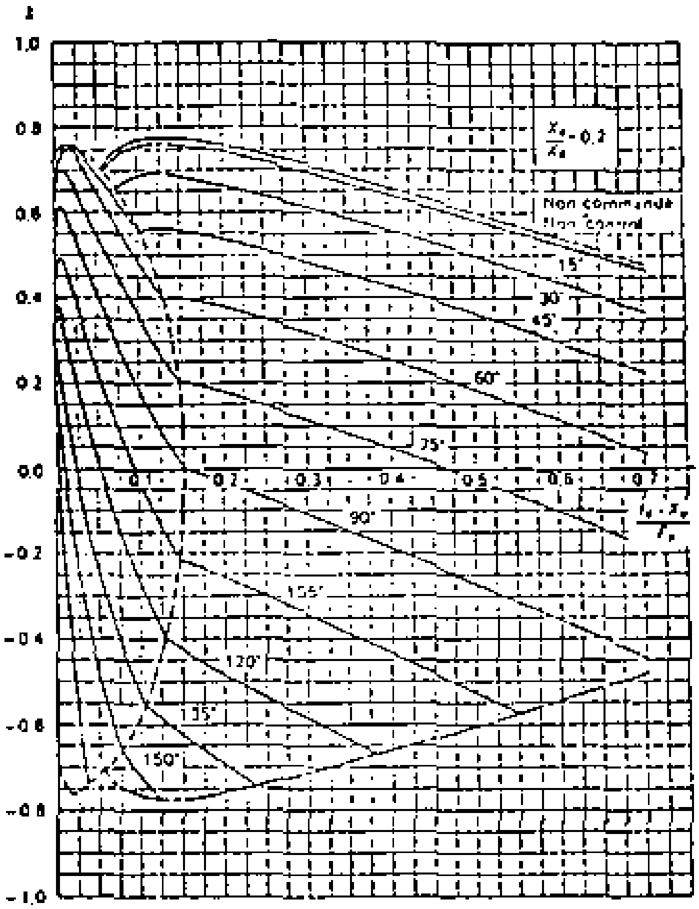


Fig. 8-36 Total Power Factor λ

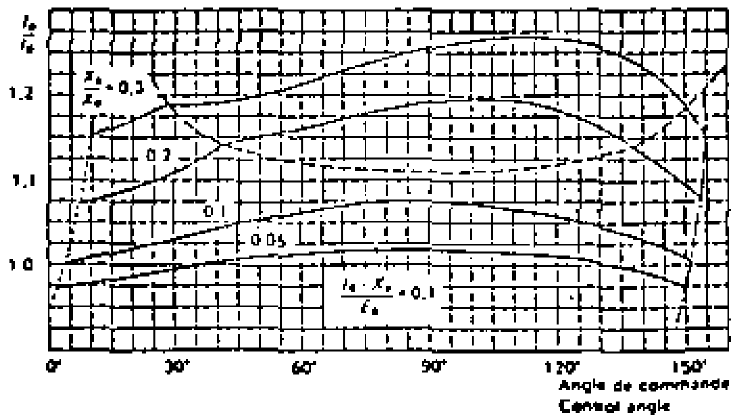


Fig. 8-37 R.M.S. Value of A.C. Side Current

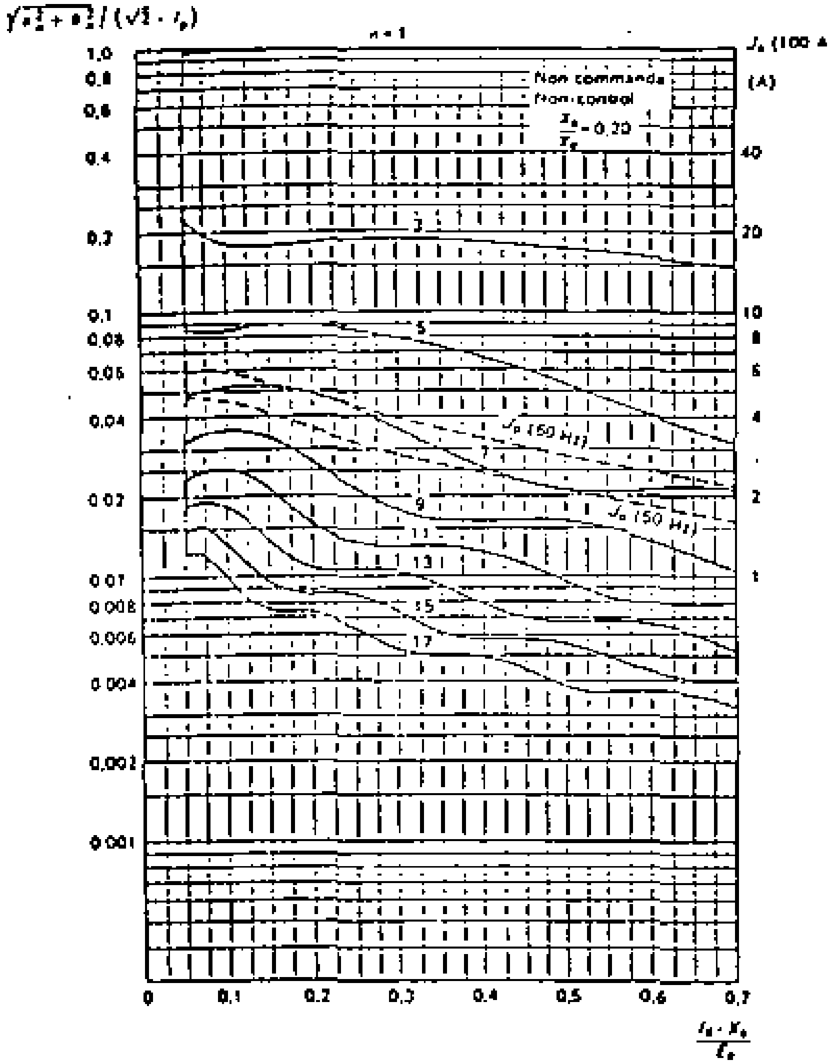


Fig. 8-38 . Content of A.C. Side Harmonic Current

(5) Characteristics of Cascade Connection Circuits

If there is only one rectifier set, power factor may deteriorate and harmonic current may increase, so it is customary to use multiple rectifiers connected in series.

Fig. 8-39 shows equivalent circuit of cascade connection circuit and Fig. 8-40 shows waveform of each part.

Voltage and current of each part is obtained as described above.

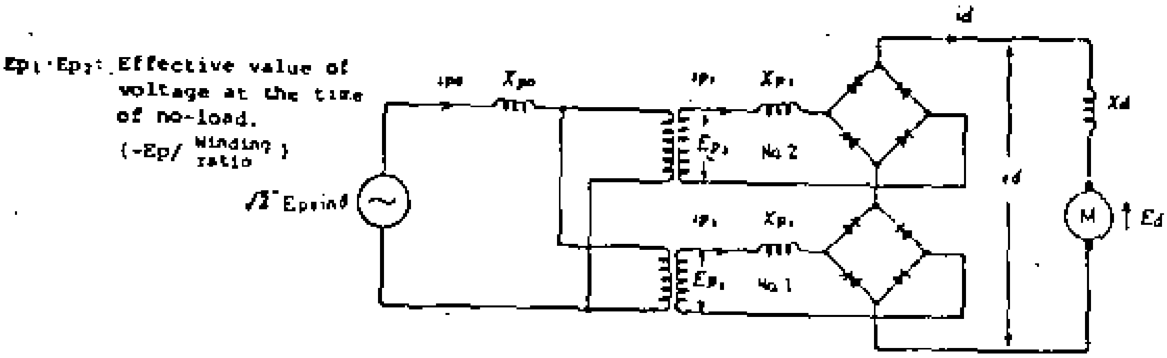


Fig. 8-39 Equivalent Circuit of Cascade Connection

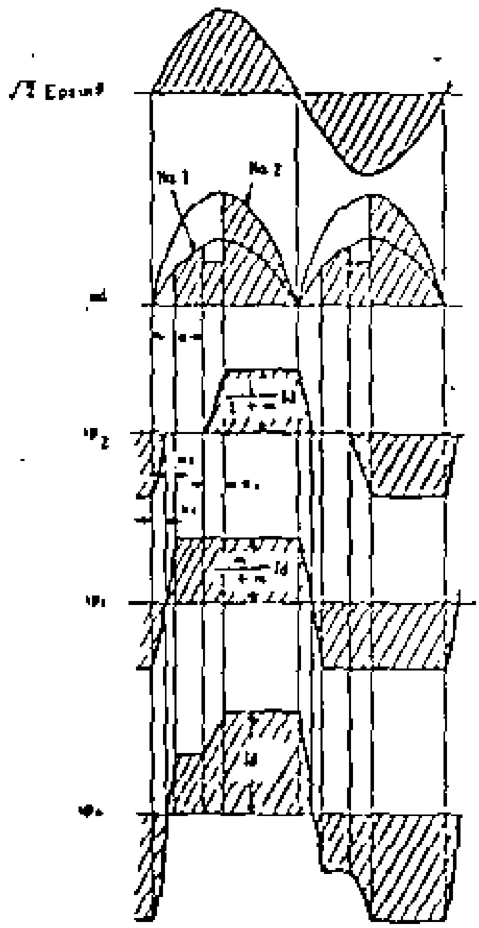


Fig. 8-40 Waveform of Each Part of Cascade Connection Circuit

As commutation is done separately by cascade connection rectifiers, the movement of AC current becomes two stage.

This makes current movement smaller and helps contribute to the reduction of harmonic current and improvement in the power factor.

Fig. 8-41 and Fig. 8-42 show power factor against cascade connection stage and improved condition of equivalent jamming power (JP) by model waveform.

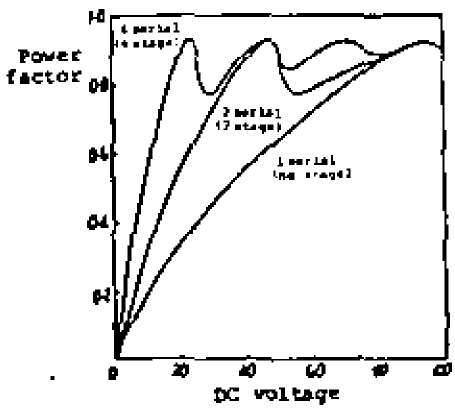


Fig. 8-41 Characteristics of Power Factor of Cascade Connection Circuit

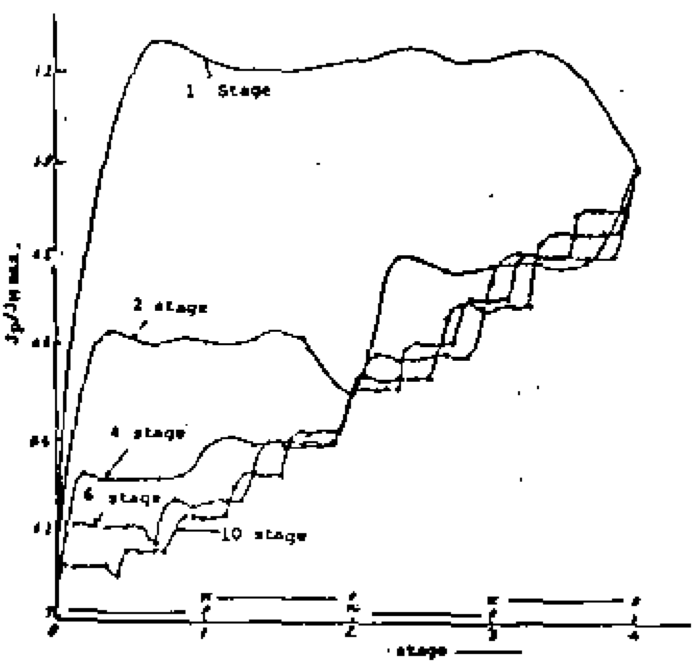


Fig. 8-42 JP under Multi Stage Control (Hybrid Bridge)

When the number of cascade connections increases, a greater effect may be brought about than those shown in Fig. 8-41 and Fig. 8-42 by commutation interference due to mutual leak reactance among the windings of the main transformer.

In particular power factor in the final condition and JP are the same regardless of cascade connection, but actually the greater the number of series connections, the greater the power factor and JP tends to decrease. As analysis of characteristics requires a complex circuit equation with many calculation elements involved and as it takes considerable time and labor for manual calculation, a computer is used for simulation. Fig. 8-43 shows a flow chart of the calculation.

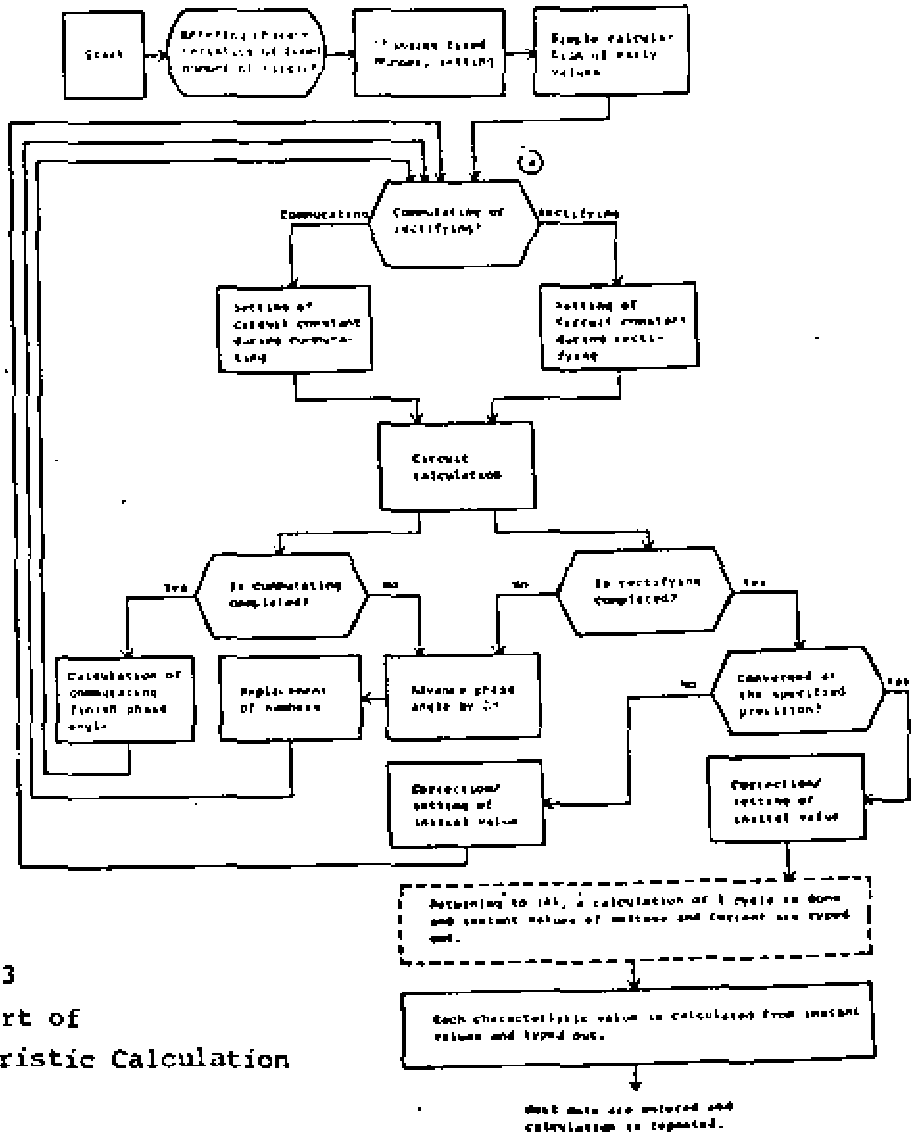


Fig. 8-43
Flow Chart of
Characteristic Calculation

Also for attesting the results of simulation and obtaining dynamic characteristics, sometimes final determination of a fixed number of circuits is made by using an exact model simulator which exactly simulates actual circuits elements and collecting various data.

8-4-2 Harmonic Influence due to the Rectifier Rolling Stock

The rectifier rolling stock by its nature includes many harmonics in voltage and current. This is because DC current is smoothed as much as possible for use and current suddenly changes by the commutation phenomenon occurring at each cycle.

Many faults occur due to such high harmonic voltage/current. The main faults inculde inductive disturbance which is caused by inducing voltage on adjacent communication lines and mostly causing noise and signal disturbance which causes mis-operation on the signal track circuit due to the passage of load current of the electric rolling stock through the rail, and the effect upon the power supply system.

(1) Feeder System and Inductive Disturbance

The inductive disturbance of communication lines includes electromagnetic induction and static induction, but in most cases only electromagnetic induction may be considered. As voltage is induced on adjacent communication lines by trolley line current and return current of the rail and ground, a method of reducing induction by collecting return current to the return circuit installed comparatively near the trolley line is adopted. The method includes the booster transformer (BT) system shown in Fig. 8-44 and the auto transformer (AT) system shown in Fig. 8-45. In the case of the BT feeder, the current of the negative feeder line and that of the trolley line are the same but in the case of the AT feeder, as current is divided in half and passes through the negative feeder line and trolley line and feeder voltage is twice as much, voltage being reduced to 1/2. Therefore, feeder distance can be extended.

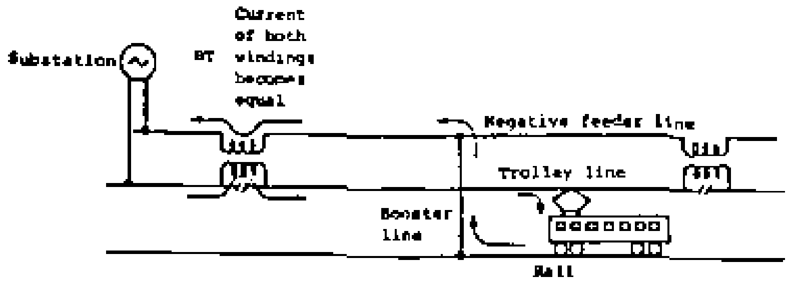


Fig. 8-44 Feeder System (BT)

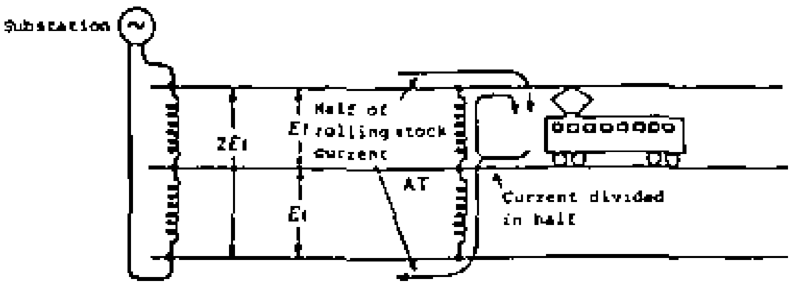


Fig. 8-45 Feeder System (AT)

(2) Method of Showing Induction Trouble and Forecasts

As a method of evaluating induction trouble, equivalent jamming power Jp is used on the trolley line side (inducing side). Jp is obtained from the following equation.

$$Jp = \sqrt{\Sigma (S_n \cdot I_n)^2}$$

Where; Sn: noise evaluation factor (Fig. 8-46)

In: n-degree harmonic current content

As an equation to forecast noise voltage induced upon communication lines from Jp, JNR uses the following equation.

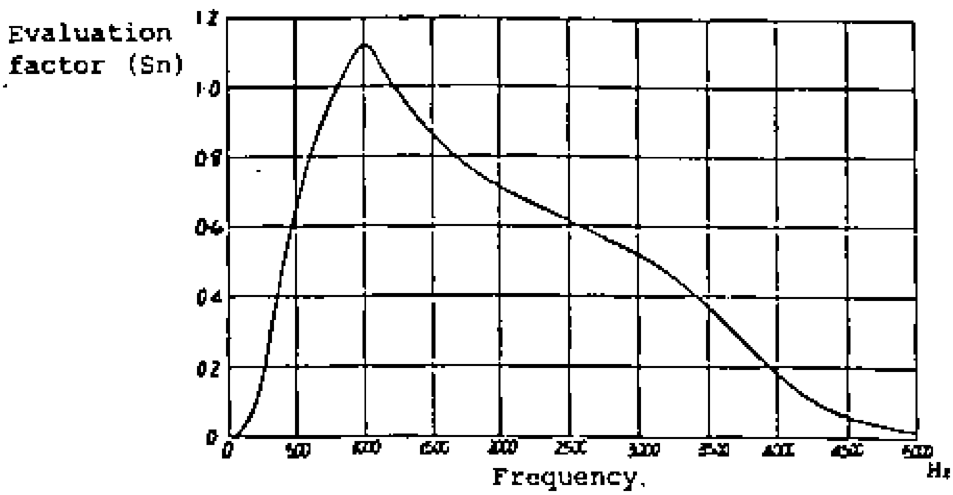


Fig. 8-46 Noise Evaluation Factor (1952 CCITT)

Noise voltage $V_N = W_{800} \cdot M_{800} \cdot Jp \cdot \ell \cdot K_{800} \times 10^{-3}$ (mV)

Provided, $W_{800} = 2\pi \times 800$

M_{800}: Mutual induction factor of trolley line and communication line at 800 Hz

ℓ: Parallel length of trolley line and communication line

K_{800}: Electromagnetic induction reduction factor at 800 Hz.

Jp obtained from the harmonic current calculated in 8-4-1 (4) is shown in Fig. 8-47. The larger the reactance on the AC side and the larger the ripple factor, the smaller Jp becomes.

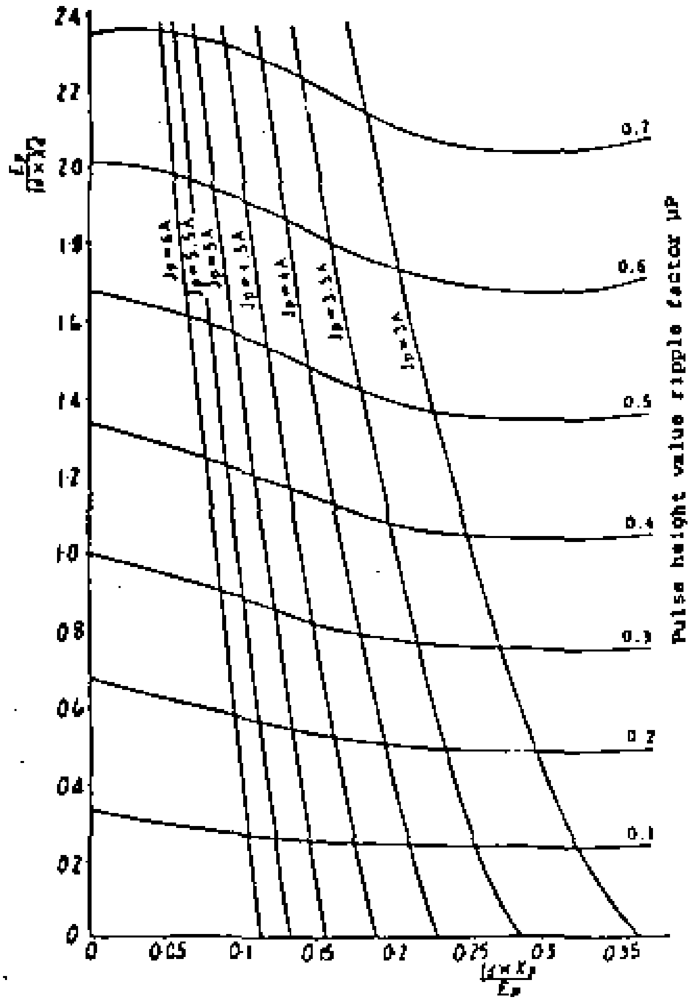


Fig. 8-47 · Relations between Ripple Factor and Jp
(No phase control)

8-4-3 Problems regarding Harmonics and Countermeasures

Generally harmonic current generated by the rolling stock on the thyristor side is larger compared with the conventional diode rectifier rolling stock and various troubles are liable to result in electrical systems, so various countermeasures are undertaken at both the rolling stock and the electrical equipment side.

(1) Multi Divisions of Secondary Winding of Main Transformer (multi-stage cascade connection)

As given in 8-4-1 (5) above, power factor can be improved and Jp can be reduced by dividing the secondary winding of the main transformer into many stages. But there is a limitation to the number of divisions from the standpoint of design and fabrication and the effect of harmonic reduction decreases when the number of divisions exceeds a certain level, so 4 or 6 stages are used in practical application. JNR uses 4 stages for 711 type, 781 type electric car and ED77, ED78 type AC locomotive and 6 stages for EF71 type AC locomotive.

(2) Vernier Phase Control System

This control system is a system of reducing harmonic current by increasing equivalent division with a small number of divisions.

200 type Shinkansen electric cars of the JNR divide the secondary winding of the main transformer into 6 sections and adopt the vernier phase control system.

Fig. 8-48 shows relations of notch orders of the master controller and the operation of rectifier units of 200 type electric cars.

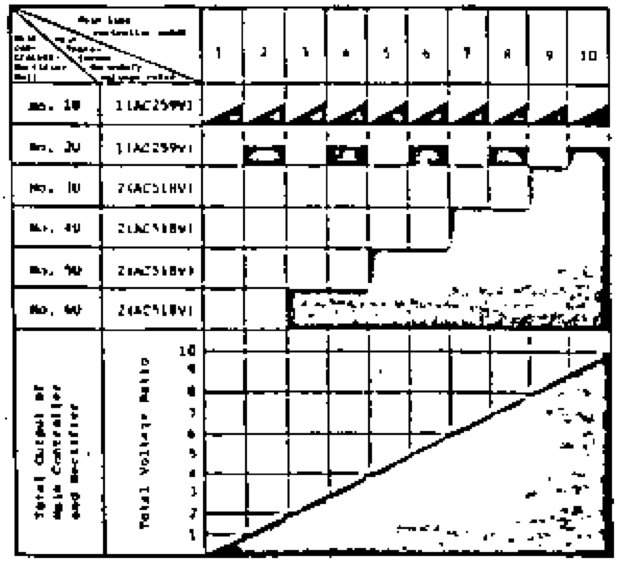


Fig. 8-48 Explanation of Notch Order and Rectifier Unit

The voltage ratio of each secondary winding of the main transformer of 200 type electric cars is, as shown in Fig. 8-48, comprised of 2 windings of ratio 1 and 4 windings of ratio 2 and equivalent 10 stages is carried out with a total of 6 sets of rectifier units (hybrid bridge). In other words, only the rectifier with winding of voltage ratio 1 of No. 1 unit (1/10 of total secondary voltage) is a continuous phase control stage and others are ON/OFF control stage at the control phase angle 0°. When the control angle of the phase control stage advances from 180° to 0° and DC output increases to its maximum, output of the phase control stage is reduced to 0 and at the same time the second unit is fully outputted and voltage is taken over. Then the phase angle of phase control stage is again controlled from 180° to 0° and voltage is gradually taken over. This is called vernier phase control.

Before and after taking over/changing of control stage voltage, DC output whole voltage is constant and continuous phase control over the full voltage range becomes possible.

Harmonic current can be made smaller by making the voltage of phase control stage smaller and using it repeatedly.

(3) Method of Increasing Commutation Reactance

Enlarging the overlap angle is effective in reducing the harmonic current. For enlarging the overlap angle, it suffices to enlarge reactance on the power supply side. But the power factor decreases and voltage regulation increases and then the specified performance of the rolling stock cannot be obtained. Such disadvantages in weight and economy are brought about with the increased rating of the main transformer (kVA) and the increase of number of stages of cascade connection due to insufficient output voltage.

JNR mostly uses around 20% of voltage regulation defined by the following equation at maximum voltage.

$$\varepsilon = \frac{Edo - Edr}{Edo} \times 100 = \frac{\Delta Ed}{Edo} \times 100$$

Provided, ε : Voltage regulation (%)

Edo: Non-load DC output voltage (V)

Edr: Rated voltage (rated voltage of main transformer × number of traction motors in series) (V)

$\Delta Ed = Edo - Edr$

ΔEd includes voltage drop of reactance of main transformer, voltage drop of DC resistance of main transformer, forward voltage drop of rectifying device and drop of DC resistance of main smoothing reactor.

If the vernier phase control system is adopted, there is a method of entering the reactor on the AC side only of the phase control as an effective method to reduce harmonic by enlarging overlap angle.

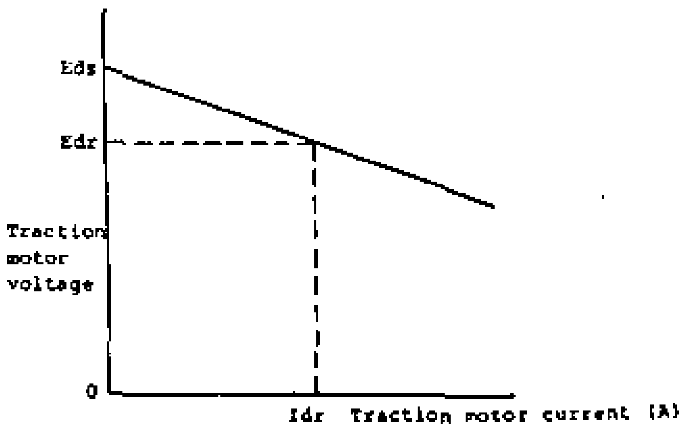


Fig. 8-49 Characteristics of D.C. Voltage Regulation

(4) Method of Controlling Thyristor Bridge as Hybrid Bridge

If the rolling stock is equipped with AC regenerative brakes, as it is necessary to have the function of reversing DC power to AC power, all arms of the bridge are comprised of thyristors. As explained before, such thyristor-bridge gate control systems have symmetrical control and asymmetrical control.

AC locomotives of the JNR equipped with the ED78 and EF71 type regenerative brakes of 1968 adopt recti-invertor type asymmetrical control. However, this system has, as shown in current waveform of Fig. 8-50, such disadvantages as getting large moving range of the current due to the existence of minimum control advance angle β min. in the low voltage (low speed) area and getting large equivalent jamming power Jp.

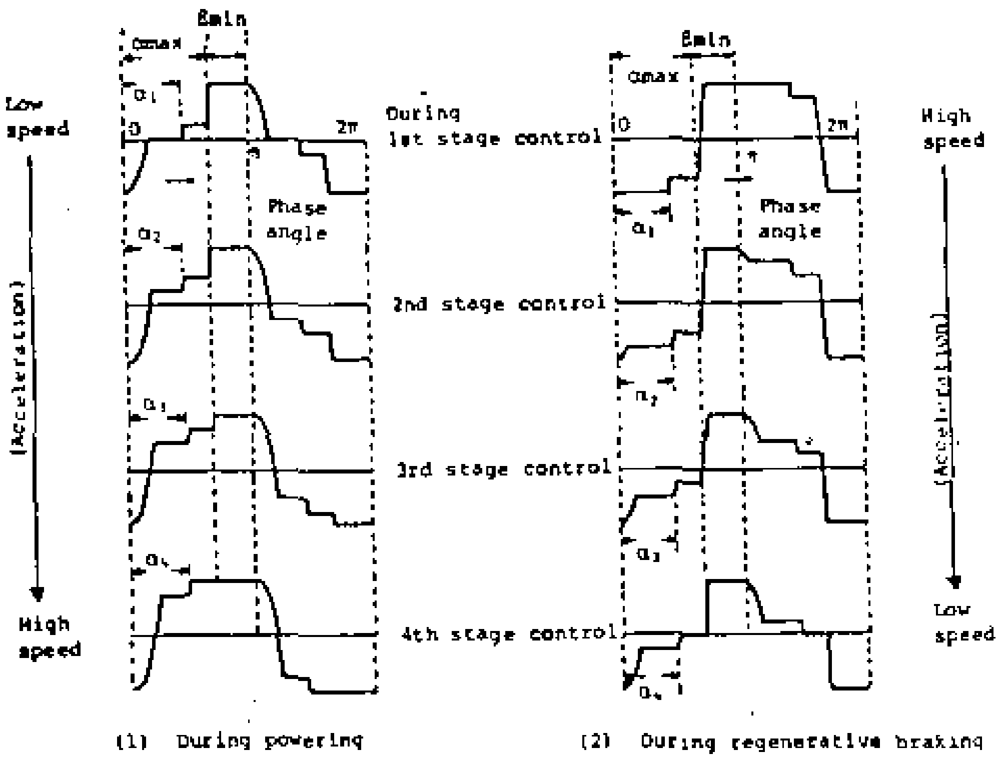


Fig. 8-50 Trolley Line Current Waveform of ED78 Type Regenerative Braking System Locomotive

As a new gate control system, a system of controlling thyristor-bridge as hybrid bridge has become the principal system of the rolling stock equipped with AC regenerative brakes for JNR in the future. This control of thyristor bridge like hybrid bridge type control (this is also a special type of asymmetrical control) is the system as shown in Fig. 8-51, where a black coated one side whole arm thyristor is fired as the free wheel diode of the hybrid bridge. By this method, the same waveform is obtained for DC current during powering as that of the hybrid bridge, and when regenerating, control is obtained by selecting AC winding according to the movement of the speed and the current moving range at β min. becomes smaller compared with recti-invertor type asymmetrical control. Fig. 8-52 shows the trolley line current waveform in the case of hybrid bridge type control.

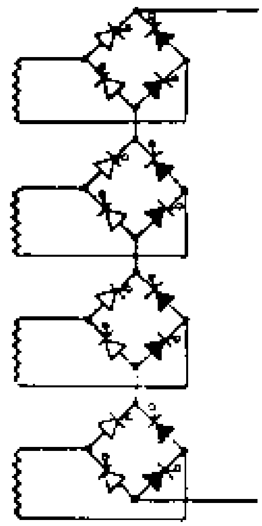


Fig. 8-51 Hybrid Bridge Type Control

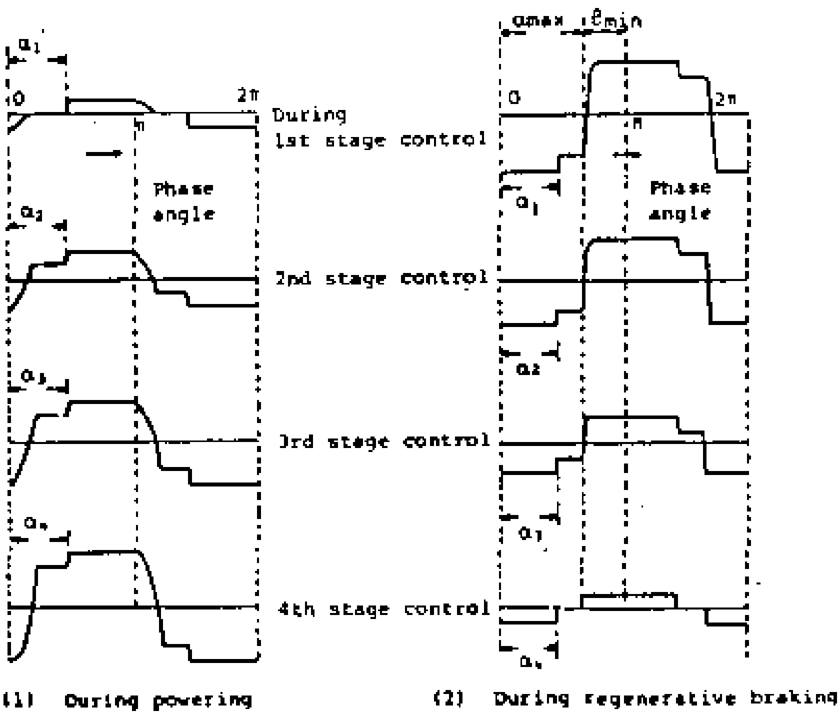


Fig. 8-52 Trolley Line Current Waveform of Hybrid Bridge Type Control

Fig. 8-53 shows a model plan to indicate the trend of Jp in the case of asymmetrical control and hybrid bridge type control. The reduction of Jp is an advantage of the hybrid bridge type control, while the current may pass through the black coated arm at all period (360°) shown in Fig. 8-51 and a thyristor of double rating is required compared with 180° DC arm.

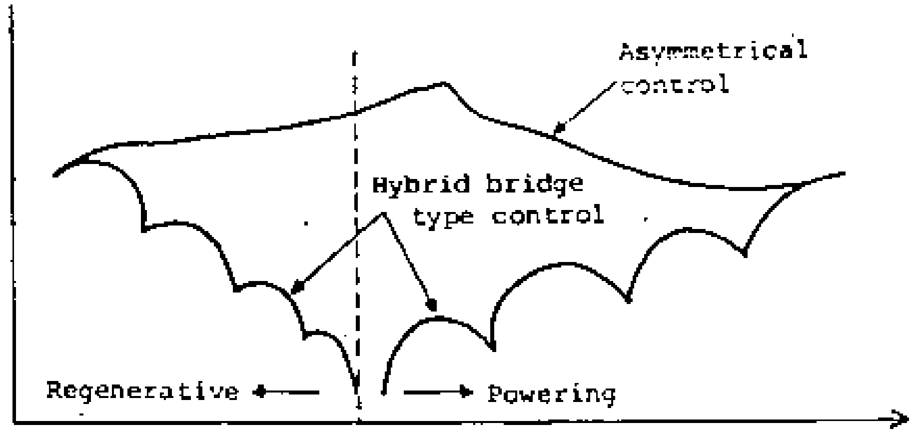


Fig. 8-53 Trend of Jp

(5) Unbalanced Reactance Viewed from Each Secondary Winding of Main Transformer toward the Power Supply Side

Nothing that making a gradual movement of primary current waveform during commutation will be effective in reducing Jp, it is possible to slow the movement of the primary current waveform by making the commutation period of each unit uneven by designing intentionally unbalanced reactance viewed from each secondary winding of the main transformer toward the primary side. Fig. 8-54 shows the AC current waveform of the rectifier unit and primary current waveform ip when magnetic coupling of each secondary winding with the primary winding is uneven.

Fig. 8-54 shows that when 4-stage rectifier units start commutation at the same time, primary current ip's movement is slowed down by sliding the commutation period (overlap angle) as shown in the figure. By using this effect, it is possible to reduce Jp without adding special parts, but sophisticated consideration is required for designing allocation of reactance of the main transformer.

(6) Method of Inserting Reactor

One of the reasons for primary current waveform becoming sharp is that AC current changes linearly during the commutation of the rectifier. Linear movements of current occur due to constant inductance at the circuit where the current changes and if induction changes with the movement of current, curved current movements are expected to occur. The saturation form reactor method shown in Fig. 8-55 is where such a saturation form reactor is used with a rectifier circuit.

As shown in the figure, the effect of slow change of current waveform is expected. The non-saturation reactor method shown in Fig. 8-55 is simply to enlarge the overlap angle and slow down current movement during commutation. But for 2 coupling type windings as shown in the figure, when the control angle is 0°, the current movement of both windings mutually offsets to show no reactance and to prevent the reduction of output voltage.

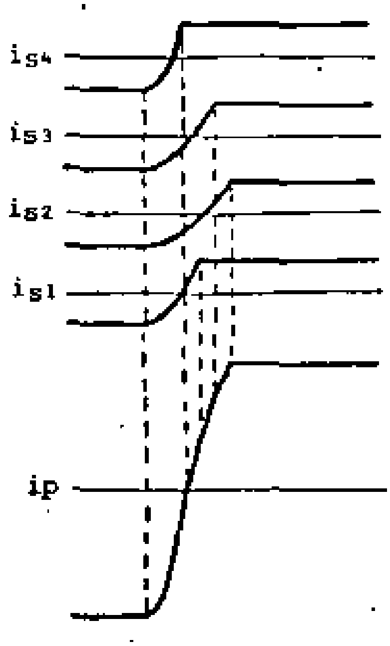


Fig. 8-54 Primary and Secondary Winding Current Waveform

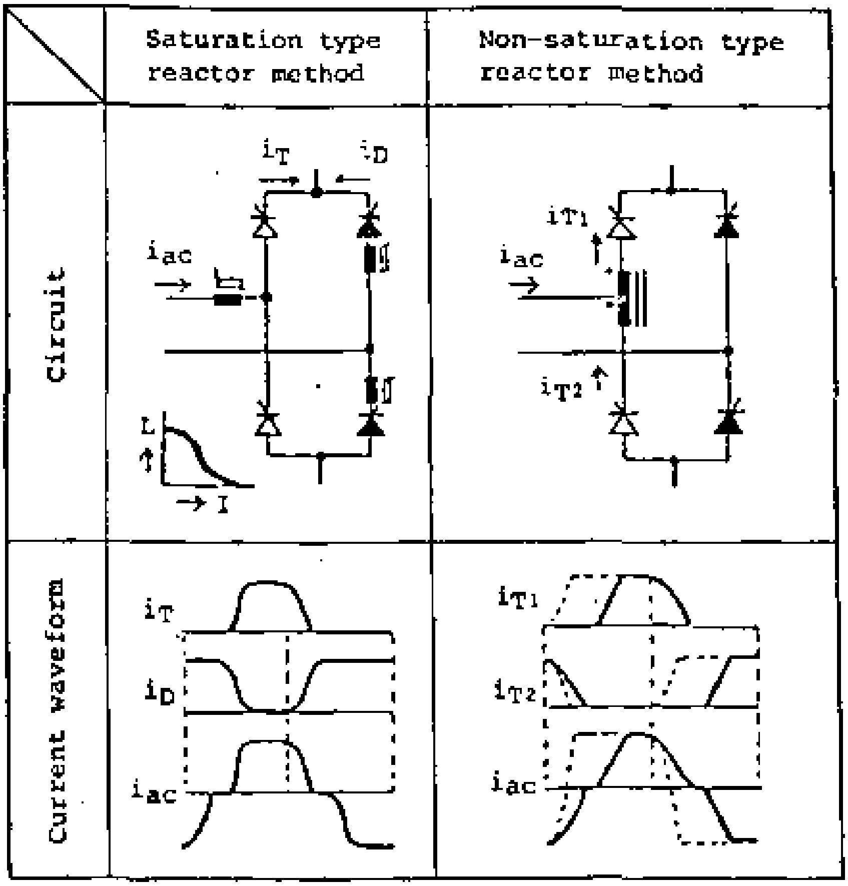


Fig. 8-55 Method of Making Obtuse Angle of Current Waveform by Reactor

8-4-4 Problems during the Regenerative Braking

Harmonic current characteristics and power factor characteristics during regenerative braking are, as during powering, greatly affected by reactance characteristics of the trolley line and main transformer and inductance of the DC side and influences by the control angle. Power factor characteristics can be improved qualitatively by setting small β min. of each thyristor bridge, which is connected in series, while JP is reduced by setting large reactance of the AC side. However, when reactance on the AC side is made larger, the overlap angle during commutation increases and then β min. increases.

As observed, the reduction of JP and improvement of power factor have contradictory conditions, so integral studies of these factors are made and reactance characteristics of the main transformer and β min. are set and the control systems are decided.

Fig. 8-56 - Fig. 8-59 show a comparison of power factor and Jp at the time of powering and regenerative braking with main transformer of the same characteristic.

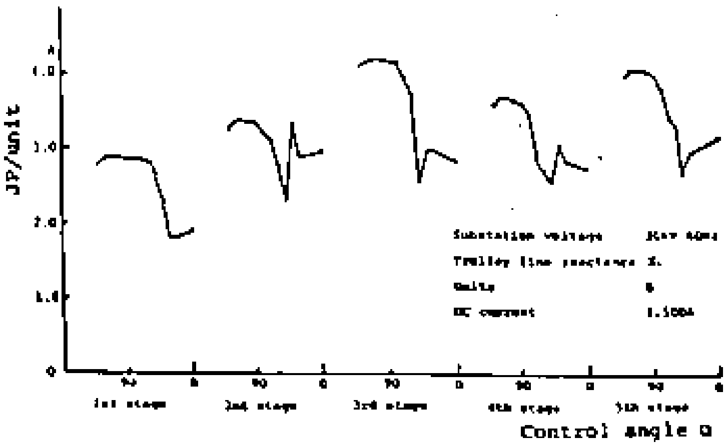


Fig. 8-56 JP Characteristic during Powering

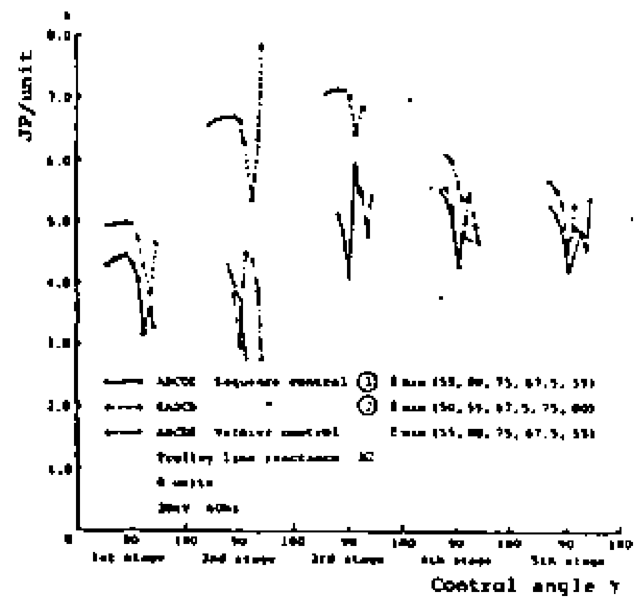


Fig. 8-57 JP during Regenerating and Winding Control Method

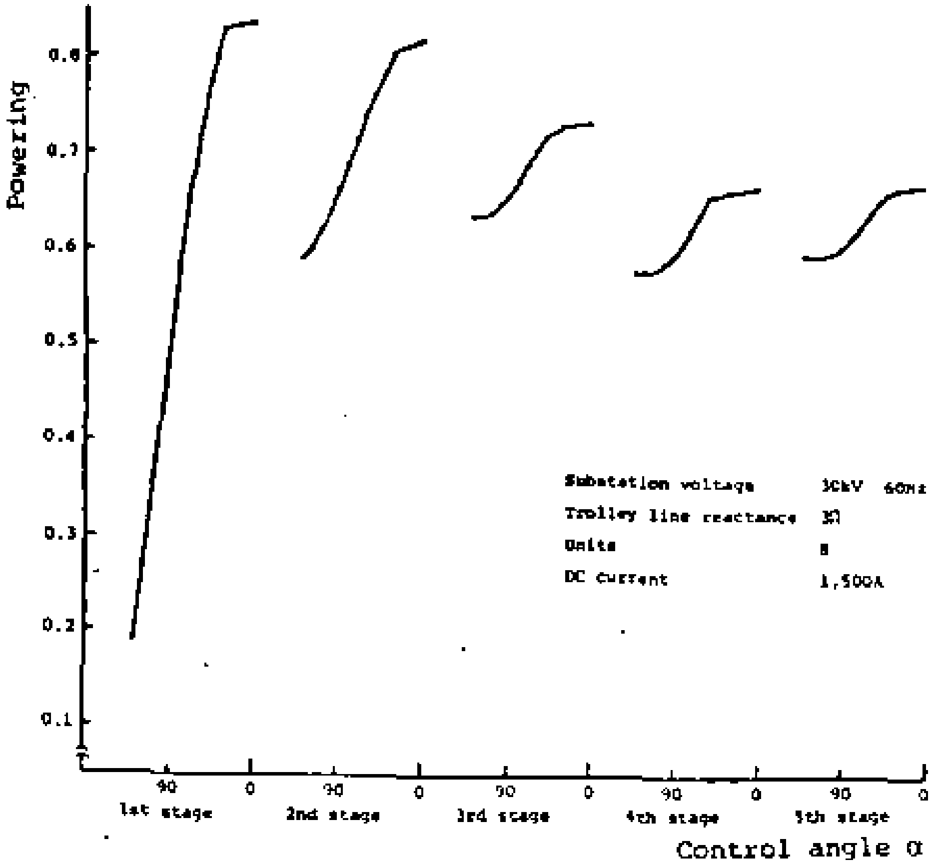


Fig. 8-58 Power Factor Characteristic during Powering

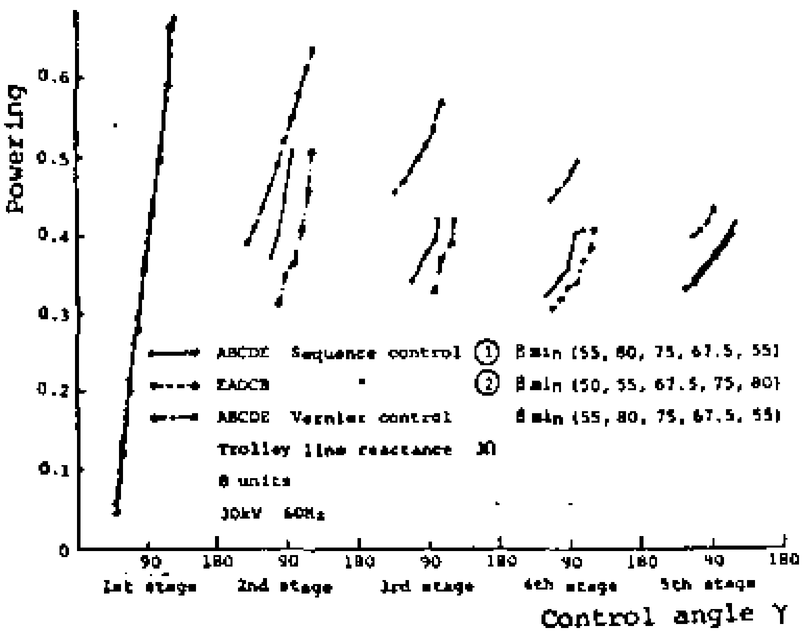


Fig. 8-59 Power Factor during Powering and Method of Winding Control

CHAPTER 9

DETERMINATION OF SPECIFICATIONS FOR MAJOR EQUIPMENT OF AC ELECTRIC ROLLING STOCK

CHAPTER 9. DETERMINATION OF SPECIFICATIONS FOR MAJOR EQUIPMENT OF AC ELECTRIC ROLLING STOCK

9-1 Co-ordination of Insulation, Co-ordination of Protection and Protection Equipment

9-1-1 Co-ordination of Insulation of Extra High Voltage System

Power system of electric railway including substation, contact line and electric rolling stock is an extra high voltage circuit of several tens of kilovolts, and countermeasures for lightning surge and switching surge are necessary as in the case of a general power system. However, it is useless and disadvantageous to have the same level of dielectric strength to substations, contact lines and electric rolling stock. Therefore, it is necessary to make rational positioning of dielectric strength requirements for each of these components, and keep clear of the range of protection role assignment for each component. An example of co-ordination of insulation for JNR's Shinkansen is shown in Fig. 9-1. Co-ordination of insulation shall be considered separately for shock waves such as lightning surges, switching surges, and abnormal voltage in commercial frequencies.

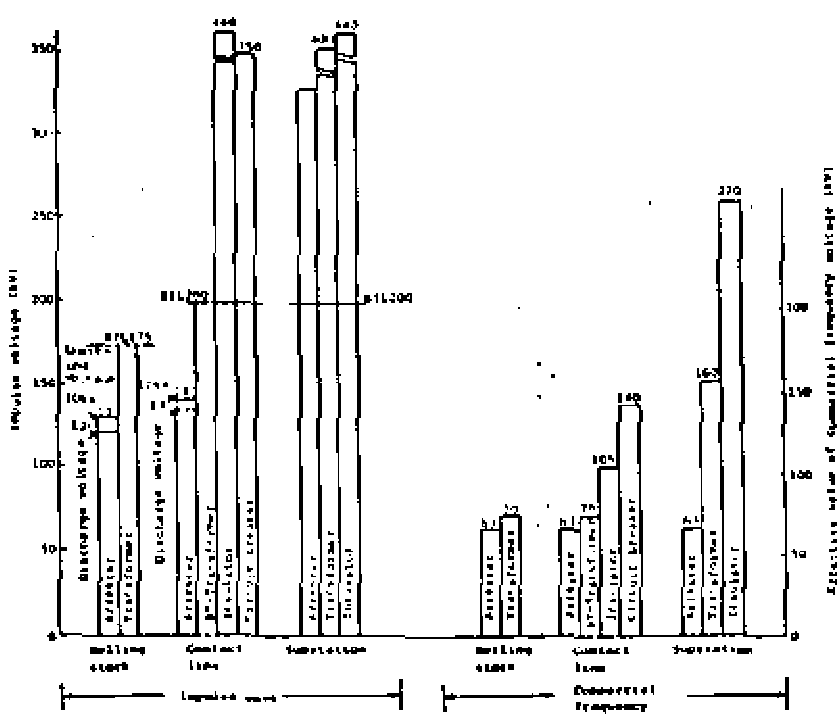


Fig. 9-1 Co-ordination of Insulation for JNR's Shinkansen 25 kV B.T. Feeder System

A direct lightning strike is discharged by the insulator line, and abnormal impulse voltage at a voltage lower than the insulator voltage is discharged by the lightning arrester, and the voltage for the lower system is restricted. Because of the large energy of the switching surge, it is generally devised not to be discharged by an arrester.

Value of the test voltage for dielectric tests, and impulse voltage tests for newly manufactured electric rolling stock equipment is determined based on the limit voltage of the arrester. Table 9-1 indicates the values of dielectric strength test voltages of international specification (IEC 77) and JNR specification (JRS). In the case of JNR, values of dielectric strength for high voltage equipment are wet condition for outdoor equipment and dry condition for cab equipment.

Table 9-1 Dielectric Strength Test Voltage

	International electrotechnical commission (IEC 77)	JNR 20[kV] system		Shinkansen 25[kV] system	
	Commercial frequency	Commercial frequency	Impulse wave	Commercial frequency	Impulse wave
Air-blast circuit breaker (interpole)	2.2E+2[kV]	70[kV]	140[kV]	70[kV]	175[kV]
" (to ground)	2.2E+2[kV]	Dry 70[kV] Wet 60[kV]	Wet 120[kV]		
Main transformer (primary side)	1.75E+1.5[kV]	50[kV] 2 min.	120[kV] Chopped wave 140[kV]	42[kV] 10 min.	175[kV]
" (secondary side)	2.25E'+2[kV]	10[kV]*		10[kV]*	

Note: Dielectric test time 1 min., except otherwise specified.
E: Effective value of nominal voltage (kV), E': Effective value of secondary side no-load voltage (kV), *: For circuit volt of 3 (kV) or less.

9-1-2 Protection System of Electric Rolling Stock

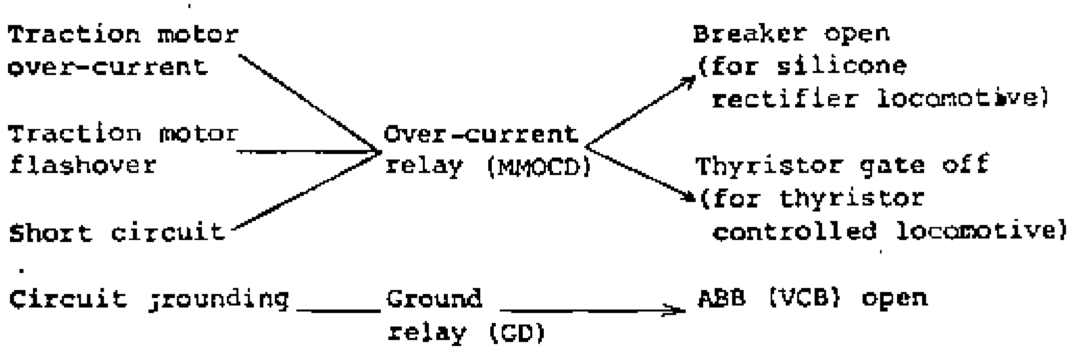
Failure in electric circuits includes insulation difficulties such as short circuits, grounding, etc., abnormal increase of voltage and/or current, temperature rise caused by failure and/or performance reduction of cooling equipment, etc. Failure detection instruments will be prepared with corresponding structure, and steps to be taken with respect to the failure are mainly taken by cutting out the circuit.

Protection units of the main circuit are classified from the end, as traction motor circuit, convertor circuit, and total circuit including main transformer. The main circuit of JNR's AC electric locomotive, type ED 77, is shown in Fig. 9-2 as a representative example of a main circuit.

(1) Protection of Traction Motor Circuit

Traction motors and their circuit switches, control equipment and cables are subjected as the object of protection, and their abnormal phenomena and dispositions against them are as shown in Table 9-2.

Table 9-2 Protection of Traction Motor Circuit



Detection sensitivity of over-current relay is desirable to be selected to operate as near as practicable to the maximum allowable current of the traction motor, taking also over-current protection into consideration. As for the protective cutout, a line breaker as normally used for circuit switching is employed as it is for the protective cutout. This method was adopted for the reason that over-current in the case of short circuit, etc., is relatively small because in an AC electric locomotive voltage drop in the main transformer and main rectifier is large and the circuit voltage is also generally low.

(2) Protection of Power Convertor Circuit

Protection of the silicon rectifier circuit and/or thyristor contorlled rectifier circuit include many items such as over-current protection, temperature protection of elements, restriction of abnormal voltage intrusion, abnormality detection of phase control device, etc. Items of detection, detection instruments and protection procedures are shown in Table 9-3.

Table 9-3 Protection of Power Convertor Circuit

Short circuit	Over-current relay (MRfOCD)	ABB (VCB) open
Element short circuit	Over-current relay (MRfOCD)	ABB (VCB) open
Grounding	Ground relay (GD)	ABB (VCB) open
Abnormal phase control	Fault detecting device	ABB (VCB) open
High temperature of element	Temperature relay	Traction motor circuit open
Abnormal element	Fault detecting device	Indication (continue operation)
Abnormal voltage	Suppressed by arrester and surge absorber	

(3) Earthing Protection

Because the secondary circuit of the main transformer is cut off from the earth (rail, body), each instrument of AC-rolling stock shall be grounded at some place to fix its voltage to ground to a certain value. Normally, earthing is made through a resistance of about 1 kΩ to restrict the current under earth fault to about several amperes as well as to detect the current to find out the earth fault. This will reduce damage to equipment caused by earth faults, and allows a highly sensitive detection of earthing. This current detector is the ground relay, which covers all the main circuit from secondary winding of the main transformer to traction motors. Therefore, the protective cutout is to be performed by cutout of the main switch (ABB) of primary side of the main transformer.

Too sensitive a ground relay may cause frequent operation even under small reduction of insulation without any actual damage.

Therefore, it is advisable to have detection at a value of about 0.2 ∿ 0.5A.

(4) Protection of Whole Circuit

Ultimate protection on AC-rolling stock will be made by an air-blast circuit breaker (ABB) or vacuum circuit breaker (VCB) which is a main switch. These main switches are operated by a signal from the various failure detectors mentioned above.

On the primary side of the main transformer an AC-over-current relay is also installed to detect over-current caused by a short circuit or earth fault of the main transformer or tap changer. This relay, however, is sometimes devised to act with about a 0.5 sec. operation time lag. The purpose of the delay is to prevent mis-operation by excitation input current of the main transformer, because of main breaker closing or reenergization at crossing the dead section. Excitation input current of the main breaker varies with the phase at the time of reenergization, and of usually 7 to 8 times the current flows and takes about 0.2 sec. until it is stabilized.

In relation to the protection of the main transformer, leakage impedance is larger for secondary side failure, and

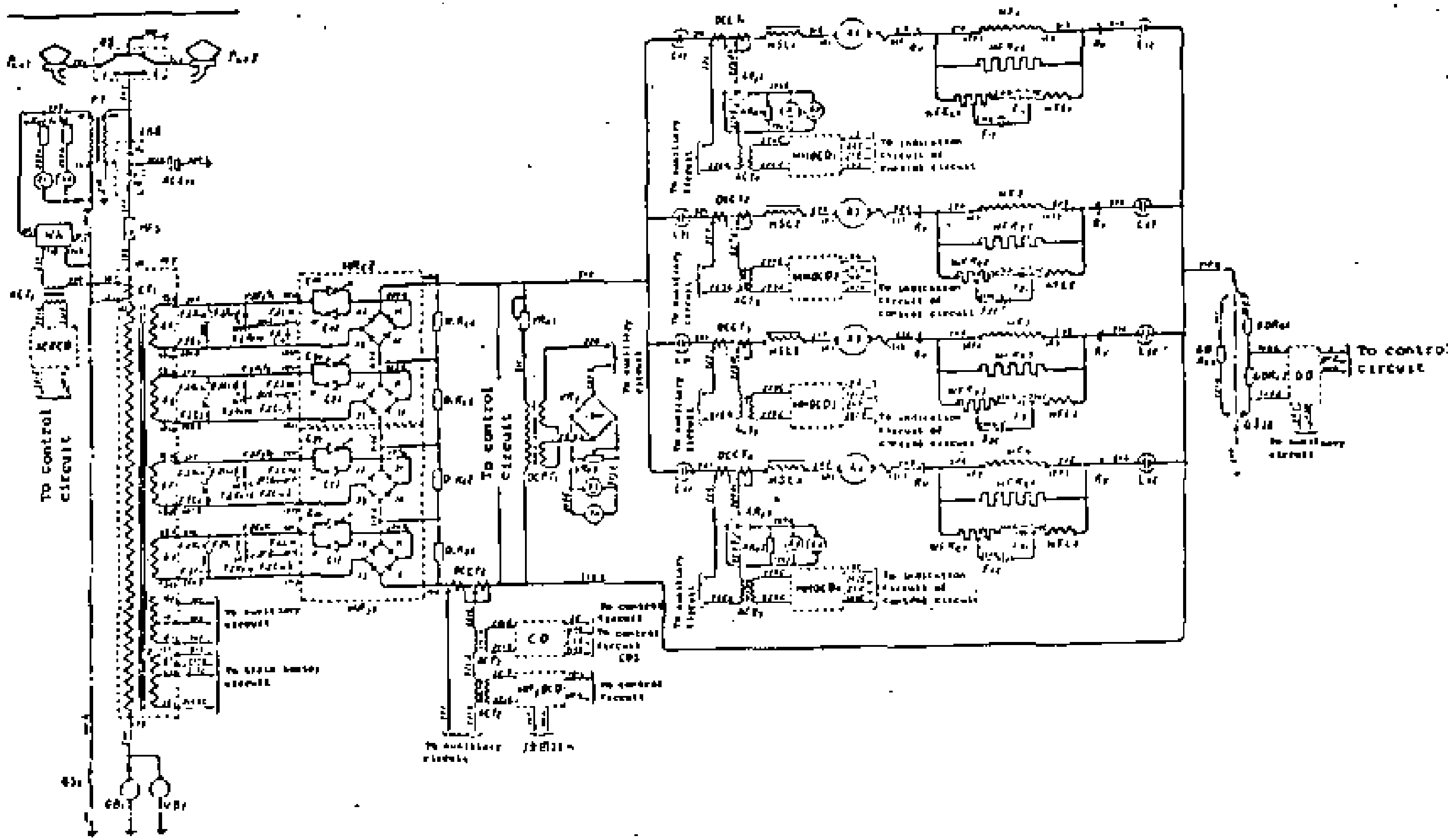


Fig. 9-2 JNR Model ED77 AC Electric Locomotive Main Circuit Diagram

the primary side fault current is relatively small, with time lag causing no problem.

On the other hand, fault current is very large with supposed primary side metallic circuit shortage, may exceed the capacity of main breaker, and when near a substation, the spread of fault by failing to cut out on the rolling stock can be considered. Therefore, protection co-ordination may sometimes be necessary to protect the primary side assigned to the on-land protection range.

9-1-3 Equipment for Protection

(1) Arrester (Lightning Protector)

An extra high voltage circuit may be intruded with abnormal voltage caused by lightning surges, etc. An arrester is installed to restrict the abnormal voltage value to a value lower than the insulation level of the equipment. In Europe, simple discharge gaps only are sometimes applied in lieu of expensive arresters. In this case, a trip arrester is installed in the substation for discharge.

The AC-arrester is made to be sealed in a double porcelain tube structure, and is filled with inert gas as shown in Fig. 9-3. As for the internal circuit, the indirect line resistance and 6 kV discharge gap unit are piled up in series in just the number appropriate for the rated voltage. The discharge gap unit is shown in Fig. 9-4.

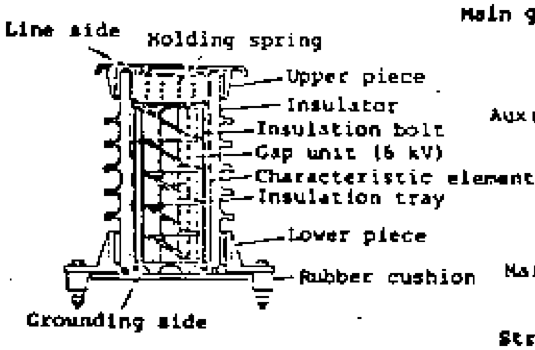


Fig. 9-3 Model LA105A Arrester

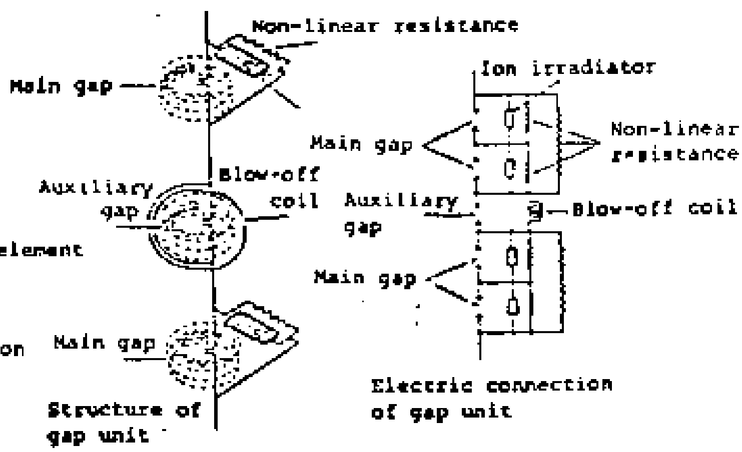


Fig. 9-4 Discharge Gap Unit (6 kV)

The specifications of JNR's standard arrester LA105 and LA201 are also shown in Table 9-4.

Table 9-4 Performance Specifications of 20 kV and 25 kV Arrester

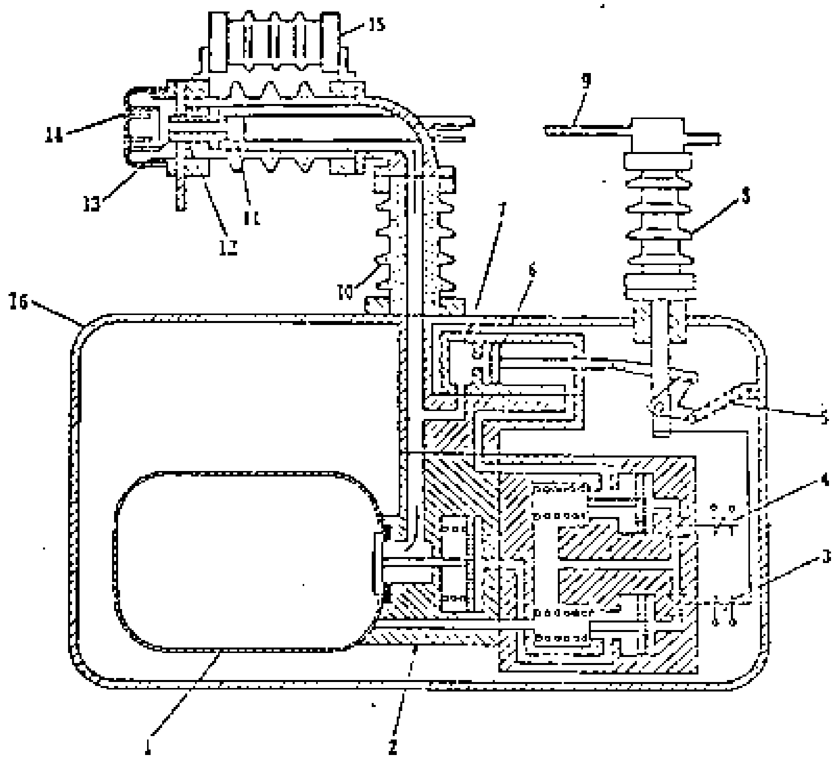
Type	LA105 (for 20 kV)	LA201 (for 25 kV)
Rated voltage (kV)	30	42
Nominal discharge current (kA)	10	10
Discharging voltage of commercial voltage (kV)	48	63
Discharging of impulse voltage (kV)	Less than 80	Less than 120
Relaxed impulse wave discharging voltage (kV)	Less than 80	90 ∿ 120
Discharge current at 5 kA	Less than 75	Less than 120
Discharge current at 10 kA	Less than 85	Less than 130

(2) AC-main Fuse

In cases where the possibility of AC-rolling stock being driven by mistake into a neighboring DC-section is foreseen, a main fuse is installed to protect the coil of the main transformer. Fusing characteristics of the main fuse will be determined from the following requirements: i) in the case of driving into a DC-section, protection shall be secured even if the contact line voltage is low, ii) co-ordination with the short-circuit current proof value of the coil shall be maintained, iii) in an AC-section the fuse shall not be fused before the ABB is cut off against fault current.

(3) Air-blast Circuit Breaker (ABB)

Fig. 9-5 indicates the structure of an air-blast circuit breaker. When closing the breaker, the disconnecting portion



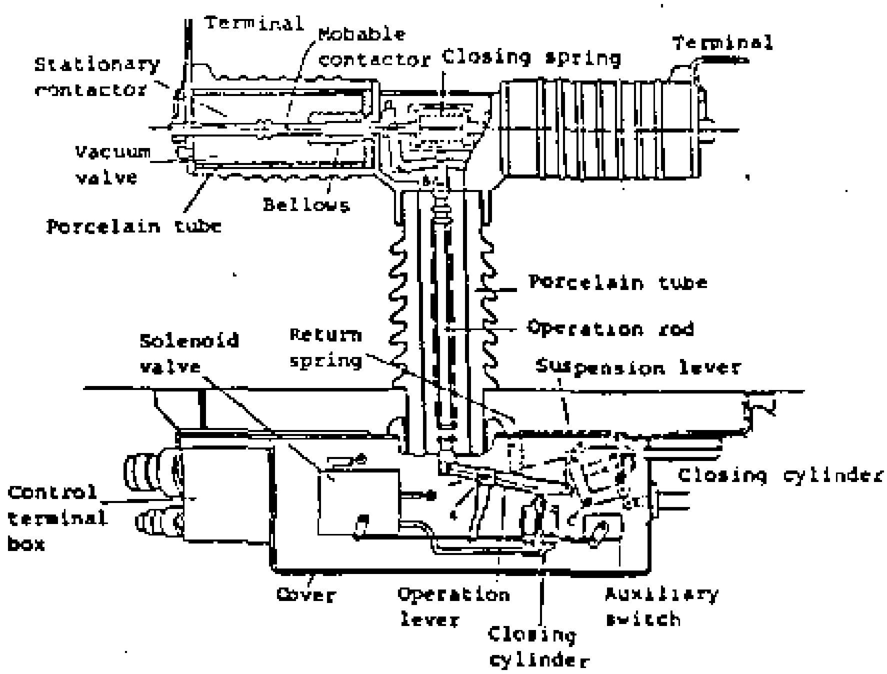
1. Air cylinder
2. Main valve
3. Circuit-opening electro-magnetic valve
4. Circuit-closing electro-magnetic valve
5. Toggle spring
6. Breaker operation piston
7. Breaker operation cylinder
8. Breaker rotary insulator
9. Blade of breaker
10. Porcelain tube for ventilation
11. Fixed contactor
12. Spring for movable contactor
13. Movable contactor
14. Cover of breaker
15. Non-linear resistance
16. Base

Fig. 9-5 Operation of Air-blast Circuit Breaker

is closed; and in the case of breaking, the main valve is opened and the disconnected portion is cut off while compressed air (7 kg/cm^2) is blown to the spot. Extinction time of the arc of the disconnecting portion is quite short to be within 1-cycle after cutoff, and the total breaking time is within 3-cycles. Because the surge voltage of the breaking circuit (switching surge) has a large influence on the excess voltage proof value and/or insulation specifications of main circuit electric equipment, non-linear resistance is connected between the poles of the disconnected portion so that abnormal voltage during switching will not exceed 200% of normal service voltage.

(4) Vacuum Circuit Breaker (VCB)

This breaker employs a vacuum valve circuit breaker for high voltage applying high dielectric strength and arc diffusion action in the vacuum, to the disconnecting portion. The structure of the breaker is shown in Fig. 9-6. Compressed air is used for making; however, the breaking is performed by the spring force by exciting the tripping coil. Because of this simple structure and small action stroke (about 30 mm), the VCB allows a very simple operation mechanism, small and lightweight in comparison with the ABB. Sufficient attention should be paid to the selection of non-linear resistance between poles, as the high performance of circuit breaking may cause cutout before



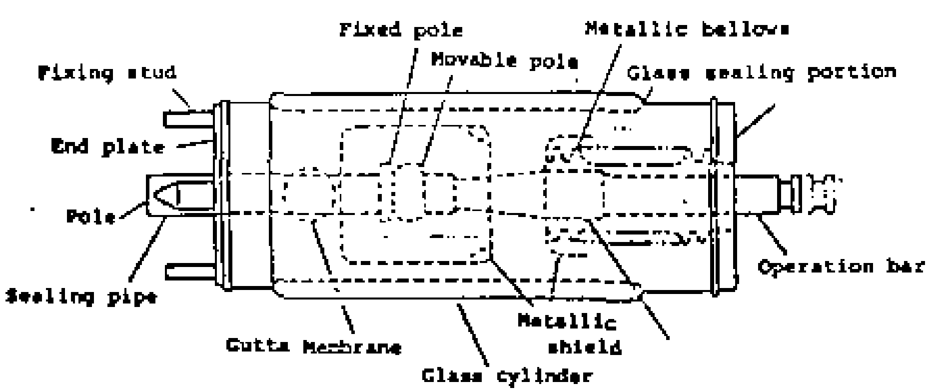


Fig. 9-6 Vacuum Circuit Breaker and Vacuum Valve

the zero point of current reversal, resulting in the yield of a large surge voltage.

Ratings of ABB and VCB being used by JNR are shown in Table 9-5.

Table 9-5 Specification of Air-blast Circuit Breaker and Vacuum Valve Circuit Breaker

Type	ABB		VCB	
Model	CB103 series (for 20 kV)	CB200 series (for 25 kV)	CB105, 106 series (for 20 kV)	CB201 series (for 25 kV)
Rated voltage (V)	24,000	30,000	24,000	30,000
Rated current (A)	300	200	300	200
Rated frequency (Hz)	50/60	60	50/60	50/60
Rated cutout capacity (MVA)	100	100	100	100
Rated contact parting time (S)	0.04	0.04	0.04	0.04
Rated interrupted time (S)	0.06	3-cycles (0.05)	0.06	3-cycles (0.05)
Operating pressure (kg/cm^2)	7	8	5	8

9-2 Pantograph

9-2-1 Outline

Various types of current collecting devices are adopted in accordance with types, structures, conditions of railways, in which pantographs and collector shoes are most widely used at present, and trolley poles, bugels, etc., are also used in smaller proportion. Among those above, pantographs are used for catenary contact line systems, and large capacity high speed electric cars; and a variety of pantographs is used according to the object of service such as system of electricity, structure of car, running condition, etc.

9-2-2 Types of Pantographs

Forms of pantographs include the Z-type and trapezoidal-type, and each of these has a variety of types in accordance with the system of raising and lowering, the system of contact line, size and structure of the framework depending on the variation of contact line heights, differences in electric system, AC or DC. A comparison of the Z-type and trapezoidal-type will be discussed later, and types of pantographs and their special features are as follows:

(1) Operation System

(a) Spring Raising and Pneumatic Lowering System

When raising a pantograph, the hook will be released by an air cylinder or a solenoid, and the pantograph is raised by the force of the spring, and is lowered by the air cylinder.

This system is applied in many of JNR's DC-cars, because it can be operated with a manual hook releasing by combined installation of such apparatus (in the case of solenoid application, it is not necessary), in cases where a compressed air source is not available, and the structure is rather simple.

(b) Pneumatic Raising and Gravity Lowering System

Force for raising the pantograph is by the spring force as in the case of spring raising, however, the spring is pulled by a pneumatic cylinder. When the pantograph is to be lowered, compressed air in the cylinder is discharged to reduce the spring force, and the pantograph will be lowered by its own weight.

This system has less possibility of damaging the contact line, because of its ability to control the raising speed, and is applied in JNR mainly for DC-electric locomotives by which the amount of current collection is large.

(c) Pneumatic Raising and Spring Lowering System

Raising and lowering action is taken by charging and discharging air in the air cylinder as in the case of pneumatic raising and gravity lowering system, however, a lowering spring is installed as well as a raising spring, and the lowering spring overrides the raising spring force when compressed air is discharged to lower the pantograph. Also, during the raising, spring force is killed by the air cylinder to raise the pantograph.

This system allows a simpler structure than that of pneumatic raising and gravity lowering system, and is used widely on AC-, AC/DC-cars, electric locomotives of JNR, etc.

(2) Size and Structure of Frame

Size of the framework is determined by the required moving range in accordance with the height variation of the contact line. Shinkansen allows the use of a small pantograph frame from its almost constant contact line height, however, in cases of large variations of height as in the conventional lines (low height portions exist in some tunnels and over-bridged lines), large moving range shall be secured and the framework consequently increases in size.

Framework is structured in most cases in trapezoidal form, however, in some cases when the occupation area on the roof is required to be reduced, crossed lower frame type, which has its lower half frame crossed, is also used.

(3) Difference by Electric System of AC and DC

There is basically no difference in pantographs according to whether AC or DC current is used; generally however, by the large difference of contact line's voltage between AC-system and DC-system, difference of collector bow and number of pantographs, different materials of the sliders are resulted in, and a large current collection type is required by DC-rolling stock. In the case of AC/DC-rolling stock, although changeover of pantograph between AC and DC sections can be adopted, at least it is necessary to prepare the large current collection ability required in the DC section.

9-2-3 Structure of Pantograph

A pantograph consists of a collector bow or bows to which sliders which contact the contact line are attached, suspension device to hold the collector bow, a framework which enables the collector to be raised and lowered in accordance with the height of the contact line, and a base frame for supporting this framework, and also operating components to raise and lower the pantograph such as springs, air an cylinder, etc. The base frame is mounted on porcelain insulators on the roof.

(1) Collector Bow

A collector bow is equipped with sliders which slide with the contact line, and the materials of the slider are sintered copper or iron base alloy, melted copper base alloy, iron, carbon, etc., and shall be selected in consideration of current collection capacity including that for requirements during stopping, resistance to wear, etc.

(2) Collector Bow Suspension Device

Various structures of the devices to support collector bow are available, and two examples from JNR are shown as representative examples of them; Fig. 9-7 indicates principle of PS-16 type for catenary contact line, and Fig. 9-8 indicates that of PS-21 type for rigid contact line (for joint operation with underground railway). Basic structure is almost the same allowing movement front and back, up and down, around and back by way of a combination of springs and links. The latter one, the PS-21 type, employs a spring system combining coil springs and rubber bellows between the collector bow and suspension arm in consideration of easy follow up to fine variation of positions, because of the rigid contact line system of subways.

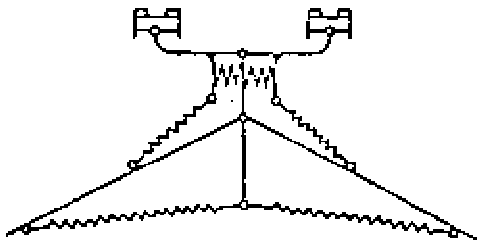


Fig. 9-7 Pantograph for Catenary Contact Line (JNR PS-16 Type)

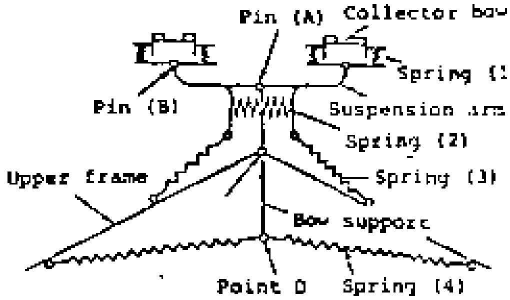


Fig. 9-8 Pantograph for rigid Contact Line (JNR PS-21 Type)

(3) Framework

A framework consists of an upper framework and a lower framework, to form an N-truss for the upper framework, N- or M-truss for the lower framework in the case of a trapezoidal structure employing steel or aluminum pipe. However, stainless pipe structures are increasingly used in recent years to cope with the requirements of maintenance free structure or prevention of strength reduction due to corrosion, etc. Lower frame crossing type employs the same upper frame structure as that of the trapezoidal type, however, tapered steel or a square stainless tube is used for the lower frame in lieu of truss structure.

9-2-4 Performance of Pantograph

(1) Upward Force Characteristics

Upward force is a static force pressing the slider of a collector bow to the contact line. It significantly affects the follow-up characteristics. The follow-up characteristics are improved with increasing upward force, however, too high an upward force may give rise to problems of inadequacy with contact line structure or increased mechanical wear of slider and contact line, and too low an upward force will cause generation of arc as a result of a reduction of follow-up characteristics and leads to the increase of electrical wear of the slider and contact line. JNR is presently adopting an upward force of 5.5 kgf in the case of DC-cars, AC/DC-cars, and the Shinkansen, and 4.5 kgf in the case of AC-cars, as the standard value, but those values lie in the lowest group from an international point of view. The most suitable value of upward force is desirable to be determined in overall consideration of collecting current, service speed, structure and condition of the contact line, weather condition, material of the slider, etc., which affect the desirable value. (Fig. 9-9)

The upward force is desirable to have flat characteristics without relation to the change of working heights of the pantograph.

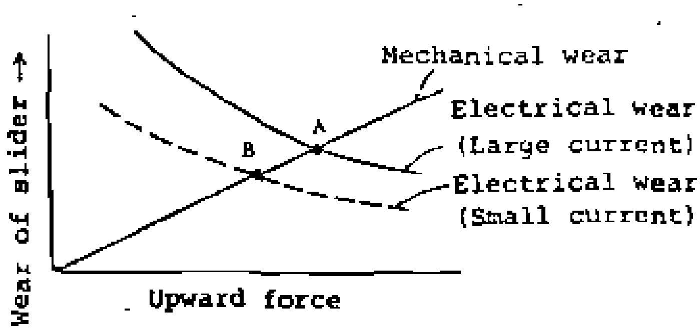


Fig. 9-9 Relations between Wear of Slider and Upward Force

(2) Follow-up Characteristics

Follow-up characteristics are one of the most important items in the current collection system.

The dewiring phenomenon is generated by improper follow-up characteristics, and consequently magnitude and frequency of dewiring and rate of dewiring are used to evaluate the follow-up characteristics. As the magnitude of dewiring, they are roughly divided into small-, medium-, and large-dewiring. Small dewiring is a phenomena of 1/100 sec or less dewiring for each time, giving rise to almost no actual damage. Medium dewiring is that of 1/100 to 1/10 sec. and in many cases arises from the jumping of the collector bow at a point of discontinuity in the contact line (hard point, variational point, etc.). This may not cause problems in cases of low frequency, however, it generates problems of increased slider wear and partial wear of contact line, etc., with increasing frequency. Large dewiring is a phenomenon of the dewiring exceeds 1/10 sec. at one time, and is mostly caused by inability of following-up by the collector bow itself at supporting points of the contact line or at section points. This may cause not only abnormal wear of slider and contact line but also may have a bad effect on electric equipment, and must be restricted as much as possible.

Dewiring rate indicates rate of the time in which pantograph is apart from the contact line during the car running, and is normally said to be desirable to be 1% or less in DC-lines and 3% or less in AC-lines. However, the value sometimes attains to several tens per cent under high speed running or by a rigid contact line, the effect of dewiring has other relations with the size and frequency of dewiring and the rate cannot be evaluated unconditionally.

(3) Capacity of Current Collection

The capacity of current collection is very much different in conditions under stopping and running and it is necessary to consider them separately.

Current collected during the stopping of cars is restricted by the temperature rise of the contact point of the contact line and slider, and it is necessary to be restricted to a certain range causing no decrease of tensile strength of the contact line (about 150°C or less), being caused by heating of the contact line. In the case of a carbon slider, resistance value, and consequently the temperature rise, is large, resulting in a small permissible current.

Current collection during running is mostly decided by the wear of the slider, the wear is also affected largely by other factors as stated, and is empirically decided by actual car tests, etc. Allowable current values by JNR are approximately as given in the Table 9-6.

Table 9-6 Criteria for Permissible Current Collection Value (per one pantograph)

	Stopping		Running	
	Continuous	Peak	Continuous	Peak
Carbon slider	150A	260A	500A	1000A
Sintered alloy slider	500A	1600A	800A	2000A

Remarks: Upward force 5.5 kg
Slider arrangement; 2 rows for carbon slider
4 rows for sintered alloy slider

(4) Wear of the Slider

Wear of the slider is affected largely by various factors such as the condition of the contact line, capacity of current collection, weather condition, etc., among these the effect of the material of the slider is the most significant.

As materials for sliders, iron base material in France, carbon base in Germany and UK are predominant. In Japan, sintered material, which has superior current collection capacity and wear resisting characteristics are most widely used, inspite of rather higher cost, however, carbon, etc., are also partially being used. Use of lubricant is effective to decrease wear of metallic sliders, and various lubricants have been studied. In AC-sections, where current collection requirement is small, use of a carbon slider which is good in lubrication characteristics is effective to prevent wear of the contact line, however, mixed use of metallic and carbon sliders in same line had better to be avoided, because of a tendency of increasing wear.

9-2-5 Comparison of Z-type Pantograph and Trapezoidal Pantograph

Z-type pantographs are widely used in France, etc., and were originally devised to reduce the installation area for application in the railway division with very large difference of contact line heights. There is basically no point which makes it superior in performance in comparison with trapezoidal pantographs. JNR once designed and test manufactured a Z-type pantograph only to find out that trapezoidal pantographs are rather superior in total weight, reduction of suspended equivalent mass as the governing factor of follow-up characteristics, and the differences of link mechanism and aerodynamical characteristic by direction of running were also smaller by trapezoidal type. Where differences in the height of the contact line is significant, and a large operation range is required, the Z-type is advantageous. Therefore, it is desirable to select a pantograph considering service condition, maintenance condition, etc.

9-2-6 Representative Example in JNR

Various types of pantographs are used by JNR for different purposes, and their representative ones are as indicated from Fig. 9-10 to Fig. 9-12.

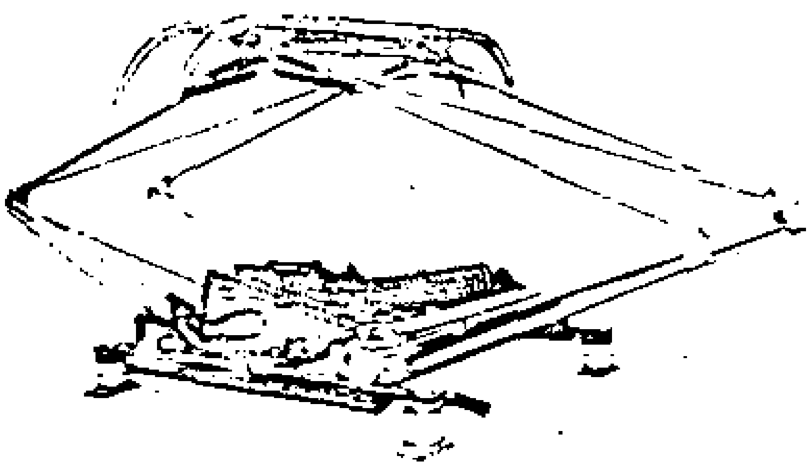


Fig. 9-10 PS-16 Type (for DC-car) Pantograph

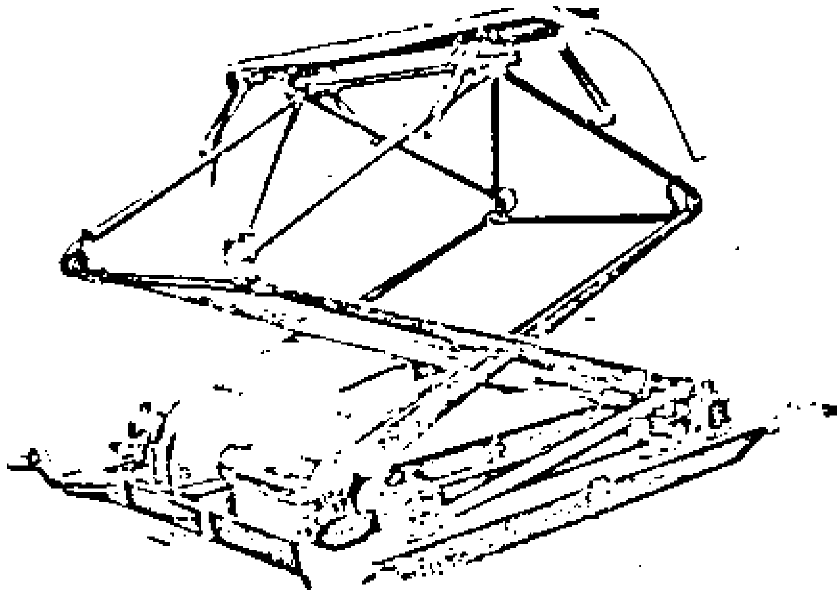


Fig. 9-11 PS-102 Type (For AC electric locomotive) Pantograph

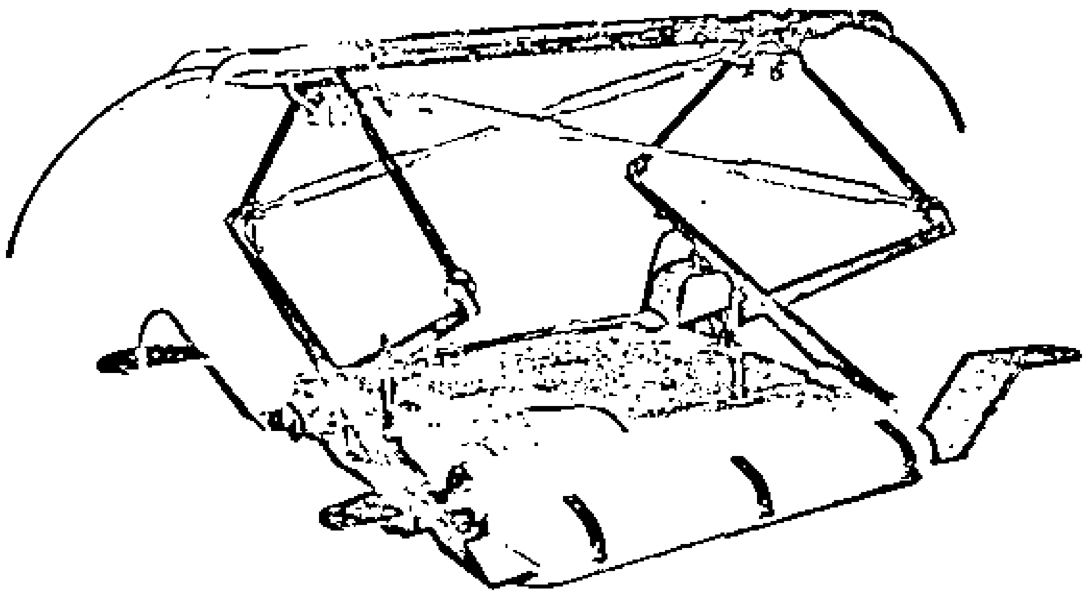


Fig. 9-12 PS-201 Type (For Tohoku-, Joetsu-Shinkansen)

9-3 Main Transformer

9-3-1 Main Transformer for Rolling Stock

The main transformer for rolling stock has special characteristics different in a variety of points from general purpose ones, including:

(1) The transformer is of single phase, and the wave forms of voltage and current are not sine wave, because it is used in combination with a rectifier.

(2) It is a special item which is compact, lightweight, and shake, shock and vibration resistant, fitting into the space for equipment.

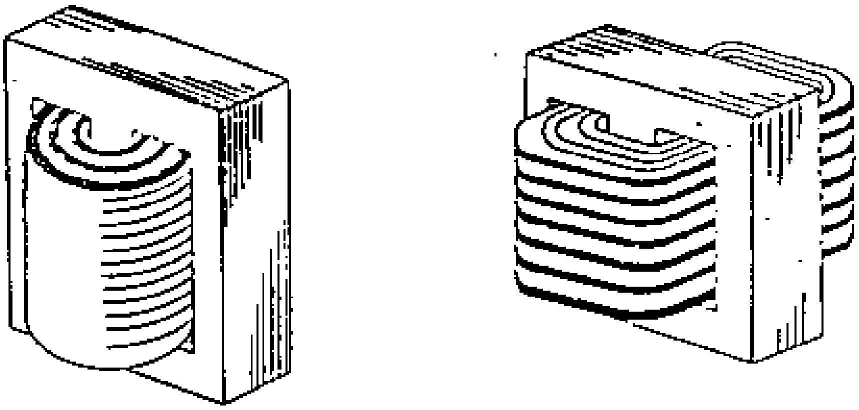
(3) Because of high current density in winding, and much loss caused by their small size and lightweight structure, the cooling design becomes an important point.

(4) The transformer has many taps for speed control, and also has many windings including a 3rd winding for auxiliary machines and a 4th winding for cabin heaters.

(5) The transformer is subjected to severe fluctuations in voltage and load.

9-3-2 Core Type and Shell Type

Transformers are classified into core type and shell type from their structure. The core type has each primary and secondary winding in cylindrical form and are arranged concentricly. On the other hand, shell type has each primary and secondary winding formed in plate type and are arranged in stratified form. Fig. 9-13 indicates the basic structure of core type and shell type transformers. Comparison of core type and shell type as main car transformer is shwon in Table 9-7.



Core type　　　　　　　Shell type

Fig. 9-13 Core Type and Shell Type

Table 9-7 Difference between Core Type and Shell Type

		Core type	Shell type
Magnetic circuit	Core secitonal area	Small	Large
	Core magnetic path length	Long	Short
Current circuit	Average coil length	Short	Long
	Voltage per turn	Small	Large
	Number of turns	Many	Few
	Coil arrangement	Cylindrical concentric	Disk winding, alternate arrange

The shell type is superior from both a structure and characteristics point of view, and JNR adopts the shell type only, except for very early designs.

The reasons for selecting the shell type are as follows:

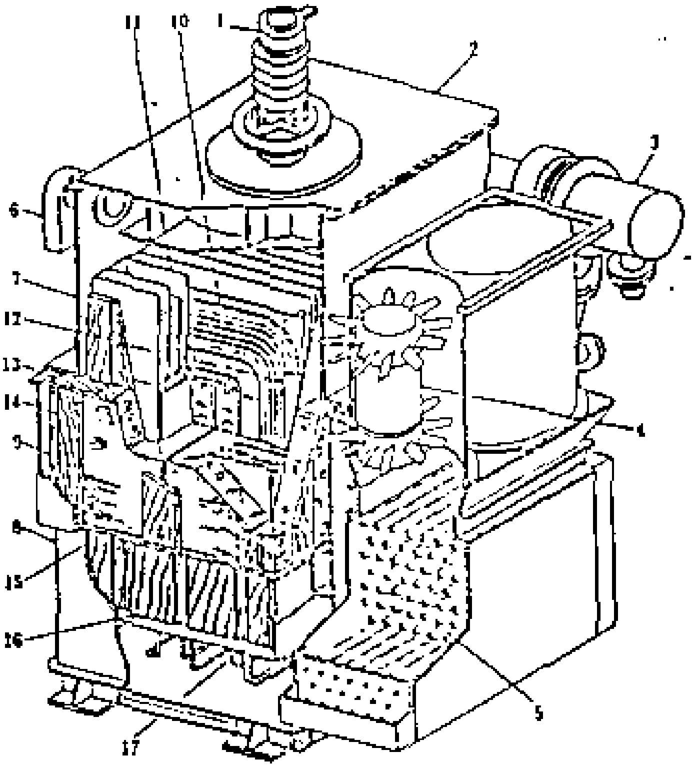
(1) Shell type allows relatively free selection from many possible arrangements of primary and secondary windings and therefore has a large freedom of design for leakage reactance. Also this type

allows us to make detailed design considerations such as intentionally giving variation to the reactance of each split winding of the secondary side, to reduce higher harmonic currents.

(2) Core and windings can be directly screwed and fixed with the tank wall, to make the arrangement of core and winding for high resistant to vibration, resulting in a higher vibration proof and shock proof structure.

(3) The square type structure as a whole can reduce dead space in rolling stock application, enabling smaller size and lighter weight, when considering an under floor structure as in the case of JNR's Shinkansen-car, the core type design is difficult.

As an example of the shell type main transformer, the structure of JNR's electric locomotive main transformer is shown in Fig. 9-14.



1. High voltage bushing
2. Tank cover
3. Oil feed pump
4. Blower
5. Cooling pipe
6. Relief valve
7. Upper tank
8. Lower tank
9. Core
10. Coil
11. Insulation board
12. Grooved insulator
13. Upper insert
14. Wooden brace
15. Lower insert
16. Wedge
17. Core receiver

Fig. 9-14 . Structure of Shell Type Transformer

9-3-3 Temperature Rise and Cooling of Main Transformer

The temperature rise limits of the main transformer is specified by JNR as shown in Table 9-8. Among these, dry insulation is disadvantageous in characteristics, heat capacity, weight, etc., therefore an oil circulation air cool system is solely used by JNR.

Table 9-8 Temperature Rise Limit of Main Transformer for Rolling Stock

(Unit: deg)

Location	Measuring method	Oil filled					Dry type		
		Natural air cooling		Oil circulation cooling					
		Normal insulating paper	Heat resisting insulating paper	Normal insulating paper	Heat resisting insulating paper	Special heat proof insulating paper	Class B	Class F	Class H
Winding	Resistance method	70	80	75	85	100	105	135	175
Oil	Thermometer method	65	65	65	65	65			

(Note) Standard ambient temperature is 25°C (10°C in winter).

From the classification by insulation, oil filled type corresponds to class A insulation (maximum allowable temperature 105°C.), however, in the case of electric locomotives, the oil circulation air cool type takes its standard ambient temperature as 25°C (for general purpose transformers, 40°C), and allows a higher temperature rise limit of winding and oil correspondingly. Temperature of winding is an average value by resistance method, and is determined to be 75 deg. in normal insulating paper assuming the difference to the maximum temperature as 10 deg. In the case of applying heat resistant insulation paper, which is superior in heat resistance, 85 deg. will be allowed and in the case of special A-class insulation (consists of polyamide paper, and silicone oil base insuation) up to 100 deg. are allowed.

Details on the temperature rise in the case of heat resistant insulation paper are shown in Fig. 9-15.

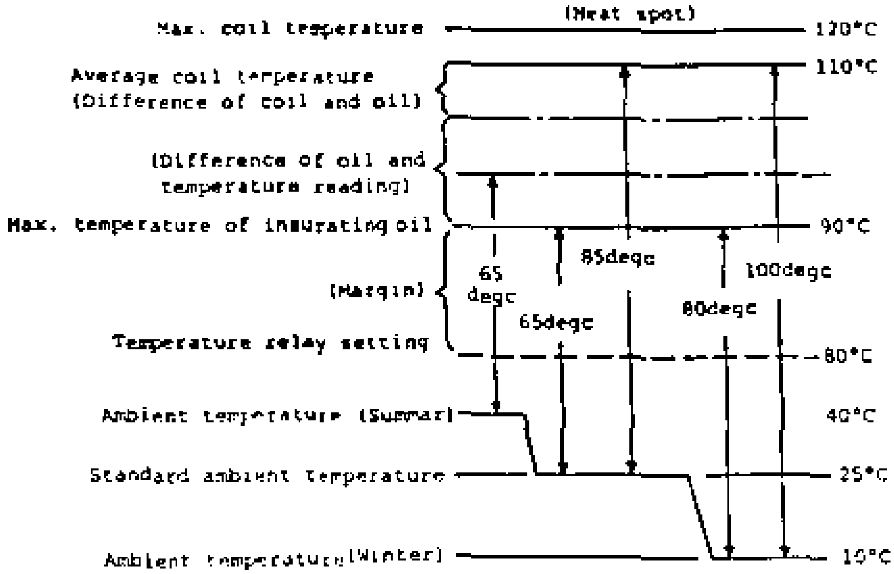


Fig. 9-15 Temperature Rise Limit of Main Transformer for Rolling Stock (with heat resisting insulating paper)

Insulation oil for transformers is used for cooling; however, if the transformer is installed under the floor, and flame proofness is required, silicone oil is used. A comparison of the characteristics of insulation oil is shown in Table 9-9.

Table 9-9 Typical Properties of Insulating Oils

Type of oil	Silicone	Mineral	PCB
Specific gravity, 25°C	0.96	0.87 (20°C)	1.53
Kinematic viscosity (cSt)	50	11	12
Pour point (°C)	<-50	<-30	<-30
Evaporation, 95°C, 5h (%)	0	0.4	2
Flash point (°C)	310	140	130 (self-extinguishing)
Coefficient of expansion (cc/cc.°C)	10.6×10^{-4}	7×10^{-4}	7.4×10^{-4}
N_2 gas solubility (%)	16	8	5
Dielectric constant, 50Hz, 50°C	2.7	2.2	5.2

9-3-4 Design of Main Transformer

A basic factor of the transformer design is to determine voltage per turn of the winding (V/t). The relation

(V/t) × Number of winding = Rated Voltage

exists. Therefore the number of windings increased by selecting smaller value of (V/t), to be so-called copper machine, resulting in increased copper loss and reactance. On the other hand, by selecting a larger (V/t) value, the number of turns is reduced, to be a so-called iron machine resulting in increased core loss and the reduced reactance. In the case of the main transformer, (V/t) is determined smaller in comparison with general transformers. A value about double that of the current density in conductor ($6A/mm^2$), in comparison with normal transformer, is selected.

Cold rolled directional silicone steel sheets are used to the core with the design to make a flux density of about 18000G under maximum contact line voltage.

Arrangement of windings will decide reactance characteristics, therefore the most suitable relation shall be made, standing on a wide range study of output characteristics, short circuit current, voltage variation under commutation, voltage variation of the third winding, etc., stability of control, reduction of higher harmonic currents.

An example of the reactance characteristics by tap changing system is shown in Fig. 9-16. Also, a design flow chart for structural design and winding arrangement is shown in Fig. 9-17.

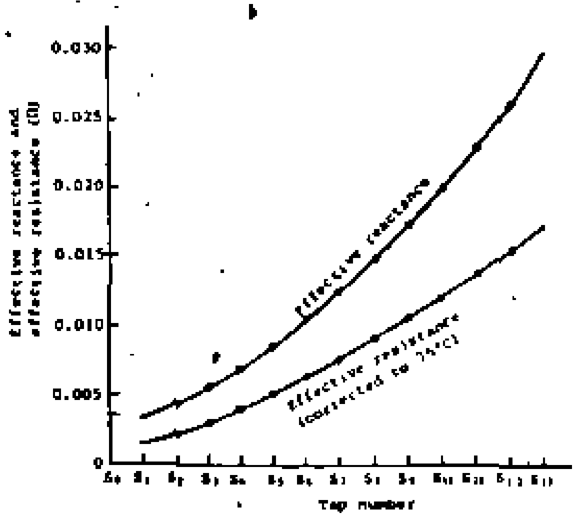


Fig. 9-16 Reactance Performance (JNR TM11)

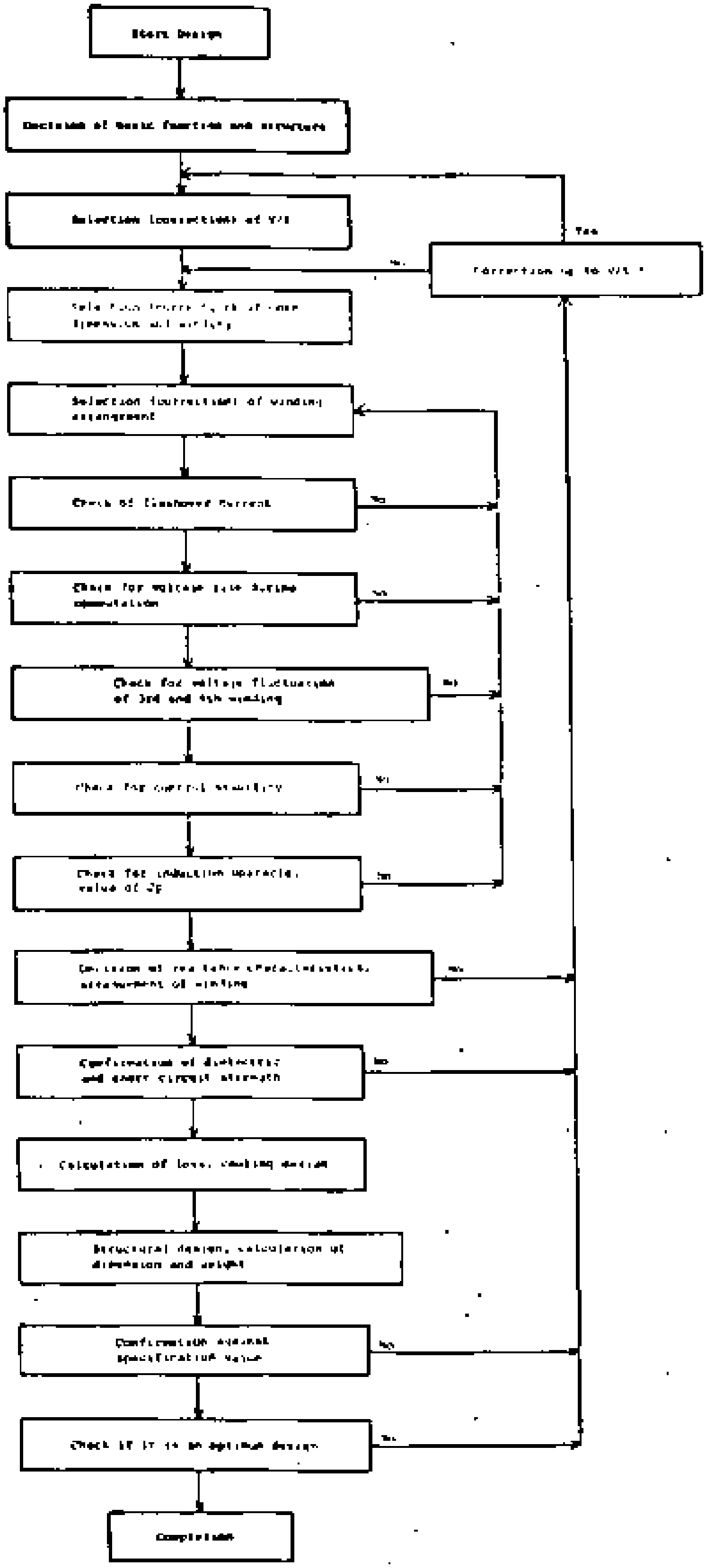


Fig. 9-17 Flow of Main Transformer Design Process

9-4 Static Power Convertor

9-4-1 Rating of Element

A static power convertor consists of silicone rectifier elements and/or thyristor elements. Accompanied with development of manufacturing technology and cooling technology, the capacity of these semiconductors has become larger. Fig. 9-18 indicates the transition of the increase of the capacity of thyristor element, and Fig. 9-19 indicates a decrease in the number of elements per unit capacity of static power convertor accompanied by increasing capacity of an element.

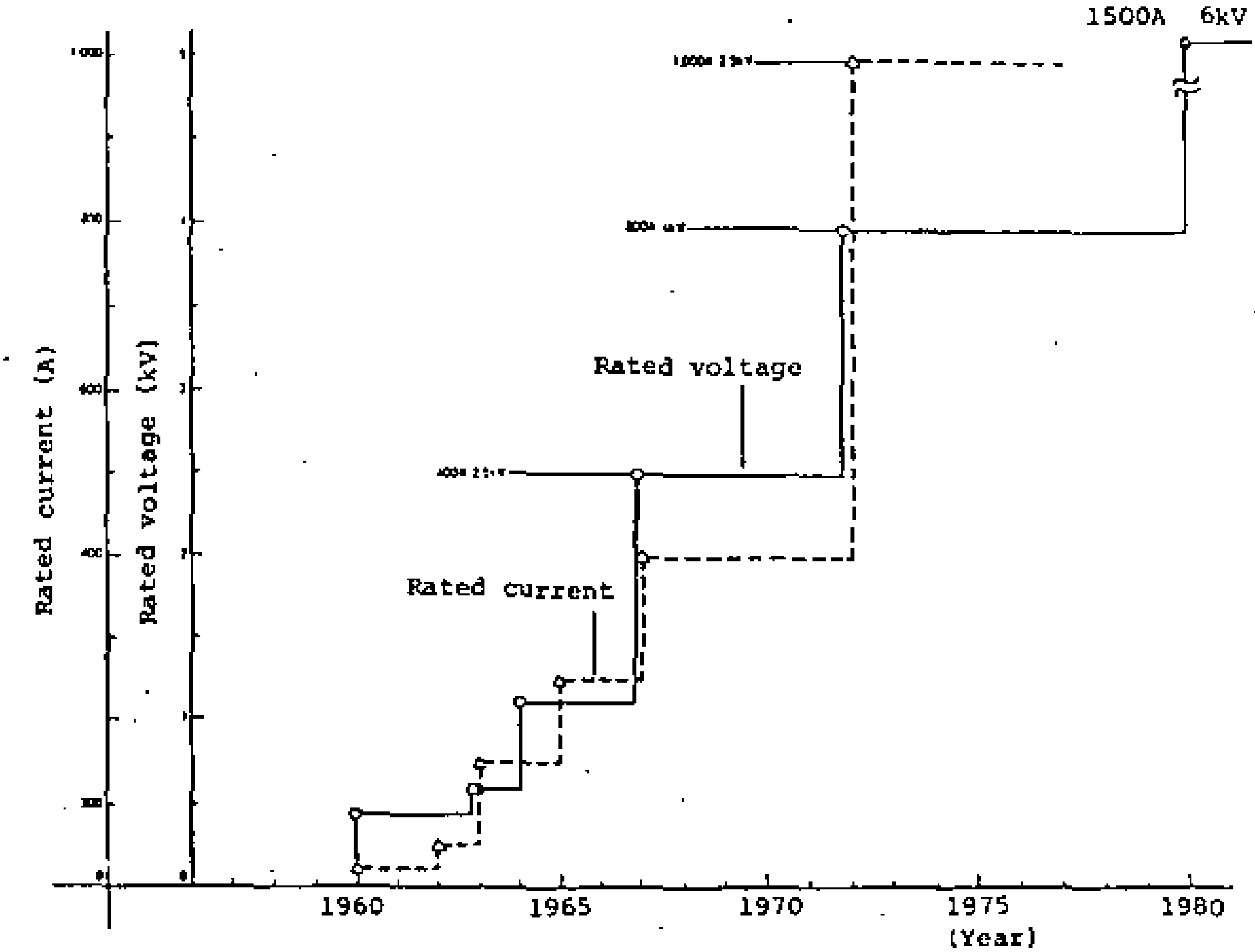


Fig. 9-18 Development of Rated Voltage, Rated Current of Thyristor Element

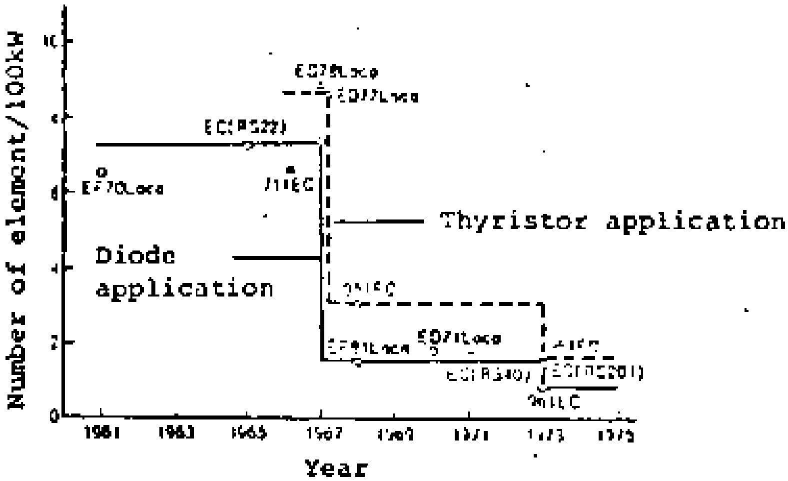


Fig. 9-19 Development of Number of Elements per Unit Capacity of Static Power Convertor

Flat type elements became standard with increasing capacity. An example of the structure of a flat type element is shown in Fig. 9-20. JNR has established specifications for each element to standardize, so that elements of different manufacturers can commonly be applied. Example characteristics of standard element being used by JNR are shown in Table 9-10 and Table 9-11.

Table 9-10 Characteristics of JNR Standard Silicone Diode

Type	SI300-12	SI800-25	SI1600-25
Structure	Stud type	Flat type	Flat type
Rated average forward current (A)	280	800	1,600
Rated working reverse voltage (V)	1,200	2,500	2,500
Rated non-repetitive peak reverse voltage (V)	1,500	2,800	2,800
Rated element junction temperature (°C)	150 (SI300C=160)	150 (SI800C=160)	150
Over-current (5-cycles) (A)	3,600	9,500	23,000
Maximum reverse current (mA)	30	50	60
Forward voltage drop (V)	1.00∿1.40	1.25∿1.50	1.20∿1.60
Thermal resistance (°C/W)	0.15	0.04 (oil cooled for both sides)	0.025

Table 9-11 Performance of JNR Standard Thyristor

Type	CSI 250-10,-12	CSI 400-25	CSI 1000-25
Structure	Stud type	Flat type	Flat type
Rated average current (A)	250	400	1,000
Rated working peak reverse voltage (V)	1,000, 1,200	2,500	2,500
Rated non-repetitive peak reverse voltage (V)	1,200, 1,450	2,750	2,750
Rated operation peak forward blocking voltage (V)	1,000, 1,200	2,500	2,500
Rated gate voltage			
Forward (V)	10	10	10
Reverse (V)	5	5	5
Rated gate trigger current (A)	2	4	10
Rated junction temperature (°C)	125	125	125
Over-current (1 cycle, A)	5,000	8,000	18,000
Forward voltage drop (V)	1.25 ∿ 1.65	1.50 ∿ 2.00	1.40 ∿ 2.00
Maximum reverse leakage current (mA)	20	30	100
Maximum forward leakage current (mA)	20	30	100
Minimum gate trigger current (normal temperature, mA)	300	300	350
Maximum gate non-trigger current (mA)	1.5	1.5	5.0
Maximum gate non-trigger voltage (V)	0.15	0.15	0.20
Turn on time (μs)	1 ∿ 6	1 ∿ 6	1 ∿ 10
Turn off time (μs)	-	-	-
Maximum thermal resistance (°C/W)	0.15	0.05 (For both sides)	0.025

9-4-2 Design of Current Bearing Value

To decide current capacity of a static power convertor the load pattern must first be established. As the load pattern, JNR assumes grade-starting following continuous operation, and two times of starting is adopted in consideration of failure in grade-starting. An example of load pattern is indicated in Fig. 9-21. The current value of continuous operation coincides with continuous rated current. Establishment of such a severe, load pattern made JNR's static power convertor exhibit far higher reliability in comparison with European ones.

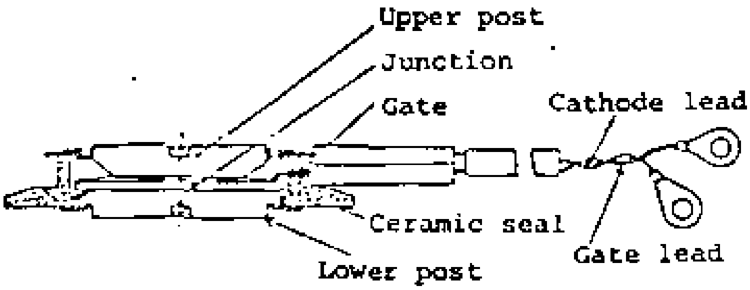


Fig. 9-20 Example Structure of Flat Type Element
(Thyristor CSI 400-25)

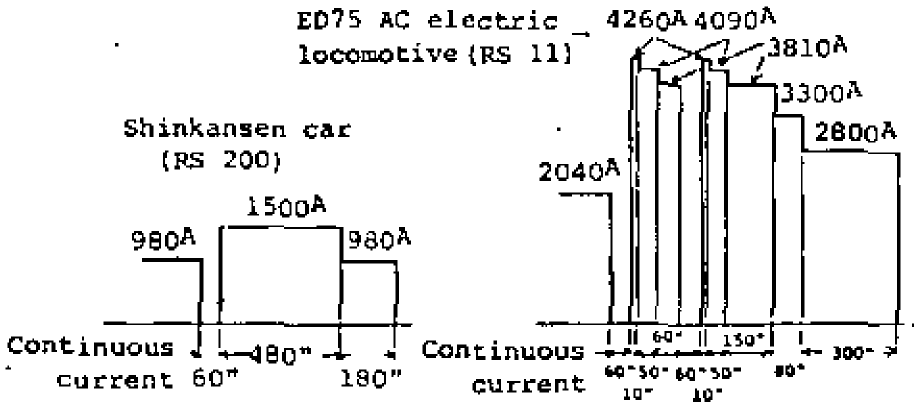


Fig. 9-21 Supposed Actual Load Pattern

Heat generation of the element is expressed by the product of forward voltage drop and forward current. A pellet of an element is very small and the thermal time constant is also very short, therefore, cooling is a very important task. In the case of temperature rise, the temperature of the element shall be designed to be kept always lower than rating junction temperature of element.

Decision of the number of the element connected in parallel shall be made in consideration of the load pattern and temperature at the junction point.

Rate of current unbalance between elements arranged in parallel differs with the method of connection as shown in Fig. 9-22, and is assumed to be 10% by string joint and 20% for mesh joint.

Rated average forward current of an element is a mean current value for one cycle when half wave is flown in 1/2 cycle, and about double of the output current may be considered as allowable by bridge connection.

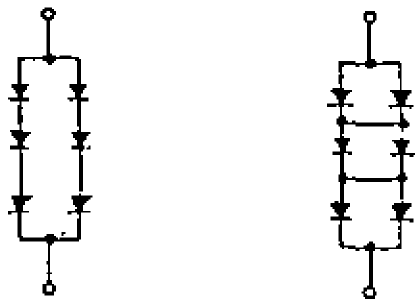


Fig. 9-22 Connection of Elements

On the other hand when phase control is to be performed by thyristors mixed bridge, allowable current value will be a value nearly equal to rated average forward current, because free wheeling current flows through the divide arm as DC when the thyristor is switched off.

9-4-3 Design of Voltage Bearing Value

Element voltage in a static power convertor is determined by abnormal voltage such as lightning surge, switching surge, etc., rather than by normally applied inverse voltage.

(1) Switching Surge

It is presumed that the crest value of surge voltage is two times larger than the crest value of maximum service voltage, and this value is transferred to the secondary side of the main transformer at the ratio of winding numbers and is applied to the elements. Rated peak working reverse voltage is designed to be the value of this or more because switching surge lasts a relatively long period, and occurs frequently.

When voltage is partially born by a series connection of plural number of each element, a 10% allowance will be included to cover the unbalance of voltage bearing.

$$\text{Number of serially arranged elements (Switching Surge)} = \frac{\sqrt{2} \times \text{Maximum Secondary Voltage of Main Transformer} \times 2 \times 1.1}{\text{Rated Peak Working Reverse Voltage of Element}}$$

(2) Lightning Surge

An arrester will operate against lightning surge and restricts the voltage, therefore, the maximum value of the surge voltage is presumed to be equal to the restricted lightning voltage of the arrester, and the surging transition rate is taken as 90% of the winding ratio including filter effect.

Reverse voltage bearing value of the element is taken as rated non-repetitive peak reverse voltage.

$$\text{Number of serially arranged elements (Lightning Surge)} = \frac{\text{Arrester Restricted Voltage}}{\text{Winding Ratio of Main Transformer}} \times 0.9 \times 1.1 \times \frac{1}{\text{Rated Operation Non-repetitive Peak Reverse Voltage of Element}}$$

9-4-4 Selection of Cooling System

A cooling system of the elements includes:

1) forced air cooling, 2) oil circulation air cooling, 3) freon boiling cooling.

(1) Forced Air Cooling System

The system is to cool the elements by forced air blowing on the element cooling fins. Because the cooling portion is impressed high voltage, consideration against dust, rain and snow, and routine maintenance are required. There are limits to the reduction of heating resistance, and a certain limit for application of modern large capacity elements is caused by cooling capacity.

(2) Oil Circulation Air Cooling System

The oil circulation air cooling system is further classified into a type which places the elements in oil, which is circulated and cooled, and a type which sends oil to cooling fins only and cools them. The former type immerses elements in oil, therefore takes more time for maintenance work such as replacing elements, however, this point will be overcome by highly reliable design. The latter one allows a more simple replacement of elements or inspection of parts, however, there is the drawback of the structure of the cooling system becoming more complicated.

(3) Freon Boiling Cooling System

A freon boiling cooling system cools the elements employing vaporizing heat of liquid freon, and is able to attain very large heat dissipation. Fig. 9-23 is a drawing indicating the principle of freon boiling cooling system, and Fig. 9-24 indicates a comparison of heat transfer coefficients by air cooling, oil cooling and freon boiling cooling. The freon boiling cooling system is also classified into two types as in the case of oil circulating air cooling system. One is an immersed type which inputs

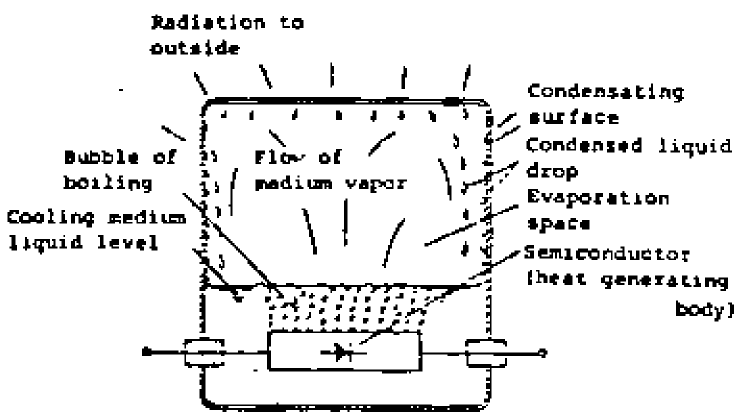


Fig. 9-23 Principle of Cooling System with Boiling

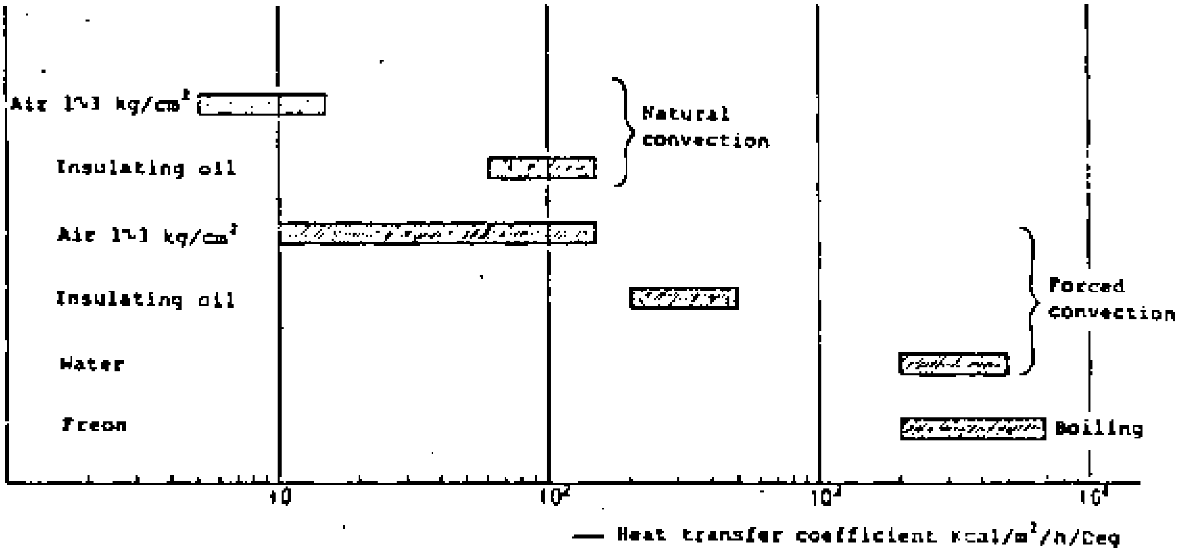


Fig. 9-24 Heat Transfer Coefficients for Various Coolants

elements and related parts in liquid freon and seal the whole. The other is a non-impressed type (independent fin cooling type) to cool only the interior of cooling fins by boiling cooling. The former is simple in structure; however, as it is sealed, replacement of parts is difficult. Therefore, it is suitable for silicone rectifiers or the like, which consist of fewer parts and have higher reliability. Structure of the immersed type is shown in Fig. 9-25.

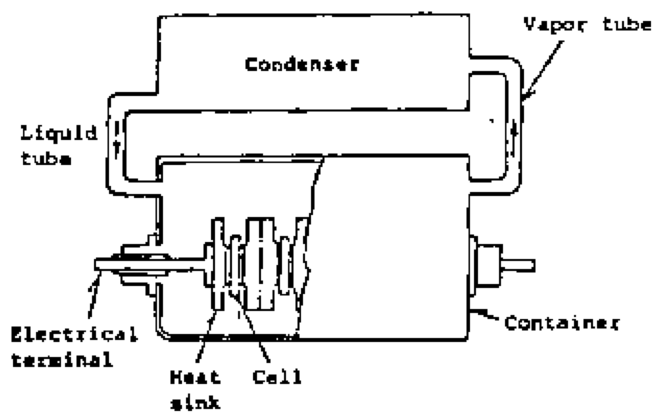


Fig. 9-25 Immersed Type

The principle of the latter, non-immersed type is shown in Fig. 9-26. This system has a complicated structure, but allows easy inspection and replacement of parts, therefore, is adequate to be applied for a thyristor power convertor which has more structural elements.

Cooling by heat exchanger (condenser) is also divided into forced air cooling and natural air cooling, and a comparison of these combination is shown in Table 9-12.

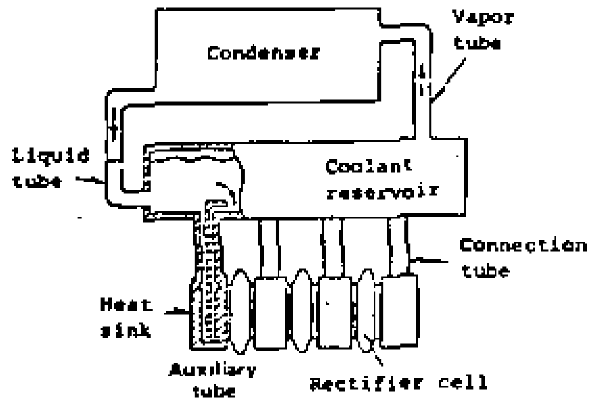


Fig. 9-26 Non-immersed Type with Linked Condenser and Reservoir

Table 9-12 Boiling-cooling Rectifiers

Type	Features
Immersed, with forced-air cooling	1. Compact 2. Simple and rigid construction
Immersed, with natural-air cooling	1. Completely static 2. Simple and rigid construction
Non-immersed, with forced-air cooling	1. Compact 2. Ease of accessibility
Non-immersed, with natural-air cooling	1. Completely static 2. Ease of accessibility

9-4-5 Gate Circuit

Gate signals are required to control thyristors. The gate circuit consists of a phase shifter, gate signal amplifier and gate transformer.

Following performance is required for the gate circuit to control main circuit of a rolling stock:

(1) shifting phase angle shall cover the whole range of 0° to 180°

(2) the gate circuit shall be suitable for temperature and voltage change, vibration, and it shall have low secular change and high reliability,

(3) synchronization of phase with contact line voltage shall be maintained,

(4) time lag shall not occur because quick response is required.

Amplifier of gate signal, is to generate gate pulse of the thyristor corresponding to the controlled phase angle signal from the phase shifter. The standard gate pulse wave form is a combination of narrow width pulses with steep and large peak values and a wide width pulse to secure stable conducting condition. The width of the pulse shall be continued until 180° point where voltage reverses for the duration that the forward current is normally flowing to thyristor. Standard gate pulse wave is shown in Fig. 9-27.

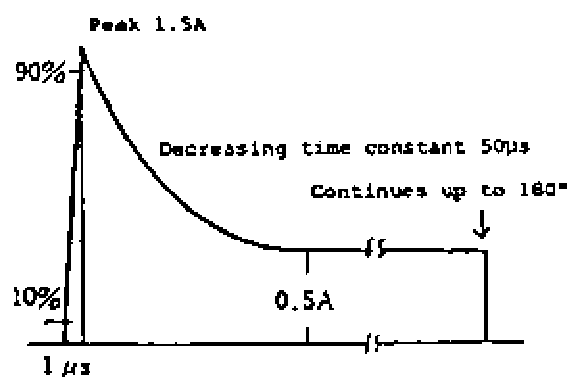


Fig. 9-27 Standard Gate Pulse Wave

9-4-6 Main Smoothing Reactor

Output voltage and current from static power convertor has a large width pulse because of single phase full wave rectification, therefore, if it is directly connected to traction motors, that cause troubles in the point of temperature rise and commutation. The pulsation factor of the wave form shown in Fig. 9-28 is specified as,

$$\text{Pulsation factor } \mu p = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100\ (\%)$$

And in the case of AC-rolling stock, the pulsation factor at near the rated power is generally restricted to 30% or less by electric locomotive by which the power of traction motor is large, and 50% or less by electric car.

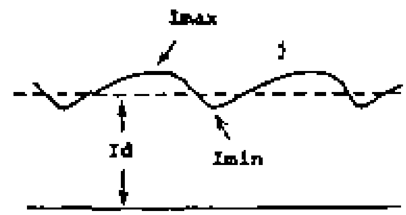


Fig. 9-28 Pulsation Wave

For the above purpose, the main smoothing reactors are inputted between the static power convertor and traction motors.

By setting the value of reactance properly, this reactor exhibits large effects also in the side of readhesion characteristics. Therefore, main smoothing reactors are inserted for each traction motor by a locomotive in which high readhesion characteristics are required.

On the other hand, pulsation factor is desirable to be raised from the viewpoint of reducing higher harmonic currents and Jp current of contact line.

The current-inductance characteristics of the main smoothing reactor are designed hyperbolic ones, so that practically a constant pulsation factor may be obtained in the practical load current range. An example of the characteristics is shown in Fig. 9-29.

9-4-7 AC-filter

AC-filter is installed between the secondary winding of main transformer and static power convertor. The main role of the AC-filter is to absorb the surge of intrusion as; 1) suppressing switching surge, 2) lowering transmission rate of lightning surge, 3) suppressing of dv/dt and current vibration when the elemtns are commutating.

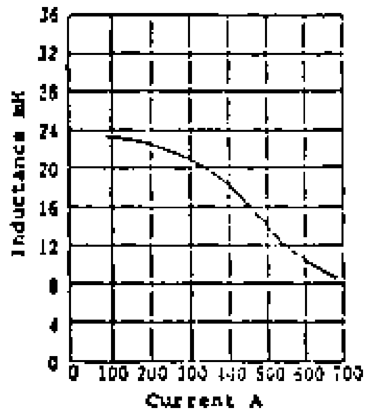


Fig. 9-29 Characteristics of Main Smoothing Reactor (JNR IC23)

An AC-filter consists of C-R filter, and each value of C and R is selected with attention given to the following:

(1) selection of value of C to suppress the voltage rise at switching surge (transition of exciting energy of the main transformer to the secondary side) to the allowable value or lower,

(2) selection of value of R to be within the non-vibration range with secondary reactance. Further, R acts as potential divided resistance for high frequency surge, and in this sense, the smaller the value is the better.

For the purpose of reducing higher harmonic currents, substantially large capacity is necessary and therefore it is generally not practical.

9-5 Traction Motor, Driving Gear

9-5-1 Selection of Traction Motor

Motors for driving wheels of electric rolling stock are called main motors or traction motors, and the following performance is required.

(1) it shall be usable at high efficiency in a wide speed range,

(2) easy speed control,

(3) large traction force at starting or in grade section,

(4) load unbalance shall be small under parallel operation,

(5) can resist a quick change of source voltage.

Series motors are best suited to satisfy the above requirements, and generally a direct current series motor is selected. However, recently separately excited motor is also able to be operated stably by virtue of power-electronics control.

On the other hand, in case the power regenerative brake is used, shunt characteristics become necessary, and a compound motor or the system to change over from series exciting winding to separate exciting only during the regenerative braking period will be applied.

What are actually required as structures of a main traction motor are the following:

(1) Because installation space is limited between axles, the motor should be small and lightweight,

(2) Because of severe contamination by rainwater and dust, water and dust prevention shall completely be prepared,

(3) In the case of non-suspended installation, the motor shall bear to 10 g (g is gravitational acceleration, 9.8 m/s^2) of instantaneous vibrational acceleration, and to about 3g even for suspended installation,

(4) In AC-electric rolling stock, pulsation of current after power convertor is large, and considerations for pulsation shall be prepared.

(5) Structure of the motor shall be made to allow easy inspection of brushes and commutator surface, easy replacement of brushes and easy mounting and dismounting of the traction motor.

9-5-2 Temperature Rise and Insulation Material of Traction Motor

Because of its size restrictions, a traction motor usually employs high class insulation material, and normally the temperature rise limit is set higher than in the case of general machines. The maximum allowable temperature limit of various insulation materials are shown in Table 9-13, and allowable temperature rise limit of a traction motor is indicated in Table 9-14. It is noted that the maximum allowable temperature limit of traction motor is raised to the value of adding ambient temperature to the allowable temperature rise limit. This due to the necessity to make the motor smaller and higher in performance even at the cost of its service life, in consideration of the fact that temperature rise in actual operations differs according to the grade, speed, load condition, etc., and the time subjected to the higher limit of temperature is rather short.

Table 9-13 Maximum Allowable Temperature for Insulators (JIS C 4004)

Class Y	90°C
Class A	105°C
Class E	120°C
Class B	130°C
Class F	155°C
Class H	180°C
Class C	More than 180°C

Table 9-14 Limit of Temperature Rise for Traction Motor (JRS)

[deg]

Location \ Class of Insulation	Class B	Class F	Class H
Stator winding (resistance method)	130	155	180
Armature winding (resistance method)	120	140	160
Commutator (electric temperature measuring method)	105		
Bearing (thermometer)	55 (Roller bearing with good heat resisting performance) 40 (Other than above)		

Current flows into the main motor always changes in accordance with grade, speed and load conditions, and a certain thermally equivalent continuous current must be set for the design of traction motor. As its value, root mean square current (RMS-current) as expressed in the following equation is calculated by computer and applied:

$$I = \sqrt{\frac{\int i^2 dt}{T}}$$

Where: I = RMS-current

i = Instantaneous current value

t = Time

T = Total operation time.

9-5-3 Structure of Traction Motor

(1) Armature Winding

Armature winding is classified into wave-winding and lap-winding; wave winding is generally suitable for high voltage and small current, and lap winding for low voltage and large current.

Lap winding requires an equalizing bar, and also difficult to manufacture, however, have such advantage to permit large reduction of commutator segment voltage, and so it is desirable to select lap winding for traction motor.

(2) Electric Loading and Magnetic Loading

Output coefficient of the traction motor is expressed as following:

$$C = (\pi^2/60) \cdot \gamma \cdot Ac \cdot Bg \times 10^{-11} \text{ (kW/rev/min}\cdot\text{cm}^3)$$

where: γ = Pole arc length/pole pitch - constant value (about 0.6) depends on the structure,

A_C = Ampare number of conductor/cm,

Bg = Flux density at Gap (gauss).

In general purpose machines, a large Bg value is selected, to obtain an iron-rich machine, the so-called iron machine, however, in traction motors, a large A_C value is selected to make a smaller and lighter machine, to obtain a copper-rich so-called copper machine.

In traction motors an A_C value of about 400∿500, Bg value of about 8000∿12000 (gauss) are standard.

(3) Commutator

The diameter of the commutator is determined by its limit to the peripheral speed (about 60 m/s) and the length by the limit of current density (about 15 A/cm^2).

Connection of armature strand and risers of commutator is performed by TIG-welding (Tungsten electrode welding in inert gas).

Determination of commutator bar voltage has a large effect on the voltage proofness or flash-over proofness.

(4) Countermeasures to Pulsation Current

As countermeasures against current pulsation, the following items are considered: 1) dividing pulsating current by diverting the main field winding with non-inductive resistance (rate of diversion is about 2% to 10% of DC value), 2) decrease the eddy current by laminating a part of the interpole and magnetic frame in addition to the main pole, 3) adopting a sufficiently large ampare-turn to interpole, and reduce the magnetic flux lag by eddy current loss, 4) adopting a smaller commutator bar reactance voltage to prevent yielding of flash over and improve commutation, 5) consider on large temperature rise.

(5) Ease of Maintenance

Routine check of the traction motor is required on commutator surface, brushes and bearings. Extension of inspection period and life is very advantageous on the maintenance side. In relation to the commutator and brush, application of a long size brush and constant spring force brush holder are advantageous. In relation to the bearing, long term maintenance free bearings employing long life grease and larger grease packs are considered.

9-5-4 Outline of Axle Driving Gear

Most electric rolling stock transmits the torque of the traction motor by reducing speed by gears to the wheel. The driving gear includes many systems, and the type and mechanism of the driving gear has a close relation to installation system, size, performance of traction motor, and it is important to make co-operative design with those items.

Methods of traction motor installation are generally classified into truck installation (suspended installation), nose suspension (half suspended) and installations in between these two. Basically a traction motor is an electric machine with precision structure, and truck installation is desirable for better vibration condition, however, in this case, flexible joint or gear box structure, which secure good meshing accuracy of gears, is necessary. These driving systems shall be selected as the best system standing on the overall findings considering factors such as use, power and performance of traction motor, characteristics of driving gear, arrangements and spaces.

9-5-5 Types and Characteristics of Driving Gear

(1) Nose Suspension Type Driving Gear

One end of the traction motor is mounted on an axle through a suspension bearing, and the other end is supported by a truck frame with a projection made to the motor, and is a very simple structure power transmission gear (Fig. 9-30). This structure makes half of the motor weight unsuspended weight, therefore, is quite liable to be affected by shock from the rail, and has difficulties such as the reduction of commutation performance of the traction motor or maintenance of bearing attached to the axle. However, this system was widely used for old type vehicles because of their simple structure. Especially in the case of narrow gauge electric locomotives, which can afford only a narrow space for installation of traction motors, this type is widely accepted for installation of high output traction motors because of eliminating the necessity for flexible coupling.

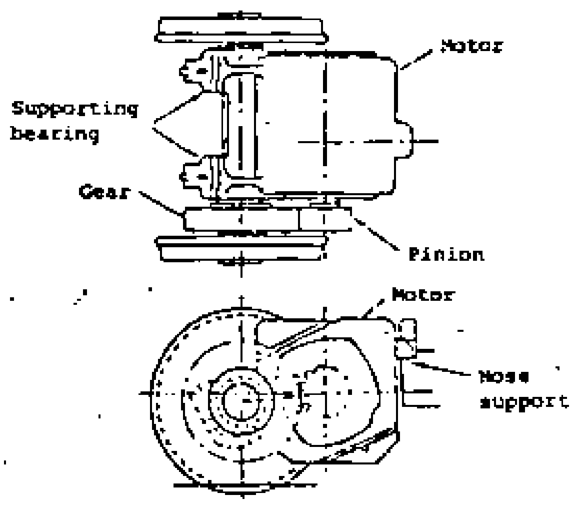


Fig. 9-30 Nose Suspension Type Driving Gear

Plane bearing has been used for conventional nose suspension, however, roller bearing was developed recently and was tested to prove no problem.

(2) Full Suspended Installation of Traction Motor

The system is to install a traction motor on a spring (truck frame), which solves problems occurs with nose suspension type as above, however, it is necessary to prepare a rigid gear box and flexible coupling to maintain meshing accuracy of gear and pinion.

In electric cars Cardan drive specially parallel Cardan drive (Fig. 9-31) are most widely used. As for the coupling, the conventional narrow gauge JNR Car has adopted a flexible plate system (Fig. 9-32) which employs a hollow shaft to the traction motor, and Shinkansen-car uses a WN-type coupling, however, many other types such as rubber-types, hollow pinion types, etc., were also developed.

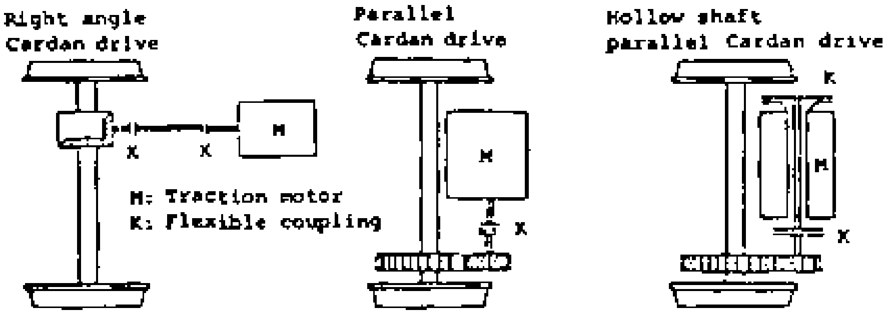


Fig. 9-31 Cardan Type Driving Gear

In the case of electric locomotives, Cardan drive using WN-coupling is also used for standard gauge, however, for narrow gauge, the quill type (Fig. 9-33), which makes a flexible coupling structure between gear and wheel, or link type driving gear (Fig. 9-34) were also used, because of the unavailability of space for the Cardan drive. For JNR's electric locomotives, the quill type was adopted for a part of the old model, however, all of those were modified to the link system, because of the self resonance of the pitching vibration of trucks, caused by the soft shock absorbing spring in the gear, had generated. Thus, selection of the rotating direction spring and the rotating mass to avoid resonance to be practically harmless is one of the important elements in adopting a certain driving gear.

(3) Others

Other than the above, a semi-nose suspension driving gear is adopted to JNR's largest powered narrow gauge electric locomotive, type EF66 (Bo-Bo-Bo, 3900 kW). This system has a hollow shaft over the axle, and an end of the traction motor is suspended onto this hollow shaft. The hollow shaft is jointed to the axle through flexible plates, and shock of the wheel is not directly transferred to the traction motor. The bearing of the mounting is a roller bearing. This system was developed for narrow gauge high speed use.

Also a system by which one traction motor drives several shafts was adopted for the type EF30 and type EF80 electric locomotive. Many of these types are adopted in French locomotives, many of which adopt a link device between gear device and wheel as a buffer.

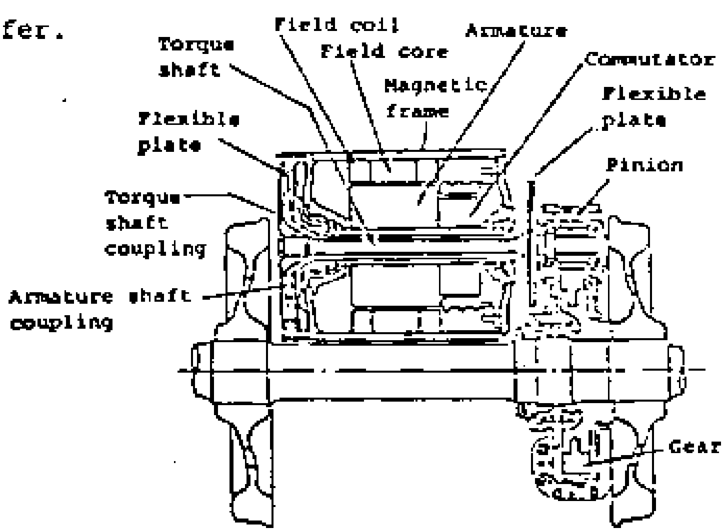


Fig. 9-32 Traction Motor and Hollow Shaft Parallel Cardan Type Driving Gear

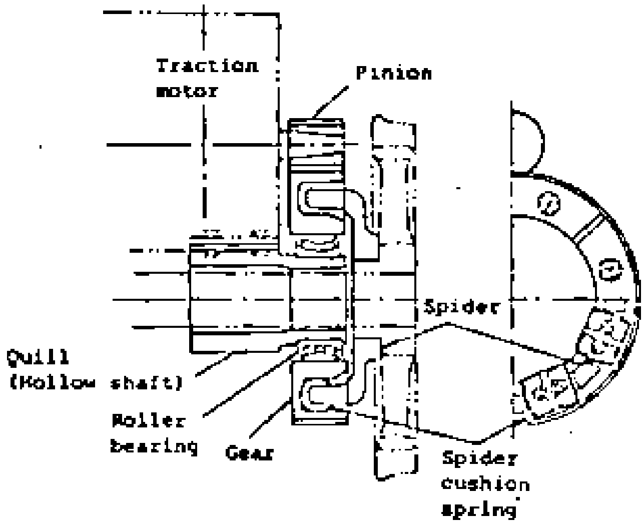


Fig. 9-33 Quill Type Driving Gear

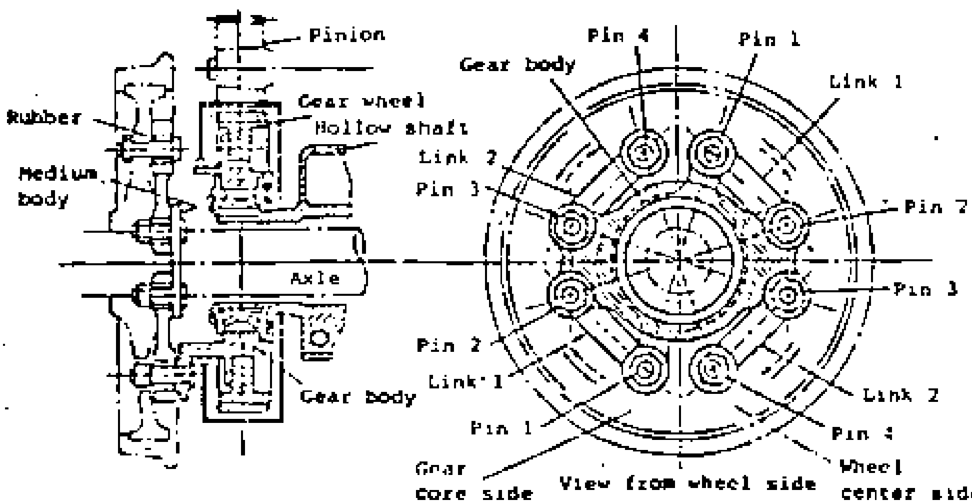


Fig. 9-34 Link Type Driving Gear

9-6 Truck

9-6-1 Outline

An electric rolling stock truck has the functions of supporting the car body and running stably on the rails, as well as transferring the rotational force of a traction motor into the form of traction force to the car body and/or coupler. Therefore, other than the truck components themselves, an electric rolling stock truck is installed with traction motor (in special cases also installed on the car body), driving gear, etc., however, those two items were already discussed and we avoid mentioning them again.

To design a truck, in case of electric cars, the ratio of the driving shaft to the total shafts of the train is higher and the adhesion performance is less important to care, but to secure comfortable riding up to the high speed range is important, therefore, a structure which places importance on preventing vibration or hunting is selected. On the other hand, although passengers do not directly ride on it, the locomotive truck is required to tract as much load as possible with a small number of driving shafts, and the most important point is how high an adhesive performance or readhesion performance will be obtained, and by reducing weight transfer between axle, how effectively large traction force is transferred to the coupler portion.

9-6-2 Structure of Truck

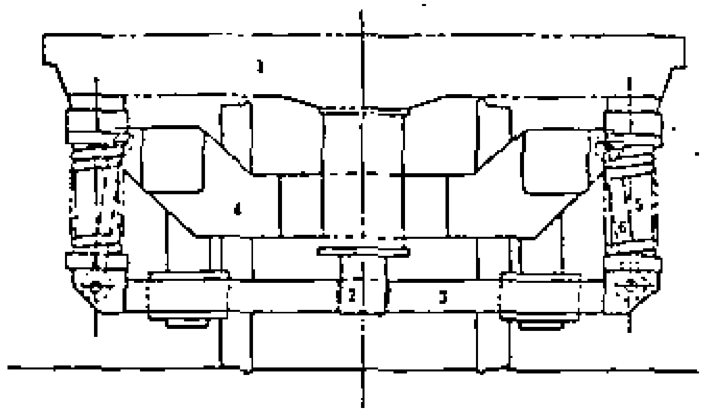
A truck generally consists of a truck frame, swing bolster device, wheels and axles, axle boxes and springs, etc.

A truck frame consists of side beam, cross beam, end beam (some trucks lack end beams). Old type trucks are mostly made of one body steel casting or composite assembly of formed steel using rivets or bolts, however, recent JNR trucks mostly consist of welded structures of pressed steel parts in consideration of improvements in welding technology and mass production structure.

Swing bolster devices are installed between the car body and truck frame to give lateral rigidity between them to relieve from lateral vibration. Swing bolster springs (coil springs or air springs) are installed between the car body and truck frame (oil dampers are jointly used in many cases). Soft spring constants are selected to obtain comfortable riding, on the other hand, an anti-rolling device is sometimes employed to prevent too much rolling.

Some rolling stock does not use a swing bolster device but applies springs directly to connect truck and car body for the purpose of simplification of structure.

As a means of supporting the weight of a car body, some truck supports major part of the weight at the center of the truck and the other supports at both sides. The former has good follow-up characteristics when passing curves or the like, but is apt to cause rolling and the latter has the reverse characteristics. An example of center pin structure is shown in Fig. 9-35.



1. Body frame
2. Center pin
3. Bolster device
4. Truck frame
5. Bolster spring
6. Hanging link

Fig. 9-35 Example of Center Pin Type Truck

As devices for transmitting traction force, the center plate system and draw bar system are the representative devices, however, the system of locmotive has immediate relation with a device to prevent transfer of axle weight and is explained later.

Roller and/or ball bearings are predominating recently for axle boxes, and coil springs are used as axle springs. Many axle box suspension systems are available, and are shown in Fig. 9-36.

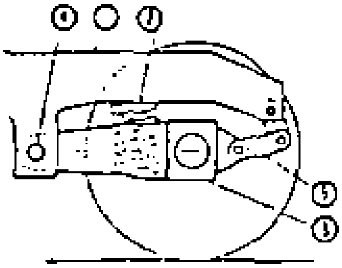
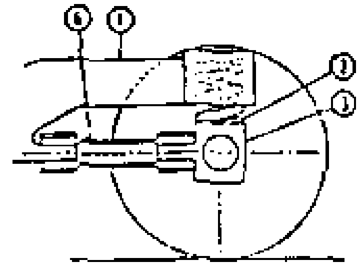
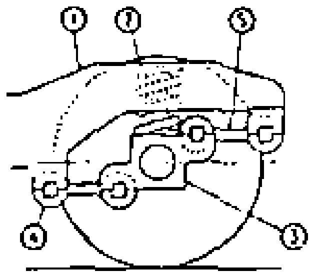
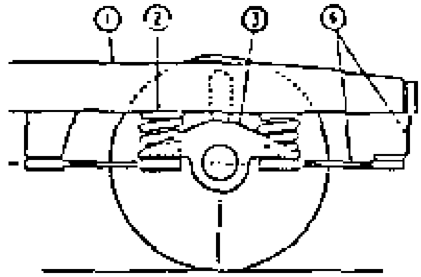
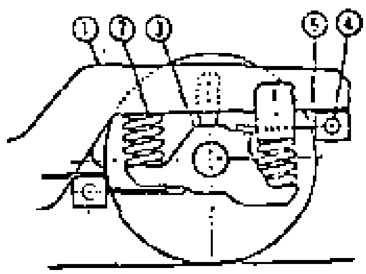
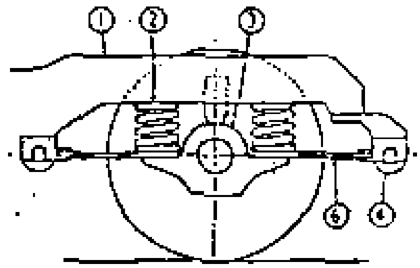
Type	Structure & characteristic	Type	Structure & characteristic
Axle beam system	 Connect axle beam, made one body with axle box (3), to truck frame (1) through cushion rubber (4) and links (5). Vertical support elasticity is mainly given by axle spring (2), and the elasticity of front and back, left and right is given by rubber around the pins. Example of supporting rigidity: Front and back 2,500 kgf/mm/axle box Left and right 500 kgf/mm/axle box	Cantilever spring system	 Vertical direction support by axle spring (2), however, axle box (3) is connected to truck frame (1) through 2-sheets of plate spring (6) to guides to front and back, left and right. No secular change occurs because no rubber parts are used. Example of supporting rigidity: Left and right about 1,500 kgf/mm/axle box
Link system (ALSTHOM type)	 Vertical support is borne the axle spring (2), however, as a guide to the direction of front and back, left and right, axle box (3) is connected to the truck frame (1) by 2-sets of links (5) having cushion rubber (4) at both ends. Example of supporting rigidity: Front and back 3,500 kgf/mm/axle box Left and right [illegible] kgf/mm/axle box	Plate spring system (welded type)	 Vertical support is borne by the axle spring (2) however, as a guide to the direction of front and back, left and right, axle box (3) is connected with truck frame (1) through 2-sets of plate spring (6) (the end is junction of vertical and horizontal plate springs). Example of supporting rigidity: Left and right about 1,400 kgf/mm/axle box
Plate spring and link system	 Vertical support is borne by the axle spring (2), however, as a support and guide to the direction of front and back, left and right, axle box (3) is connected to the symmetrical opposite position of truck frame (1) through plate spring (6) having cushion rubber to the truck frame side. Example of supporting rigidity: Front and back 2,800 kgf/mm/axle box Left and right 850 kgf/mm/axle box	I-S system	 Vertical support is borne by axle box (3), however, as support and guide to the direction of front and back, left and right, axle box (3) is connected to the truck frame (1) through 2-sets of plate springs (6) and cushion rubber installed to one end of the plate spring. Example of supporting rigidity: Front and back about 1,000 kgf/mm/axle box Left and right about 1,500 kgf/mm/axle box

Fig. 9-36 Axle Box Suspension to Truck Frame (1)

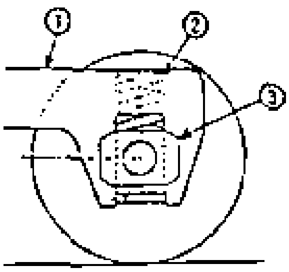
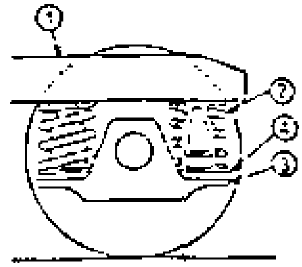
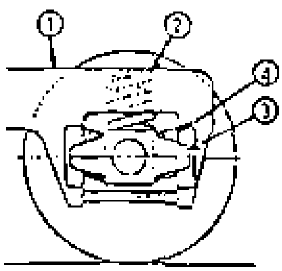
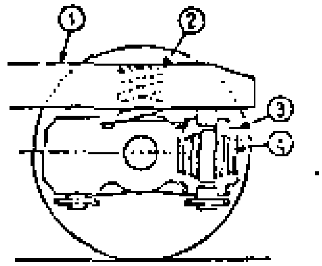
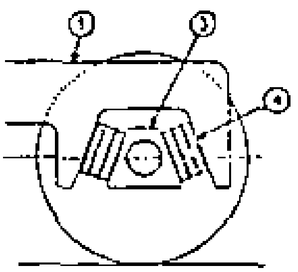
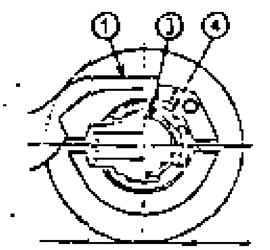
Type	Structure & characteristic	Type	Structure & characteristic
Axle guard (pedestal) system	 Load in vertical direction is supported by axle spring (2), but for load in longitudinal or lateral direction, axle box (3) is restrained by axle guard (pedestal) on truck frame (1). When the clearance between axle box (3) and axle guard increase upon wearing, hunting motion tends to occur in a wheel axle so that the clearance must be kept as small as possible.	Cylinder guide system	Vertical load is supported by axle spring (2) and cushion rubber (4), and for load in longitudinal or lateral direction, 2-sets of guide cylinder provided inside axle spring (2) guide axle box (3). Guide cylinders are connected across cushion rubber (4) to axle box (3). Guide cylinder which combines hydraulic damper is also used. (Schlieren type, SIG type)  Example of supporting rigidity: Longitudinal 900 kgf/mm/Axle box Transversal 900 kgf/mm/Axle box (Schlieren system) Longitudinal 2,700 kgf/mm/Axle box Transversal 500 kgf/mm/Axle box (JNR suburban electric car)
Cushion rubber (pedestal) system	Axle spring (2) bears vertical load, and for load in longitudinal or lateral direction, axle box (3) is guided through cushion rubber (4) to axle guard. With no sliding parts, does not wear or change over time.  To compensate for low transversal rigidity of rubber, extended part of axle box (3) serves as stopper for great amplitude. Example of supporting rigidity: Longitudinal 1,100 kgf/mm/Axle box Transversal 100 kgf/mm/Axle box	Cushion rubber (cylinder guide) system	 Axle spring (2) bears vertical support, while axle box (3) is elastically coupled to truck frame in both longitudinal and lateral directions by means of cushion rubber (4). With no sliding parts, does not wear or change over time. Example of supporting rigidity: Longitudinal 3,800 kgf/mm/Axle box Transversal 850 kgf/mm/Axle box
Cushion rubber (Chevron) system	 Obliquely disposed cushion rubber (4) supports vertical, longitudinal and transversal load elastically. Vertical rigidity (axle spring constant) is greater than that with metallic axle spring. Example of supporting rigidity: Vertical 300 kgf/mm/Axle box Longitudinal 5,000 kgf/mm/Axle box Transversal 1,000 kgf/mm/Axle box	Cushion rubber (axle box beam) system	 Cushion rubber (4) provided around axle box (3) bears loads in vertical, longitudinal and transversal directions elastically. Left and right truck frames (1) (side beam) are not fixed to each other but have some degree of freedom given normally. Vertical rigidity (axle spring constant) is greater than that of Chevron system. Example of supporting rigidity: Vertical 390 kgf/mm/Axle box Longitudinal 3,100 kgf/mm/Axle box Transversal 600 kgf/mm/Axle box

Fig. 9-36 Axle Box Suspension to Truck Frame (2)

9-6-3 Comparison of 2-axle and 3-axle Bogies

As trucks for electric locomotive of 6 driving axles, 3 sets of 2-axle trucks (B_O-B_O-B_O) and two sets of 3-axle trucks (C_O-C_O) are considered.

JNR used 3-axle trucks for type EF62, however, 2-axle trucks are mostly used recently.

The three axle truck has the merit of small weight transfer between axles, and effective utilization of under floor space by reducing space for trucks, however, it also has the demerit that side pressure increases at sections of many curves causing excessive wear of rails and wheel flanges. JNR once made comparative experiments of type EF 62 with 3-axle trucks and type EF63 with 2-axle trucks under the same condition, the results of the test are shown in Fig. 9-37 and Fig. 9-38.

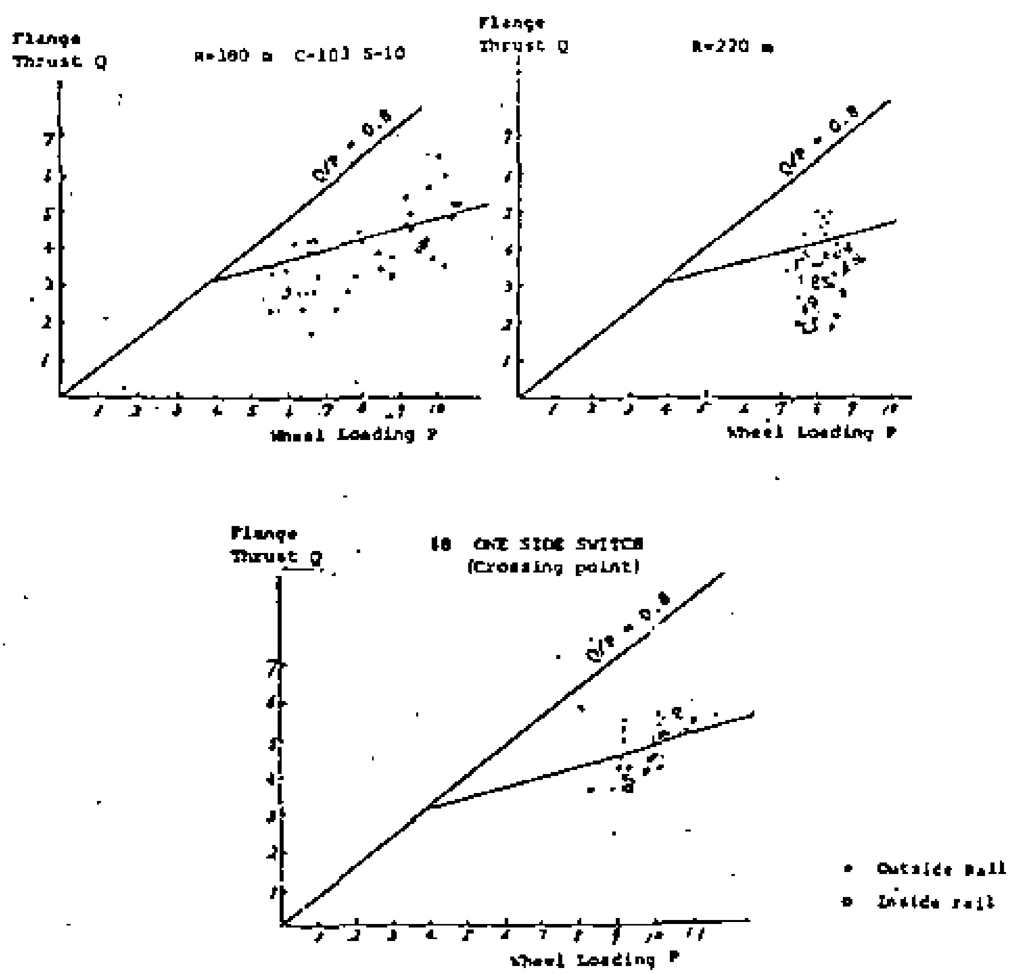


Fig. 9-37 EF-62 C_O-C_O Electric Locomotive Flange Thrust vs Wheel Loading Ratio (Static Axle Loading 16 tons)

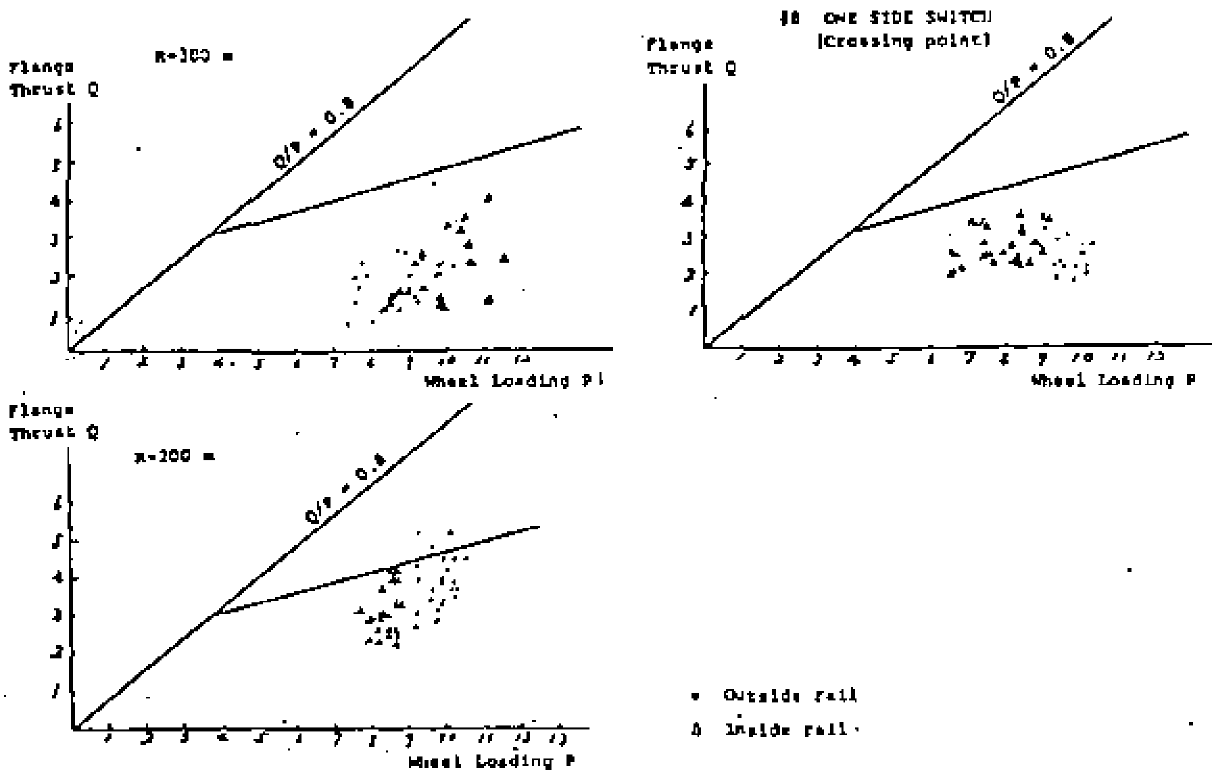


Fig. 9-38 EF-63 B_O-B_O-B_O Electric Locomotive Flange Thrust vs Wheel Loading Ratio (Static Axle Loading 18 tons)

The figures clearly indicate the difference of the side pressure. In Japan, almost all recent locomotives are adopting a 2-axle truck, considering the many curved sections in Japanese railways, as one of the reasons. In the case of B_O-B_O-Bo arrangement, middle truck is required to be made for easy side movement (about 100 mm on a curve of 100 m radius), and two methods are available for it, one is to employ longer hanging links, and the other is to provide a roller for transfer to side direction.

A simple comparison of the B_O-B_O-B_O system and C_O-C_O system is shown in Table 9-15.

Table 9-15 Comparison of 3-axle Trucks and 2-axle Trucks

Wheel arrangement	Advantages	Disadvantages
C_O-C_O	1) Total bogie weight can be slightly decreased compared with B_O-B_O-B_O. 2) More space between bogies, where fuel tanks or large items of electrical equipment can be installed.	1) Each axle, especially the center axle, must allow a large lateral degree of freedom to decrease the flange-force. It complicates the construction of the motor suspension, brake rigging, and axle guides. 2) Motor suspension direction must be the same in order to decrease weight transfer, which restricts freedom of design.
B_O-B_O-B_O	1) Lower flange force than C_O-C_O. 2) Easy dynamic analysis when selecting the suitable stiffness for each member or compornent. 3) No need to permit large lateral axle movements. 4) Simple construction, which simplifies manufacture and maintenance.	1) The center bogie must have a large degree of lateral movement to follow track curves. Some consideration must be given to this in the design.

9-6-4 Transfer of Axle Weight and Device to Prevent It

In the case of tracting a train, the difference in the heights between coupler and rail surface where traction forces are acting causes moment. This moment is supported vertically between trucks, and between axles within a truck, causing a difference in the axle weight of each axle to that occurs during stopping. This condition is called transfer of axle weight.

An example for axle weight transfer of a 4-axle locomotive is shown in the following (see Fig. 9-39)

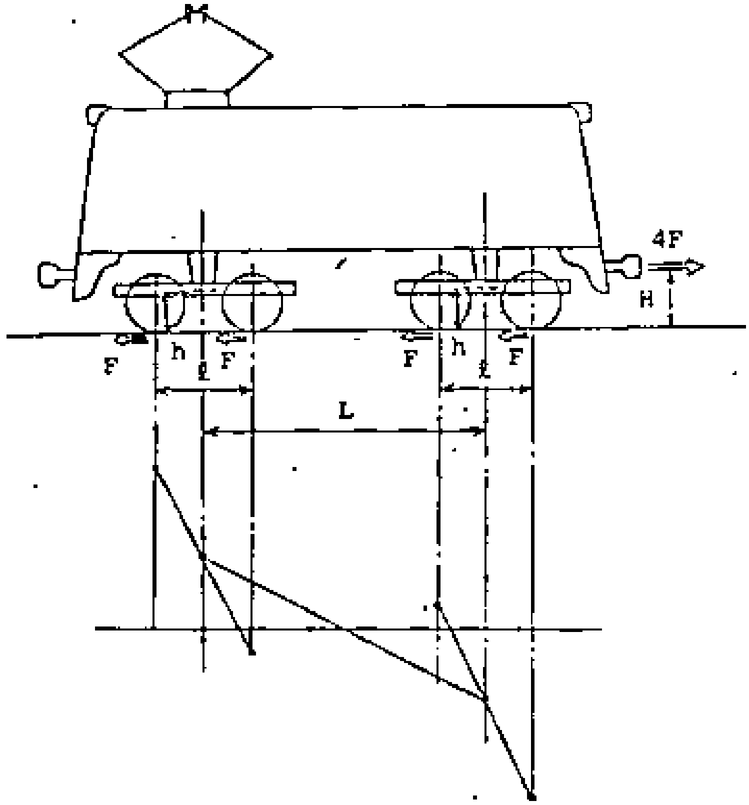


Fig. 9-39 Explanation of Transition of Axle Weight of 4-axle Locomotives

No. 1 Axle $\Delta W_1 = -\frac{2F(H-h)}{L} - \frac{2Fh}{\ell}$

No. 2 Axle $\Delta W_2 = -\frac{2F(H-h)}{L} + \frac{2Fh}{\ell}$

No. 3 Axle $\Delta W_3 = \frac{2F(H-h)}{L} - \frac{2Fh}{\ell}$

No. 4 Axle $\Delta W_4 = \frac{2F(H-h)}{L} + \frac{2Fh}{\ell}$

Where: F: Traction force per axle

H: Height of the coupler

h: Height of the center plate or the traction force transferring point

L: Distance between center plates

ℓ: Distance of axles.

In these equations, the first term is transfer of axle weight between trucks, and the second term is transfer of axle weight within a truck.

In the case of a 6 axle locomotive, a similar principle can be applied.

Method of controlling current to traction motor for each shaft in accordance with such axle weight transfer as can be used, however, in most cases traction motors and other components are made to the same performance, therefore, it is desirable to mechanically reduce axle weight transfer as far as possible.

As a means of preventing this axle weight transfer, it is desirable to make force transmission vectors of couplers meet as near to the rail as possible. Many devices are proposed for this purpose, including a low center plate system, V-shape link system and long-link system as representative ones, and examples of each of those are shown in Figs. 9-40 ∿ 9-42.

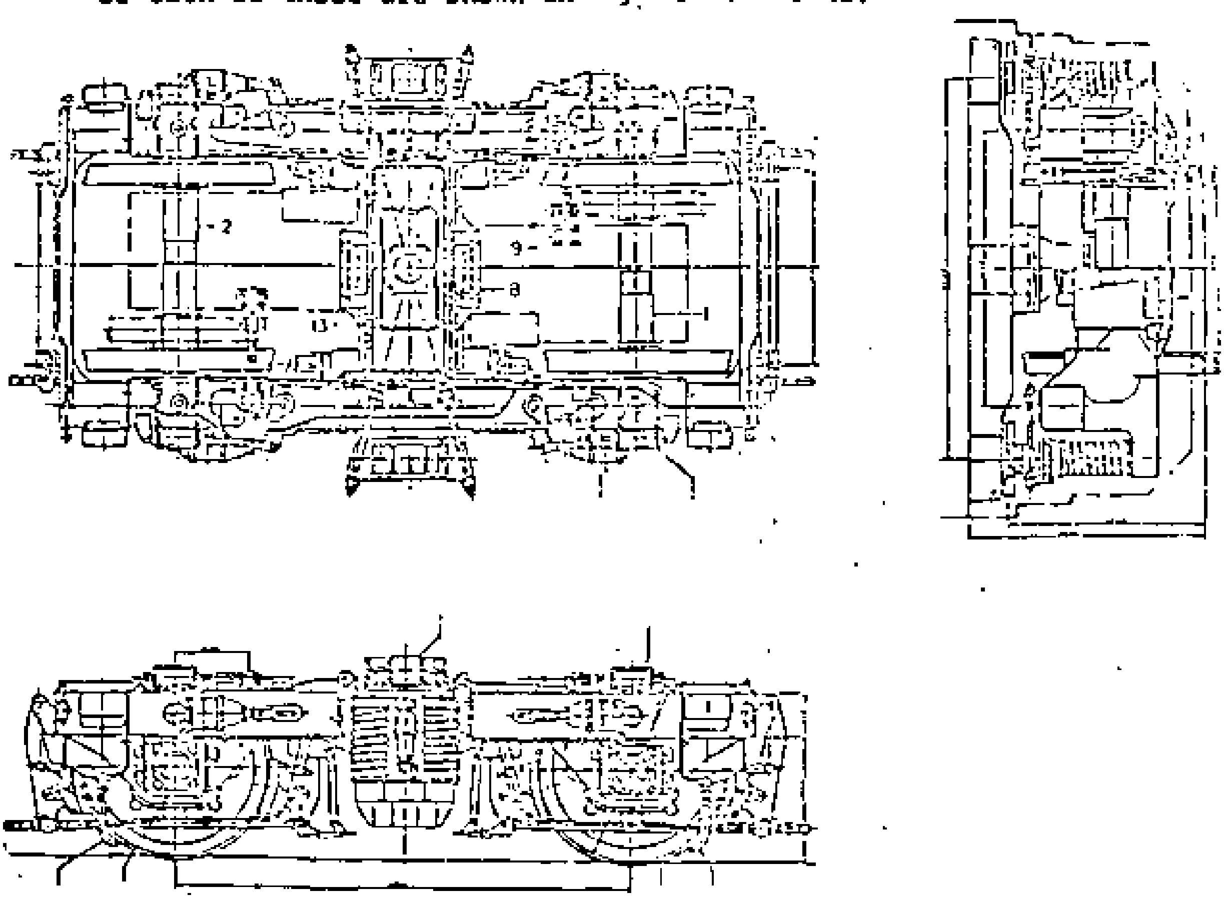
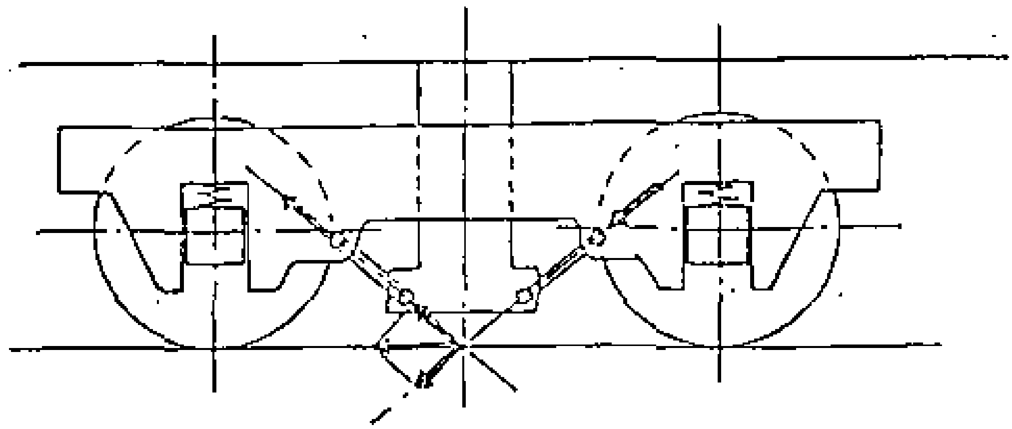


Fig. 9-40 Example of Low Center Plate Truck (Type EF71)



(Theoretical explanation)

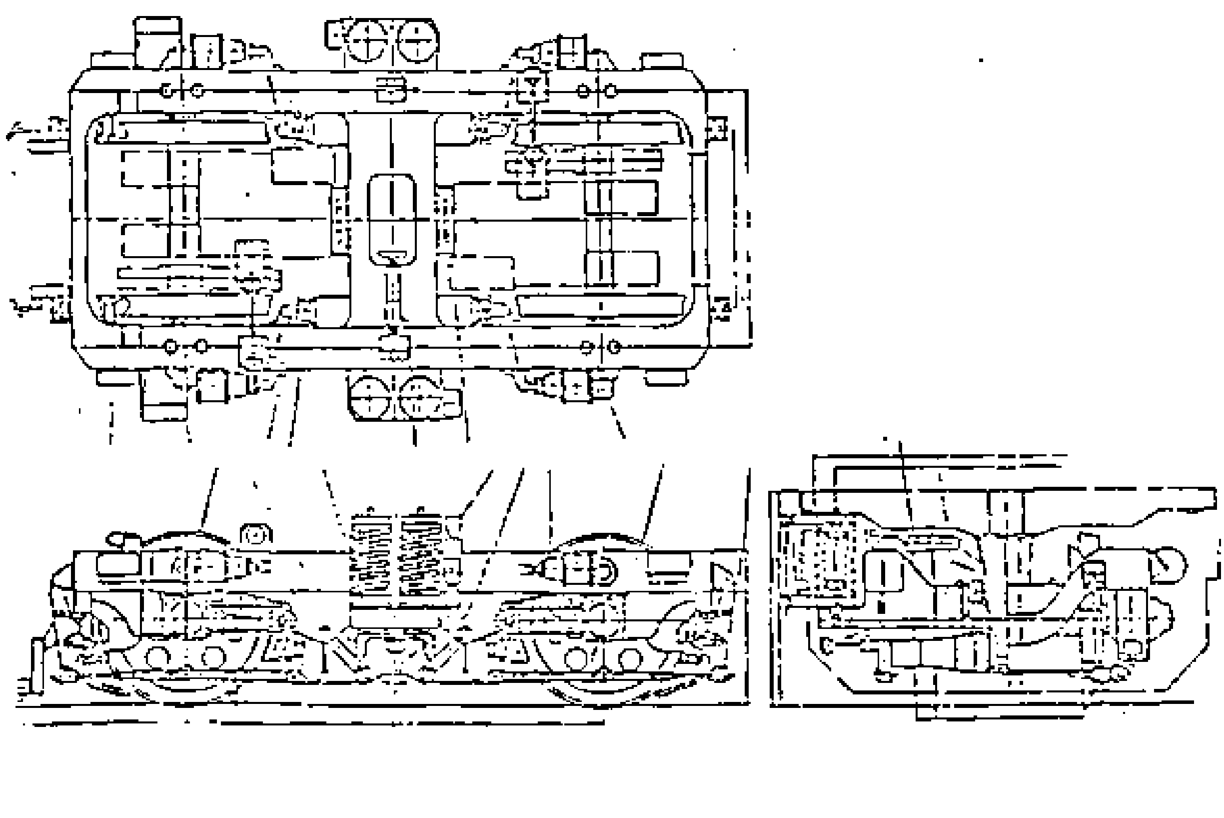


Fig. 9-41 Theoretical Explanation and Actual Example (Type ED72) of V-form Link Truck

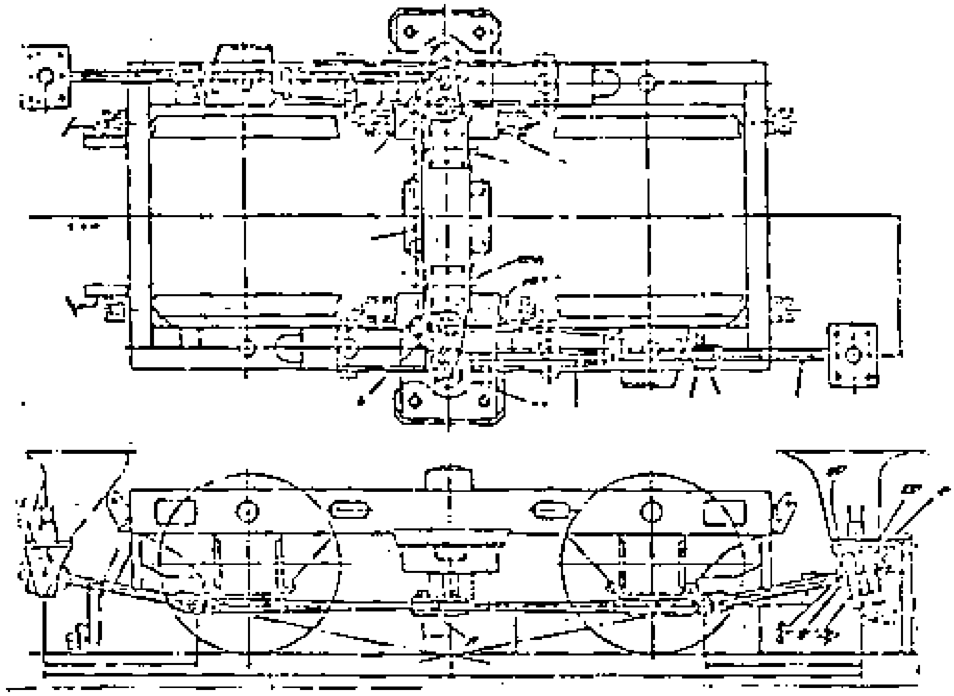


Fig. 9-42 Link Device for Long Link System Axle Weight Transition Preventing Truck (Type ED75)

The low center plate system theoretically cannot perfectly prevent the transfer of axle weight, however, is widely adopted for its simple structure.

V-shape link system, long-link system can theoretically bring the force acting point on the rail, and in the case of certain exclusive locmotive for a grade section, can prevent axle weight transfer corresponding to the grading. Most of the former mechanism is receiving traction force with V-shape link by swing bolster and center pin of body, in this case, attention shall be paid to keep the coefficient of friction to the vertical direction of the center pin low.

The latter is used relatively widely, partially in consideration of the merit of allowing to make axle distance smaller, however, a controllable device is necessary for the change of body support height, and the angle of the link by wear-out of the wheel.

9-7 Control Equipment

9-7-1 High Voltage Tap Changer

A high voltage tap changer is a piece of equipment for changing output voltage by an arrangement in which two rollers or brushes move on segments connected to a single wind coil tap of main transformer as shown in Fig. 9-43. Changing is performed by a circuit breaker operated under link motion with the roller so that the main current will not be interrupted in the midway of changing. Generally the roller and segment are placed in oil and attached to the body of the main transformer. Intermediate voltage between taps may sometimes be taken out, by using a current limiting reactor instead of current limiting resistance, resulting in an approximate doubling of the number of the notches.

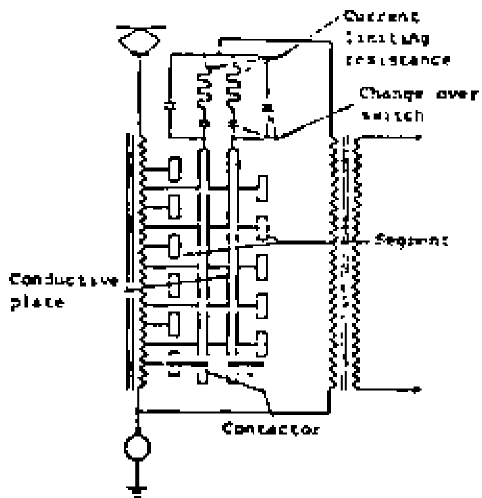


Fig. 9-43 High Voltage Tap Changeover Control

Segments are arranged in longitudinal or cylindrical form, and a small electric motor is employed for operation.

9-7-2 Low Voltage Tap Changer

A low voltage tap changer is connected to taps of the secondary winding of the main transformer, and consists of a combination of changeover switches which break current and selection switches which do not break current. In the case of a large current capacity, breaking of the current becomes difficult, and magnetic amplifiers or thyristors are used in the circuit to change switch under no-arc, and controls voltage between taps continuously. Fig. 9-44 indicates the principle of no-arc tap control.

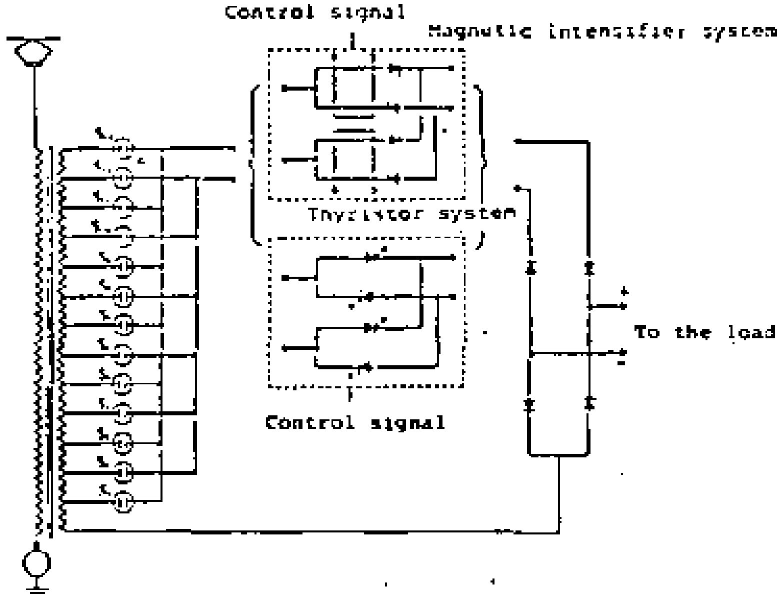


Fig. 9-44 Low Voltage No-arc Tap Control

9-7-3 Main Circuit Switches

(1) Unit Switch

A unit switch is an electromagnetic air-blast switch, with a short interrupting time by use of pressured air for switching. Also, a large contact pressure is obtained.

The operation is performed by electromagnetic valve.

(2) Electromagnetic Contactor

An electromagnetic contactor operates movable contact piece by electromagnetic pulling force without using pressured air, and operates under the same principle with that of electromagnetic relay used in control circuits.

(3) Cam Contactor

A combination of cam-shift controller and cam contactor is advantageous, when the switching sequence is predetermined as the selection switch of low voltage tap changer. This equipment is also used for the control of dynamic brakes, etc. Table 9-16 indicates characteristics of JNR's representative main circuit switch, and Table 9-17 indicates the temperature rise limit.

Table 9-16 Performance of Circuit Breakers

Type	Model	Rating (A)	Breaking performance		Weight (kg)
Cam contactor	SR16	350	20[mH]	300[A]	6.5
Electromagnetic contactor	SR601	500	0[mH] 20[mH]	500[A] 350[A]	11
Electromagnetic air switch (unit switch)	SR114	540	20[mH] 80[mH]	2,400[A] 1,200[A]	40
High speed circuit breaker	CB16	1,500	4[mH] 20[mH] 40[mH] 80[mH]	10,000[A] 6,000[A] 2,500[A] 1,000[A]	205

Note: Rated voltage is 1,500[V]

Table 9-17 Temperature Rise Limit of Rolling Stock Control Equipment

Location		Temperature rise limit (deg)	
		Resistance method	Thermometer method
Winding	Class A insulation	85	60 (85)
	Class E insulation	100	80 (100)
	Class B insulation	110	90 (110)
	Class F insulation	135	115 (135)
	Class H insulation	160	140 (160)
Contacting portion	Main contactor	-	75
	Knife edge contactor (self force)	-	35
	Knife edge contactor (other force)	-	40
Terminal		-	60
Flexible conductor		90 (No harm shall be given to the near portion)	
Bare conductor, bare winding		No harm shall be given to the near portion	

Note: Temperature rise in ( ) is applicable in the case of large currents and a low number of turns, such as the blow-out coil or current coil.

9-7-4 Equipment for the Control Circuit

(1) Electromagnetic Relay

This equipment is used to detect over-current, over-voltage, earthing, no-voltage, differential current, etc., for protective purpose. Current limiting-, voltage limiting- and time-delay-relay are also available, for control application, and the equipment is also used to relay or amplify signals. Some of these relays are similar to those used for general industrial purposes. However, those designed for exclusive rolling stock use with increased reliability and vibration proofness are adopted.

Vacuum relay which adopts a vacuum switch in lieu of a lead switch is also available for the improvement of the reliability of contact point and ease of maintenance.

(2) . Contactless Relay

Mechanical life of normal relays is about 5-million times, and electrical life is about 500-thousand times. Although dependent on the structure, contingent contact failure occurs in once in hundreds of thousands of time. Therefore preventive maintenance is difficult for those being used more frequently than 100,000 times/year, and adoption of contactless equipment is desirable. Further, electronized equipment is desirable when quick operation speed, high operation accuracy or small difference of operation and release point is required.

A contactless relay is an electronics circuit, applying thyristors and consists in a printed circuit or enclosed in casing and connector used in electromagnetic relay.

Contactless relays are being applied to many sections including skid detectors, protection relay such as over-current, over-voltage, etc., cam shaft motor short circuit relay for cam shaft controller.

9-8 Auxiliary Machine System and Auxiliary Rotary Machine

9-8-1 Comparison of Auxiliary Machine System

AC-electric rolling stock requires many auxiliary motors for cooling of equipment, etc. Power source system of those auxiliary rotary machine is classified as single phase AC, DC and 3-phase AC.

(1) Single Phase AC System

The source is obtained by direct use of the third winding of the main transformer. Because of single phase, the motor comes to be a single phase induction motor, and capacitors for starting are necessary, with starting torque low. Range of voltage fluctuation is large, and also will directly be affected by supply cutout at crossing dead sections.

(2) DC-system

This system is to rectify (with voltage control device) output of the 3rd winding of main transformer and supply as constant voltage DC, the therefore a DC-motor is used as an auxiliary motor, and can be said to be disadvantageous in view of weight, price and maintenance.

One of the DC-systems to use current transformer (CT) in the main circuit is available, which operates the auxiliary machine with current proportional to the main circuit current, this system has some merits in that the revolution speed can be controlled; however it has many problems, because the motor stops as soon as main circuit is cut off.

(3) 3-phase AC-system

Single phase AC is changed to 3-phase current, by way of a phase convertor, motor-generator, inverter, etc. This system allows the use of a 3-phase induction motor, and is most advantageous for small lightweight motor use.

9-8-2 Phase Convertor

A circuit diagram and vector diagram of a phase convertor are shown in Fig. 4-45. Winding of the phase convertor is the same as that of a 2-phase induction motor and the rotor is a squirrel cage type. When the rotor is operating at a speed near the synchronizing speed, a voltage of 90° phase difference with the source voltage is induced in auxiliary winding and a three phase voltage as shown in the drawing is obtained.

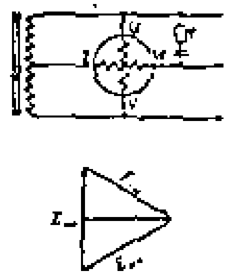


Fig. 9-45 Circuit and Vector Diagram of Phase Convertor

9-8-3 Motor-generator

A motor-generator systems are also classified into single phase induction motor, DC-motor system and thyristor motor system to be selected in accordance with the motor side system; and whichever system is adopted, the output voltage can be fixed in spite of fluctuation of line voltage.

(1) Single Phase Induction Motor System

This system is advantageous for small capacity, however, when the capacity is large, the phase convertor mentioned above is more advantageous.

(2) DC Motor System

This system is more disadvantageous than the phase convertor in weight, price, and maintenance. However, it has the special feature of being excellent in accuracy of frequency, and voltage fluctuation range:

(3) Thyristor motor system

This is to adopt a thyristor motor by which the commutator portion of a DC motor is converted to contactless by way of thyristors, and also is called a brushless motor-generator (BLMG). Although disadvantageous in terms of high initial investment and with increment of conversion part, it is very attractive because of the substantial simplification of maintenance. This system together with the inverter mentioned below is considered to be a leading equipment in the future. Fig. 9-46 indicates the principle of BLMG and Fig. 9-47 indicates the section of rotational machine body.

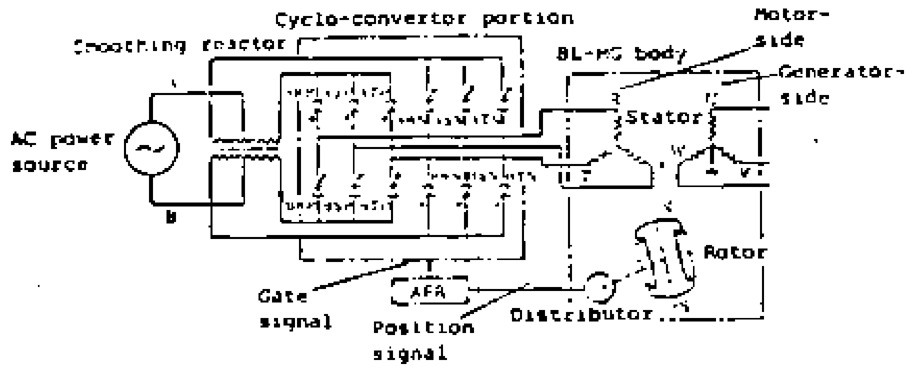


Fig. 9-46 Schematic Diagram of A.C. Brushless Motor-generator

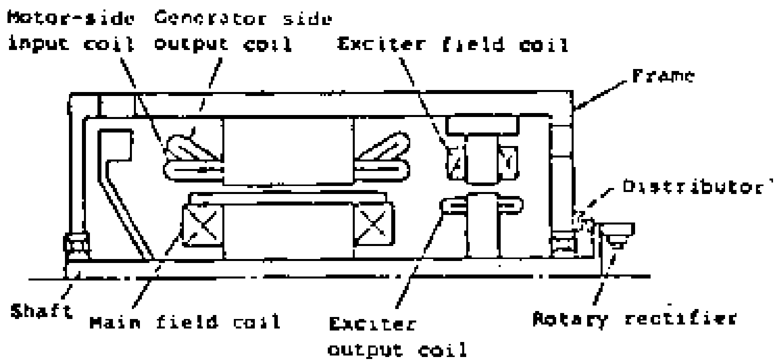


Fig. 9-47 Sectional View of Brushless Motor-generator

9-8-4 Inverter

Accompanying the development of the large capacity GTO (gate turn off thyristor), small size, lightweight and highly efficient inverter became available. This system is expected to make significant development in spite of its weak point of not able to cope with power source cutout such as point of crossing dead section (in the case of rotary machine, continuous supply is available by inertia force).

9-8-5 Auxiliary Rotary Machine

(1) Motor Driven Air Compressor

This equipment is compressing air for use in brake equipment and control equipment, and consists of a motor portion and air compressor portion. Smaller machines are made in one body, and large capacity machines are made to be driven by a belt, raising the motor speed to result in smaller, light weight design. The motor is rated for short time (30 min) operation because of intermittent operation.

On the other hand, in AC-electric rolling stock compressed air is used for closing of air-blast circuit breaker and raising pantograph. Therefore, a small motor compressor using a battery for drive shall separately be installed.

(2) Motor Driven Blower

The blower is used for cooling the traction motor, main transformer, static convertor, reactor, etc., and a centrifugal type blower is used for large air quantity requirement, and an axial flow type is used for cooling the reactor or heat exchanger.

The capacity of the motor for driving blower is given by the following equation:

$$\frac{Q \cdot H}{102} \times \frac{100}{\eta} \times k \ \text{[kW]}$$

Where; Q: Vol. of air (m^3/min)

H: Air press. (mm Aq)

η: Efficiency of the blower (%)

k: A constant determined by the blower, about 1.3 in this case

(3) Motor Driven Oil Pump

Oil circulation pump is necessary for main transformer or static power convertor of oil circulation air cooling system. A centrifugal pump is used in many cases as the oil pump.

CHAPTER 10

MAINTENANCE OF AC ELECTRIC ROLLING STOCK

10-1 Principles of Rolling Stock Maintenance

10-1-1 Life Cycle and Maintenance of Rolling Stocks

The life of A.C. electric rolling stocks, as is the case with that of all industrial products, comes to an end, going through a process of manufacture to use and then to disuse. Until this process is over, there is a need to maintain them as good as at the time of their manufacture in terms of function and performance. It is equally important for the sake of railway management to prolong their life as long as possible. With this in mind, it is necessary to take regular and temporary measures in order to restore to normalcy the devices and parts the function and performance of which have deteriorated in the course of their use. These measures, known inclusively as maintenance, are considered important factors in the life cycle of any rolling stock.

10-1-2 Aging and Failure of Rolling Stocks

After the use of rolling stocks for certain spans of time from their manufacture, there appear a wide variety of degenerating phenomena, such as wear-and-tear and abrasion which vary according to the conditions of their use and operation, and failure and wear-and-tear as a result of decoloration and erosion which take place, depending on the number of years of their use. The phenomena might perhaps be calssified in the three patterns of initial failure, accidental failure and failure due to wear-and-tear (degeneration).

"Initial falure" is one which breaks out due to an impropriety of quality control in the manufacture process and other reasons. It occurs in the relatively early phase of the use.

"Accidental failure" is caused by an abrupt and excessive stress. For example, it takes place when an electric or mechanical shock, an intrusion of dust, sand, water, etc., and an overheating greater than anticipated at the designing time have been produced.

"Failure due to wear-and-tear" or "failure due to degeneration" as rolling stocks have come to the limit of their life span due to wear-and-tear exhaustion during their use and to decoloration and erosion which take place in proportion as the rolling stocks have been in use.

Initial and accidental failure may be technically coped with to some extent primarily with improvements in the production and quality control systems or subsequent improvements. Insofar as failure due to wear-and-tear is concerned, however, there is a need to replace or replace components as they have completed their life span due to their wear-and-tear, deterioration or exhaustion during the course of their use.

The failure ratio of such products varies, depending on the lapse of time. The conventional quality control system is inadequate with no consideration provided to a lapse of time, so much so that quality control must be done with full heed given to a lapse of time.

Electric rolling stocks use large numbers of electric appliances and parts. Because of this, the occurrence of electric degeneration and failure (degenerated insulation, electrolytic corrosion, improper electric contact, etc.) is higher than is the case with other types of rolling stocks.

Electric degeneration and failure may be greatly reduced and the life span of the devices and parts may also be greatly extended by accurately grasping changes in their characteristics with a lapse of time and by doing prevention and maintenance.

10-1-3 Maintenance of Rolling Stocks

In case rolling stocks and equipment have degenerated and their functions have dropped to a point where they are no longer serviceable, it is desirable that the conditions be normalized before their failure to maintain rolling stocks in good condition at all times.

In carrying out the check, inspection and repair of rolling stocks, daily checks and maintenance are normally performed at the depot and for regular inspections and repairs, which may be likened to preventive medicine, to be conducted at the workshop.

The equipment and components the functions of which have degenerated should once again be made fully serviceable by restoring the functions to normalcy in one of the following methods.

(1) The equipment and parts in question will be replaced with new ones (to be thrown away after use).

(2) The degenerated sections and components will be repaired (to be maintained and reused).

Here, whether they are to be thrown away or maintained and once again to put use is determined by assessing the following factors:

(a) Degree of difficulty in acquisition: Purchase, storage and manufacture

(b) Prospects for recovery of functions: Technology, facilities and number of days to be required

(c) Cost-effectiveness: Price and number of work processes.

The maintenance of rolling stocks is closely tied in with the planning, designing, manufacture, operation and scrapping of rolling stocks and the like. For the maintenance and control of rolling stocks and equipment, it is necessary to acquire information about the rolling stocks designing and operation, supply information about their maintenance to the design or operation sector and manage the enterprise in an efficient manner to assure their normal operation at all times and raise their operation coefficiency.

10-2 Systems of Maintenance

10-2-1 Types of Maintenance Systems

The kind of inspection and repair which is to be conducted for the maintenance of rolling stocks' performance and safety is determined in all aspects from the standpoint of cost-effectiveness as a matter of course. Here, there is a need to establish the "method" and "cycle" of inspections and repairs in the most economical system, and this is known as a "system of maintenance."

The basic system of maintaining rolling stocks may roughly be divided as follows:

(a) While laying hold of the tendency of rolling stocks' failure, their maintenance is performed in advance according to some rule. (Preventive maintenance)

(b) A major functional recovery or improvement is conducted. (Maintenance for improvement)

(c) Maintenance is performed after the performance of rolling stocks has dropped due to their failure or degeneration and they have reached the service limit. (Break down maintenance)

(1) Preventive Maintenance

When equipment have greatly failed or degenerated, it requires huge amounts of money to restore their functions to normalcy and a great impact is produced on their safe operation. The preventive maintenance system in which maintenance and repair work are done on a regular basis before the degree of failure or degeneration does not go beyond the prescribed limit is quite instrumental in assuring the safety and extending the life span of the rolling stocks.

For preventive maintenance, it is a fundamental rule to determine and enforce a cycle of inspections (number of months gone by or number of kilometers operated) which starts with a daily inspection and ends with an overall inspection.

As for degeneration, the ratio of electric degeneration (degeneration with insulation, electrolytic corrosion, improper electric contact, etc.), rather than degeneration with abrasion, is greater for electric rolling stocks than for steam and diesel rolling stocks.

When electric degeneration has passed the limit and developed into a failure, the damage becomes exceedingly great and a huge amount of money is required in many cases. Given this factor, there is a need to realize the tendency of electric degeneration and the life span and carry out preventive maintenance at an appropriate time.

(2) Maintenance for Improvement

As the time span in which rolling stocks are used is long, they may be left behind the advance of technology and become obsolete. To prevent this, the latest technology is sometimes introduced, in part, to improve them to a level where their performance is better than at the time of their production.

To a line to which new rolling stocks have been assigned, moreover, rolling stocks sometimes have to be improved, depending on the conditions of the line, as it is necessary to prevent the occurrence of failure of the kind which is peculiar to the line.

(3) Failure Maintenance

As regards the sections and equipment which are required for the maintenance of rolling stocks' performance and the assurance of their safe operation, it is necessary to keep them normal with preventive maintenance.

However, in respect to the sections and equipment (customers' service facilities, service equipment, etc.) which are not directly tied in with the maintenance of rolling stocks' performance and safe operation, it sometimes is better, in terms of cost-effectiveness, to carry out break down maintenance, as it does not directly hinder the operation.

For the railways of foreign nations, the causes which may lead to failure maintenance are summarized as follows with reference to those which are required for the maintenance of rolling stocks' performance and the assurance of their safe operation.

(a) Economic problem: Shortage of budget and hard currency, belated acquisition of parts, shortage of spare parts and lack of rolling stocks.

(b) Technological problem: Extremely small capacity of facilities, improper inspection cycle, technological inexperience and extremely small number of rolling stocks by type.

(c) Informational problem: Inadequate grasping of the conditions of rolling stocks' maintenance and insufficient records.

(d) Others: Robbery of rolling stock parts and damage by accidents at railway crossings.

(4) Comparison of Maintenance

The merits and demerits of preventive and break down maintenance are compared below.

Table 10-1 shows a comparison of cost between preventive and break down maintenance. The number of rolling stocks, frequency of their operations, volume of their transportation, cost required for them, etc., vary, depending on the railway, so much so that there is a need to compute all costs and compare and assess them in a comprehensive manner.

The systems of maintenance may be divided into the following four types.

(a) Preventive maintenance is done on all rolling stocks and equipment.

(b) Rolling stocks are subjected to preventive maintenance and, in part, to break down maintenance.

(c) Failure maintenance is conducted on all rolling stocks and equipment.

(d) All rolling stocks and equipment are discarded without break down maintenance (repair work).

Now that rolling stocks and equipment are relatively dear, have a long service life and are important as assets, it is a normal practice for each railway to formulate and operate a system of maintenance on the premise that their preventive maintenance will be conducted.

Table 10-1 Comparison between Preventive Maintenance and Bread Down Maintenance

Cost \ Maintenance type	Preventive maintenance	Break down maintenance
Normal maintenance cost	Large	Small
Repair cost	Small	Large
Incurred loss	Small	Large

10-2-2 Types of Inspections

(1) Definition of Inspection

Inspection, as referred to here, is one in which the degree of degeneration of each assembly of rolling stocks and equipment and whether a failure has occurred is checked before their use or before and after their repair so that their use may not be hindered after a functional adjustment and compensation.

(2) Types and Organization of Inspections

The inspections come in two types -- a periodic inspection performed on a regular basis and an incidental inspection conducted as occasion demands. One example is shown in Table 10-2.

Table 10-2 Types of Inspections

Periodic inspection	Daily inspection	Check of train (as operated)
		Check of the train condition and function
	Intermediate inspection	Check of principal parts (travel, drive power, brake)
	Overall inspection	General check on disassembled principal parts
Inspection according to necessity	Operation inspection	Check and countermeasuring of trouble point during operation
	Special inspection	Special check of a whole or part of rail-cars after the occurrence of trouble

The establishments which will take charge of the maintenance of rolling stocks are determined, depending on the number of rolling stocks, geographical conditions, types of gauges, organization and capacity (facilities, necessary personnel, work process and materials) but not necessarily constant.

In other words, it is advisable to select the most cost-effective establishment while taking account of the return of rolling stocks, transport of equipment, number of days with rolling stocks' operation suspended, etc.

An example of the types of inspections and the establishments in charge of the maintenance is shown in Table 10-3.

Table 10-3 Inspecting Establishments

Type of inspection	Place of inspection
Overall inspection	Workshop
Intermediate inspection	Workshop, Depot
Daily inspection	Depot
Operation inspection	Depot
Special inspection	Workshop, Depot

Incidentally, the JNR's example is shown in Table 10-4.

Table 10-4 Names of Inspections by Type

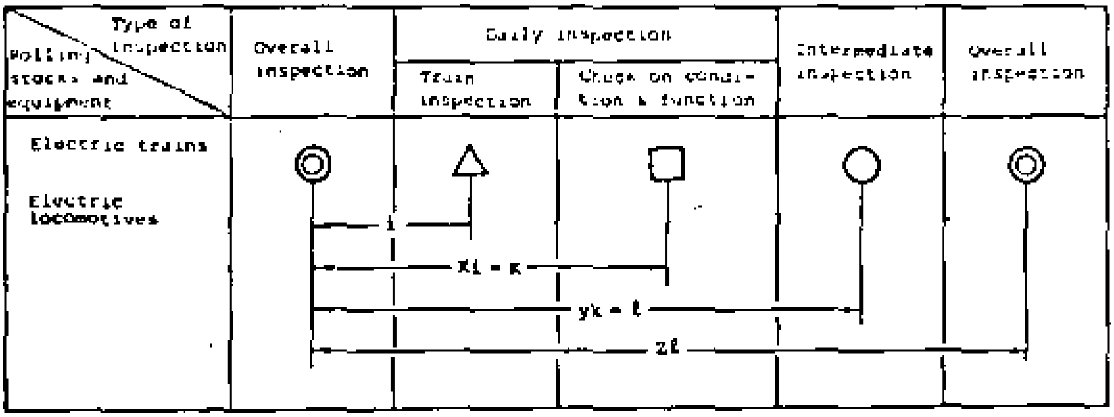
<table>
<tr><th rowspan="4">Type of inspection / Type of rolling stock</th><th colspan="6">Periodic inspection</th><th colspan="2">Inspection carried out, wherever necessary</th></tr>
<tr><th colspan="3">Routine inspection</th><th colspan="2">Intermediate inspection</th><th rowspan="3">Overall inspection</th><th rowspan="3">In operation</th><th rowspan="3">Incidental inspection</th></tr>
<tr><th colspan="3">Inspection of conditions and actions</th><th colspan="2" rowspan="2">Inspection of major components</th></tr>
<tr><th colspan="2">External inspection</th><th>Inspection with rolling stocks left left they are</th></tr>
<tr><td>EC
EC</td><td colspan="2">Trip inspection</td><td>Periodic inspection</td><td>Bogie inspection</td><td>Specified-part inspection</td><td>Overall inspection</td><td>+</td><td>•</td></tr>
<tr><td>DL
DC</td><td colspan="2">Trip inspection</td><td>Periodic inspection (A)</td><td>Periodic inspection (B)</td><td>Specified-part inspection</td><td>Overall inspection</td><td>+</td><td>•</td></tr>
<tr><td>PC</td><td>Trip inspection (A)</td><td>Trip inspection (B)</td><td>Periodic inspection</td><td>Periodic inspection (exchange of specified parts)</td><td></td><td>Overall inspection</td><td>-</td><td>-</td></tr>
</table>

10-2-3 Inspection Cycle

Periodic inspections are performed in a combination of overall, intermediate and daily inspections. The intermediate and daily inspections are not one type of inspection but several kinds. One example is given in Table 10-5.

As regards a combination of inspections, a daily inspection is repeated and at the time of an inspection after a certain period (running distance in kilometers), an inspection of the next higher level is performed. After this inspection is repeated, an inspection of the further higher level is conducted. Finally, overall inspection is performed.

Table 10-5 Combination of Inspections



Notes:
- i: Train inspection period
- X: Frequency of train inspections
- Y: Frequency of inspections of conditions and actions
- Z: Frequency of intermediate inspections
- K: Daily inspection period
- L: Intermediate inspection period

10-2-4 Determination of Inspection Cycle

The rolling stock comprises the car body plus various equipment, pipings and wirings. These components are divided into a group developing gradual wear and deterioration in operation and a group suffering deterioration as time passes, regardless of whether they are operated or not. The trend and status of deterioration widely differ, depending on the environmental conditions (gradient, sand and dust, weather, rainfall, salt) of the section, operating kilometers, operation frequency, and running speed.

The life span of rolling stocks is relatively long and the technical level prevalent at the time of their manufacture reflects their function and construction. Given this factor, there is much difference in degeneration, and the degree of degeneration also varies, depending on the date of manufacture and the number of years gone by even for one and the same time of rolling stocks.

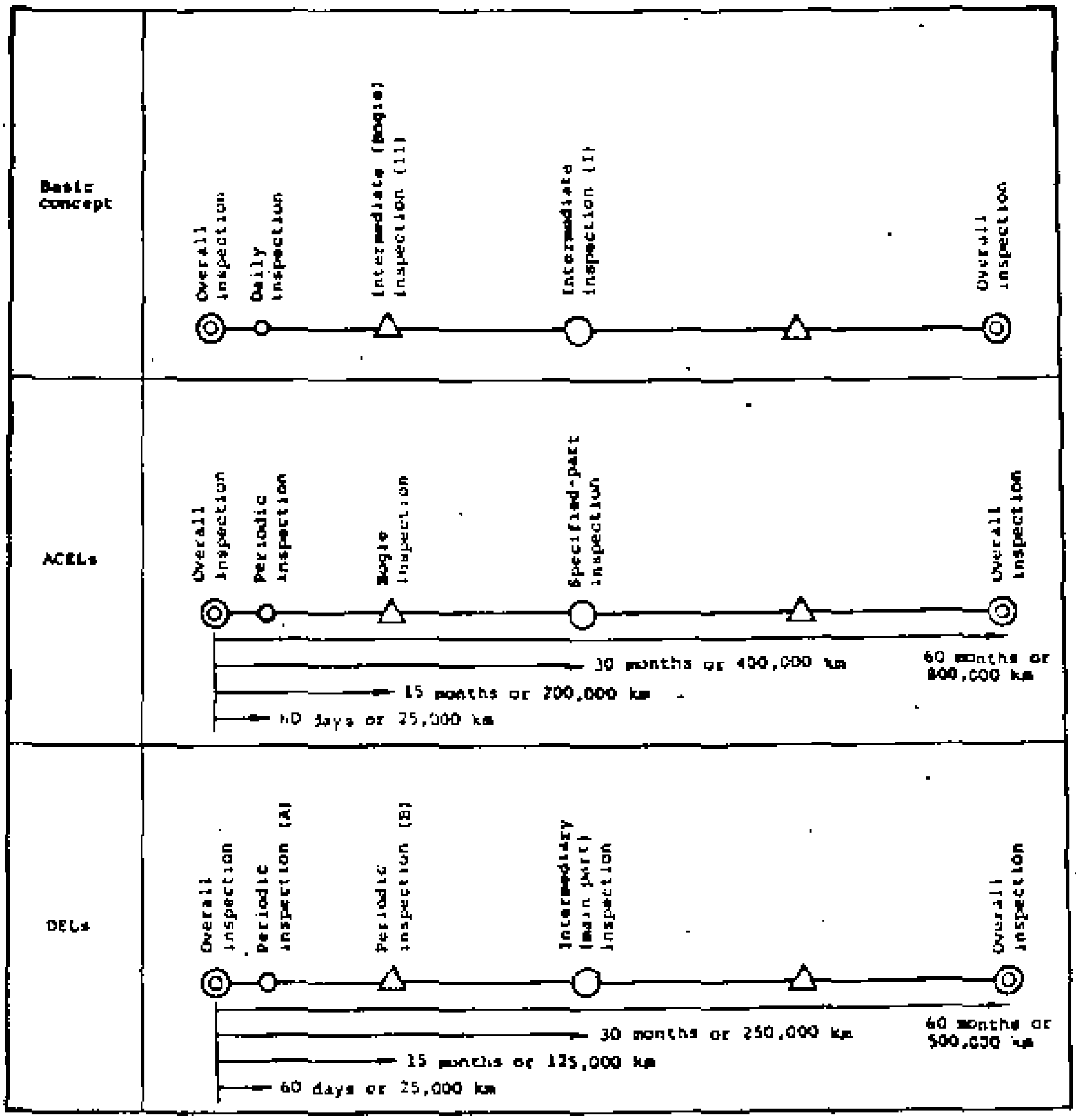
The period of a regular inspection of rolling stocks must be determined with these factors taken into account so that it may be performed at an appropriate time. For this, there is a need to check, record and update degrees of degeneration and wear-and-tear at each periodic inspection.

With the aggregate running distance (kilometers operated) and the length of hours gone by (period), the period of a periodic inspection will be made coincident with a cycle of kilometers operated or periods.

An example of the JNR is given in Table 10-6.

Table 10-6 JNR's Inspection System

Comparison of A.C. Electric Locomotives (ACELs) and Diesel Electric Locomotives (DELs)



The above table shows the running distance in kilometers which restricts the return is different between the ACEL and the DEL. This is because the maintenance of expendables (cylinder liners, etc.) for the engine are taken into account. In the same vein, the period of an inspection also differs between electric and diesel truck cars.

10-2-5 Substance of Inspections

(1) Daily Inspection

(a) Operation Inspection

This inspection is directly tied in with the operation of rolling stocks and carried out in a cycle of short periods before their use. In this inspection, expendables and abraded parts are supplied or replaced, and the action and function of pantographs, bogie trucks, driving gear, wheel and axle sets, brakes, electric appliances, door locking devices, indoor systems are checked.

The inspection, which is designed primarily to check the functions, is conducted while an electric train remains organized or an electric locomotive remains as singler units in the yard.

Incidentally, as regards diesel rolling stocks, the action and function of their engines, power generators, etc., are ascertained in addition to the above points.

(b) Inspection of Conditions and Functions

In this inspection, the conditions and functions of specified parts which are directly tied in with the operation and safety of rolling stocks are ascertained. With each assembly of a rolling stock remaining as it is, the check cover of each assembly is taken off and a tester used to measure the degree of degeneration and the value of the characteristic of each assembly. The maintenance, cleaning, refueling and adjustment of contact and sliding plates in the electric appliances are conducted; carbon brushes, pantograph slippers, electric contacts, brake blocks and other expendables are replenished or replaced, and insulation and resistance tests are performed on electric parts.

As regards diesel rolling stocks, their engines are checked and refueled with the rolling stocks left as they are in addition to the above components.

Table 10-7 Inspection of Major Equipment and Parts

System	Equipment	Rolling stock type: ACEL	Rolling stock type: DEL	Classification of disassembling: Overall inspection (comprehensive inspection)	Classification of disassembling: Intermediate inspection (specified-part inspection)
Main circuit system	Pantograph	o		o	o
	Air blast circuit breaker	o		o	o
	Unit switch and breaker	o		o	o
	Main transformer	o	o	Δ	Δ
	Main (control) rectifier	o	o	▲	▲
	Truction motor	o	o	o	o
Motive power unit	Engine		o	o	o
	Generator		o	o	o
Control system	Trays	o	o	▲	▲
	Fuel control		o	o	o
Coupler	Coupler	o	o	o	o
	Buffer	o	o	o	o
Running gear	Bogie frame	o	o	Δ	Δ
	Swing system	o	o	o	o
	Spring	o	o	▲	▲
	Wheel and axle	o	o	▲	▲
Brake system	Foundation brake rigging	o	o	o	o
	Air control valves	o	o	o	o
Auxiliary devices	Auxiliary motor	o	o	o	o
Safety devices	Train stop	o	o	▲	▲
	Instrument	o	o	o	o

o : Inspection with the machine taken off and disassembled

▲ : Inspection with the part taken off but not disassembled

O : Inspection with the machine left fitted and disassembled

Δ : Inspection with the part fitted and left as it is

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[illegible] του καθηγητή [illegible]	[illegible]
[illegible] ροή [illegible] του καθηγητή [illegible]	[illegible]
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10-3-2 Facilities

For the maintenance of rolling stocks, inspection facilities should be indispensable. In substance, however, the facilities vary, depending on the number of days of inspection, types of rolling stocks to be inspected or whether rolling stocks of one and the same type are to be exclusively inspected or those of many types are to be inspected in all aspects.

Without taking note of systematization according to the number of rolling stocks for an inspection and other factors, the facilities unique to ACELs and DELs are shown in Table 10-8.

Table 10-8 Comparison of Major Locomotive Repair Facilities at Workshops

Work	Machine	ACEL	DEL
Fittings and bogie	Bogie air blast system	o	o
	Bogie painting system	o	o
	Set of cargo handling devices, such as ceiling cranes	o	o
Inspection and repair of bogie truck	Bogie truck cleaning system	o	o
	Bogie truck painting system	o	o
	Damage detector	o	o
	Set of other cargo handling devices, etc.	o	o
Inspection and repair of wheel and axle	Cleaning and polishing devices	o	o
	Damage detector	o	o
	Wheel lathe	o	o
	Wheel and axle press	o	o
	Tire boring machine	o	o
	Tire shrinkage fit	o	o
	Axle grinder	o	o
	Set of other cargo handling devices, etc.	o	o
Inspection and repair of revolving machines	Cleaning device	o	o
	Magnetic frame and armature automatic inspecting system	o	o
	Armature rotation inspecting system	o	o
	Commutator surface grinder and corrector	o	o
	Commutator groove cutter	o	o
	Set of other devices	o	o

Work	
Inspection repair electric	[illegible]
Engine repair [illegible]	[illegible]
Inspection and repair of engine	[illegible]
Transportation movement	[illegible]

The table [illegible]
are required for [illegible]
The overall [illegible]
that of the rep [illegible]
much so that it [illegible]
work proceeds [illegible]
the coefficient [illegible]
much.

Work	Machine	ACEL	DEL
Inspection and repair of electric parts	VCB tester	o	x
	Lightning arrester tester	o	x
	Main commutator tester	o	o
	Pantograph tester	o	x
	Engine parts tester	x	o
	Set of other testers	o	o
Inspection and repair of air brakes	Cleaning device	o	o
	Brake tester	o	o
	Distributing valve tester	o	o
	Set of other testers, etc.	o	o
Inspection and repair of engine	Cleaning and polishing devices	x	o
	Damage detector	x	o
	Jet valve pump tester	x	o
	Governor tester	x	o
	Cylinder head tester	x	o
	Engine performance tester	x	o
	Set of other cargo handling devices, etc.	x	o
Inspection for move-out	Comprehensive circuit testing device	o	o
	Fuel supply device	x	o
	Trolley wire	o	x
	Set of other testers, etc.	o	o

The table shows considerable facilities and therefore land are required for the inspection and repair of DELs.

The overhaul of engines normally takes much more days than that of the repair of other devices and parts or the bogie, so much so that it becomes necessary to do it by extending the whole work process or to do repair work in circles with spare engines. The coefficiency of use of the site is accordingly dropped that much.

aintenance Cost

1 Concept

The maintenance of rolling stocks is conducted according to concept and system mentioned in 10-1 and 10-2. In the phase each inspection, therefore, the balance between the A.C. ictric equipment and the engine plus the generator represents balance of maintenance work both for ACELs and DELs. In addition, the maintenance cost could be made smaller ACELs than DELs to the degree to which the interval of inspection is cut cort for the sake of inspections.

Even with one and the same output, ACELs features a greater overload durability than DELs, and the number of rolling stocks ced and the overall maintenance cost could be reduced.

The JNR has experienced in having DELs of the 1,200 PS class, which are equipped with old-type D.C. generators. On the basis of ome maintenance costs of DELs of this type and DHLs of the latest ype, the maintenance costs of DELs of a three-phase generator ype with highly reliable engines of the latest type and ACELs of the latest thyristor type are computed for the sake of comparison under the JNR's maintenance system.

-4-2 Comparison of Maintenance Cost

For the computation, the locomotives are considered in the following manner.

The concept of the basic system is indicated in Fig. 10-2. For DELs, three-phases A.C. generators are used because they are excellent in terms of maintenance and other factors from the standpoint of the latest technology. Consequently, we would consider that the transformer and the components which come after it are common. As regards the maintenance cost at the workshop, the portion for the engine generator is dropped whereas those for the pantograph and the breaker are increased. When computation is made under the JNR's inspection system, the maintenance cost is some 30% lower for ACELs than for DELs per rolling stock.

When the number of DELs required for the actual operations, the difference in maintenance cost will become further bigger as a whole.

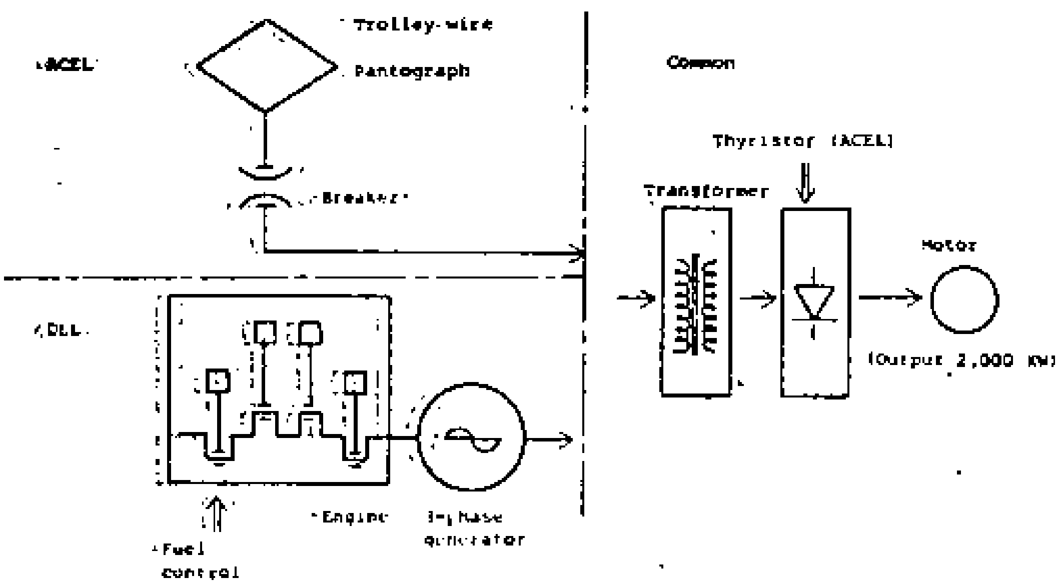

Fig. 10-2 Basic System of Locomotive