DIVISIÓN DE EDUCACIÓN
CONTINUA Y A DISTANCIA

DIPLOMADO
DISEÑO Y CÁLCULO DE INSTALACIONES ELÉCTRICAS
(RESIDENCIALES, INDUSTRILAES Y ESPECIALES)

MÓDULO II
CA 416 LÍNEAS AÉREAS

Del 08 al 10 de Noviembre de 2007

EXPOSITOR: ING. FERNANDO TOLEDO TOLEDO

SECRETARÍA DE LA DEFENSA NACIONAL

PARÁMETROS DE LÍNEAS DE TRANSMISIÓN

Tanto la inductancia como la capacitancia de una Línea de Transmisión (LT) dependen de la configuración geométrica, el arreglo que tienen los conductores en la estructura de soporte, poste, torre o ducto.

Este aspecto es significativamente importante sobre todo para las LT aéreas, debido a que representan un alto porcentaje del total de las líneas en redes de potencia. Aquí, el dieléctrico es el aire y el límite térmico de conducción de corriente (ampacidad) es mucho más alto que en el caso de las líneas de transmisión subterráneas, en donde el aislante utilizado representa una limitación térmica importante. Los parámetros RLC en una LT se encuentran distribuidos uniformemente (figura 1).

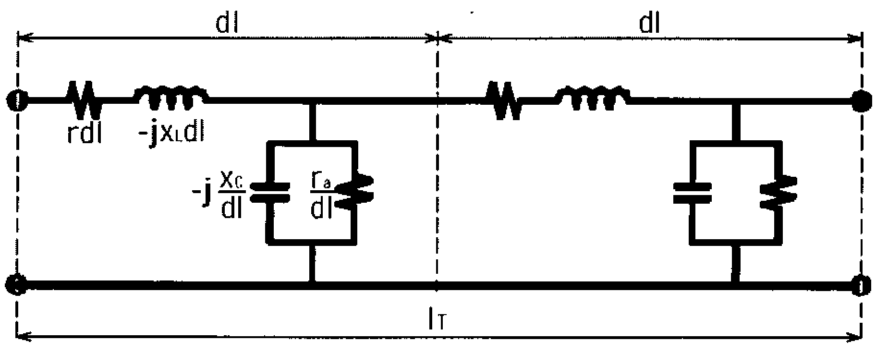


Figura 1. Parámetros de una línea de transmisión.

Donde:

r: Resistencia por unidad de longitud O/km.
x_L: Reactancia inductiva por unidad de longitud O/km.
x_C: Reactancia capacitiva por unidad de longitud O•km.
r_a: Resistencia de aislamiento por unidad de longitud O•km.

Una vez conocidos los parámetros por unidad de longitud de la LT, podemos calcular la resistencia total por fase de la línea:

$$R ? rl_T$$

donde:

l_T: longitud total de la línea.

$X_L ? x_L l_T$

$X_C ? \frac{x_a}{l_T}$

$R_a ? \frac{r_a}{l_T}$ = resistencia de aislamiento total por fase.

$z_S ? r ? jx_L$ = impedancia serie por unidad de longitud.

$z_P ? \frac{-jx_C r_a}{r_a - jx_C}$ = impedancia paralelo por unidad de longitud.

Se pueden tomar dos tipos de modelos para LT.

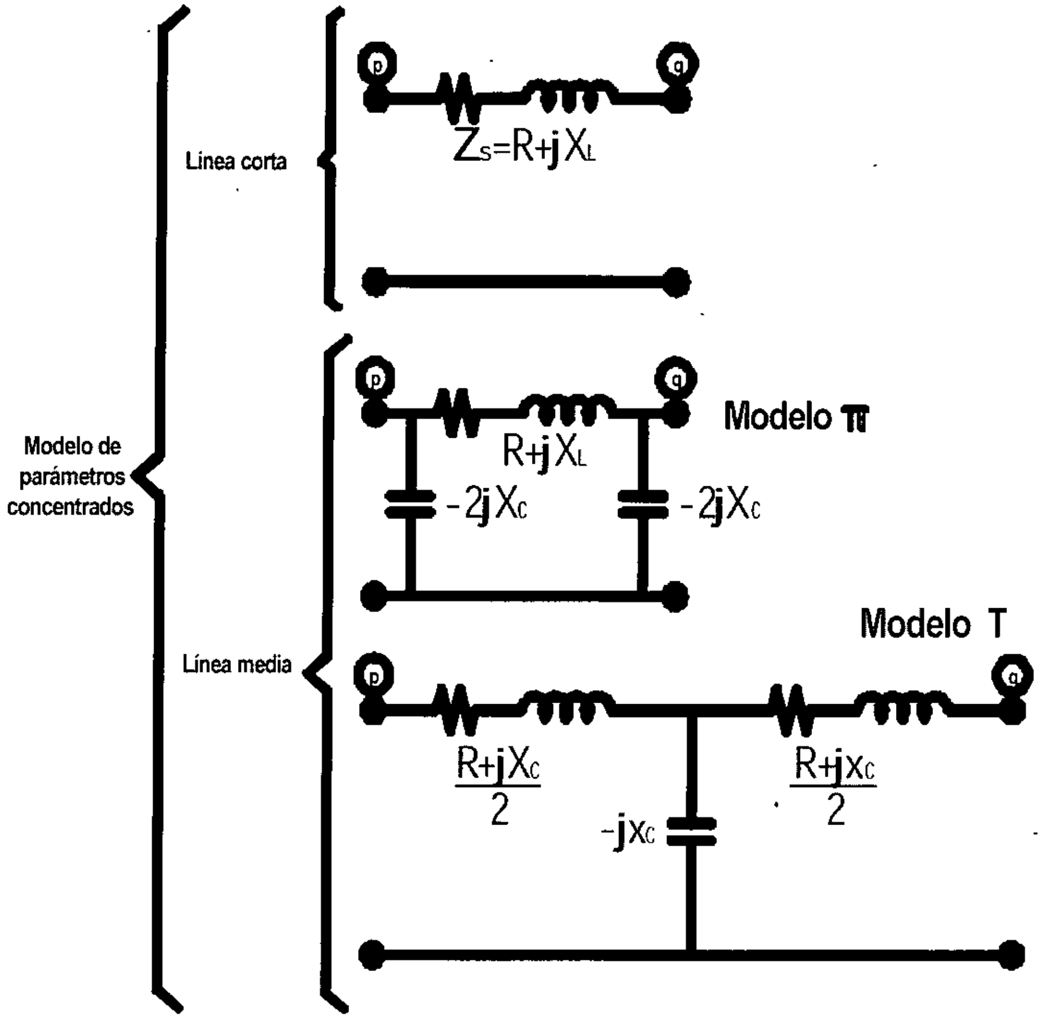


Figura 2. Modelo de parámetros concentrados.

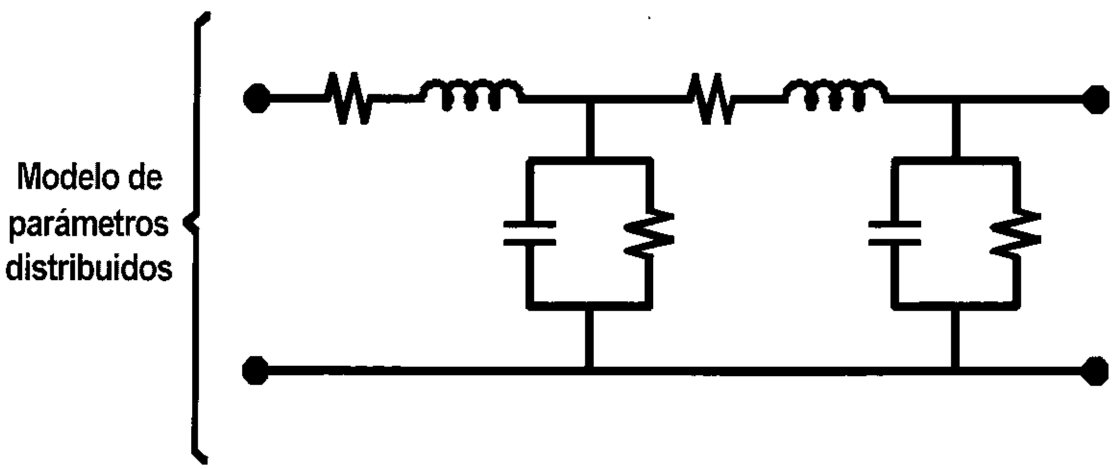


Figura 3. Modelo de parámetros distribuidos.

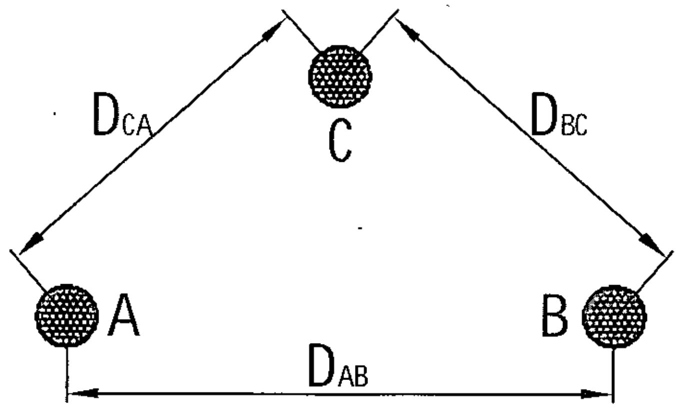


Figura 4. Línea de transmisión con un conductor por fase.

Inductancia (para circuitos trifásicos): Este parámetro está en función de líneas de flujo magnético producidas por otro conductor y enlazado por el conductor. El número de líneas de flujo enlazados depende de la intensidad de campo magnético y de la distancia.

La inductancia por fase por unidad de longitud, es:

$$L ? 2x10^{-7} \ln ? \frac{DMG}{RMG} ?? H/m ?$$

donde:

DMG: Distancia media geométrica de las distancias de separación entre conductores: $DMG ? \sqrt[3]{D_{AB} D_{BC} D_{CA}}$

D_{AB}? D_{BC}? D_{CA}: Flujo magnético enlazado por los conductores.

RMG: Radio Medio Geométrico.

Para que el flujo magnético enlazado sea el mismo es necesario transponer las líneas (figura 5), así las impedancias por fase se equilibran.

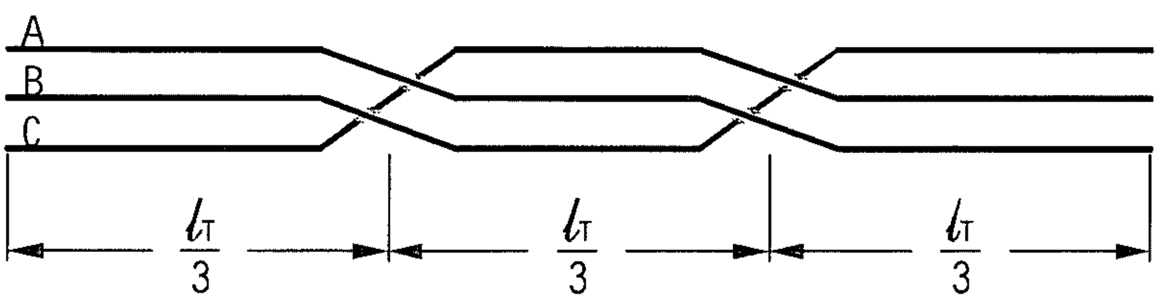


Figura 5. Flujo magnético igual en toda la LT.

El flujo total producido por el conductor puede agruparse en:

Flujo interno: que es producido por el conductor pero interno a él.
Flujo externo: producido por el conductor externo a él.

Se define el radio medio geométrico como el radio de un conductor hipotético de pared infinitesimal (hueco) de tal manera que el flujo total es exterior a él y equivalente al del conductor original.

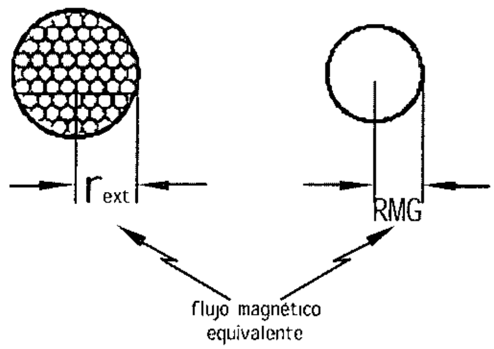


Figura 6. Radio Medio Geométrico.

Los conductores pueden ser cables o alambres (figura 6), de cobre (Cu) o de aluminio (Al) del tipo ASCR (conductor de aluminio con alma de acero), de tal manera que para conductores sólidos $RMG=r_{ext}\,e^{-1/4}$.

Ejemplo 1:

Sea una LT con 2CF, tal como se muestra en la figura 7 (transpuesta).

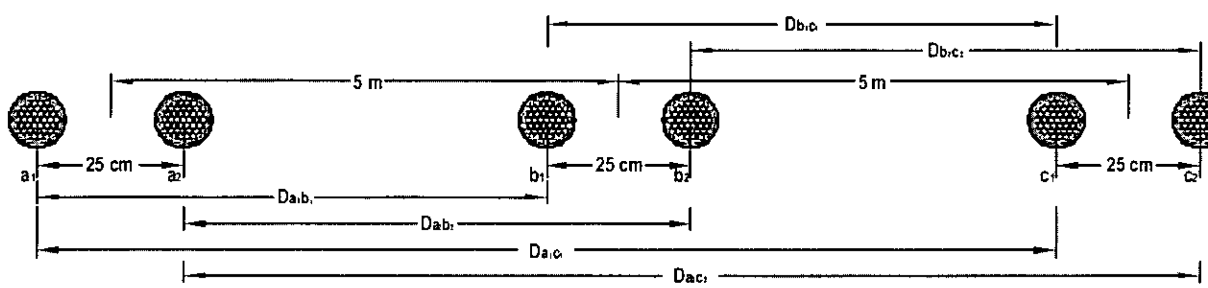


Figura 7. Configuración de la línea de transmisión del ejemplo.

Obtener la DMG del arreglo

$D_{a_1b_1}$? $D_{a_2b_2}$? $D_{b_1c_1}$? $D_{b_2c_2}$? D_1 ? $500cm$

$D_{b_1c_2}$? D_2 ? $525cm$

$D_{b_2c_1}$? D_3 ? $475cm$

$D_{a_1c_1}$? $D_{a_2c_2}$? D_4 ? $1000cm$

entonces

$DMG ? \sqrt[12]{D_1^4 D_2^2 D_3^2 D_4^2 D_{a_1c_2} D_{a_2c_1}} ? \sqrt[12]{D_1^4 (D_2 D_3 D_4)^2 D_{a_1c_2} D_{a_2c_1}}$

$DMG ? \sqrt[12]{500^4 (525 * 475 * 1000)^2 (1025)(975)} ? \sqrt[12]{3.88431395X10^{33}}$

$DMG ? 629.6649614cm$

RADIO MEDIO GEOMÉTRICO PARA ARREGLOS MULTICONDUCTORES.

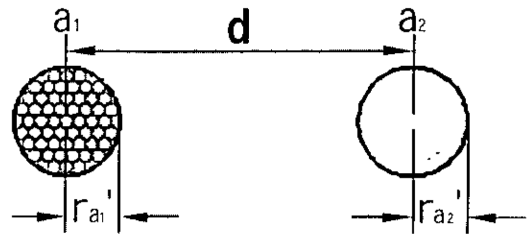


Figura 8. Radio Medio Geométrico para un arreglo de dos conductores por fase.

El RMG es un valor que representa un radio hipotético, este radio es siempre menor que el radio exterior designado con r' el RMG, para la figura 1.

$$RMG_A = \sqrt[4]{r_{a_1}' d_{a_1 a_2} r_{a_2}' d_{a_2 a_1}}$$

Si se tienen conductores iguales (como es común), entonces:

$$RMG_A = \sqrt{r_a' d_{a_1 a_2}}$$

$$RMG_{ABC} = \sqrt[3]{RMG_A RMG_B RMG_C}$$

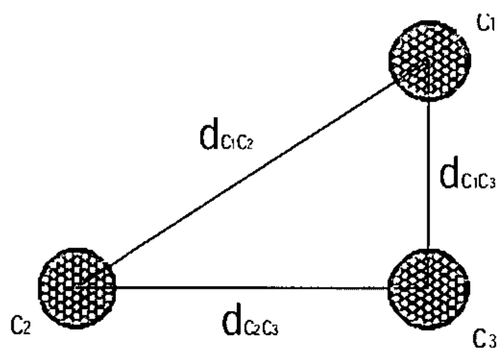


Figura 9.

$$RMG_C = \sqrt[6]{r_{c_1}' r_{c_2}' r_{c_3}' d_{c_1 c_2} d_{c_2 c_3} d_{c_1 c_3}}$$

$$Z_s = R + jX_L \; [\Omega / f]$$

$$X_L = 2 \pi f L_T$$

L_T: Inductancia total de la línea ? $L_T = L\, l_T$
L: Inductancia por unidad de longitud.
l_T: Longitud total.
Z_s: Es una limitancia fundamental de la capacitancia de transferencia de la LT (es indispensable que Z_s sea pequeña).

$$L = 2x10^{-7} \ln\left(\frac{DMG}{RMG}\right) \left[\frac{H}{m}\right]$$

Existen dos denominaciones para el calibre de conductores:

1) **CU** Circular Mils: Medida de área de un círculo que tene como radio una milésima de pulgada.
2) **AWG** American Wire Gage: Galgas Americanas de conductor.

Los materiales empleados en conductores para LT, son:

- Cobre (Cu).
- Aluminio (Al).
- Acero (operativamente como refuerzo).

Ejemplo 2:

Sea una LT (transpuesta), con l_T= 40km y 3.5m de separación entre conductores de cobre de 250 MCM con 12 hilos (fig. 10) a 6,9kV.

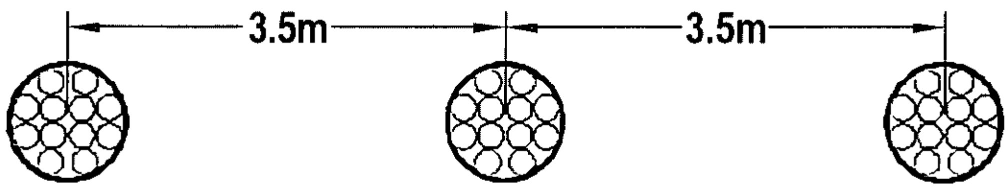


Figura 10. Línea de Transmisión del ejemplo.

Determine:

a) Impedancia serie por unidad de longitud.

$Z_s = r + jX_L$ (O/km).

b) Impedancia total por fase (O/fase).

c) Cálculo con tablas.

Solución:

Sea $r=r_a 0.257$ O/milla=0.159726538 O/km

$$X_L \ ? \ 2?f \left(2x10^{-7}\right) \ln ? \frac{DMG}{RMG} ?$$

entonces:

$$DMG \ ? \ \sqrt[3]{3.5?3.5?7} \ ? \ 4.409723675m$$

$$RMG \ ? \ 0.01902ft \ ? \ 5.797296x10^{-3} m$$

$$X_L \ ? \ 2?(60Hz)\left(2x10^{-7}\right) \ln ? \frac{4.409723675m}{5.797296x10^{-3} m} ?$$

$$X_L \ ? \ 0.5002050638x10^{-3} ? \ /m \ ? \ 0.5002050638? \ /km$$

Z_s = (0.159726538+j 0.5602050638) O/km

Que es la impedancia serie por unidad de longitud.

CAPACITANCIA Y REACTANCIA CAPACITIVA.

La capacitancia está en relación con el campo eléctrico este emana radialmente del exterior de los conductores que tienen potencial. El valor de la capacitancia depende de la distancia de separación y de las características del medio dieléctrico.

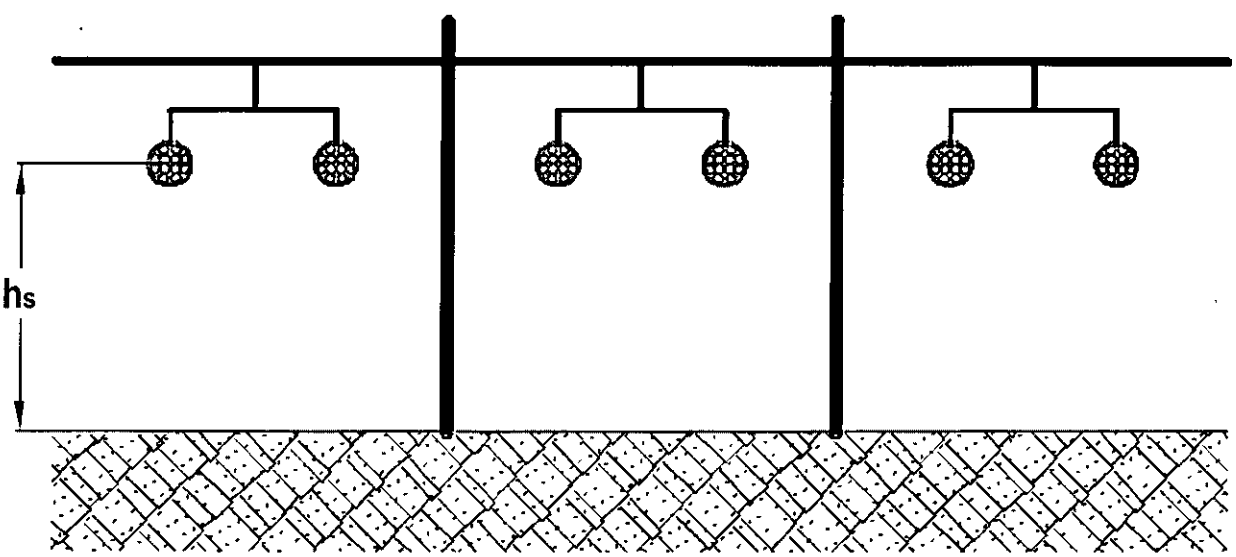
Valores por unidad de longitud

$$\left\{\begin{array}{l} C_n = \dfrac{0.02412\,k}{\log_{10}\left(\dfrac{DMG}{RMG_c}\,\dfrac{2HMG}{\sqrt{4(HMG)^2+(DMG)^2}}\right)} \quad \left(\mu F/km\ fase\right) \\ X_n = \dfrac{6.596}{f\,k}\log_{10}\left(\dfrac{DMG}{RMG_c}\,\dfrac{2HMG}{\sqrt{4(HMG)^2+(DMG)^2}}\right) \quad \left(M\Omega\ km\right) \end{array}\right.$$

Es un parámetro que por su valor en algunos casos se desprecia para una LT aérea depende fundamentalmente de su voltaje nominal y de su longitud. Estos parámetros establecen (como se verá más adelante), la clasificación de la LT.

De las expresiones de Cn y Xc descritas arriba, los parámetros asociados son:

- K: Constante dieléctrico del medio aislante. Para el aire k=1.
- DMG: Distancia media geométrica (igual a la utilización en el cálculo de la inductancia).
- RMG_c: Radio medio geométrico considerando radios individuales externos (no radios utilizados en el cálculo de inductancias).
- HMG: Altura media geométrica[1], considerando las alturas de los conductores sobre la estructura de soporte (figura 11) y el perfil de los mismos en el claro intercostal (figura 12).



[1] Considerando el efecto de la tierra (suelo) sobre la capacitancia.

Figura 11.

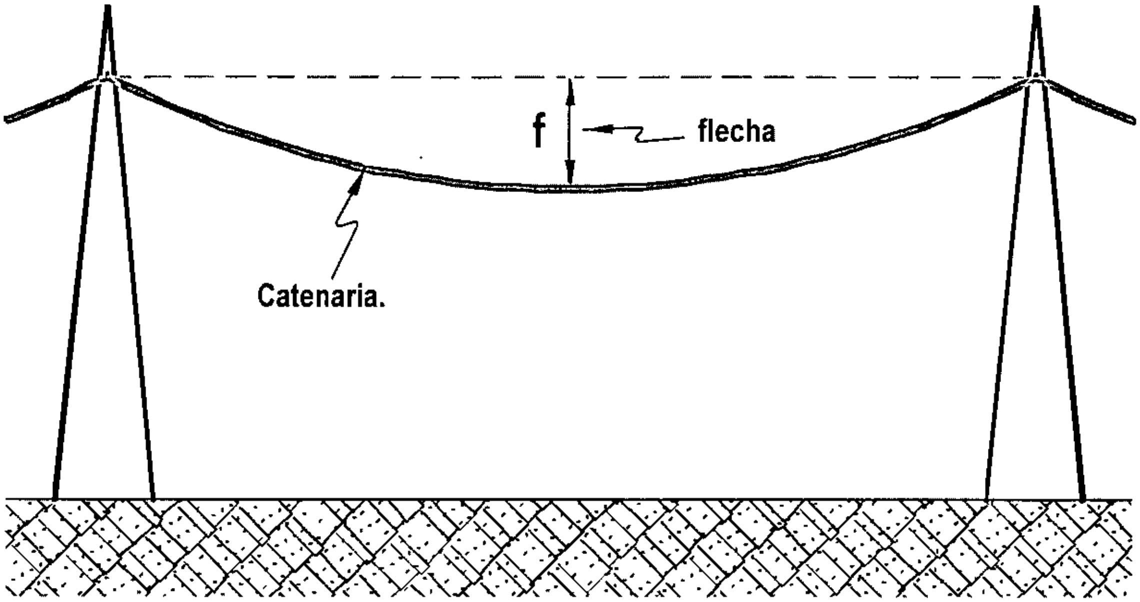


Figura 12.

Altura media: h_b=-0.7f con una frecuencia de 60Hz. Si se trata de una línea de transmisión o subtransmisión hasta 115kV (MT) ? HMG>>DMG y entonces:

$$\frac{2HMG}{\sqrt{4(HMG)^2 + (DMG)^2}} \approx 1,$$ con k=1 para todas las líneas aéreas.

De donde: $$C_n = \frac{0.02412}{\log_{10}\left(\frac{DMG}{RMG_c}\right)} \left[\mu F/km\ fase\right]$$

Ejemplo 3:

Para el ejemplo 2 de estudio (1CF) determine la capacitancia y reactancia capacitiva por unidad de longitud y total de la línea (ver ejemplo 2 y figura 13).

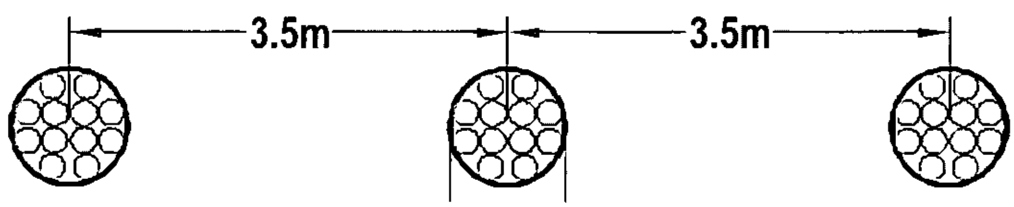


Figura 13.

Solución:

Como se mencionó arriba, con la expresión para C_n, en el caso donde se tiene 1CF, RMG_c es el radio exterior, el diámetro exterior en éste caso es $?_{ext}$=0.6 pulg.=0.01524m y DMG = 14.4676ft = 4.4097m, de tal modo que:

$$RMG_c ? \frac{?_{ext}}{2} ? \frac{0.01524}{2} ? 7.62x10^{?3} m$$

Luego, la capacitancia al neutro por unidad de longitud es calculada de la siguiente manera:

$$C_n ? \frac{0.02412\ k}{\log_{10} ? \frac{?DMG?}{?RMG_c?} ?} ? \frac{0.02412}{\log_{10} ? \frac{?\ 4.4097m\ ?}{?7.62x10^{?3} m?} ?} ? 8.731367x10^{?3}\ ?F/km$$

La capacitancia total por fase:

$$C_T ? C_n ?l_T ? ?8.731367x10^{?3}\ ?F/km??40km?$$

$$?\quad C_T ? 0.349255\ ?F/fase$$

Análogamente la reactancia capacitiva por unidad de longitud es:

$$x_c ? \frac{1}{2?? ?f ?C_n} ? \frac{1}{2?? ??60Hz??8.731367x10^{?3}\ ?F/km?}$$

$$?\quad x_c ? 0.303799M? ?km$$

La reactancia capacitiva total:

$$X_c ? \frac{x_c}{l_T} ? \frac{0.303799M? \cdot km}{40km} ? 7.59498x10^{?3} M?/fase$$

Finalmente determinamos x_c y X_c por tablas. Así, de la tabla 8 tenemos:

$$14ft ?\ 0.0781? ?milla?$$
$$15ft ?\ 0.0803? ?milla?$$

de tal manera que para 1ft calculamos por regla de tres $0.0022? ?milla ? 1.028714192x10^{-3}? ?ft$

$$x_c ? 0.0781 ? 1.028714192x10^{?3}$$

$$x_c ? 8.03425784x10^{?6}? ?milla$$

LÍNEA DE TRANSMISIÓN TRANSPUESTA.

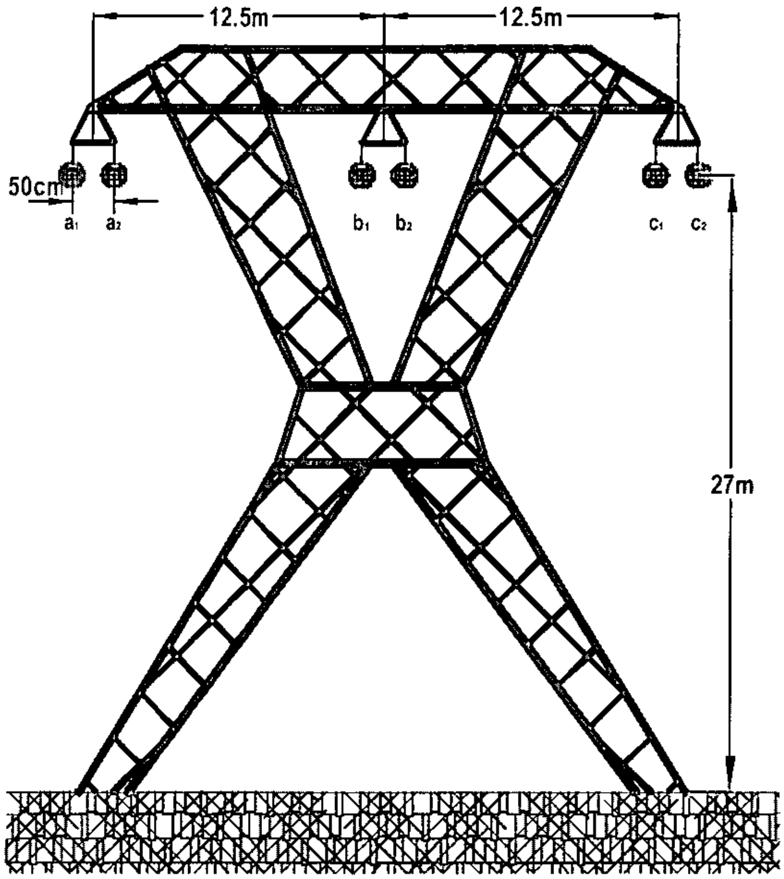


Figura 14.

Ejemplo 4.

Conductor ACSR $?_{ext}$=32mm, calibre 1033.5MCM, l_T=350km, f=15m y V_{nom}=400kV.

1. Determinar de acuerdo a tablas cual es el conductor más cercano y tomarlo como dato.
2. calcular las impedancias serie y paralelo por unidad de longitud y total de la línea.

Solución:

$$?_{ext} ? 32mm ? \frac{1pulg}{25.4mm} ? ? 1.2598pulg$$

$$?_{ext} ? 1.246pulg$$

Por otra parte, de tablas tenemos RMG = 0.0420ft y de un conductor por fase X_a ? 0.385 O ?conductor/milla .

$$RMG = 0.0420ft\left(\frac{0.3048m}{1ft}\right) = 0.0128016m$$

$$RMG = 0.0128016m = r_{a_1}' = r_{b_1}' = r_{c_1}'$$

$$RMG_A = RMG_B = RMG_C$$

$$RMG_A = \sqrt{r_{a_1}' d_{a_1a_2}} = \sqrt{(0.0128016m)(0.5m)}$$

$$RMG_A = 0.080005m = 0.2625ft$$

Luego el radio medio geométrico del arreglo es:

$$RMG_{ABC} = \sqrt[3]{RMG_A RMG_B RMG_C} = RMG_A$$

$$RMG_{ABC} = 0.2625ft = 0.080005m$$

$$DMG_{ABC} = \sqrt[3]{DMG_{AB} DMG_{AC} DMG_{BC}}$$

$$DMG_{AB} = \sqrt[4]{d_{a_1b_1} d_{a_1b_2} d_{a_2b_1} d_{a_2b_2}} = DMG_{BC}$$

donde

$$d_{a_1b_1} = d_{a_2b_2} = 12.5m$$

$$d_{a_1b_2} = 13m$$

$$d_{a_2b_1} = 12m$$

$$DMG_{AB} = \sqrt[4]{(12.5)^2(13)(12)} = 12.495m = DMG_{BC}$$

$$DMG_{AC} = \sqrt[4]{(25)^2(25.5)(24.5)} = 24.998m$$

$$DMG_{ABC} = \sqrt[3]{(12.495)^2(24.998)} = 15.744m$$

Entonces la inductancia por unidad de longitud:

$$L = 2X10^{-7}\ln\left(\frac{DMG}{RMG}\right)\left[H/m\right] = 2X10^{-7}\ln\left(\frac{15.744m}{0.080005m}\right)\left[H/m\right]$$

$$L = 1.05643\ \mu H/m$$

La reactancia inductiva por unidad de longitud.

$$x_L = 2\pi fL = 2\pi(60Hz)(1.05643)\mu H/m$$

$$x_L = 0.3983\ \Omega/km$$

Análogamente la impedancia serie por unidad de longitud es $z_S = r + j\,x_L$, en donde r es la resistencia por unidad de longitud que de acuerdo a tablas

$$r = 0.0565\ \Omega/conductor/km.$$

Pero tenemos dos conductores, entonces $r = \frac{0.0565\ \Omega/conductor/km}{2conductores} = 0.0282\ \Omega/km$.

Así, la impedancia es finalmente:

$$z_S = (0.0282 + j0.3982)\ \Omega/km/fase$$

Del mismo modo, la impedancia serie total por fase de la línea, es:

$$Z_s = z_S\, l_T = \left[(0.0282 + j0.3982)\ \Omega/km\right](350km)$$
$$Z_s = (9.87 + j139.37)\ \Omega/fase = (139.72\angle 85.95^0)\ \Omega/fase$$

donde la relación x/r está determinada por:

$$\frac{x}{r} = \frac{139.37}{9.87} = \tan(85.95^0) = 14.12$$

SECCIÓN DE CONDUCTORES

En la práctica, las secciones de conductores se mide en mm², cm², in², CM (circular mil). El CM es la unidad del sistema ingles cuya definición es la siguiente: Un CM es el área de un círculo cuyo diámetro es una milésima de pulgada.

$$CM ? \frac{?}{4}\left(10^{?3}\right)^{?} ? \frac{?}{4}10^{?6}\, pulg \qquad (1)$$

Si calculamos el área de una sección circular con el diámetro expresado en pulgadas se tiene:

$$A ? \frac{?}{4}D^2\, pulg^2 \qquad (2)$$

Para expresar ésta área (2) en CM realizamos

$$\frac{A}{CM} ? \frac{\frac{?}{4}D^2}{\frac{?}{4}10^{?6}} 10^6 D^2 \; ? \quad A ? 10^6 D^2 (CM) \qquad \text{donde D es el diámetro} \qquad (3)$$

En nuestro país se ha adoptado la norma AWG (American Wire Gage) con las siguientes especificaciones.

a) El conductor más grueso es el número 4/0 que tiene un diámetro de 0.460in y el más delgado del número 36 que tiene un diámetro de 0.005 pulg.
b) Entre el conductor 4/0 y el número 36, se tienen 38 calibres intermedios que se designan con diámetro decreciente, de la siguiente manera: 4/0, 3/0, 2/0, 1/0, 1, 2, 3, 4, ..., 36; es decir la norma consta de 40 calibres.
c) Los diámetros forman la progresión: D, Dr, Dr^2, Dr^3, ..., Dr^{39}. Donde D=0.460pulg y

$$Dr^{39} ? 0.005\, pulg \qquad ? \qquad r ? \sqrt[39]{\frac{0.005}{0.460}} ? 0.8905257 \qquad (4)$$

con $$D_n ? Dr^{(n?1)} ? \quad D_{n?1} ? Dr^n ? \quad \frac{D_{n?1}}{D_n} ? \frac{Dr^n}{Dr^{(n?1)}} ? r ? 0.8905257$$

$$? \qquad D_{n?1} ? 0.8905527 ? D_n \qquad (5)$$

De tal manera que de la ecuación (5) observamos que a medida que el número de calibre aumenta, el diámetro disminuye.

$$D_{n?a} ? (0.8905257)^{?a} D_n$$

Como caso particular, si a = 6, entonces:

$$(0.8905257)^{?6} ? 0.4987452 ? 0.5 ? \quad D_{n?6} ? 0.5 D_n$$

Por cada 6 números que aumenta el calibre, el diámetro se reduce a la mitad.

MANEJO DE TABLAS DE REACTANCIA INDUCTIVA

$$X_L \ ?\ 0.00289\ ?\ \log_{10}\frac{DMG}{RMG}\ ?\ /Km/fase\ ?\ 0.00289\ ?\ ?\log_{10}\frac{1}{RMG}??\ 0.00289?\log_{10} DMG?$$

Por una parte, el primer término, representa la reactancia debida al flujo interno desde una distancia unitaria en cm, ft o m; dependiendo de las unidades del RMG. Por otra, el segundo término representa la reactancia debida al flujo externo desde la distancia unidad hasta la DMG.

$$X_l\ ?\ 0.00465\ ?\ \log\frac{DMG}{RMG}\ ?\ /milla/cond$$

$$si \quad x_a\ ?\ 0.004657\ ?\ \log?\frac{1}{RMG}?\ ?\ /milla/cond$$

$$y \quad x_d\ ?\ 0.004657\ ?\ \log?DMG?\ ?\ /milla/cond$$

entonces

$$X_l\ ?\ x_a\ ?\ x_b$$

DIVISIÓN DE EDUCACIÓN
CONTINUA Y A DISTANCIA

ANEXOS

EXPOSITOR: ING. FERNANDO TOLEDO TOLEDO

SECRETARÍA DE LA DEFENSA NACIONAL

Annex 4A
Typical impedance data for short-circuit studies

(informative)

The following tables and figures appear in this annex:

The following tables appear in other chapters:

Table 4A-1—Typical reactance values for induction and synchronous machines, in per unit of machine kVA ratings[*]

	X_d'	X_d''
Turbine generators[†]		
2 poles	0.09	0.15
4 poles	0.15	0.23
Salient-pole generators with damper windings[†]		
12 poles or less	0.16	0.33
14 poles or less	0.21	0.33
Synchronous motors		
6 poles	0.15	0.23
8–14 poles	0.20	0.30
16 poles or more	0.28	0.40
Synchronous condensers[†]	0.24	0.37
Synchronous converters[†]		
600 V direct current	0.20	—
250 V direct current	0.33	—
Individual large induction motors, usually above 600 V	0.17	—
Smaller motors, usually 600 V and below	See tables 4-1 and 4-2.	

NOTE—Approximate synchronous motor kVA bases can be found from motor horsepower ratings as follows:
0.8 power factor motor—kVA base = hp rating
1.0 power factor motor—kVA base = 0.8 · hp rating

[*]Use manufacturer's specified values if available.
[†]X_d' not normally used in short-circuit calculations.

Table 4A-2—Representative conductor spacings for overhead lines

Nominal system voltage (volts)	Equivalent delta spacing (inches)
120	12
240	12
480	18
600	18
2400	30
4160	30
6900	36
13 800	42
23 000	48
34 500	54
69 000	96
115 000	204

NOTE—When the cross section indicates conductors are arranged at points of a triangle with spacings A, B, and C between pairs of conductors, the following formula may be used:

$$\text{equivalent delta spacing} = \sqrt[3]{A \cdot B \cdot C}$$

When the conductors are located in one place and the outside conductors are equally spaced at distance A from the middle conductors, the equivalent is 1.26 times the distance A:

$$\text{equivalent delta spacing} = \sqrt[3]{A \cdot A \cdot 2A}$$
$$= 1.26A$$

Table 4A-3—Constants of copper conductors for 1 ft symmetrical spacing*

Size of conductor		Resistance R at 50 °C, 60 Hz	Reactance X_A at 1 ft spacing, 60 Hz
(cmil)	(AWG No.)	(Ω/conductor/1000 ft)	(Ω/conductor/1000 ft)
1 000 000		0.0130	0.0758
900 000		0.142	0.0769
800 000		0.0159	0.0782
750 000		0.0168	0.0790
700 000		0.0179	0.0800
600 000		0.0206	0.0818
500 000		0.0246	0.0839
450 000		0.0273	0.0854
400 000		0.0307	0.0867
350 000		0.0348	0.0883
300 000		0.0407	0.0902
250 000		0.0487	0.0922
211 600	4/0	0.0574	0.0953
167 800	3/0	0.0724	0.0981
133 100	2/0	0.0911	0.101
105 500	1/0	0.115	0.103
83 690	1	0.145	0.106
66 370	2	0.181	0.108
52 630	3	0.227	0.111
41 740	4	0.288	0.113
33 100	5	0.362	0.116
26 250	6	0.453	0.121
20 800	7	0.570	0.123
16 510	8	0.720	0.126

NOTE—For a three-phase circuit the total impedance, line to neutral, is $Z = R + j (X_A + X_B)$.

*Use spacing factors of X_B of tables 4A-5 and 4A-6 for other spacings.

Table 4A-4—Constants of aluminum cable, steel reinforced (ACSR), for 1 ft symmetrical spacing*

Size of conductor		Resistance R at 50 °C, 60 Hz	Reactance X_A at 1 ft spacing, 60 Hz
(cmil)	(AWG No.)	(Ω/conductor/1000 ft)	(Ω/conductor/1000 ft)
1 590 000		0.0129	0.0679
1 431 000		0.0144	0.0692
1 272 000		0.0161	0.0704
1 192 500		0.0171	0.0712
1 113 000		0.0183	0.0719
954 000		0.0213	0.0738
795 000		0.0243	0.0744
715 500		0.0273	0.0756
636 000		0.0307	0.0768
556 500		0.0352	0.0786
477 000		0.0371	0.0802
397 500		0.0445	0.0824
336 400		0.0526	0.0843
266 800		0.0662	0.0945
	4/0	0.0835	0.1099
	3/0	0.1052	0.1175
	2/0	0.1330	0.1212
	1/0	0.1674	0.1242
	1	0.2120	0.1259
	2	0.2670	0.1215
	3	0.3370	0.1251
	4	0.4240	0.1240
	5	0.5340	0.1259
	6	0.6740	0.1273

NOTE—For a three-phase circuit the total impedance, line to neutral, is $Z = R + j(X_A + X_B)$.

*Use spacing factors of X_B from tables 4A-5 and 4A-6 for other spacings.

Table 4A-5—60 Hz reactance spacing factor X_B, in ohms per conductor per 1000 ft

	Separation (inches)											
(ft)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0	—	–0.0571	–0.0412	–0.0319	–0.0252	–0.0201	–0.0159	–0.0124	–0.0093	–0.0066	–0.0042	–0.0020
1	—	0.0018	0.0035	0.0051	0.0061	0.0080	0.0093	0.0106	0.0117	0.0129	0.0139	0.0149
2	0.0159	0.0169	0.0178	0.0186	0.0195	0.0203	0.0211	0.0218	0.0255	0.0232	0.0239	0.0246
3	0.0252	0.0259	0.0265	0.0271	0.0277	0.0282	0.0288	0.0293	0.0299	0.0304	0.0309	0.0314
4	0.0319	0.0323	0.0328	0.0333	0.0337	0.0341	0.0346	0.0350	0.0354	0.0358	0.0362	0.0366
5	0.0370	0.0374	0.0377	0.0381	0.0385	0.0388	0.0392	0.0395	0.0399	0.0402	0.0405	0.0409
6	0.0412	0.0415	0.0418	0.0421	0.0424	0.0427	0.0430	0.0433	0.0436	0.0439	0.0442	0.0445
7	0.0447	0.0450	0.0453	0.0455	0.0458	0.0460	0.0463	0.0466	0.0468	0.0471	0.0473	0.0476
8	0.0478											

Table 4A-6—60 Hz reactance spacing factor X_B, in ohms per conductor per 1000 ft

Separation (quarter inches)				
(inches)	0	1/4	2/4	3/4
0	—	—	–0.072 9	–0.063 6
1	–0.0571	–0.051 9	–0.047 7	–0.044 3
2	–0.0412	–0.038 4	–0.035 9	–0.033 9
3	–0.0319	–0.030 1	–0.028 2	–0.026 7
4	–0.0252	–0.023 8	–0.022 5	–0.021 2
5	–0.0201	–0.017 95	–0.017 95	–0.016 84
6	–0.0159	–0.014 94	–0.013 99	–0.013 23
7	–0.0124	–0.011 52	–0.010 78	–0.010 02
8	–0.0093	–0.008 52	–0.007 94	–0.007 19
9	–0.0066	–0.006 05	–0.005 29	–0.004 74
10	–0.0042	—	—	—
11	–0.0020	—	—	—
12	—	—	—	—

Table 4A-7—60 Hz impedance data for three-phase copper cable circuits, in approximate ohms per 1000 ft at 75 °C*

(a) Three single conductors

AWG or kcmil	In magnetic duct						In nonmagnetic duct					
	600 V and 5 kV nonshielded			5 kV shielded and 15 kV			600 V and 5 kV nonshielded			5 kV shielded and 15 kV		
	R	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*
8	0.811	0.0754	0.814	0.811	0.0860	0.816	0.811	0.0603	0.813	0.811	0.0688	0.814
8 (solid)	0.786	0.0754	0.790	0.786	0.0860	0.791	0.786	0.0603	0.788	0.786	0.0688	0.789
6	0.510	0.0685	0.515	0.510	0.0796	0.516	0.510	0.0548	0.513	0.510	0.0636	0.514
6 (solid)	0.496	0.0685	0.501	0.496	0.0796	0.502	0.496	0.0548	0.499	0.496	0.0636	0.500
4	0.321	0.0632	0.327	0.321	0.0742	0.329	0.321	0.0506	0.325	0.321	0.0594	0.326
4 (solid)	0.312	0.0632	0.318	0.312	0.0742	0.321	0.312	0.0506	0.316	0.312	0.0594	0.318
2	0.202	0.0585	0.210	0.202	0.0685	0.214	0.202	0.0467	0.207	0.202	0.0547	0.209
1	0.160	0.0570	0.170	0.160	0.0675	0.174	0.160	0.0456	0.166	0.160	0.0540	0.169
1/0	0.128	0.0540	0.139	0.128	0.0635	0.143	0.127	0.0432	0.134	0.128	0.0507	0.138
2/0	0.102	0.0533	0.115	0.103	0.0630	0.121	0.101	0.0426	0.110	0.102	0.0504	0.114
3/0	0.0805	0.0519	0.0958	0.0814	0.0605	0.101	0.0766	0.0415	0.0871	0.0805	0.0484	0.0939
4/0	0.0640	0.0497	0.0810	0.0650	0.0583	0.0929	0.0633	0.0398	0.0748	0.0640	0.0466	0.0792
250	0.0552	0.0495	0.0742	0.0557	0.570	0.0797	0.0541	0.0396	0.0670	0.0547	0.0456	0.0712
300	0.0464	0.0493	0.0677	0.0473	0.0564	0.0736	0.0451	0.0394	0.0599	0.0460	0.0451	0.0644
350	0.0378	0.0491	0.0617	0.0386	0.0562	0.0681	0.0368	0.0393	0.0536	0.0375	0.0450	0.0586
400	0.0356	0.0490	0.0606	0.0362	0.0548	0.0657	0.0342	0.0392	0.0520	0.0348	0.0438	0.0559
450	0.0322	0.0480	0.0578	0.0328	0.0538	0.0630	0.0304	0.0384	0.0490	0.0312	0.0430	0.0531
500	0.0294	0.0466	0.0551	0.0300	0.0526	0.0505	0.0276	0.0373	0.0464	0.0284	0.0421	0.0508
600	0.0257	0.0463	0.0530	0.0264	0.0516	0.0580	0.0237	0.0371	0.0440	0.0246	0.0412	0.0479
750	0.0216	0.0445	0.0495	0.0223	0.0497	0.0545	0.0194	0.0356	0.0405	0.0203	0.0396	0.0445

NOTE—Resistance based on tinned copper at 60 Hz; 600 V and 5 kV nonshielded cable based on varnished cambric insulation; 5 kV shielded and 15 kV cable based on neoprene insulation.

*Resistance values (R_L) at lower copper temperatures (T_L) are obtained by using the formula $R_L = \frac{R_{75}\,(234.5 + T_L)}{309.5}$.

Table 4A-7—60 Hz impedance data for three-phase copper cable circuits, in approximate ohms per 1000 ft at 75 °C[*]
(b) Three-conductor cable

	In magnetic duct and steel interlocked armor						In nonmagnetic duct and aluminum interlocked armor					
AWG or kcmil	600 V and 5 kV nonshielded			5 kV shielded and 15 kV			600 V and 5 kV nonshielded			5 kV shielded and 15 kV		
	R	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*
8	0.811	0.0577	0.813	0.811	0.0658	0.814	0.811	0.0503	0.812	0.811	0.0574	0.813
8 (solid)	0.786	0.0577	0.788	0.786	0.0658	0.789	0.786	0.0503	0.787	0.786	0.0574	0.788
6	0.510	0.0525	0.513	0.510	0.0610	0.514	0.510	0.0457	0.512	0.510	0.0531	0.513
6 (solid)	0.496	0.0525	0.499	0.496	0.0610	0.500	0.496	0.0457	0.498	0.496	0.0531	0.499
4	0.321	0.0483	0.325	0.321	0.0568	0.326	0.321	0.0422	0.324	0.321	0.0495	0.325
4 (solid)	0.312	0.0483	0.316	0.312	0.0508	0.317	0.312	0.0422	0.315	0.312	0.0495	0.316
2	0.202	0.0448	0.207	0.202	0.0524	0.209	0.202	0.0390	0.206	0.202	0.0457	0.207
1	0.160	0.0436	0.166	0.160	0.0516	0.168	0.160	0.0380	0.164	0.160	0.0450	0.166
1/0	0.128	0.0414	0.135	0.128	0.0486	0.137	0.127	0.0360	0.132	0.128	0.0423	0.135
2/0	0.102	0.0407	0.110	0.103	0.0482	0.114	0.101	0.0355	0.107	0.102	0.0420	0.110
3/0	0.0805	0.0397	0.0898	0.0814	0.0463	0.0936	0.0766	0.0346	0.0841	0.0805	0.0403	0.090
4/0	0.0640	0.0381	0.0745	0.0650	0.0446	0.0788	0.0633	0.0332	0.0715	0.0640	0.0389	0.0749
250	0.0552	0.0379	0.0670	0.0557	0.0436	0.0707	0.0541	0.0330	0.0634	0.0547	0.0380	0.0666
300	0.0464	0.0377	0.0598	0.0473	0.0431	0.0640	0.0451	0.0329	0.0559	0.0460	0.0376	0.0596
350	0.0378	0.0373	0.0539	0.0386	0.0427	0.0576	0.0368	0.0328	0.0492	0.0375	0.0375	0.0530
400	0.0356	0.0371	0.0514	0.0362	0.0415	0.0551	0.0342	0.0327	0.0475	0.0348	0.0366	0.0505
450	0.0322	0.0361	0.0484	0.0328	0.0404	0.0520	0.0304	0.0320	0.0441	0.0312	0.0359	0.0476
500	0.0294	0.0349	0.0456	0.0300	0.0394	0.0495	0.0276	0.0311	0.0416	0.0284	0.0351	0.0453
600	0.0257	0.0343	0.0429	0.0264	0.0382	0.0464	0.0237	0.0309	0.0389	0.0246	0.0344	0.0422
750	0.0216	0.0326	0.0391	0.0223	0.0364	0.0427	0.0197	0.0297	0.0355	0.0203	0.0332	0.0389

NOTE—Resistance based on tinned copper at 60 Hz. 600 V and 5 kV nonshielded cable based on varnished cambric insulation; 5 kV shielded and 15 kV cable based on neoprene insulation

[*]Resistance values (R_L) at lower copper temperatures (T_L) are obtained by using the formula $R_L = \frac{R_{75}(234.5 + T_L)}{309.5}$.

Table 4A-8—60 Hz impedance data for three-phase aluminum cable circuits, in approximate ohms per 1000 ft at 90 °C*

(a) Three single conductors

AWG or kcmil	In magnetic duct: 600 V and 5 kV nonshielded			In magnetic duct: 5 kV shielded and 15 kV			In nonmagnetic duct: 600 V and 5 kV nonshielded			In nonmagnetic duct: 5 kV shielded and 15 kV		
	R	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*
6	0.847	0.053	0.849	—	—	—	0.847	0.042	0.848	—	—	—
4	0.532	0.050	0.534	0.532	0.068	0.536	0.532	0.040	0.534	0.532	0.054	0.535
2	0.335	0.046	0.338	0.335	0.063	0.341	0.335	0.037	0.337	0.335	0.050	0.339
1	0.265	0.048	0.269	0.265	0.059	0.271	0.265	0.035	0.267	0.265	0.047	0.269
1/0	0.210	0.043	0.214	0.210	0.056	0.217	0.210	0.034	0.213	0.210	0.045	0.215
2/0	0.167	0.041	0.172	0.167	0.055	0.176	0.167	0.033	0.170	0.167	0.044	0.173
3/0	0.133	0.040	0.139	0.132	0.053	0.142	0.133	0.037	0.137	0.132	0.042	0.139
4/0	0.106	0.039	0.113	0.105	0.051	0.117	0.105	0.031	0.109	0.105	0.041	0.113
250	0.0896	0.0384	0.0975	0.0892	0.0495	0.102	0.0894	0.0307	0.0945	0.0891	0.0396	0.0975
300	0.0750	0.0375	0.0839	0.0746	0.0479	0.0887	0.0746	0.0300	0.0804	0.0744	0.0383	0.0837
350	0.0644	0.0369	0.0742	0.0640	0.0468	0.0793	0.0640	0.0245	0.0705	0.0638	0.0374	0.0740
400	0.0568	0.0364	0.0675	0.0563	0.0459	0.0726	0.0563	0.0291	0.0634	0.0560	0.0367	0.0700
500	0.0459	0.0355	0.0580	0.0453	0.0444	0.0634	0.0453	0.0284	0.0535	0.0450	0.0355	0.0573
600	0.0388	0.0359	0.0529	0.0381	0.0431	0.0575	0.0381	0.0287	0.0477	0.0377	0.0345	0.0511
700	0.0338	0.0350	0.0487	0.0332	0.0423	0.0538	0.0330	0.0280	0.0433	0.0326	0.0338	0.0470
750	0.0318	0.0341	0.0466	0.0310	0.0419	0.0521	0.0309	0.0273	0.0412	0.0304	0.0335	0.0452
1000	0.0252	0.0341	0.0424	0.0243	0.0414	0.0480	0.0239	0.0273	0.0363	0.0234	0.0331	0.0405

NOTE—Cross-linked polyethylene insulated cable.

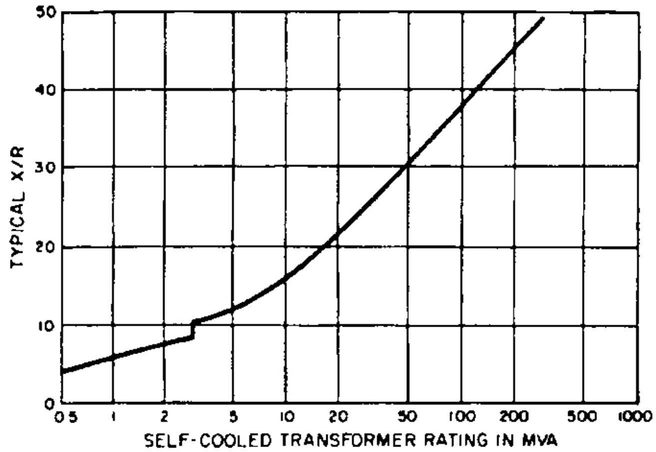
*Resistance values (R_L) at lower aluminum temperatures (T_L) are obtained by using the formula $R_L = \frac{R_{90}(228.1 + T_L)}{318.1}$.

Table 4A-8—60 Hz impedance data for three-phase aluminum cable circuits, in approximate ohms per 1000 ft at 90 °C*
(b) Three-conductor cable

AWG or kcmil	In magnetic duct						In nonmagnetic duct					
	600 V and 5 kV nonshielded			5 kV shielded and 15 kV			600 V and 5 kV nonshielded			5 kV shielded and 15 kV		
	R	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*	*R*	*X*	*Z*
6	0.847	0.053	0.849	—	—	—	0.847	0.042	0.848	—	—	—
4	0.532	0 050	0.534	—	—	—	0.532	0.040	0.534	—	—	—
2	0.335	0.046	0.338	0.335	0.056	0.340	0.335	0.037	0.337	0.335	0.045	0.338
1	0.265	0.048	0.269	0.265	0.053	0.270	0.265	0.035	0.267	0 265	0.042	0.268
1/0	0.210	0.043	0.214	0.210	0.050	0.216	0.210	0.034	0.213	0.210	0.040	0.214
2/0	0.167	0.041	0.172	0.167	0.049	0.174	0.167	0.033	0.170	0.167	0.039	0.171
3/0	0.133	0 040	0.139	0.133	0.048	0.141	0.133	0.037	0.137	0.132	0.038	0.138
4/0	0.106	0.039	0.113	0.105	0.045	0.114	0.105	0.031	0.109	0.105	0.036	0.111
250	0.0896	0.0384	0.0975	0.0895	0.0436	0.100	0 0894	0.0307	0.0945	0.0893	0.0349	0.0959
300	0.0750	0.0375	0.0839	0 0748	0.0424	0.0860	0 0746	0.0300	0.0804	0.0745	0.0340	0.0819
350	0.0644	0.0369	0.0742	0.0643	0.0418	0.0767	0 0640	0.0245	0.0705	0.0640	0.0334	0.0722
400	0.0568	0.0364	0.0675	0.0564	0.0411	0 0700	0.0563	0.0291	0.0634	0.0561	0.0329	0.0650
500	0.0459	0.0355	0.0580	0.0457	0.0399	0.0607	0.0453	0.0284	0.0535	0.0452	0.0319	0.0553
600	0.0388	0.0359	0.0529	0.0386	0.0390	0.0549	0.0381	0.0287	0.0477	0.0380	0.0312	0.0492
700	0.0338	0.0350	0.0487	0.0335	0.0381	0.0507	0.0330	0.0280	0.0433	0.0328	0.0305	0.0448
750	0.0318	0.0341	0.0466	0.0315	0.0379	0.0493	0.0309	0.0273	0.0412	0.0307	0.0303	0.0431
1000	0.0252	0.0341	0.0424	0.0248	0.0368	0.0444	0.0239	0.0273	0.0363	0 0237	0.0294	0.0378

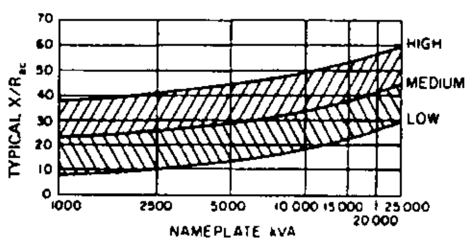
NOTE—Cross-linked polyethylene insulated cable.

*Resistance values (R_L) at lower aluminum temperatures (T_L) are obtained by the formula $R_L = \frac{R_{90}(228.1 + T_L)}{318.1}$.



Source: Based on IEEE Std C37.010-1979.

Figure 4A-1—*X/R* ratio of transformers



Source: Reprinted from IEEE Std C37.010-1979.

Figure 4A-2—*X/R* range for small generators and synchronous motors (solid rotor and salient pole)

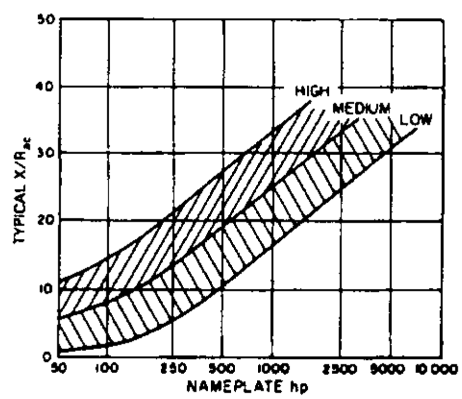


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Figure 4A-3—*X/R* range for three-phase induction motors

CHAPTER 3

CHARACTERISTICS OF AERIAL LINES

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IN the design, operation, and expansion of electrical power systems it is necessary to know electrical and physical characteristics of conductors used in the construction of aerial distribution and transmission lines.

This chapter presents a description of the common types of conductors along with tabulations of their important electrical and physical characteristics. General formulas are presented with their derivation to show the basis of the tabulated values and as a guide in calculating data for other conductors of similar shapes, dimensions, composition and operating conditions.

Also included are the more commonly used symmetrical-component-sequence impedance equations that are applicable to the solution of power system problems involving voltage regulation, load flow, stability, system currents, and voltages under fault conditions, or other system problems where the electrical characteristics of aerial lines are involved.

Additional formulas are given to permit calculation of approximate current-carrying capacity of conductors taking into account such factors as convection and radiation losses as influenced by ambient temperature, wind velocity, and permissible temperature rise.

I. TYPES OF CONDUCTORS

In the electric-power field the following types of conductors are generally used on high-voltage power transmission lines: stranded copper conductors, hollow copper conductors, and ACSR (aluminum cable, steel reinforced).

Other types of conductors such as Copperweld and Copperweld-copper conductors are also used for transmission and distribution lines. Use is made of Copperweld, bronze, copper bronze, and steel for current-carrying conductors on rural lines, as overhead ground wires for transmission lines, as buried counterpoises at the base of transmission towers, and also for long river crossings.

A stranded conductor, typical of both copper and steel conductors in the larger sizes, is shown in Fig. 1. A stranded conductor is easier to handle and is more flexible than a solid conductor, particularly in the larger sizes.

A typical ACSR conductor is illustrated in Fig. 2. In this type of conductor, aluminum strands are wound about a core of stranded steel. Varying relationships between tensile strength and current-carrying capacity as well as overall size of conductor can be obtained by varying the proportions of steel and aluminum. By the use of a filler, such as paper, between the outer aluminum strands and the inner steel strands, a conductor of large diameter can be obtained for use in high voltage lines. This type of conductor is known as "expanded" ACSR and is shown in Fig. 3.

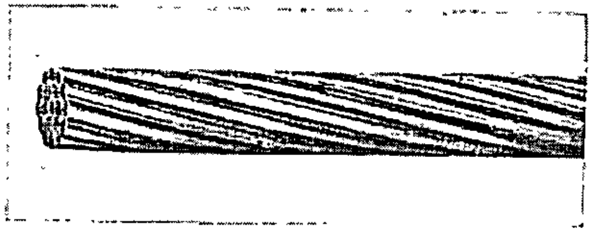
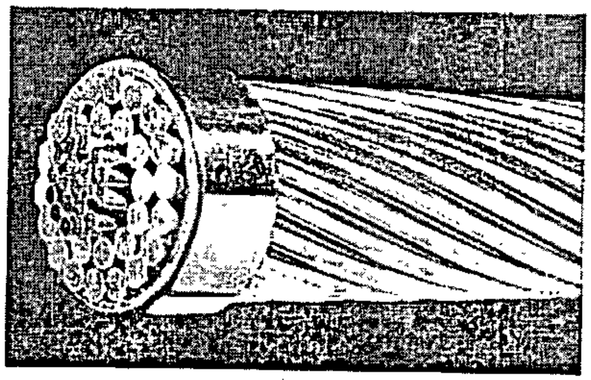
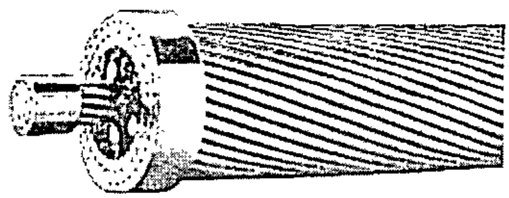


Fig. 1—A typical stranded conductor, (bare copper).



Courtesy of Aluminum Company of America
Fig. 2—A typical ACSR conductor.



Courtesy of Aluminum Company of America
Fig. 3—A typical "expanded" ACSR conductor.

Courtesy of Anaconda Wire and Cable Company
Fig. 4—A typical Anaconda Hollow Copper Conductor.

In Fig. 4 is shown a representative Anaconda Hollow Copper Conductor. It consists of a twisted copper "I"

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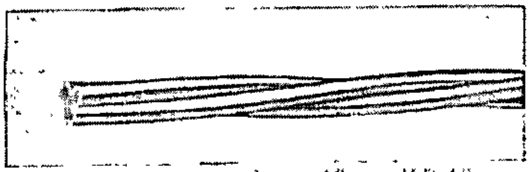
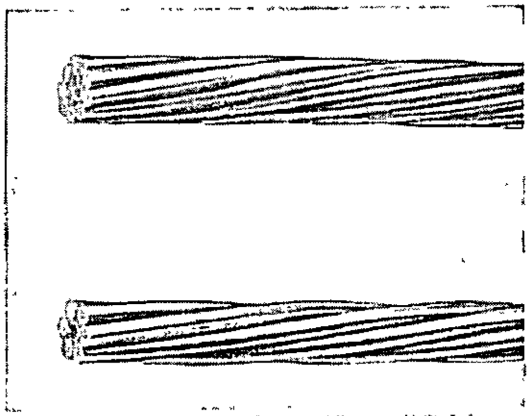
Courtesy of General Cable Corporation

Fig. 5—A typical General Cable Type HH.



Courtesy of Copperweld Steel Company

Fig. 6—A typical Copperweld conductor.



Courtesy of Copperweld Steel Company

Fig. 7—Typical Copperweld-Copper conductors

(a) Upper photograph–Type V
(b) Lower photograph–Type F

beam as a core about which strands of copper wire are wound. The "I" beam is twisted in a direction opposite to that of the inner layer of strands.

Another form of hollow copper conductor is shown in Fig. 5. Known as the General Cable Type HH hollow copper conductor, it is made up of segmental sections of copper mortised into each other to form a self-supporting hollow cylinder. Hollow copper conductors result in conductors of large diameter for a given cross section of copper. Corona losses are therefore smaller. This construction also produces a reduction in skin effect as well as inductance as compared with stranded conductors. A discussion of large diameter conductors and their characteristics is given in reference 1.

Copperweld conductors consist of different numbers of copper coated steel strands, a typical conductor being illustrated in Fig. 6. Strength is provided by the core of steel and protection by the outer coating of copper.

When high current-carrying capacities are desired as well as high tensile strength, copper strands are used with Copperweld strands to form Copperweld-Copper conductors as shown in Fig. 7. Different relationships between current-carrying capacity, outside diameter, and tensile strength can be obtained by varying the number and size of the Copperweld and copper strands.

II. ELECTRICAL CHARACTERISTICS OF AERIAL CONDUCTORS

The following discussion is primarily concerned with the development of electrical characteristics and constants of aerial conductors, particularly those required for analysis of power-system problems. The constants developed are particularly useful in the application of the principles of symmetrical components to the solution of power-system problems involving positive-, negative-, and zero-sequence impedances of transmission and distribution lines. The basic quantities needed are the positive-, negative-, and zero-sequence resistances, inductive reactances and shunt capacitive reactances of the various types of conductors and some general equations showing how these quantities are used.

1. Positive- and Negative-Sequence Resistance

The resistance of an aerial conductor is affected by three factors: temperature, frequency, current density. Practical formulas and methods will now be given to take into account these factors.

Temperature Effect on Resistance—The resistance of copper and aluminum conductors varies almost directly with temperature. While this variation is not strictly linear for an extremely wide range of temperatures, for practical purposes it can be considered linear over the range of temperatures normally encountered.

When the d-c resistance of a conductor at a given temperature is known and it is desired to find the d-c resistance at some other temperature, the following general formula may be used.

$$\frac{R_{t2}}{R_{t1}}=\frac{M+t_2}{M+t_1} \qquad (1)$$

where

R_{t2} = d-c resistance at any temperature t_2 degree C.
R_{t1} = d-c resistance at any other temperature t_1 degree C.
M = a constant for any one type of conductor material.
= inferred absolute zero temperature.
= 234.5 for annealed 100 percent conductivity copper.
= 241.5 for hard drawn 97.3 percent conductivity copper.
= 228.1 for aluminum.

The above formula is useful for evaluating changes in d-c resistance only, and cannot be used to give a-c resistance variations unless skin effect can be neglected. For small conductor sizes the frequency has a negligible effect on resistance in the d-c to 60-cycle range. This is generally true for conductor sizes up to 2/0.

The variations of resistance with temperature are usually unimportant because the actual ambient temperature is indefinite as well as variable along a transmission line. An illustration of percentage change in resistance is when temperature varies from winter to summer over a range of 0 degree C to 40 degrees C (32 degrees F to 104 degrees F) in which case copper resistance increases 17 percent.

TABLE 2-A—CHARACTERISTICS OF ALUMINUM CABLE STEEL REINFORCED

(Aluminum Company of America)

Circular Mils or A.W.G. Aluminum	Aluminum Strands	Aluminum Layers	Aluminum Strand Dia. Inches	Steel Strands	Steel Strand Dia. Inches	Outside Diameter Inches	Copper Equivalent* Circular Mils or A.W.G.	Ultimate Strength Pounds	Weight Pounds per Mile	Geometric Mean Radius at 60 Cycles Feet	Approx. Current Carrying Capacity† Amps	r_a Resistance Ohms per Conductor per Mile 25°C (77°F) Small Currents d-c	25 cycles	50 cycles	60 cycles	50°C (122°F) Current Approx. 75% Capacity‡ d-c	25 cycles	50 cycles	60 cycles	x_a Inductive Reactance Ohms per Conductor per Mile at 1 Ft. Spacing All Currents 25 cycles	50 cycles	60 cycles	x_a' Shunt Capacitive Reactance Megohms per Conductor per Mile at 1 Ft. Spacing 25 cycles	50 cycles	60 cycles
1 590 000	54	3	0.1716	19	0.1030	1.545	1 000 000	56 000	10 777	0.0520	1 380	0.0587	0.0588	0.0590	0.0591	0.0646	0.0656	0.0675	0.0684	0.1495	0.299	0.359	0.1953	0.0977	0.0814
1 510 500	54	3	0.1673	19	0.1004	1.506	950 000	53 200	10 237	0.0507	1 340	0.0618	0.0619	0.0621	0.0622	0.0680	0.0690	0.0710	0.0720	0.1508	0.302	0.362	0.1971	0.0986	0.0821
1 431 000	54	3	0.1628	19	0.0977	1.465	900 000	50 400	9 699	0.0493	1 300	0.0652	0.0653	0.0655	0.0656	0.0718	0.0729	0.0749	0.0760	0.1522	0.304	0.365	0.1991	0.0996	0.0830
1 351 000	54	3	0.1582	19	0.0949	1.424	850 000	47 600	9 160	0.0479	1 250	0.0691	0.0692	0.0694	0.0695	0.0761	0.0771	0.0792	0.0803	0.1536	0.307	0.369	0.201	0.1006	0.0838
1 272 000	54	3	0.1535	19	0.0921	1.382	800 000	44 800	8 621	0.0465	1 200	0.0734	0.0735	0.0737	0.0738	0.0808	0.0819	0.0840	0.0851	0.1551	0.310	0.372	0.203	0.1015	0.0847
1 192 500	54	3	0.1486	19	0.0892	1.338	750 000	42 100	8 082	0.0450	1 160	0.0783	0.0784	0.0786	0.0788	0.0862	0.0872	0.0894	0.0906	0.1568	0.314	0.376	0.206	0.1028	0.0857
1 113 000	54	3	0.1436	19	0.0862	1.293	700 000	40 200	7 544	0.0435	1 110	0.0839	0.0840	0.0842	0.0844	0.0924	0.0935	0.0957	0.0969	0.1585	0.317	0.380	0.208	0.1040	0.0867
1 033 500	54	3	0.1384	7	0.1384	1.246	650 000	37 100	7 019	0.0420	1 060	0.0903	0.0905	0.0907	0.0909	0.0994	0.1005	0.1025	0.1035	0.1603	0.321	0.385	0.211	0.1053	0.0878
954 000	54	3	0.1329	7	0.1329	1.196	600 000	34 200	6 479	0.0403	1 010	0.0979	0.0980	0.0981	0.0982	0.1078	0.1089	0.1118	0.1128	0.1624	0.325	0.390	0.214	0.1068	0.0890
900 000	54	3	0.1291	7	0.1291	1.162	566 000	32 300	6 112	0.0391	970	0.104	0.104	0.104	0.104	0.1145	0.1155	0.1175	0.1185	0.1639	0.328	0.393	0.216	0.1078	0.0898
874 500	54	3	0.1273	7	0.1273	1.146	550 000	31 400	5 940	0.0386	950	0.107	0.107	0.107	0.108	0.1178	0.1188	0.1218	0.1228	0.1646	0.329	0.395	0.217	0.1085	0.0903
795 000	54	3	0.1214	7	0.1214	1.093	500 000	28 500	5 399	0.0368	900	0.117	0.118	0.118	0.119	0.1288	0.1308	0.1358	0.1378	0.1670	0.334	0.401	0.220	0.1100	0.0917
795 000	26	2	0.1749	7	0.1360	1.108	500 000	31 200	5 770	0.0375	900	0.117	0.117	0.117	0.117	0.1288	0.1288	0.1288	0.1288	0.1660	0.332	0.399	0.219	0.1095	0.0912
795 000	30	2	0.1628	19	0.0977	1.140	500 000	38 400	6 517	0.0393	910	0.117	0.117	0.117	0.117	0.1288	0.1288	0.1288	0.1288	0.1637	0.327	0.393	0.217	0.1085	0.0904
715 500	54	3	0.1151	7	0.1151	1.036	450 000	26 300	4 859	0.0349	830	0.131	0.131	0.131	0.132	0.1442	0.1452	0.1472	0.1482	0.1697	0.339	0.407	0.224	0.1119	0.0932
715 500	26	2	0.1659	7	0.1290	1.051	450 000	28 100	5 193	0.0355	840	0.131	0.131	0.131	0.131	0.1442	0.1442	0.1442	0.1442	0.1687	0.337	0.405	0.222	0.1111	0.0925
715 500	30	2	0.1544	19	0.0926	1.081	450 000	34 600	5 865	0.0372	840	0.131	0.131	0.131	0.131	0.1442	0.1442	0.1442	0.1442	0.1664	0.333	0.399	0.221	0.1104	0.0920
666 600	54	3	0.1111	7	0.1111	1.000	419 000	24 500	4 527	0.0337	800	0.140	0.140	0.141	0.141	0.1541	0.1571	0.1591	0.1601	0.1715	0.343	0.412	0.226	0.1132	0.0943
636 000	54	3	0.1085	7	0.1085	0.977	400 000	23 600	4 319	0.0329	770	0.147	0.147	0.148	0.148	0.1618	0.1638	0.1678	0.1688	0.1726	0.345	0.414	0.228	0.1140	0.0950
636 000	26	2	0.1564	7	0.1216	0.990	400 000	25 000	4 616	0.0335	780	0.147	0.147	0.147	0.147	0.1618	0.1618	0.1618	0.1618	0.1718	0.344	0.412	0.227	0.1135	0.0946
636 000	30	2	0.1456	19	0.0874	1.019	400 000	31 500	5 213	0.0351	780	0.147	0.147	0.147	0.147	0.1618	0.1618	0.1618	0.1618	0.1693	0.339	0.406	0.225	0.1125	0.0937
605 000	54	3	0.1059	7	0.1059	0.953	380 500	22 500	4 109	0.0321	750	0.154	0.155	0.155	0.155	0.1695	0.1715	0.1755	0.1775	0.1739	0.348	0.417	0.230	0.1149	0.0957
605 000	26	2	0.1525	7	0.1186	0.966	380 500	24 100	4 391	0.0327	760	0.154	0.154	0.154	0.154	0.1700	0.1720	0.1720	0.1720	0.1730	0.346	0.415	0.229	0.1144	0.0953
556 500	26	2	0.1463	7	0.1138	0.927	350 000	22 400	4 039	0.0313	730	0.168	0.168	0.168	0.168	0.1849	0.1859	0.1859	0.1859	0.1751	0.350	0.420	0.232	0.1159	0.0965
556 500	30	2	0.1362	7	0.1362	0.953	350 000	27 200	4 588	0.0328	730	0.168	0.168	0.168	0.168	0.1849	0.1859	0.1859	0.1859	0.1728	0.346	0.415	0.230	0.1149	0.0957
500 000	30	2	0.1291	7	0.1291	0.904	314 500	24 400	4 122	0.0311	690	0.187	0.187	0.187	0.187	0.206				0.1754	0.351	0.421	0.234	0.1167	0.0973
477 000	26	2	0.1355	7	0.1054	0.858	300 000	19 430	3 462	0.0290	670	0.196	0.196	0.196	0.196	0.216				0.1790	0.358	0.430	0.237	0.1186	0.0988
477 000	30	2	0.1261	7	0.1261	0.883	300 000	23 300	3 933	0.0304	670	0.196	0.196	0.196	0.196	0.216				0.1766	0.353	0.424	0.235	0.1176	0.0980
397 500	26	2	0.1236	7	0.0961	0.783	250 000	16 190	2 885	0.0265	590	0.235				0.259				0.1836	0.367	0.441	0.244	0.1219	0.1015
397 500	30	2	0.1151	7	0.1151	0.806	250 000	19 980	3 277	0.0278	600	0.235		Same as d-c		0.259		Same as d-c		0.1812	0.362	0.435	0.242	0.1208	0.1006
336 400	26	2	0.1138	7	0.0885	0.721	4/0	14 050	2 442	0.0244	530	0.278				0.306				0.1872	0.376	0.451	0.250	0.1248	0.1039
336 400	30	2	0.1059	7	0.1059	0.741	4/0	17 040	2 774	0.0255	530	0.278				0.306				0.1855	0.371	0.445	0.248	0.1238	0.1032
300 000	26	2	0.1074	7	0.0835	0.680	188 700	12 650	2 178	0.0230	490	0.311				0.342				0.1908	0.382	0.458	0.254	0.1269	0.1057
300 000	30	2	0.1000	7	0.1000	0.700	188 700	15 430	2 473	0.0241	500	0.311				0.342				0.1883	0.377	0.452	0.252	0.1258	0.1049
266 800	26	2	0.1013	7	0.0788	0.642	3/0	11 250	1 936	0.0217	460	0.350				0.385				0.1936	0.387	0.465	0.258	0.1289	0.1074

Circular Mils or A.W.G. Aluminum	Aluminum Strands	Aluminum Layers	Aluminum Strand Dia. Inches	Steel Strands	Steel Strand Dia. Inches	Outside Diameter Inches	Copper Equivalent*	Ultimate Strength Pounds	Weight Pounds per Mile	Geometric Mean Radius For Current Approx. 75% Capacity‡	Amps	r_a 25°C d-c	25 cycles	50 cycles	60 cycles	r_a 50°C d-c	25 cycles	50 cycles	60 cycles	x_a Single Layer Conductors: Small Currents 25 cycles	50 cycles	60 cycles	Current Approx. 75% Capacity‡ 25 cycles	50 cycles	60 cycles	x_a' 25 cycles	50 cycles	60 cycles
266 800	6	1	0.2109	7	0.0703	0.633	3/0	9 645	1 802	0.00684	460	0.351	0.351	0.351	0.352	0.386	0.430	0.510	0.552	0.194	0.388	0.466	0.252	0.504	0.605	0.259	0.1294	0.1079
4/0	6	1	0.1878	1	0.1878	0.563	2/0	8 420	1 542	0.00814	340	0.441	0.442	0.444	0.445	0.485	0.514	0.567	0.592	0.218	0.437	0.524	0.242	0.484	0.581	0.267	0.1336	0.1113
3/0	6	1	0.1672	1	0.1672	0.502	1/0	6 675	1 223	0.00600	300	0.556	0.557	0.559	0.560	0.612	0.642	0.697	0.723	0.225	0.450	0.540	0.259	0.517	0.621	0.275	0.1377	0.1147
2/0	6	1	0.1490	1	0.1490	0.447	1	5 345	970	0.00510	270	0.702	0.702	0.704	0.706	0.773	0.806	0.866	0.895	0.231	0.462	0.554	0.267	0.534	0.641	0.284	0.1418	0.1182
1/0	6	1	0.1327	1	0.1327	0.398	2	4 280	769	0.00446	230	0.885	0.885	0.887	0.888	0.974	1.01	1.05	1.12	0.237	0.473	0.568	0.273	0.547	0.656	0.292	0.1460	0.1216
1	6	1	0.1182	1	0.1182	0.355	3	3 480	610	0.00418	200	1.12	1.12	1.12	1.12	1.23	1.27	1.34	1.38	0.242	0.483	0.580	0.277	0.554	0.665	0.300	0.1500	0.1250
2	6	1	0.1052	1	0.1052	0.316	4	2 790	484	0.00418	180	1.41	1.41	1.41	1.41	1.55	1.59	1.65	1.69	0.247	0.493	0.592	0.277	0.554	0.665	0.306	0.1532	0.1276
2	7	1	0.0974	1	0.1299	0.325	4	3 525	566	0.00504	180	1.41	1.41	1.41	1.41	1.55	1.59	1.62	1.65	0.247	0.493	0.592	0.267	0.535	0.642	0.306	0.1532	0.1276
3	6	1	0.0937	1	0.0937	0.281	5	2 250	384	0.00430	160	1.78	1.78	1.78	1.78	1.95	1.95	2.04	2.07	0.252	0.503	0.604	0.275	0.551	0.661	0.317	0.1583	0.1320
4	6	1	0.0834	1	0.0834	0.250	6	1 830	304	0.00437	140	2.24	2.24	2.24	2.24	2.47	2.50	2.54	2.57	0.257	0.514	0.611	0.274	0.549	0.659	0.325	0.1627	0.1355
4	7	1	0.0772	1	0.1029	0.257	6	2 288	356	0.00452	140	2.24	2.24	2.24	2.24	2.47	2.50	2.53	2.55	0.257	0.515	0.618	0.273	0.545	0.655	0.323	0.1615	0.1346
5	6	1	0.0743	1	0.0743	0.223	7	1 460	241	0.00416	120	2.82	2.82	2.82	2.82	3.10	3.12	3.16	3.18	0.262	0.525	0.630	0.279	0.557	0.665	0.333	0.1666	0.1388
6	6	1	0.0661	1	0.0661	0.198	8	1 170	191	0.00394	100	3.56	3.56	3.56	3.56	3.92	3.94	3.97	3.98	0.268	0.536	0.643	0.281	0.561	0.673	0.342	0.1708	0.1423

* Based on copper 97 percent, aluminum 61 percent conductivity.
† For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2 ft/sec), frequency = 60 cycles.
‡ "Current Approx. 75% Capacity" is 75% of the "Approx. Current Carrying Capacity in Amps." and is approximately the current which will produce 50°C. conductor temp. (25°C. rise) with 25°C. air temp., wind 1.4 miles per hour.

TABLE 2-B—CHARACTERISTICS OF "EXPANDED" ALUMINUM CABLE STEEL REINFORCED

(Aluminum Company of America)

Circular Mils or A.W.G. Aluminum	Aluminum Strands	Aluminum Layers	Aluminum Strand Dia. Inches	Steel Strands	Steel Strand Dia. Inches	Filler Section Aluminum Strands	Aluminum Strand Dia. Inches	Paper Strands	Paper Layers	Outside Diameter Inches	Copper Equivalent Circular Mils or A.W.G.	Ultimate Strength Pounds	Weight Pounds per Mile	Geometric Mean Radius at 60 Cycles Feet	Approx. Current Carrying Capacity Amps	r_a Resistance Ohms per Conductor per Mile 25°C (77°F) Small Currents d-c	25 cycles	50 cycles	60 cycles	50°C (122°F) Current Approx. 75% Capacity d-c	25 cycles	50 cycles	60 cycles	x_a Inductive Reactance Ohms per Conductor per Mile at 1 Ft. Spacing All Currents 25 cycles	50 cycles	60 cycles	x_a' Shunt Capacitive Reactance Megohms per Conductor per Mile at 1 Ft. Spacing 25 cycles	50 cycles	60 cycles
850 000	54	2	0.1255	19	0.0834	4	0.1182	23	2	1.15	534 000	35 371	7 200	(1)	(1)	(1)				(1)				(1)	(1)	(1)	(1)	(1)	(1)
1 150 000	54	2	0.1409	19	0.0921	4	0.1353	24	2	1.65	724 000	41 900	9 070																
1 338 000	66	2	0.1350	19	0.1000	4	0.1410	18	2	1.75	840 000	49 278	11 340																

(1) Electrical Characteristics not available until laboratory measurements are completed.

TABLE 3-A—CHARACTERISTICS OF ANACONDA HOLLOW COPPER CONDUCTORS

(Anaconda Wire & Cable Company)

Design Number	Size of Conductor Circular Mils or A.W.G.	Wires: Number	Wires: Diameter Inches	Outside Diameter Inches	Breaking Strain Pounds	Weight Pounds per Mile	Geometric Mean Radius at 60 Cycles Feet	Approx. Current Carrying Capacity Amps‡	r_a Resistance Ohms per Conductor per Mile, 25°C. (77°F.) d-c 25 cycles	25°C. (77°F.) 50 cycles 60 cycles	50°C. (122°F.) d-c 25 cycles	50°C. (122°F.) 50 cycles 60 cycles	x_a Inductive Reactance Ohms per Conductor per Mile at 1 Ft. Spacing, 25 cycles	50 cycles	60 cycles	x_a' Shunt Capacitive Reactance Megohms per Conductor per Mile at 1 Ft. Spacing, 25 cycles	50 cycles	60 cycles
959	890 500	28	0.1610	1.650	38 000	15 085	0.0612	1395	0.0671	0.0676	0.0734	0.0739	0.1412	0.282	0.339	0.1097	0.0533	0.0704
96R1	750 000	42	0.1296	1.155	34 200	12 345	0.0408	1160	0.0756	0.0791	0.0860	0.0865	0.1617	0.323	0.388	0.216	0.1080	0.0900
939	650 000	50	0.1097	1.126	29 500	10 761	0.0406	1060	0.0900	0.0915	0.0994	0.1001	0.1621	0.324	0.389	0.218	0.1090	0.0908
850R1	600 000	50	0.1053	1.007	27 500	9 205	0.0387	1020	0.0984	0.0991	0.1077	0.1084	0.1644	0.329	0.395	0.221	0.1105	0.0921
938	550 000	50	0.1009	1.036	25 200	9 103	0.0373	960	0.1076	0.1081	0.1177	0.1183	0.1663	0.333	0.399	0.224	0.1119	0.0932
4R5	510 000	60	0.0970	1.000	22 700	8 483	0.0360	910	0.1173	0.1178	0.1283	0.1290	0.1681	0.336	0.404	0.226	0.1131	0.0943
827R3	500 000	18	0.1558	1.080	21 400	8 263	0.0394	900	0.1178	0.1184	0.1289	0.1296	0.1630	0.326	0.391	0.221	0.1104	0.0920
933	450 000	21	0.1353	1.074	19 300	7 476	0.0395	850	0.1319	0.1324	0.1443	0.1448	0.1630	0.326	0.391	0.221	0.1106	0.0922
924	400 000	21	0.1227	1.014	17 200	6 642	0.0376	810	0.1485	0.1491	0.1624	0.1631	0.1655	0.332	0.398	0.225	0.1126	0.0939
925R1	380 500	22	0.1211	1.003	16 300	6 331	0.0373	780	0.1565	0.1572	0.1712	0.1719	0.1663	0.333	0.399	0.226	0.1130	0.0942
563R1	350 000	21	0.1196	0.950	15 100	5 813	0.0353	750	0.1695	0.1700	0.1854	0.1860	0.1691	0.338	0.406	0.230	0.1150	0.0958
936	350 000	15	0.1444	0.900	15 400	5 776	0.0311	740	0.1690	0.1695	0.1849	0.1854	0.1764	0.351	0.421	0.237	0.1185	0.0988
378R1	350 000	30	0.1059	0.736	16 100	5 739	0.0253	700	0.1685	0.1690	0.1843	0.1849	0.1860	0.372	0.446	0.248	0.1241	0.1034
934	325 000	22	0.1113	0.920	13 850	5 343	0.0340	700	0.1831	0.1836	0.202	0.203	0.1710	0.342	0.410	0.232	0.1161	0.0968
935	300 000	18	0.1205	0.839	13 100	4 984	0.0307	670	0.1980	0.1985	0.216	0.217	0.1761	0.352	0.423	0.239	0.1194	0.0995
903R1	300 000	15	0.1338	0.797	13 200	4 953	0.0289	660	0.1969	0.1975	0.216	0.216	0.1793	0.359	0.430	0.242	0.1212	0.1010
176R2	300 000	12	0.1507	0.750	13 050	4 937	0.0264	650	0.1964	0.1969	0.215	0.216	0.1833	0.367	0.440	0.247	0.1234	0.1028
926	250 000	18	0.1100	0.766	10 950	4 155	0.0279	600	0.238	0.239	0.260	0.261	0.1810	0.362	0.434	0.245	0.1226	0.1022
915R1	250 000	15	0.1214	0.725	11 000	4 148	0.0266	590	0.237	0.238	0.259	0.260	0.1834	0.367	0.440	0.249	0.1246	0.1038
24R1	250 000	12	0.1368	0.683	11 600	4 133	0.0246	580	0.237	0.238	0.259	0.260	0.1876	0.375	0.450	0.253	0.1267	0.1056
923	4/0	18	0.1005	0.700	9 300	3 521	0.0255	530	0.281	0.282	0.307	0.308	0.1855	0.371	0.445	0.252	0.1258	0.1049
922	4/0	15	0.1100	0.663	9 300	3 510	0.0238	520	0.281	0.282	0.307	0.308	0.1889	0.378	0.453	0.256	0.1278	0.1065
50R2	4/0	14	0.1152	0.650	9 300	3 510	0.0234	520	0.280	0.281	0.306	0.307	0.1898	0.380	0.455	0.257	0.1285	0.1071
158R1	3/0	16	0.0961	0.606	7 500	2 785	0.0221	460	0.354	0.355	0.387	0.388	0.1928	0.386	0.463	0.262	0.1310	0.1091
495R1	3/0	15	0.0996	0.595	7 600	2 785	0.0214	460	0.353	0.354	0.386	0.387	0.1943	0.389	0.466	0.263	0.1316	0.1097
570R2	3/0	12	0.1123	0.560	7 600	2 772	0.0201	450	0.352	0.353	0.385	0.386	0.1976	0.395	0.474	0.268	0.1338	0.1115
909R2	2/0	15	0.0880	0.530	5 950	2 213	0.0191	370	0.446	0.446	0.487	0.487	0.200	0.400	0.481	0.271	0.1357	0.1131
412R2	2/0	14	0.0913	0.515	6 000	2 207	0.0184	370	0.446	0.446	0.487	0.487	0.202	0.404	0.485	0.274	0.1368	0.1140
937	2/0	13	0.0950	0.505	6 000	2 203	0.0181	370	0.446	0.446	0.487	0.487	0.203	0.406	0.487	0.275	0.1375	0.1146
930	125 600	14	0.0885	0.500	5 650	2 083	0.0180	360	0.473	0.473	0.517	0.517	0.203	0.406	0.487	0.276	0.1378	0.1149
931	121 300	15	0.0836	0.500	5 400	2 015	0.0179	350	0.491	0.491	0.537	0.537	0.203	0.407	0.488	0.276	0.1378	0.1149
901	119 400	12	0.0936	0.470	5 300	1 979	0.0165	340	0.507	0.507	0.555	0.555	0.207	0.415	0.498	0.280	0.1400	0.1167

‡For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2 ft/sec), frequency = 60 cycles, average tarnished surface.

TABLE 3-B—CHARACTERISTICS OF GENERAL CABLE TYPE HH HOLLOW COPPER CONDUCTORS

(General Cable Corporation)

Conductor Size Circular Mils or A.W.G.	Outside(1) Diameter Inches	Wall Thickness Inches	Weight Pounds per Mile	Breaking Strength Pounds	Geometric Mean Radius Feet	Approx. Current Carrying Capacity(2) Amps	r_a Resistance Ohms per Conductor per Mile, 25°C. (77°F.) d-c	25°C. 25 cycles	25°C. 50 cycles	25°C. 60 cycles	50°C. (122°F.) d-c	50°C. 25 cycles	50°C. 50 cycles	50°C. 60 cycles	x_a Inductive Reactance Ohms per Conductor per Mile at 1 Foot Spacing, 25 cycles	50 cycles	60 cycles	x_a' Shunt Capacitive Reactance Megohms per Conductor per Mile at 1 Foot Spacing, 25 cycles	50 cycles	60 cycles
1 000 000	2.103	0.150*	16 160	43 190	0.0833	1620	0.0576	0.0576	0.0577	0.0577	0.0630	0.0630	0.0631	0.0631	0.1257	0.251	0.302	0.1734	0.0867	0.0722
950 000	2.025	0.147*	15 350	41 030	0.0805	1565	0.0606	0.0606	0.0607	0.0607	0.0663	0.0664	0.0664	0.0664	0.1274	0.255	0.306	0.1757	0.0879	0.0732
900 000	1.960	0.144*	14 540	38 870	0.0778	1505	0.0640	0.0640	0.0641	0.0641	0.0700	0.0701	0.0701	0.0701	0.1291	0.258	0.310	0.1782	0.0891	0.0742
850 000	1.901	0.140*	13 730	36 710	0.0751	1450	0.0677	0.0678	0.0678	0.0678	0.0741	0.0742	0.0742	0.0742	0.1309	0.262	0.314	0.1805	0.0903	0.0752
800 000	1.820	0.137*	12 920	34 550	0.0722	1390	0.0720	0.0720	0.0720	0.0721	0.0788	0.0788	0.0788	0.0788	0.1329	0.266	0.319	0.1833	0.0917	0.0764
750 000	1.650	0.121†	12 760	34 120	0.0646	1335	0.0729	0.0729	0.0730	0.0730	0.0797	0.0798	0.0799	0.0799	0.1385	0.277	0.332	0.1906	0.0953	0.0794
750 000	1.750	0.133*	12 120	32 390	0.0691	1325	0.0768	0.0768	0.0768	0.0769	0.0840	0.0840	0.0841	0.0841	0.1351	0.270	0.324	0.1864	0.0932	0.0777
700 000	1.686	0.130*	11 310	30 230	0.0665	1265	0.0823	0.0823	0.0823	0.0823	0.0900	0.0900	0.0901	0.0901	0.1370	0.274	0.329	0.1891	0.0945	0.0788
650 000	1.610	0.126*	10 500	28 070	0.0635	1200	0.0886	0.0886	0.0886	0.0887	0.0969	0.0970	0.0970	0.0970	0.1394	0.279	0.335	0.1924	0.0962	0.0802
600 000	1.558	0.123*	9 692	25 910	0.0615	1140	0.0959	0.0960	0.0960	0.0960	0.1050	0.1051	0.1051	0.1051	0.1410	0.282	0.339	0.1947	0.0974	0.0811
550 000	1.478	0.119*	8 884	23 750	0.0583	1075	0.1047	0.1048	0.1048	0.1048	0.1146	0.1146	0.1147	0.1147	0.1437	0.287	0.345	0.1985	0.0992	0.0827
512 000	1.400	0.115*	8 270	22 110	0.0551	1020	0.1124	0.1125	0.1125	0.1125	0.1230	0.1230	0.1231	0.1231	0.1466	0.293	0.352	0.202	0.1012	0.0843
500 000	1.390	0.115*	8 076	21 590	0.0547	1003	0.1151	0.1151	0.1152	0.1152	0.1260	0.1260	0.1260	0.1260	0.1469	0.294	0.353	0.203	0.1014	0.0845
500 000	1.268	0.109†	8 074	21 590	0.0494	978	0.1151	0.1152	0.1152	0.1152	0.1259	0.1260	0.1260	0.1261	0.1521	0.304	0.365	0.209	0.1047	0.0872
500 000	1.100	0.130†	8 068	21 590	0.0420	937	0.1150	0.1151	0.1152	0.1153	0.1258	0.1259	0.1260	0.1260	0.1603	0.321	0.385	0.219	0.1095	0.0913
500 000	1.020	0.144†	8 063	21 590	0.0384	915	0.1150	0.1150	0.1152	0.1152	0.1258	0.1259	0.1260	0.1261	0.1649	0.330	0.396	0.225	0.1124	0.0937
450 000	1.317	0.111*	7 268	19 430	0.0515	939	0.1279	0.1280	0.1280	0.1280	0.1400	0.1401	0.1401	0.1401	0.1496	0.299	0.359	0.207	0.1035	0.0861
450 000	1.155	0.105†	7 266	19 430	0.0462	910	0.1278	0.1279	0.1279	0.1280	0.1399	0.1400	0.1400	0.1401	0.1554	0.311	0.373	0.214	0.1070	0.0892
400 000	1.216	0.106*	6 460	17 270	0.0478	864	0.1439	0.1440	0.1440	0.1440	0.1575	0.1576	0.1576	0.1576	0.1537	0.307	0.369	0.212	0.1061	0.0884
400 000	1.103	0.100†	6 458	17 270	0.0428	838	0.1438	0.1439	0.1439	0.1440	0.1574	0.1575	0.1575	0.1576	0.1593	0.319	0.382	0.219	0.1097	0.0914
350 000	1.126	0.107*	5 653	15 110	0.0443	790	0.1644	0.1645	0.1645	0.1645	0.1799	0.1800	0.1800	0.1800	0.1576	0.315	0.378	0.218	0.1090	0.0907
350 000	1.014	0.096†	5 650	15 110	0.0393	764	0.1644	0.1645	0.1645	0.1645	0.1799	0.1800	0.1800	0.1801	0.1637	0.328	0.393	0.225	0.1127	0.0939
300 000	1.020	0.096*	4 845	12 950	0.0399	709	0.1918	0.1919	0.1919	0.1919	0.210	0.210	0.210	0.210	0.1628	0.326	0.391	0.225	0.1124	0.0937
300 000	0.919	0.091†	4 843	12 950	0.0355	687	0.1917	0.1918	0.1918	0.1919	0.210	0.210	0.210	0.210	0.1688	0.338	0.405	0.232	0.1162	0.0968
250 000	0.914	0.091*	4 037	10 790	0.0357	626	0.230	0.230	0.230	0.230	0.252	0.252	0.252	0.252	0.1685	0.337	0.404	0.233	0.1163	0.0970
250 000	0.818	0.086†	4 036	10 790	0.0315	600	0.230	0.230	0.230	0.230	0.252	0.252	0.252	0.252	0.1749	0.350	0.420	0.241	0.1203	0.1002
250 000	0.766	0.094†	4 034	10 790	0.0292	584	0.230	0.230	0.230	0.230	0.252	0.252	0.252	0.252	0.1787	0.357	0.429	0.245	0.1226	0.1022
214 500	0.650	0.098†	3 450	9 265	0.0243	534	0.268	0.268	0.268	0.268	0.293	0.293	0.293	0.294	0.1879	0.376	0.451	0.257	0.1285	0.1071
4/0	0.733	0.082†	3 415	9 140	0.0281	539	0.272	0.272	0.272	0.272	0.297	0.297	0.298	0.298	0.1806	0.361	0.433	0.248	0.1242	0.1035
3/0	0.608	0.080†	2 707	7 240	0.0230	454	0.343	0.343	0.343	0.343	0.375	0.375	0.375	0.375	0.1907	0.381	0.458	0.262	0.1309	0.1091
2/0	0.500	0.080†	2 146	5 750	0.0186	382	0.432	0.432	0.432	0.432	0.472	0.473	0.473	0.473	0.201	0.403	0.483	0.276	0.1378	0.1149

Notes: *Thickness at edges of interlocked segments. †Thickness uniform throughout.

(1) Conductors of smaller diameter for given cross-sectional area also available; in the naught sizes, some additional diameter expansion is possible.

(2) For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2 ft/sec), frequency = 60 cycles.

TABLE 4-A—CHARACTERISTICS OF COPPERWELD-COPPER CONDUCTORS

(Copperweld Steel Company)

Nominal Designation	Size of Conductor: Number and Diameter of Wires: Copperweld	Copper	Outside Diameter Inches	Copper Equivalent Circular Mils or A.W.G.	Rated Breaking Load Lbs.	Weight Lbs. per Mile	Geometric Mean Radius at 60 Cycles Feet	Approx. Current Carrying Capacity at 60 Cycles Amps*	r_a Resistance Ohms per Conductor per Mile at 25°C (77°F) Small Currents: d-c	25 cycles	50 cycles	60 cycles	r_a Resistance Ohms per Conductor per Mile at 50°C (122°F) Current Approx. 75% of Capacity**: d-c	25 cycles	50 cycles	60 cycles	x_a Inductive Reactance Ohms per Conductor per Mile One ft. Spacing Average Currents: 25 cycles	50 cycles	60 cycles	x_a' Capacitive Reactance Megohms per Conductor per Mile One ft. Spacing: 25 cycles	50 cycles	60 cycles
350 E	7x.1576"	12x.1576"	0.735	350 000	32 420	7 409	0.0220	660	0.1658	0.1728	0.1789	0.1812	0.1812	0.1915	0.201	0.204	0.1929	0.386	0.463	0.243	0.1216	0.1014
350 EK	4x.1470"	15x.1470"	0.726	350 000	23 850	6 536	0.0245	680	0.1658	0.1682	0.1700	0.1705	0.1812	0.1845	0.1873	0.1882	0.1875	0.375	0.450	0.245	0.1225	0.1021
350 V	3x.1751"	9x.1893"	0.754	350 000	23 480	6 578	0.0226	650	0.1655	0.1725	0.1800	0.1828	0.1809	0.1910	0.202	0.205	0.1913	0.383	0.460	0.244	0.1232	0.1027
300 E	7x.1459"	12x.1459"	0.680	300 000	27 770	6 351	0.0204	600	0.1934	0.200	0.207	0.209	0.211	0.222	0.233	0.235	0.1969	0.394	0.473	0.249	0.1244	0.1037
300 EK	4x.1361"	15x.1361"	0.672	300 000	20 960	5 602	0.0227	610	0.1934	0.1958	0.1976	0.1981	0.211	0.215	0.219	0.219	0.1914	0.383	0.460	0.251	0.1256	0.1047
300 V	3x.1621"	9x.1752"	0.698	300 000	20 730	5 639	0.0209	590	0.1930	0.200	0.208	0.210	0.211	0.222	0.233	0.237	0.1954	0.391	0.469	0.252	0.1259	0.1050
250 E	7x.1332"	12x.1332"	0.660	250 000	23 920	5 292	0.01859	540	0.232	0.239	0.245	0.248	0.254	0.266	0.276	0.279	0.202	0.403	0.484	0.255	0.1276	0.1064
250 EK	4x.1242"	15x.1242"	0.621	250 000	17 840	4 669	0.0207	540	0.232	0.235	0.236	0.237	0.254	0.258	0.261	0.261	0.1960	0.392	0.471	0.260	0.1301	0.1084
250 V	3x.1480"	9x.1600"	0.637	250 000	17 420	4 699	0.01911	530	0.232	0.239	0.246	0.249	0.253	0.264	0.276	0.281	0.200	0.400	0.480	0.256	0.1292	0.1077
4/0 E	7x.1225"	12x.1225"	0.613	4/0	20 730	4 479	0.01711	480	0.274	0.281	0.287	0.290	0.300	0.312	0.322	0.326	0.206	0.411	0.493	0.261	0.1306	0.1088
4/0 G	2x.1944"	5x.1944"	0.583	4/0	15 640	4 168	0.01409	460	0.273	0.284	0.294	0.298	0.299	0.318	0.336	0.342	0.215	0.431	0.517	0.265	0.1324	0.1103
4/0 EK	4x.1143"	15x.1143"	0.571	4/0	15 370	3 951	0.01903	490	0.274	0.277	0.278	0.279	0.300	0.304	0.307	0.308	0.200	0.401	0.481	0.266	0.1331	0.1109
4/0 V	3x.1361"	9x.1472"	0.586	4/0	15 000	3 977	0.01758	470	0.274	0.281	0.288	0.291	0.299	0.311	0.323	0.328	0.204	0.409	0.490	0.264	0.1322	0.1101
4/0 F	1x.1833"	6x.1833"	0.550	4/0	12 290	3 750	0.01558	470	0.273	0.280	0.285	0.287	0.299	0.309	0.318	0.322	0.210	0.421	0.505	0.269	0.1344	0.1120
3/0 E	7x.1091"	12x.1091"	0.545	3/0	16 800	3 552	0.01521	420	0.346	0.353	0.359	0.361	0.378	0.391	0.402	0.407	0.212	0.423	0.508	0.270	0.1348	0.1123
3/0 J	3x.1851"	4x.1851"	0.555	3/0	16 170	3 732	0.01156	410	0.344	0.356	0.367	0.372	0.377	0.398	0.419	0.428	0.225	0.451	0.541	0.268	0.1341	0.1118
3/0 G	2x.1731"	5x.1731"	0.519	3/0	12 860	3 305	0.01254	400	0.344	0.355	0.365	0.369	0.377	0.397	0.416	0.423	0.221	0.443	0.531	0.273	0.1365	0.1137
3/0 EK	4x.1018"	15x.1018"	0.509	3/0	12 370	3 134	0.01697	420	0.346	0.348	0.350	0.351	0.378	0.382	0.386	0.386	0.206	0.412	0.495	0.274	0.1372	0.1143
3/0 V	3x.1311"	9x.1311"	0.522	3/0	12 220	3 154	0.01588	410	0.345	0.352	0.360	0.362	0.377	0.390	0.403	0.408	0.210	0.420	0.504	0.273	0.1363	0.1136
3/0 F	1x.1632"	6x.1632"	0.490	3/0	9 980	2 974	0.01388	410	0.344	0.351	0.356	0.358	0.377	0.388	0.397	0.401	0.216	0.432	0.519	0.277	0.1385	0.1155
2/0 K	4x.1780"	3x.1780"	0.534	2/0	17 600	3 411	0.00912	360	0.434	0.447	0.459	0.466	0.475	0.499	0.524	0.535	0.237	0.476	0.570	0.271	0.1355	0.1129
2/0 J	3x.1648"	4x.1648"	0.494	2/0	13 430	2 960	0.01029	350	0.434	0.446	0.457	0.462	0.475	0.498	0.520	0.530	0.231	0.463	0.555	0.277	0.1383	0.1152
2/0 G	2x.1542"	5x.1542"	0.463	2/0	10 510	2 622	0.01119	350	0.434	0.445	0.456	0.459	0.475	0.497	0.518	0.525	0.227	0.454	0.545	0.281	0.1406	0.1171
2/0 V	3x.1080"	9x.1167"	0.465	2/0	9 846	2 500	0.01395	360	0.435	0.442	0.450	0.452	0.476	0.489	0.504	0.509	0.216	0.432	0.518	0.281	0.1404	0.1170
2/0 F	1x.1454"	6x.1454"	0.436	2/0	8 094	2 359	0.01235	350	0.434	0.441	0.446	0.448	0.475	0.487	0.497	0.501	0.222	0.444	0.533	0.285	0.1427	0.1189
1/0 K	4x.1585"	3x.1585"	0.475	1/0	14 490	2 703	0.00812	310	0.548	0.560	0.573	0.579	0.599	0.625	0.652	0.664	0.243	0.487	0.584	0.279	0.1397	0.1164
1/0 J	3x.1467"	4x.1467"	0.440	1/0	10 970	2 346	0.00917	310	0.548	0.559	0.570	0.576	0.599	0.624	0.648	0.659	0.237	0.474	0.569	0.285	0.1423	0.1186
1/0 G	2x.1373"	5x.1373"	0.412	1/0	8 563	2 078	0.00996	310	0.548	0.559	0.568	0.573	0.599	0.623	0.645	0.654	0.233	0.466	0.559	0.289	0.1447	0.1206
1/0 F	1x.1294"	6x.1294"	0.388	1/0	6 536	1 870	0.01099	310	0.548	0.554	0.559	0.562	0.599	0.612	0.622	0.627	0.229	0.458	0.547	0.294	0.1469	0.1224
1 N	5x.1546"	2x.1546"	0.464	1	15 410	2 541	0.00638	290	0.691	0.705	0.719	0.726	0.755	0.787	0.818	0.832	0.250	0.512	0.614	0.281	0.1405	0.1171
1 K	4x.1412"	3x.1412"	0.423	1	11 900	2 144	0.00723	270	0.691	0.704	0.716	0.722	0.755	0.784	0.813	0.825	0.249	0.499	0.599	0.285	0.1427	0.1189
1 J	3x.1307"	4x.1307"	0.392	1	9 000	1 861	0.00817	270	0.691	0.703	0.714	0.719	0.755	0.783	0.808	0.820	0.243	0.486	0.583	0.291	0.1455	0.1221
1 G	2x.1222"	5x.1222"	0.367	1	6 956	1 649	0.00887	260	0.691	0.702	0.712	0.716	0.755	0.781	0.805	0.815	0.239	0.478	0.573	0.296	0.1480	0.1234
1 F	1x.1153"	6x.1153"	0.346	1	5 266	1 483	0.00980	270	0.691	0.698	0.704	0.705	0.755	0.769	0.781	0.786	0.234	0.468	0.561	0.302	0.1508	0.1257
2 P	6x.1540"	1x.1540"	0.462	2	16 870	2 487	0.00501	250	0.871	0.886	0.901	0.909	0.952	0.988	1.024	1.040	0.268	0.536	0.643	0.281	0.1406	0.1172
2 N	5x.1377"	2x.1377"	0.413	2	12 680	2 015	0.00568	240	0.871	0.885	0.899	0.906	0.952	0.986	1.020	1.035	0.261	0.523	0.627	0.289	0.1444	0.1203
2 K	4x.1257"	3x.1257"	0.377	2	9 730	1 701	0.00644	240	0.871	0.884	0.896	0.902	0.952	0.983	1.014	1.028	0.255	0.510	0.612	0.294	0.1470	0.1225
2 J	3x.1164"	4x.1164"	0.349	2	7 322	1 476	0.00727	230	0.871	0.883	0.894	0.899	0.952	0.982	1.010	1.022	0.249	0.498	0.598	0.300	0.1500	0.1250
2 A	1x.1699"	2x.1699"	0.366	2	5 876	1 356	0.00763	240	0.869	0.875	0.880	0.882	0.950	0.962	0.973	0.979	0.247	0.493	0.592	0.298	0.1489	0.1241
2 G	2x.1089"	5x.1089"	0.327	2	5 626	1 307	0.00790	230	0.871	0.882	0.892	0.896	0.952	0.980	1.006	1.016	0.245	0.489	0.587	0.306	0.1529	0.1275
2 F	1x.1026"	6x.1026"	0.308	2	4 233	1 176	0.00873	230	0.871	0.878	0.884	0.885	0.952	0.967	0.979	0.985	0.230	0.479	0.575	0.310	0.1551	0.1292
3 P	6x.1371"	1x.1371"	0.411	3	13 910	1 973	0.00445	220	1.098	1.113	1.127	1.136	1.200	1.239	1.273	1.296	0.274	0.547	0.657	0.290	0.1448	0.1207
3 N	5x.1226"	2x.1226"	0.368	3	10 390	1 598	0.00506	210	1.098	1.112	1.126	1.133	1.200	1.237	1.273	1.290	0.267	0.534	0.641	0.298	0.1487	0.1239
3 K	4x.1120"	3x.1120"	0.336	3	7 910	1 349	0.00574	210	1.098	1.111	1.123	1.129	1.200	1.233	1.267	1.281	0.261	0.522	0.626	0.304	0.1520	0.1266
3 J	3x.1036"	4x.1036"	0.311	3	5 955	1 171	0.00648	200	1.098	1.110	1.121	1.126	1.200	1.232	1.262	1.275	0.255	0.509	0.611	0.309	0.1547	0.1289
3 A	1x.1513"	2x.1513"	0.326	3	4 810	1 075	0.00679	210	1.096	1.102	1.107	1.109	1.198	1.211	1.225	1.229	0.252	0.503	0.600	0.306	0.1531	0.1275
4 P	6x.1221"	1x.1221"	0.366	4	11 420	1 564	0.00397	190	1.385	1.400	1.414	1.421	1.514	1.555	1.598	1.616	0.280	0.560	0.671	0.298	0.1490	0.1241
4 N	5x.1092"	2x.1092"	0.328	4	8 460	1 267	0.00451	180	1.385	1.399	1.413	1.420	1.514	1.554	1.593	1.610	0.273	0.546	0.655	0.306	0.1529	0.1274
4 D	2x.1615"	1x.1615"	0.348	4	7 340	1 191	0.00468	190	1.382	1.389	1.396	1.399	1.511	1.529	1.544	1.542	0.262	0.523	0.628	0.301	0.1507	0.1256
4 A	1x.1347"	2x.1347"	0.290	4	3 938	853	0.00604	180	1.382	1.388	1.393	1.395	1.511	1.525	1.540	1.545	0.258	0.517	0.620	0.314	0.1572	0.1310
5 P	6x.1087"	1x.1087"	0.326	5	9 311	1 240	0.00353	160	1.747	1.762	1.776	1.785	1.909	1.954	2.00	2.02	0.285	0.571	0.685	0.306	0.1531	0.1275
5 D	2x.1438"	1x.1438"	0.310	5	6 035	944	0.00504	160	1.742	1.749	1.756	1.759	1.905	1.924	1.941	1.939	0.268	0.535	0.642	0.310	0.1548	0.1290
5 A	1x.1200"	2x.1200"	0.258	5	3 193	676	0.00448	160	1.742	1.748	1.753	1.755	1.905	1.920	1.936	1.941	0.264	0.528	0.634	0.323	0.1614	0.1345
6 D	2x.1281"	1x.1281"	0.276	6	4 942	749	0.00449	140	2.20	2.21	2.21	2.22	2.40	2.42	2.44	2.44	0.273	0.547	0.656	0.318	0.1590	0.1325
6 A	1x.1068"	2x.1068"	0.230	6	2 585	536	0.00479	140	2.20	2.20	2.21	2.21	2.40	2.42	2.41	2.44	0.270	0.540	0.648	0.331	0.1655	0.1379
6 C	1x.1046"	2x.1046"	0.225	6	2 143	514	0.00469	130	2.20	2.20	2.21	2.21	2.40	2.42	2.41	2.44	0.271	0.542	0.651	0.333	0.1663	0.1386
7 D	2x.1141"	1x.1141"	0.246	7	4 022	594	0.00400	120	2.77	2.78	2.79	2.79	3.03	3.05	3.07	3.07	0.279	0.558	0.670	0.326	0.1631	0.1359
7 A	1x.1266"	2x.0953"	0.223	7	2 754	495	0.00441	120	2.77	2.78	2.79	2.79	3.03	3.05	3.07	3.07	0.274	0.548	0.658	0.333	0.1666	0.1388
8 D	2x.1016"	1x.1016"	0.219	8	3 256	471	0.00356	110	3.49	3.50	3.51	3.51	3.82	3.84	3.86	3.86	0.285	0.570	0.684	0.334	0.1671	0.1393
8 A	1x.1127"	2x.0797"	0.199	8	2 233	392	0.00394	100	3.49	3.50	3.51	3.51	3.82	3.84	3.86	3.87	0.280	0.560	0.672	0.341	0.1706	0.1422
8 C	1x.0808"	2x.0851"	0.179	8	1 362	320	0.00373	100	3.49	3.50	3.51	3.51	3.82	3.84	3.86	3.86	0.283	0.565	0.679	0.349	0.1744	0.1453
9½ D	2x.0808"	1x.0808"	0.174	9½	1 743	298	0.00283	85	4.91	4.92	4.93	4.93	5.37	5.39	5.42	5.42	0.297	0.593	0.712	0.351	0.1754	0.1462

*Based on a conductor temperature of 75°C. and an ambient of 25°C., wind 1.4 miles per hour (2 ft/sec.), frequency = 60 cycles, average tarnished surface.
**Resistances at 50°C. total temperature, based on an ambient of 25°C. plus 25°C. rise due to heating effect of current. The approximate magnitude of current necessary to produce the 25°C. rise is 75% of the "Approximate Current Carrying Capacity at 60 cycles."

finding the appropriate table for a particular conductor. For these figures open circles, solid circles, and cross-hatched circles represent copper, steel, and aluminum conductors respectively. The double cross hatched area in the insert for Table 2-B, Characteristics of "EXPANDED" Aluminum Cable Steel Reinforced, represents stranded paper.

The authors wish to acknowledge the cooperation of the conductor manufacturers in supplying the information for compiling these tables.

TABLE 4-B—CHARACTERISTICS OF COPPERWELD CONDUCTORS

(Copperweld Steel Company)

Nominal Conductor Size	Number and Size of Wires	Outside Diameter Inches	Area of Conductor Circular Mils	Rated Breaking Load Pounds — Strength: High	Extra High	Weight Pounds per Mile	Geometric Mean Radius at 60 cycles and Average Currents Feet	Approx. Current Carrying Capacity* Amps at 60 Cycles	r_a Resistance Ohms per Conductor per Mile at 25°C. (77°F.) Small Currents: d-c	25 cycles	50 cycles	60 cycles	r_a Resistance Ohms per Conductor per Mile at 75°C. (167°F.) Current Approx. 75% of Capacity**: d-c	25 cycles	50 cycles	60 cycles	x_a Inductive Reactance Ohms per Conductor per Mile One Ft. Spacing Average Currents: 25 cycles	50 cycles	60 cycles	x_a' Capacitive Reactance Megohms per Conductor per Mile One Ft. Spacing: 25 cycles	50 cycles	60 cycles
30% Conductivity																						
7/8"	19 No. 5	0.910	628 900	55 570	66 910	9 344	0.00758	620	0.306	0.316	0.326	0.331	0.363	0.419	0.476	0.499	0.261	0.493	0.592	0.233	0.1165	0.0971
13/16"	19 No. 6	0.810	498 800	45 830	55 530	7 410	0.00675	540	0.386	0.396	0.406	0.411	0.458	0.518	0.580	0.605	0.267	0.505	0.605	0.241	0.1206	0.1005
23/32"	19 No. 7	0.721	395 500	37 740	45 850	5 877	0.00601	470	0.486	0.498	0.506	0.511	0.577	0.643	0.710	0.737	0.273	0.517	0.621	0.250	0.1248	0.1040
21/32"	19 No. 8	0.642	313 700	31 040	37 690	4 660	0.00535	410	0.613	0.623	0.633	0.638	0.728	0.799	0.872	0.902	0.279	0.529	0.635	0.258	0.1290	0.1074
9/16"	19 No. 9	0.572	248 800	25 500	30 810	3 696	0.00477	360	0.773	0.783	0.793	0.798	0.917	0.995	1.075	1.106	0.285	0.541	0.649	0.266	0.1330	0.1109
5/8"	7 No. 4	0.613	292 200	24 780	29 430	4 324	0.00511	410	0.656	0.664	0.672	0.676	0.778	0.824	0.870	0.887	0.281	0.533	0.640	0.261	0.1306	0.1088
9/16"	7 No. 5	0.546	231 700	20 470	24 650	3 429	0.00455	360	0.827	0.835	0.843	0.847	0.981	1.000	1.080	1.099	0.287	0.545	0.654	0.269	0.1347	0.1122
1/2"	7 No. 6	0.486	183 800	16 890	20 460	2 719	0.00405	310	1.012	1.036	1.058	1.062	1.237	1.290	1.343	1.364	0.293	0.557	0.668	0.278	0.1388	0.1157
7/16"	7 No. 7	0.433	145 700	13 910	16 890	2 157	0.00361	270	1.315	1.323	1.331	1.335	1.560	1.617	1.675	1.697	0.299	0.569	0.683	0.286	0.1429	0.1191
3/8"	7 No. 8	0.385	115 600	11 440	13 890	1 710	0.00321	230	1.658	1.666	1.674	1.678	1.967	2.03	2.09	2.12	0.305	0.581	0.697	0.294	0.1471	0.1226
11/32"	7 No. 9	0.343	91 650	9 393	11 280	1 356	0.00286	200	2.09	2.10	2.11	2.11	2.48	2.55	2.61	2.64	0.311	0.592	0.711	0.303	0.1512	0.1260
5/16"	7 No. 10	0.306	72 680	7 758	9 196	1 076	0.00255	170	2.64	2.64	2.65	2.66	3.13	3.20	3.27	3.30	0.316	0.604	0.725	0.311	0.1553	0.1294
3 No. 5	3 No. 5	0.392	99 310	9 262	11 860	1 467	0.00457	220	1.028	1.031	1.036	1.039	2.29	2.31	2.34	2.36	0.299	0.545	0.654	0.293	0.1465	0.1221
3 No. 6	3 No. 6	0.349	78 750	7 639	9 754	1 163	0.00407	190	2.43	2.43	2.44	2.44	2.95	2.91	2.94	2.95	0.305	0.556	0.668	0.301	0.1506	0.1255
3 No. 7	3 No. 7	0.311	62 450	6 291	7 922	922.4	0.00363	160	3.06	3.07	3.07	3.07	3.63	3.66	3.70	3.71	0.301	0.568	0.682	0.310	0.1547	0.1289
3 No. 8	3 No. 8	0.277	49 530	5 174	6 282	731.5	0.00323	140	3.86	3.87	3.87	3.87	4.58	4.61	4.63	4.65	0.307	0.580	0.696	0.318	0.1589	0.1324
3 No. 9	3 No. 9	0.247	39 280	4 230	5 129	580.1	0.00288	120	4.87	4.87	4.88	4.88	5.78	5.81	5.83	5.86	0.313	0.591	0.710	0.326	0.1629	0.1358
3 No. 10	3 No. 10	0.220	31 150	3 600	4 160	460.0	0.00257	110	6.14	6.14	6.15	6.16	7.29	7.32	7.35	7.38	0.319	0.603	0.724	0.334	0.1671	0.1392
40% Conductivity																						
7/8"	19 No. 5	0.910	628 900	50 240	...	9 344	0.01175	690	0.229	0.239	0.249	0.254	0.272	0.321	0.371	0.391	0.236	0.449	0.539	0.233	0.1165	0.0971
13/16"	19 No. 6	0.810	498 800	41 600	...	7 410	0.01046	610	0.289	0.299	0.309	0.314	0.343	0.396	0.450	0.472	0.241	0.461	0.553	0.241	0.1206	0.1005
23/32"	19 No. 7	0.721	395 500	34 390	...	5 877	0.00931	530	0.365	0.375	0.385	0.390	0.433	0.490	0.549	0.573	0.247	0.473	0.567	0.250	0.1248	0.1040
21/32"	19 No. 8	0.642	313 700	28 380	...	4 660	0.00829	470	0.460	0.470	0.480	0.485	0.546	0.608	0.672	0.698	0.253	0.485	0.582	0.258	0.1290	0.1074
9/16"	19 No. 9	0.572	248 800	23 390	...	3 696	0.00739	410	0.580	0.590	0.600	0.605	0.688	0.756	0.826	0.853	0.259	0.496	0.595	0.266	0.1330	0.1109
5/8"	7 No. 4	0.613	292 200	22 310	...	4 324	0.00792	470	0.492	0.500	0.508	0.512	0.584	0.624	0.664	0.680	0.255	0.489	0.587	0.261	0.1306	0.1088
9/16"	7 No. 5	0.546	231 700	18 510	...	3 429	0.00705	410	0.620	0.628	0.636	0.640	0.736	0.780	0.843	0.840	0.261	0.501	0.601	0.269	0.1347	0.1122
1/2"	7 No. 6	0.486	183 800	15 330	...	2 719	0.00628	350	0.782	0.790	0.798	0.802	0.928	0.973	1.021	1.040	0.267	0.513	0.615	0.278	0.1388	0.1157
7/16"	7 No. 7	0.433	145 700	12 670	...	2 157	0.00559	310	0.986	0.994	1.002	1.006	1.170	1.220	1.271	1.291	0.273	0.524	0.629	0.286	0.1429	0.1191
3/8"	7 No. 8	0.385	115 600	10 460	...	1 710	0.00497	270	1.244	1.252	1.260	1.264	1.476	1.530	1.584	1.606	0.279	0.536	0.644	0.294	0.1471	0.1226
11/32"	7 No. 9	0.343	91 650	8 616	...	1 356	0.00443	230	1.568	1.576	1.584	1.588	1.861	1.918	1.978	2.00	0.285	0.548	0.658	0.303	0.1512	0.1260
5/16"	7 No. 10	0.306	72 680	7 121	...	1 076	0.00395	200	1.978	1.986	1.994	1.998	2.35	2.41	2.47	2.50	0.291	0.560	0.671	0.311	0.1553	0.1294
3 No. 5	3 No. 5	0.392	99 310	8 373	...	1 467	0.00621	250	1.445	1.450	1.455	1.457	1.714	1.738	1.762	1.772	0.269	0.514	0.617	0.293	0.1465	0.1221
3 No. 6	3 No. 6	0.349	78 750	6 931	...	1 163	0.00553	220	1.821	1.826	1.831	1.833	2.16	2.19	2.21	2.22	0.275	0.526	0.631	0.301	0.1506	0.1255
3 No. 7	3 No. 7	0.311	62 450	5 732	...	922.4	0.00492	190	2.30	2.30	2.31	2.31	2.72	2.75	2.78	2.79	0.281	0.537	0.645	0.310	0.1547	0.1289
3 No. 8	3 No. 8	0.277	49 530	4 730	...	731.5	0.00439	160	2.90	2.90	2.91	2.91	3.44	3.47	3.50	3.51	0.286	0.549	0.659	0.318	0.1589	0.1324
3 No. 9	3 No. 9	0.247	39 280	3 898	...	580.1	0.00391	140	3.65	3.66	3.66	3.66	4.33	4.37	4.40	4.41	0.292	0.561	0.673	0.326	0.1629	0.1358
3 No. 10	3 No. 10	0.220	31 150	3 221	...	460.0	0.00348	120	4.61	4.61	4.62	4.62	5.46	5.50	5.53	5.55	0.297	0.572	0.687	0.334	0.1671	0.1392
3 No. 12	3 No. 12	0.174	19 590	2 236		289.3	0.00276	90	7.32	7.33	7.33	7.34	8.69	8.73	8.77	8.78	0.310	0.596	0.715	0.351	0.1754	0.1462

*Based on conductor temperature of 125°C. and an ambient of 25°C.
**Resistance at 75°C. total temperature, based on an ambient of 25°C. plus 50°C. rise due to heating effect of current.
The approximate magnitude of current necessary to produce the 50°C. rise is 75% of the "Approximate Current Carrying Capacity at 60 Cycles."

TABLE 5—SKIN EFFECT TABLE

X	K	X	K	X	K	X	K
0.0	1.00000	1.0	1.00519	2.0	1.07816	3.0	1.31809
0.1	1.00000	1.1	1.00758	2.1	1.09375	3.1	1.35102
0.2	1.00001	1.2	1.01071	2.2	1.11126	3.2	1.38504
0.3	1.00004	1.3	1.01470	2.3	1.13069	3.3	1.41999
0.4	1.00013	1.4	1.01969	2.4	1.15207	3.4	1.45570
0.5	1.00032	1.5	1.02582	2.5	1.17538	3.5	1.49202
0.6	1.00067	1.6	1.03323	2.6	1.20056	3.6	1.52879
0.7	1.00124	1.7	1.04205	2.7	1.22753	3.7	1.56587
0.8	1.00212	1.8	1.05240	2.8	1.25620	3.8	1.60314
0.9	1.00340	1.9	1.06440	2.9	1.28644	3.9	1.64051

TABLE 6—INDUCTIVE REACTANCE SPACING FACTOR (x_d) OHMS PER CONDUCTOR PER MILE

FUNDAMENTAL EQUATIONS

$$z_1 = z_2 = r_a + j(x_a + x_d)$$
$$z_0 = r_a + r_e + j(x_a + x_e - 2x_d)$$

25 CYCLES

x_d at 25 cycles
$x_d = 0.1164 \log_{10} d$
d = separation, feet.

Feet	SEPARATION — INCHES 0	1	2	3	4	5	6	7	8	9	10	11
0	–	-0.1256	-0.0906	-0.0701	-0.0555	-0.0443	-0.0350	-0.0273	-0.0205	-0.0146	-0.0092	-0.0044
1	0	0.0040	0.0078	0.0113	0.0145	0.0176	0.0205	0.0232	0.0255	0.0283	0.0306	0.0329
2	0.0350	0.0371	0.0391	0.0410	0.0428	0.0446	0.0463	0.0480	0.0496	0.0511	0.0527	0.0541
3	0.0555	0.0569	0.0583	0.0596	0.0609	0.0621	0.0633	0.0645	0.0657	0.0668	0.0679	0.0690
4	0.0701	0.0711	0.0722	0.0732	0.0741	0.0751	0.0760	0.0770	0.0779	0.0788	0.0797	0.0805
5	0.0814	0.0822	0.0830	0.0838	0.0846	0.0854	0.0862	0.0869	0.0877	0.0884	0.0892	0.0899
6	0.0906	0.0913	0.0920	0.0927	0.0933	0.0940	0.0946	0.0953	0.0959	0.0965	0.0972	0.0978
7	0.0984	0.0990	0.0996	0.1002	0.1007	0.1013	0.1019	0.1024	0.1030	0.1035	0.1041	0.1046
8	0.1051											
9	0.1111											
10	0.1164											
11	0.1212											
12	0.1256											
13	0.1297											
14	0.1334											
15	0.1369											
16	0.1402											
17	0.1432											
18	0.1461											
19	0.1489											
20	0.1515											
21	0.1539											
22	0.1563											
23	0.1585											
24	0.1607											
25	0.1627											
26	0.1647											
27	0.1666											
28	0.1685											
29	0.1702											
30	0.1720											
31	0.1736											
32	0.1752											
33	0.1768											
34	0.1783											
35	0.1798											
36	0.1812											
37	0.1826											
38	0.1839											
39	0.1852											
40	0.1865											
41	0.1878											
42	0.1890											
43	0.1902											
44	0.1913											
45	0.1925											
46	0.1936											
47	0.1947											
48	0.1957											
49	0.1968											

50 CYCLES

x_d at 50 cycles
$x_d = 0.2328 \log_{10} d$
d = separation, feet.

Feet	SEPARATION — Inches 0	1	2	3	4	5	6	7	8	9	10	11
0	–	-0.2513	-0.1812	-0.1402	-0.1111	-0.0885	-0.0701	-0.0545	-0.0410	-0.0291	-0.0184	-0.0088
1	0	0.0081	0.0156	0.0226	0.0291	0.0352	0.0410	0.0465	0.0517	0.0566	0.0613	0.0658
2	0.0701	0.0742	0.0782	0.0820	0.0857	0.0892	0.0927	0.0960	0.0992	0.1023	0.1053	0.1082
3	0.1111	0.1139	0.1166	0.1192	0.1217	0.1242	0.1267	0.1291	0.1314	0.1337	0.1359	0.1380
4	0.1402	0.1423	0.1443	0.1463	0.1483	0.1502	0.1521	0.1539	0.1558	0.1576	0.1593	0.1610
5	0.1627	0.1644	0.1661	0.1677	0.1693	0.1708	0.1724	0.1739	0.1754	0.1769	0.1783	0.1798
6	0.1812	0.1826	0.1839	0.1853	0.1866	0.1880	0.1893	0.1906	0.1918	0.1931	0.1943	0.1956
7	0.1965	0.1980	0.1991	0.2003	0.2015	0.2026	0.2037	0.2049	0.2060	0.2071	0.2081	0.2092
8	0.2103											
9	[illegible]											
10	0.2328											
11	0.2425											
12	0.2513											
13	0.2594											
14	0.2669											
15	0.2738											
16	0.2804											
17	0.2865											
18	0.2923											
19	0.2977											
20	0.3029											
21	0.3078											
22	0.3125											
23	0.3170											
24	0.3214											
25	0.3255											
26	0.3294											
27	0.3333											
28	0.3369											
29	0.3405											
30	0.3439											
31	0.3472											
32	0.3504											
33	0.3536											
34	0.3566											
35	0.3595											
36	0.3624											
37	0.3651											
38	0.3678											
39	0.3704											
40	0.3730											
41	0.3755											
42	0.3779											
43	0.3803											
44	0.3826											
45	0.3849											
46	0.3871											
47	0.3893											
48	0.3914											
49	0.3935											

60 CYCLES

x_d at 60 cycles
$x_d = 0.2794 \log_{10} d$
d = separation, feet.

Feet	SEPARATION — Inches 0	1	2	3	4	5	6	7	8	9	10	11
0	–	-0.3015	-0.2174	-0.1682	-0.1333	-0.1062	-0.0841	-0.0654	-0.0492	-0.0349	-0.0221	-0.0106
1	0	0.0097	0.0187	0.0271	0.0349	0.0423	0.0492	0.0558	0.0620	0.0679	0.0735	0.0789
2	0.0841	0.0891	0.0938	0.0984	0.1028	0.1071	0.1112	0.1152	0.1190	0.1227	0.1264	0.1299
3	0.1333	0.1366	0.1399	0.1430	0.1461	0.1491	0.1520	0.1549	0.1577	0.1604	0.1631	0.1657
4	0.1682	0.1707	0.1732	0.1756	0.1779	0.1802	0.1825	0.1847	0.1869	0.1891	0.1912	0.1933
5	0.1953	0.1973	0.1993	0.2012	0.2031	0.2050	0.2069	0.2087	0.2105	0.2123	0.2140	0.2157
6	0.2174	0.2191	0.2207	0.2224	0.2240	0.2256	0.2271	0.2287	0.2302	0.2317	0.2332	0.2347
7	0.2361	0.2376	0.2390	0.2404	0.2418	0.2431	0.2445	0.2458	0.2472	0.2485	0.2498	0.2511
8	0.2523											
9	0.2666											
10	0.2794											
11	0.2910											
12	0.3015											
13	0.3112											
14	0.3202											
15	0.3286											
16	0.3364											
17	0.3438											
18	0.3507											
19	0.3573											
20	0.3635											
21	0.3694											
22	0.3751											
23	0.3805											
24	0.3854											
25	0.3906											
26	0.3953											
27	0.3999											
28	0.4043											
29	0.4086											
30	0.4127											
31	0.4167											
32	0.4205											
33	0.4243											
34	0.4279											
35	0.4314											
36	0.4348											
37	0.4382											
38	0.4414											
39	0.4445											
40	0.4476											
41	0.4506											
42	0.4535											
43	0.4564											
44	0.4592											
45	0.4619											
46	0.4646											
47	0.4672											
48	0.4697											
49	0.4722											

TABLE 7—ZERO-SEQUENCE RESISTANCE AND INDUCTIVE REACTANCE FACTORS (r_e, x_e)*

Ohms per Conductor per Mile

	ρ Meter Ohm	FREQUENCY 25 Cycles	50 Cycles	60 Cycles
r_e	All	0.1192	0.2383	0.2860
x_e	1	0.921	1.736	2.050
	5	1.043	1.980	2.343
	10	1.095	2.085	2.469
	50	1.217	2.329	2.762
	100†	1.270	2.434	2.888
	500	1.392	2.679	3.181
	1000	1.444	2.784	3.307
	5000	1.566	3.028	3.600
	10 000	1.618	3.133	3.726

*From Formulae:

$r_e = 0.004764 f$

$x_e = 0.006985 f \log_{10} 4\,665\,600 \frac{\rho}{f}$

where f = frequency
ρ = Resistivity (meter-ohm)

†This is an average value which may be used in the absence of definite information.

TABLE 8—SHUNT CAPACITIVE REACTANCE SPACING FACTOR (x_d') MEGOHMS PER CONDUCTOR PER MILE

FUNDAMENTAL EQUATIONS

$$x_1' = x_2' = x_a' + x_d'$$
$$x_0' = x_a' + x_e' - 2x_d'$$

25 CYCLES

x_d' at 25 cycles
$x_d' = .1640 \log_{10} d$
d = separation, feet.

Separation: Feet	Inches: 0	1	2	3	4	5	6	7	8	9	10	11
0	—	-0.1709	-0.1276	-0.0957	-0.0752	-0.0623	-0.0494	-0.0384	-0.0289	-0.0205	-0.0130	-0.0062
1	0	0.0057	0.0110	0.0159	0.0205	0.0248	0.0289	0.0327	0.0364	0.0398	0.0432	0.0463
2	0.0494	0.0523	0.0551	0.0577	0.0600	0.0625	0.0652	0.0676	0.0698	0.0720	0.0742	0.0762
3	0.0782	0.0802	0.0821	0.0839	0.0857	0.0875	0.0892	0.0909	0.0925	0.0941	0.0957	0.0972
4	0.0987	0.1002	0.1016	0.1030	0.1044	0.1058	0.1071	0.1084	0.1097	0.1109	0.1122	0.1134
5	0.1146	0.1158	0.1169	0.1181	0.1192	0.1203	0.1214	0.1225	0.1235	0.1246	0.1256	0.1266
6	0.1276	0.1286	0.1295	0.1305	0.1314	0.1324	0.1333	0.1342	0.1351	0.1360	0.1368	0.1377
7	0.1386	0.1394	0.1402	0.1411	0.1419	0.1427	0.1435	0.1443	0.1450	0.1458	0.1466	0.1473
8	0.1481											
9	0.1565											
10	0.1640											
11	0.1707											
12	0.1770											
13	0.1826											
14	0.1879											
15	0.1929											
16	0.1974											
17	0.2017											
18	0.2058											
19	0.2097											
20	0.2133											
21	0.2168											
22	0.2201											
23	0.2233											
24	0.2263											
25	0.2292											
26	0.2320											
27	0.2347											
28	0.2373											
29	0.2398											
30	0.2422											
31	0.2446											
32	0.2468											
33	0.2490											
34	0.2511											
35	0.2532											
36	0.2552											
37	0.2571											
38	0.2590											
39	0.2609											
40	0.2627											
41	0.2644											
42	0.2661											
43	0.2678											
44	0.2695											
45	0.2711											
46	0.2726											
47	0.2742											
48	0.2756											
49	0.2771											

50 CYCLES

x_d' at 50 cycles
$x_d' = 0.08198 \log_{10} d$
d = separation, feet.

Separation: Feet	Inches: 0	1	2	3	4	5	6	7	8	9	10	11
0	-	-0.0885	-0.0638	-0.0494	-0.0391	-0.0312	-0.0247	-0.0192	-0.0144	-0.0102	-0.0065	-0.0031
1	0	0.0028	0.0055	0.0079	0.0102	0.0124	0.0144	0.0164	0.0182	0.0199	0.0216	0.0232
2	0.0247	0.0261	0.0275	0.0289	0.0302	0.0314	0.0326	0.0338	0.0349	0.0360	0.0371	0.0381
3	0.0391	0.0401	0.0410	0.0420	0.0429	0.0437	0.0446	0.0454	0.0463	0.0471	0.0478	0.0486
4	0.0494	0.0501	0.0508	0.0515	0.0522	0.0529	0.0535	0.0542	0.0548	0.0555	0.0561	0.0567
5	0.0573	0.0579	0.0585	0.0590	0.0596	0.0601	0.0607	0.0612	0.0618	0.0623	0.0628	0.0633
6	0.0638	0.0643	0.0648	0.0652	0.0657	0.0662	0.0666	0.0671	0.0675	0.0680	0.0684	0.0689
7	0.0693	0.0697	0.0701	0.0705	0.0709	0.0713	0.0717	0.0721	0.0725	0.0729	0.0733	0.0737
8	0.0740											
9	0.0782											
10	0.0920											
11	0.0854											
12	0.0885											
13	0.0913											
14	0.0940											
15	0.0964											
16	0.0987											
17	0.1094											
18	0.1029											
19	0.1048											
20	0.1067											
21	0.1084											
22	0.1100											
23	0.1116											
24	0.1131											
25	0.1146											
26	0.1160											
27	0.1173											
28	0.1156											
29	0.1199											
30	0.1211											
31	0.1223											
32	0.1234											
33	0.1245											
34	0.1255											
35	0.1266											
36	0.1276											
37	0.1286											
38	0.1295											
39	0.1304											
40	0.1313											
41	0.1322											
42	0.1331											
43	0.1339											
44	0.1347											
45	0.1355											
46	0.1363											
47	0.1371											
48	0.1378											
49	0.1386											

60 CYCLES

x_d' at 60 cycles
$x_d' = 0.06831 \log_{10} d$
d = separation, feet.

Separation: Feet	Inches: 0	1	2	3	4	5	6	7	8	9	10	11
0	-	-0.0737	-0.0532	-0.0411	-0.0326	-0.0260	-0.0206	-0.0160	-0.0120	-0.0085	-0.0054	-0.0026
1	0	0.0024	0.0046	0.0066	0.0085	0.0103	0.0120	0.0136	0.0152	0.0166	0.0180	0.0193
2	0.0206	0.0218	0.0229	0.0241	0.0251	0.0262	0.0272	0.0282	0.0291	0.0300	0.0309	0.0318
3	0.0326	0.0334	0.0342	0.0350	0.0357	0.0365	0.0372	0.0379	0.0385	0.0392	0.0399	0.0405
4	0.0411	0.0417	0.0423	0.0429	0.0435	0.0441	0.0446	0.0452	0.0457	0.0462	0.0467	0.0473
5	0.0478	0.0482	0.0487	0.0492	0.0497	0.0501	0.0506	0.0510	0.0515	0.0519	0.0523	0.0527
6	0.0532	0.0536	0.0540	0.0544	0.0548	0.0552	0.0555	0.0559	0.0563	0.0567	0.0570	0.0574
7	0.0577	0.0581	0.0584	0.0588	0.0591	0.0594	0.0598	0.0601	0.0604	0.0608	0.0611	0.0614
8	0.0617											
9	0.0652											
10	0.0683											
11	0.0711											
12	0.0737											
13	0.0761											
14	0.0783											
15	0.0803											
16	0.0823											
17	0.0841											
18	0.0858											
19	0.0874											
20	0.0889											
21	0.0903											
22	0.0917											
23	0.0930											
24	0.0943											
25	0.0955											
26	0.0967											
27	0.0978											
28	0.0989											
29	0.0999											
30	0.1009											
31	0.1019											
32	0.1028											
33	0.1037											
34	0.1046											
35	0.1055											
36	0.1063											
37	0.1071											
38	0.1079											
39	0.1087											
40	0.1094											
41	0.1102											
42	0.1109											
43	0.1116											
44	0.1123											
45	0.1129											
46	0.1136											
47	0.1142											
48	0.1149											
49	0.1155											

TABLE 9—ZERO-SEQUENCE SHUNT CAPACITIVE REACTANCE FACTOR x_e'

Megohms per Conductor per Mile

Conductor Height Above Ground Feet	Frequency: 25 Cycles	50 Cycles	60 Cycles
10	0.640	0.320	0.267
15	0.727	0.363	0.303
20	0.788	0.394	0.328
25	0.836	0.418	0.349
30	0.875	0.437	0.364
40	0.936	0.468	0.390
50	0.984	0.492	0.410
60	1.023	0.511	0.426
70	1.056	0.528	0.440
80	1.084	0.542	0.452
90	1.109	0.555	0.462
100	1.132	0.566	0.472

$$x_e' = \frac{12.30}{f} \log_{10} 2h$$

where h = height above ground.
f = frequency.

CHAPTER 4

ELECTRICAL CHARACTERISTICS OF CABLES

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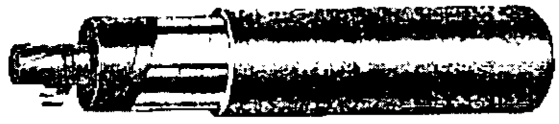
CABLES are classified according to their insulation as paper, varnished-cambric, rubber, or asbestos, each of these materials having unique characteristics which render it suitable for particular applications. Because cables for power transmission and distribution are composed of so many different types of insulation, conductors and sheathing materials, the discussion here must be limited to those cable designs most commonly used. Reasonable estimates of electrical characteristics for cables not listed can be obtained in most cases by reading from the table for a cable having similar physical dimensions.

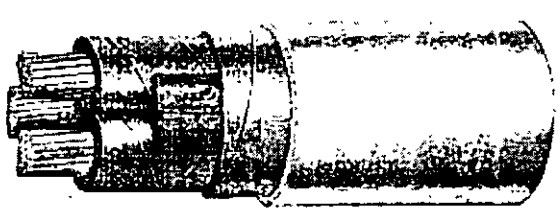
Paper can be wound onto a conductor in successive layers to achieve a required dielectric strength, and this is the insulation generally used for cables operating at 10 000 volts and higher. Paper insulation is impregnated in different ways, and accordingly cables so insulated can be subdivided into solid, oil-filled, or gas-filled types.

Solid paper-insulated cables are built up of layers of paper tape wound onto the conductor and impregnated with a viscous oil, over which is applied a tight-fitting, extruded lead sheath. Multi-conductor solid cables are also available, but the material shown here covers only single- and three-conductor types. Three-conductor cables are of either belted or shielded construction. The belted assembly consists of the three separately insulated conductors cabled together and wrapped with another layer of impregnated paper, or belt, before the sheath is applied. In the shielded construction each conductor is individually insulated and covered with a thin metallic non-magnetic shielding tape; the three conductors are then cabled together, wrapped with a metallic binder tape, and sheathed with lead. The purpose of the metallic shielding tape around each insulated conductor is to control the electrostatic stress, reduce corona formation, and decrease the thermal resistance. To minimize circulating current under normal operating conditions and thus limit the power loss, shielding tape only three mils in thickness is used. Solid single-conductor cables are standard for all voltages from 1 to 69 kv; solid three-conductor cables are standard from 1 to 46 kv. Sample sections of paper-insulated single-conductor, three-conductor belted, and three-conductor shielded cables are shown in Fig. 1(a), (b), and (c) respectively.

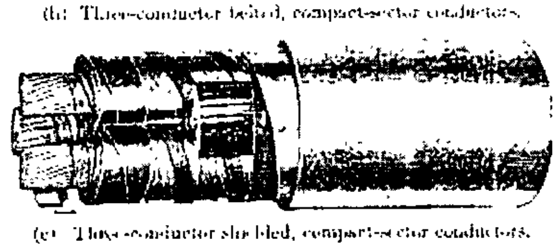
Oil-filled paper-insulated cables are available in single- or three-conductor designs. Single-conductor oil-filled cable consists of a concentric stranded conductor built around an open helical spring core, which serves as a channel for the flow of low-viscosity oil. This cable is insulated and sheathed in the same manner as solid cables, as a comparison of Figs. 1(a) and 1(d) indicates. Three-conductor oil-filled cables are all of the shielded design, and have three oil channels composed of helical springs that extend through the cable in spaces normally occupied by filler material. This construction is shown in Fig. 1(e). Oil-filled cables are relatively new and their application has become widespread in a comparatively short time. The oil used is only slightly more viscous than transformer oil, and



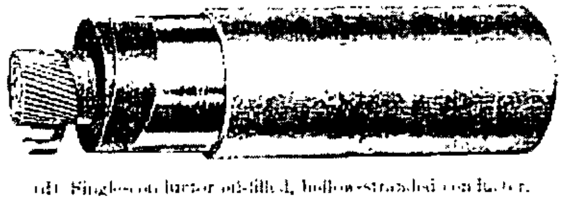
(a) Single-conductor solid, compact-round conductor.



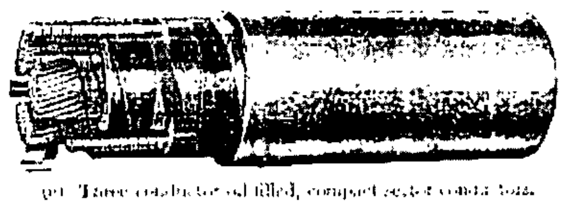
(b) Three-conductor belted, compact-sector conductors.



(c) Three-conductor shielded, compact-sector conductors.



(d) Single-conductor oil-filled, hollow-stranded conductor.



(e) Three-conductor oil-filled, compact sector conductors.

Fig. 1 Paper-insulated cables.

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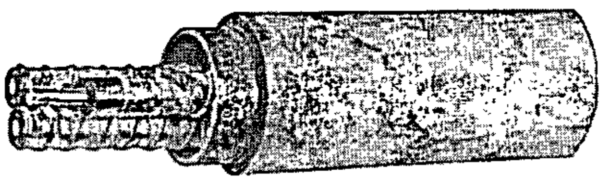
remains fluid at all operating temperatures. The oil in the cable and its connected reservoirs is maintained under moderate pressure so that during load cycles oil may flow between the cable and the reservoirs to prevent the development of voids or excessive pressure in the cable. The prevention of void formation in paper insulation permits the use of greatly reduced insulation thickness for a given operating voltage. Another advantage of oil-filled cables is that oil will seep out through any crack or opening which develops in the sheath, thereby preventing the entrance of water at the defective point. This action prevents the occurrence of a fault caused by moisture in the insulation, and since operating records show that this cause accounts for a significant percentage of all high-voltage cable faults, it is indeed a real advantage. Single-conductor oil-filled cables are used for voltages ranging from 69 to 230 kv; the usual range for three-conductor oil-filled cables is from 23 to 69 kv.

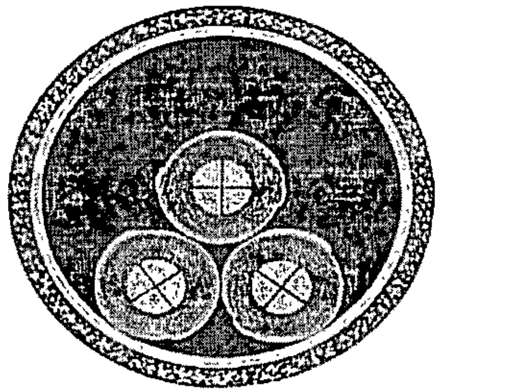
Gas-filled cables of the low-pressure type have recently become standard up to 46 kv. The single-conductor type employs construction generally similar to that of solid cables, except that longitudinal flutes or other channels are provided at the inner surface of the sheath to conduct nitrogen along the cable. The three-conductor design employs channels in the filler spaces among the conductors, much like those provided in oil-filled three-conductor cables. The gas is normally maintained between 10 and 15 pounds per square inch gauge pressure, and serves to fill all cable voids and exclude moisture at faulty points in the sheath or joints.



Courtesy of the Okonite-Callender Cable Company

Fig. 2—High-pressure pipe-type oil-filled cable.

High-pressure cables, of either the oil- or gas-filled variety, are being used widely for the higher range of voltages. The physical and electrical characteristics are fairly well known, but their specifications are not yet standardized. The usual application calls for pressure of about 200 pounds per square inch, contained by a steel pipe into which three single-conductor cables are pulled. The immediate presence of the iron pipe makes difficult the calculations of circuit impedance, particularly the zero-sequence quantities. Most high-pressure cables are designed so that the oil or gas filler comes into direct contact with the conductor insulation; in oil-filled pipe-type cables a temporary lead sheath can be stripped from the cable as it is pulled into the steel pipe; in gas-filled pipe-type cables the lead sheath surrounding each conductor remains in place, with nitrogen introduced both inside and outside the sheath so that no differential pressure develops across the sheath. Examples of oil- and gas-filled pipe-type cables are shown in Figs. 2 and 3.



Courtesy of General Cable Corporation

Fig. 3—Cross-section of high-pressure pipe-type gas-filled cable. Oil-filled pipe-type cable may have a similar cross-section.

Compression cable is another high-pressure pipe-type cable in which oil or nitrogen gas at high pressure is introduced within a steel pipe containing lead-sheathed solid-type single-conductor cables; no high-pressure oil or gas is introduced directly inside the lead sheaths, but voids within the solid-type insulation are prevented by pressure exerted externally on the sheaths. This construction is sketched in Fig. 4.

During recent years there has been a trend toward the modification of cable conductors to reduce cost and improve operating characteristics, particularly in multi-conductor cables. Referring to Fig. 5, the first departure from concentric round conductors was the adoption of sector-shaped conductors in three-conductor cables. More recently a crushed stranding that results in a compacted sector has been developed and has found widespread use for conductor sizes of 1/0 A.W.G. and larger. Its use in smaller conductors is not practical. The principal advantages of such a conductor are: reduced overall diameter for a given copper cross-section; elimination of space between the conductor and the insulation, which results in higher

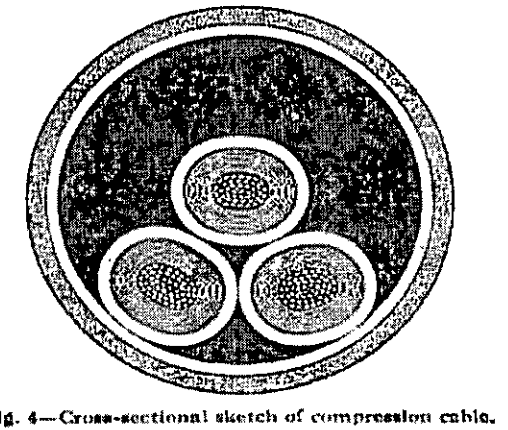
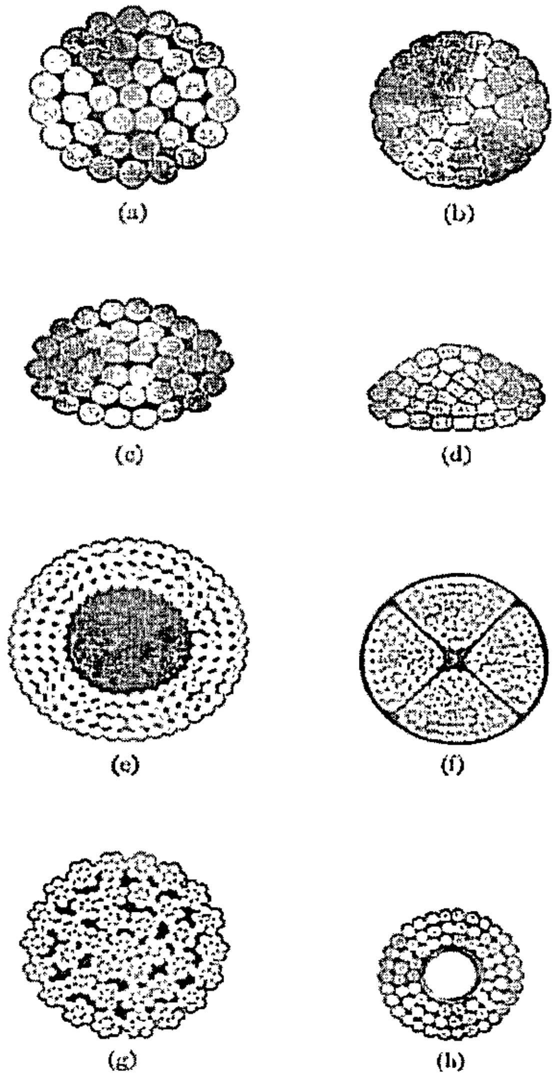


Fig. 4—Cross-sectional sketch of compression cable.



Photographs in this figure furnished by the Okonite-Callender Cable Company

Fig. 5—Cable conductors.

(a) Standard concentric stranded.
(b) Compact round.
(c) Non-compact sector.
(d) Compact sector.
(e) Annular stranded (rope core).
(f) Segmental.
(g) Rope stranded.
(h) Hollow core.

electrical breakdown; low a-c resistance due to minimizing of proximity effect; retention of the close stranding during bending; and for solid cables, elimination of many longitudinal channels along which impregnating compound can migrate. While most single-conductor cables are of the concentric-strand type, they may also be compact-round, annular-stranded, segmental, or hollow-core.

I. ELECTRICAL CHARACTERISTICS

The electrical characteristics of cables have been discussed comprehensively in a series of articles[1] upon which much of the material presented here has been based. This chapter is primarily concerned with the determination of the electrical constants most commonly needed for power-system calculations, particular emphasis being placed on quantities necessary for the application of symmetrical components.[2] A general rule is that regardless of the complexity of mutual inductive relations between component parts of individual phases, the method of symmetrical components can be applied rigorously whenever there is symmetry among phases. All the three-conductor cables inherently satisfy this condition by the nature of their construction; single-conductor cables may or may not, although usually the error is small in calculating short-circuit currents. Unsymmetrical spacing and change in permeability resulting from different phase currents when certain methods of eliminating sheath currents are used, may produce dissymmetry.

Those physical characteristics that are of general interest in electrical application problems have been included along with electrical characteristics in the tables of this section.

All linear dimensions of radius, diameter, separation, or distance to equivalent earth return are expressed in inches in the equations in this chapter. This is unlike overhead transmission line theory where dimensions are in feet; the use of inches when dealing with cable construction seems appropriate. Many equations contain a factor for frequency, f, which is the circuit operating frequency in cycles per second.

1. Geometry of Cables

The space relationship among sheaths and conductors in a cable circuit is a major factor in determining reactance, capacitance, charging current, insulation resistance, dielectric loss, and thermal resistance. The symbols used in this chapter for various cable dimensions, both for single-conductor and three-conductor types, are given in Figs. 6 and 7. Several factors have come into universal use for defining the cross-section geometry of a cable circuit, and some of these are covered in the following paragraphs.[1,2]

Geometric Mean Radius (GMR)—This factor is a property usually applied to the conductor alone, and depends on the material and stranding used in its construction. One component of conductor reactance[3] is normally calculated by evaluating the integrated flux-linkages both inside and outside the conductor within an overall twelve-inch radius. Considering a solid conductor, some of the flux lines lie within the conductor and contribute to total flux-linkages even though they link only a portion of the total conductor current; if a tubular conductor having an infinitely thin wall were substituted for the solid conductor, its flux would necessarily all be external to the tube. A theoretical tubular conductor, in order to be inductively equivalent to a solid conductor, must have a smaller radius so

TABLE 1—CHARACTERISTICS OF COPPER CONDUCTORS, HARD DRAWN, 97.3 PERCENT CONDUCTIVITY

Size of Conductor		Number of Strands	Diameter of Individual Strands Inches	Outside Diameter Inches	Breaking Strength Pounds	Weight Pounds per Mile	Approx Current Carrying Capacity* Amps	Geometric Mean Radius at 60 Cycles Feet	r_a Resistance Ohms per Conductor per Mile								x_a Inductive Reactance Ohms per Conductor Per Mile At 1 Ft. Spacing			x_a' Shunt Capacitive Reactance Megohms per Conductor Per Mile At 1 Ft Spacing		
									25°C. (77°F.)				50°C. (122°F.)									
Circular Mils	A.W.G. or B & S								d-c	25 cycles	50 cycles	60 cycles	d-c	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles	25 cycles	50 cycles	60 cycles
1 000 000	...	37	0.1644	1.151	43 830	16 300	1 300	0.0308	0.0585	0.0594	0.0620	0.0634	0.0640	0.0648	0.0672	0.0685	0.1666	0.333	0.400	0.216	0.1081	0.0901
900 000	...	37	0.1560	1.092	39 510	14 670	1 220	0.0349	0.0650	0.0658	0.0682	0.0695	0.0711	0.0718	0.0740	0.0752	0.1693	0.339	0.406	0.220	0.1100	0.0916
800 000	...	37	0.1470	1.029	35 120	13 040	1 130	0.0329	0.0731	0.0739	0.0760	0.0772	0.0800	0.0806	0.0826	0.0837	0.1722	0.344	0.413	0.224	0.1121	0.0934
750 000	...	37	0.1424	0.997	33 400	12 230	1 090	0.0319	0.0780	0.0787	0.0807	0.0818	0.0853	0.0859	0.0878	0.0888	0.1739	0.348	0.417	0.226	0.1132	0.0943
700 000	...	37	0.1375	0.963	31 170	11 410	1 040	0.0308	0.0836	0.0842	0.0861	0.0871	0.0914	0.0920	0.0937	0.0947	0.1759	0.352	0.422	0.229	0.1145	0.0954
600 000	...	37	0.1273	0.891	27 020	9 781	940	0.0285	0.0975	0.0981	0.0997	0.1006	0.1066	0.1071	0.1086	0.1095	0.1799	0.360	0.432	0.235	0.1173	0.0977
500 000	...	37	0.1162	0.814	22 510	8 151	840	0.0260	0.1170	0.1175	0.1188	0.1196	0.1280	0.1283	0.1296	0.1303	0.1845	0.369	0.443	0.241	0.1205	0.1004
500 000	...	19	0.1622	0.811	21 500	8 151	840	0.0256	0.1170	0.1175	0.1188	0.1196	0.1280	0.1283	0.1296	0.1303	0.1853	0.371	0.445	0.241	0.1206	0.1005
450 000	...	19	0.1539	0.770	19 750	7 336	780	0.0243	0.1300	0.1304	0.1316	0.1323	0.1422	0.1426	0.1437	0.1443	0.1879	0.376	0.451	0.245	0.1224	0.1020
400 000	...	19	0.1451	0.726	17 560	6 521	730	0.0229	0.1462	0.1466	0.1477	0.1484	0.1600	0.1603	0.1613	0.1619	0.1909	0.382	0.458	0.249	0.1245	0.1038
350 000	...	19	0.1357	0.679	15 590	5 706	670	0.0214	0.1671	0.1675	0.1684	0.1690	0.1828	0.1831	0.1840	0.1845	0.1943	0.389	0.466	0.254	0.1269	0.1058
350 000	...	12	0.1708	0.710	15 140	5 706	670	0.0225	0.1671	0.1675	0.1684	0.1690	0.1828	0.1831	0.1840	0.1845	0.1918	0.384	0.460	0.251	0.1253	0.1044
300 000	...	19	0.1257	0.629	13 510	4 891	610	0.01987	0.1950	0.1953	0.1961	0.1966	0.213	0.214	0.214	0.215	0.1982	0.396	0.476	0.259	0.1296	0.1080
300 000	...	12	0.1581	0.657	13 170	4 891	610	0.0208	0.1950	0.1953	0.1961	0.1966	0.213	0.214	0.214	0.215	0.1957	0.392	0.470	0.256	0.1281	0.1068
250 000	...	19	0.1147	0.574	11 360	4 076	540	0.01813	0.234	0.234	0.235	0.235	0.256	0.256	0.257	0.257	0.203	0.406	0.487	0.266	0.1329	0.1108
250 000	...	12	0.1443	0.600	11 130	4 076	540	0.01902	0.234	0.234	0.235	0.235	0.256	0.256	0.257	0.257	0.200	0.401	0.481	0.263	0.1313	0.1094
211 600	4/0	19	0.1055	0.528	9 617	3 450	480	0.01668	0.276	0.277	0.277	0.278	0.302	0.303	0.303	0.303	0.207	0.414	0.497	0.272	0.1359	0.1132
211 600	4/0	12	0.1328	0.552	9 483	3 450	490	0.01750	0.276	0.277	0.277	0.278	0.302	0.303	0.303	0.303	0.205	0.409	0.491	0.269	0.1343	0.1119
211 600	4/0	7	0.1739	0.522	9 154	3 450	480	0.01579	0.276	0.277	0.277	0.278	0.302	0.303	0.303	0.303	0.210	0.420	0.503	0.273	0.1363	0.1136
167 800	3/0	12	0.1183	0.492	7 556	2 736	420	0.01550	0.349	0.349	0.349	0.350	0.381	0.381	0.382	0.382	0.210	0.421	0.505	0.277	0.1384	0.1153
167 800	3/0	7	0.1548	0.464	7 366	2 736	420	0.01404	0.349	0.349	0.349	0.350	0.381	0.381	0.382	0.382	0.216	0.431	0.518	0.281	0.1405	0.1171
133 100	2/0	7	0.1379	0.414	5 926	2 170	360	0.01252	0.440	0.440	0.440	0.440	0.481	0.481	0.481	0.481	0.222	0.443	0.532	0.289	0.1445	0.1205
105 500	1/0	7	0.1228	0.368	4 752	1 720	310	0.01113	0.555	0.555	0.555	0.555	0.606	0.607	0.607	0.607	0.227	0.455	0.546	0.298	0.1488	0.1240
83 690	1	7	0.1093	0.328	3 804	1 364	270	0.00992	0.699	0.699	0.699	0.699	0.765				0.233	0.467	0.560	0.306	0.1528	0.1274
83 690	1	3	0.1670	0.360	3 620	1 351	270	0.01016	0.692	0.692	0.692	0.692	0.757				0.232	0.464	0.557	0.299	0.1495	0.1246
66 370	2	7	0.0974	0.292	3 045	1 082	230	0.00883	0.881	0.882	0.882	0.882	0.964				0.239	0.478	0.574	0.314	0.1570	0.1308
66 370	2	3	0.1487	0.320	2 913	1 071	240	0.00903	0.873				0.955				0.238	0.476	0.571	0.307	0.1537	0.1281
66 370	2	1	.....	0.258	3 003	1 061	220	0.00836	0.864				0.945				0.242	0.484	0.581	0.323	0.1614	0.1345
52 630	3	7	0.0867	0.260	2 433	858	200	0.00787	1.112				1.216				0.245	0.490	0.588	0.322	0.1611	0.1343
52 630	3	3	0.1325	0.285	2 350	850	200	0.00805	1.101				1.204				0.244	0.488	0.585	0.316	0.1578	0.1315
52 630	3	1	.....	0.229	2 439	841	190	0.00746	1.090		Same as d-c		1.192		Same as d-c		0.248	0.496	0.595	0.331	0.1656	0.1380
41 740	4	3	0.1180	0.254	1 879	674	180	0.00717	1.388				1.518				0.250	0.499	0.599	0.324	0.1619	0.1349
41 740	4	1	.....	0.204	1 970	667	170	0.00663	1.374				1.503				0.254	0.507	0.609	0.339	0.1697	0.1415
33 100	5	3	0.1050	0.226	1 505	534	150	0.00638	1.750				1.914				0.256	0.511	0.613	0.332	0.1661	0.1384
33 100	5	1	.....	0.1819	1 591	529	140	0.00590	1.733				1.895				0.260	0.519	0.623	0.348	0.1738	0.1449
26 250	6	3	0.0935	0.201	1 205	424	130	0.00568	2.21				2.41				0.262	0.523	0.628	0.341	0.1703	0.1419
26 250	6	1	.....	0.1620	1 280	420	120	0.00526	2.18				2.39				0.265	0.531	0.637	0.356	0.1779	0.1483
20 820	7	1	.....	0.1443	1 030	333	110	0.00468	2.75				3.01				0.271	0.542	0.651	0.364	0.1821	0.1517
16 510	8	1	.....	0.1285	826	264	90	0.00417	3.47				3.80				0.277	0.554	0.665	0.372	0.1862	0.1552

* For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2 ft/sec), frequency=60 cycles.

carrying capacity based on 50°C rise above an ambient of 25°C, (75°C total conductor temperature), tarnished surface ($E = 0.5$), and an air velocity of 2 feet per second. These conditions were used after discussion and agreement with the conductor manufacturers. These thermal limitations are based on continuous loading of the conductors.

The technical literature shows little variation from these conditions as line design limits.[7] The ambient air temperature is generally assumed to be 25°C to 40°C whereas the temperature rise is assumed to be 10°C to 60°C. This gives a conductor total temperature range of 35°C to 100°C. For design purposes copper or ACSR conductor total temperature is usually assumed to be 75°C as use of this value has given good conductor performance from an annealing standpoint, the limit being about 100°C where annealing of copper and aluminum begins.

Using Schurig and Frick's formulas, Fig. 25 and Fig. 26 have been calculated to show how current-carrying capacity of copper and aluminum conductors varies with ambient temperature assuming a conductor temperature of 75.C and wind velocity of 2 feet per second. These values are conservative and can be used as a guide in normal line design. For those lines where a higher conductor temperature may be obtained that approaches 100°C, the conductor manufacturer should be consulted for test data or other more accurate information as to conductor temperature limitations. Such data on copper conductors has been presented rather thoroughly in the technical literature.[7]

III TABLES OF CONDUCTOR CHARACTERISTICS

The following tables contain data on copper, ACSR, hollow copper, Copperweld-copper, and Copperweld conductors, which along with the previously derived equations, permit the determination of positive-, negative-, and zero-sequence impedances of conductors for use in the solution of power-system problems. Also tabulated are such conductor characteristics as size, weight, and current-carrying capacity as limited by heating.

The conductor data (r_a, x_a, x_a') along with inductive and shunt-capacitive reactance spacing factors (x_d, x_d') and zero-sequence resistance, inductive and shunt-capacitive reactance factors (r_e, x_e, x_e') permit easy substitution in the previously derived equations for determining the symmetrical component sequence impedances of aerial circuits.

The cross-sectional inserts in the tables are for ease in