Power Electronics Notes 30G
Cabling and Wire Charts

Marc T. Thompson, Ph.D.
Thompson Consulting, Inc.
9 Jacob Gates Road
Harvard, MA 01451
Phone: (978) 456-7722
Fax: (240) 414-2655
Email: marctt@thompsonrd.com
Web: http://www.thompsonrd.com

Overview

- Wire size is denoted by AWG (American Wire Gage)
- Wire diameter varies by a factor of 2 every 6 AWG
- #36 AWG is defined to be 0.005" (5 mil) diameter
- "Circular mils" is the diameter in mils, squared. (1 mil = 0.001")

To find wire diameter d based on AWG number:

In inches: $$d = (0.005'') \times 92^{\frac{36-AWG}{39}}$$

In millimeters: $$d = (25.4) \times (0.005'') \times 92^{\frac{36-AWG}{39}}$$

Example 1: AWG Conversion

- AWG #0

In inches:

$$d = (0.005'') \times 92^{\frac{36-AWG}{39}}$$

$$= (0.005'') \times 92^{\frac{36-0}{39}} = 0.3249''$$

Example 2: AWG Conversion for #4/0

- For 00, 000, 0000 etc. gauges, use -1, -2, -3 etc. for AWG
- Example: AWG 0000 (i.e. #4/0)

$$d = (0.005'') \times 92^{\frac{36-AWG}{39}}$$

In inches:

$$= (0.005'') \times 92^{\frac{36-(-3)}{39}} = 0.46''$$

Resistance of a Piece of Copper Wire

$$R = \frac{\rho l}{A}$$

ρ = copper resistivity = 1.7×10^{-8} Ω-m at 25 °C
l = wire length [m]
A = wire cross-sectional area [m^2]

Copper Temperature Coefficient of Resistivity

- Copper resistivity goes up as temperature goes up
- So, the total resistance of a piece of wire goes up as it heats up
- Temperature coefficient of resistivity is about +0.004/^{o}C, or about 0.4% per degree C

Aluminum Wire

- Aluminum has higher resistivity than copper (about 70% higher), with resistivity $\rho = 2.9\times10^{-8}\ \Omega$-m
- A 15-amp branch circuit made with #14 copper would require #12 aluminum, by the NEC
- Similar TC to copper
- Aluminum is much lighter than copper (about 33% of the weight per unit volume)
- Often used in power transmission (good ratio of resistivity to weight)
- Corrosion when joining aluminum to copper lugs; differing thermal expansion

Copper Wire Chart, Part 1

Table 20.1 Copper Wire Data

AWG SIZE	DIAMETER (MM)	Ω/KM (75°C)	KG/KM	TURNS/CM^2
0	8.25	0.392	475	
1	7.35	0.494	377	
2	6.54	0.624	299	
3	5.83	0.786	237	
4	5.19	0.991	188	
5	4.62	1.25	149	
6	4.12	1.58	118	
7	3.67	1.99	93.8	
8	3.26	2.51	74.4	
9	2.91	3.16	59.0	
10	2.59	3.99	46.8	14
11	2.31	5.03	37.1	17
12	2.05	6.34	29.4	22

Reference: Kassakian, Schlecht, Verghese, *Principles of Power Electronics*, Addison-Wesley, 1991

Copper Wire Chart, Part 2

11	[illegible]			
12	2.05	6.34	29.4	22
13	1.83	7.99	23.3	27
14	1.63	10.1	18.5	34
15	1.45	12.7	14.7	40
16	1.29	16.0	11.6	51
17	1.15	20.2	9.23	63
18	1.02	25.5	7.32	79
19	0.912	32.1	5.80	98
20	0.812	40.5	4.60	123
21	0.723	51.1	3.65	153
22	0.644	64.4	2.89	192
23	0.573	81.2	2.30	237
24	0.511	102	1.82	293
25	0.455	129	1.44	364
26	0.405	163	1.15	454
27	0.361	205	1.10	575
28	0.321	259	1.39	710
29	0.286	327	1.75	871
30	0.255	412	2.21	1090

1LB
330 FEET

Sizing of Power Cables

- Large power cables are available in copper and aluminum
- Wire is sized by AWG (American Wire Gage) or thousands of circular mils (kcmils)
- He smallest wire used in power distribution is #14 AWG, typically a solid conductor with an outside diameter of 0.0641", or 64.1 mils
- The largest AWG is #4/0, (0000) with a diameter of approximately 0.522" for a 7-strand conductor
- The area of larger conductors is expressed in circular mils. To find the area in cmils, square the diameter in mils by itself. For example, a #10 solid conductor with a diameter of 162 mils has an area of (162 mils)^2 = 26244 cmils, or 26.2 kcmil

Large Power Cables

Gauge	Washburn & Moen	British Imperial Standard (S.W.G.)	Birmingham or Stubs	American (A.W.G.) or Brown & Sharpe
7/0	.4900"	.500"	---	---
6/0	.4615"	.464"	---	.5800"
5/0	.4305"	.432"	.500"	.5165"
4/0	.3938"	.400"	.454"	.4600"
3/0	.3625"	.372"	.425"	.4096"
2/0	.3310"	.348"	.380"	.3648"
1/0	.3065"	.324"	.340"	.3249"
1	.2830"	.300"	.300"	.2893"
2	.2625"	.276"	.284"	.2576"
3	.2437"	.252"	.259"	.2294"
4	.2253"	.232"	.238"	.2043"
5	.2070"	.212"	.220"	.1819"
6	.1920"	.192"	.203"	.1620"
7	.1770"	.176"	.180"	.1442"
8	.1620"	.160"	.165"	.1284"
9	.1483"	.144"	.148"	.1144"

Reference: http://www.unc.edu/~rowlett/units/scales/wiregauge.html

Power Cables and Cable Impedance

- Power cables have a finite resistance (due to the resistivity of the conductor) and a finite inductance (due to the geometry of the cable)
- Cable impedance results in voltage drops, power loss, and heating in the cable

AC Cable Resistance

- DC resistance of a piece of wire:

$$R = \frac{l}{\sigma A}$$

- A = cross sectional area of wire, l = length, and σ = electrical conductivity
- However, AC resistance is higher than DC resistance, due to skin effect and proximity effect
- Wire resistance can be found in a “wire chart” for an isolated wire (i.e. in air, no metallic conduit, no other current-carrying wires nearby)

Copper Wire Data

Kassakian, Schlecht & Verghese - Principles of Power Electronics Addison-Wesley 1991

Table 20.1 Copper Wire Data

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12	2.05	6.34	29.4	22
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14	1.63	10.1	18.5	34
15	1.45	12.7	14.7	40
16	1.29	16.0	11.6	51
17	1.15	20.2	9.23	63
18	1.02	25.5	7.32	79
19	0.912	32.1	5.80	98
20	0.812	40.5	4.60	123
21	0.723	51.1	3.65	153
22	0.644	64.4	2.89	192
23	0.573	81.2	2.30	237
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25	0.455	129	1.44	364
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29	0.286	327	1.75	871
30	0.255	412	2.21	1090

1LB 330 FEET

Copper Wire Data

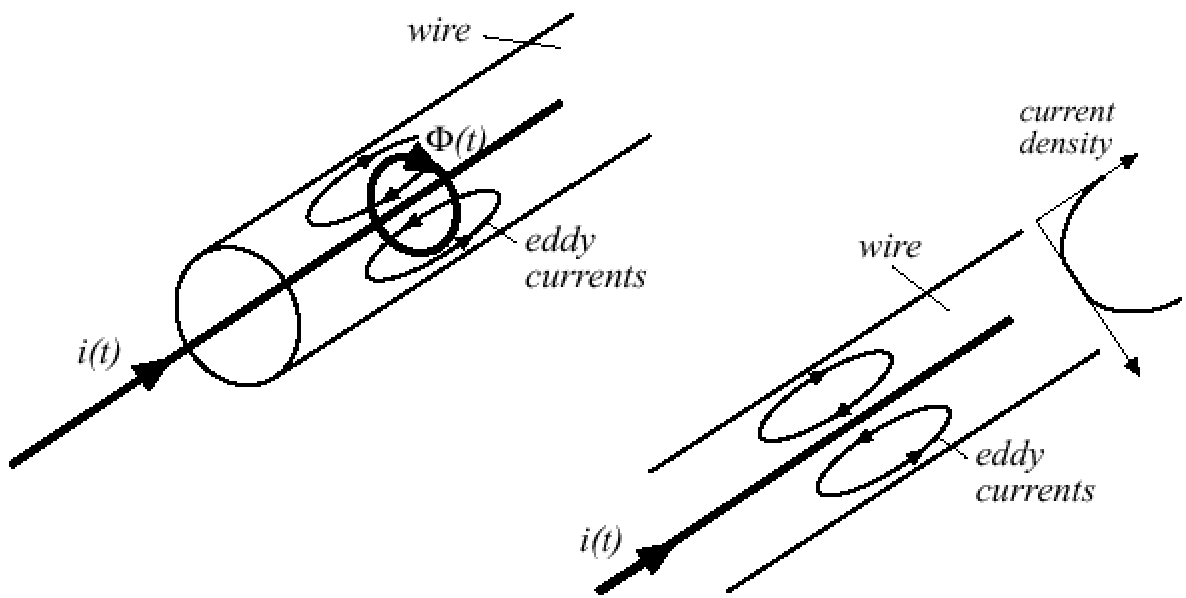
TABLE 11.1
Standard Wire Sizes and Current Capabilities

AWG Number	Diameter (mm)	Cross-Sectional Area (mm^2)	Resistance, mΩ/m at 25°C	Current Capacity, 500 A/cm^2	Current Capacity, 100 A/cm^2
4	5.189	21.15	0.8314	105.8	21.15
6	4.115	13.30	1.322	66.51	13.30
8	3.264	8.366	2.102	41.83	8.366
10	2.588	5.261	3.343	26.31	5.261
12	2.053	3.309	5.315	16.54	3.309
14	1.628	2.081	8.451	10.40	2.081
16	1.291	1.309	13.44	6.543	1.309
18	1.024	0.8230	21.36	4.115	0.8230
20	0.8118	0.5176	33.96	2.588	0.5176
22	0.6438	0.3255	54.00	1.628	0.3255
24	0.5106	0.2047	85.89	1.024	0.2047
26	0.4049	0.1288	136.5	0.6438	0.1288
28	0.3211	0.08098	217.1	0.4049	0.08098
30	0.2546	0.05093	345.1	0.2546	0.05093
32	0.2019	0.03203	549.3	0.1601	0.03203
34	0.1601	0.02014	873.3	0.1007	0.02014
36	0.127000	0.0126677	1389.	0.06334	0.0126677
38	0.1007	0.007967	2208.	0.03983	0.007967
40	0.07987	0.005010	3510.	0.02505	0.005010

Reference: P. Krein, _Elements of Power Electronics_, 3d edition

Causes of Skin Effect

- Self-field of wire causes current to crowd on the surface of the wire, raising the AC resistance
- Method:
  - Current *i(t)* $\Rightarrow$ changing magnetic flux density *B(t)* $\Rightarrow$ reaction currents



Reference: http://ece-www.colorado.edu/~pwrelect/book/slides/Ch12slide.pdf

Consequences of Skin Effect

- For high frequencies, current is concentrated in a layer approximately one skin depth δ thick
- Skin depth varies with frequency

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \sqrt{\frac{1}{\pi f\mu\sigma}}$$

- σ = electrical conductivity = $5.9\times10^{7}\ \Omega^{-1}\ m^{-1}$ for copper at 300K
- μ = magnetic permeability of material = $4\pi\times10^{-7}$ H/m in free space

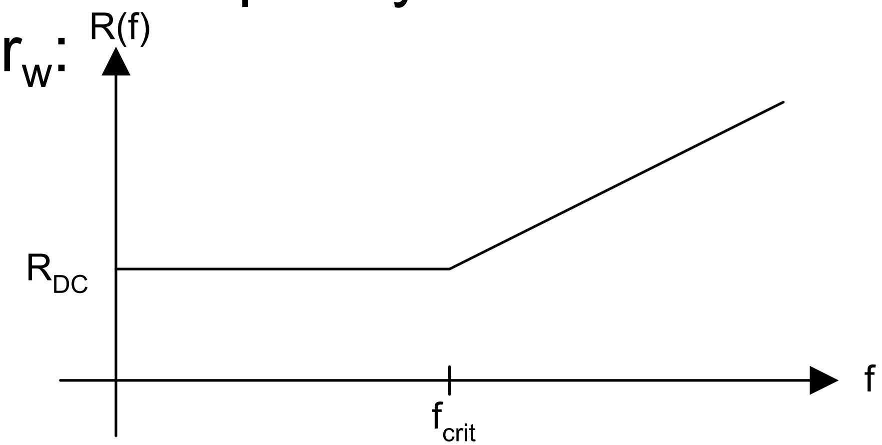
Skin depth in copper at 300K		
cond	5.90E+07	
mu	1.26E-06	
f	***skin depth (meter)***	
1	6.55E-02	
10	2.07E-02	
100	6.55E-03	
1000	2.07E-03	
1.00E+04	6.55E-04	
1.00E+05	2.07E-04	
1.00E+06	6.55E-05	

Skin Effect --- Increase in Wire Resistance

- For high frequencies, resistance of wire increases
- DC resistance of wire: $R_{DC} = \frac{l}{\sigma(\pi r_w^2)}$
- For frequencies above critical frequency where skin depth equals wire radius r_w:

$$R_{AC} = \frac{l}{\sigma(2\pi r_w \delta)} = R_{DC}\left(\frac{2\delta}{r_w}\right)$$

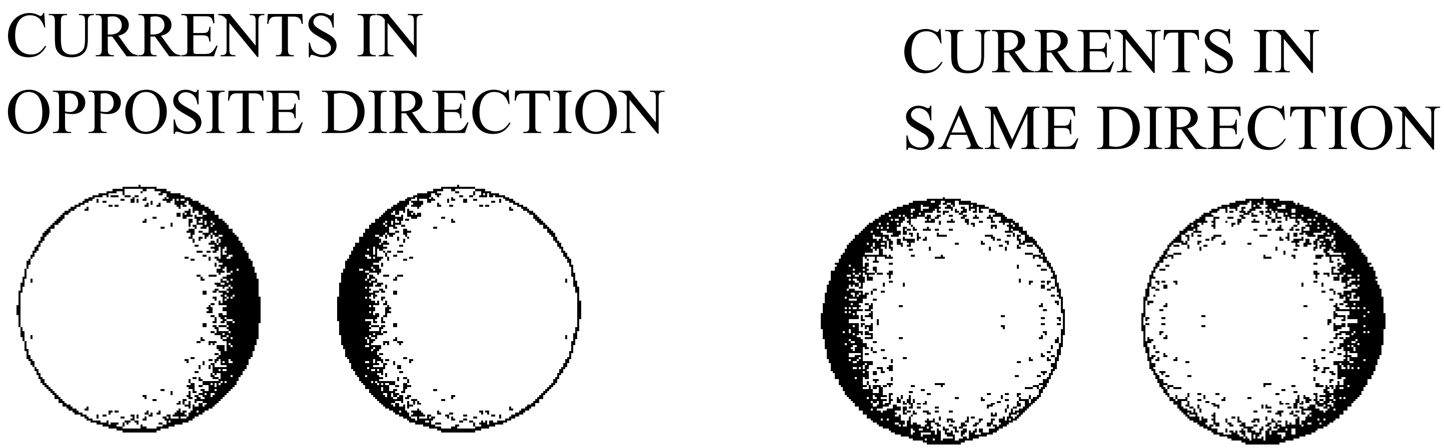
$$f_{crit} = \frac{1}{\pi r_w^2 \mu \sigma}$$



- Result: for high frequency operation, don't bother making wire radius > δ
  - Skin depth in copper at 60 Hz is approximately 8 mm

Proximity Effect

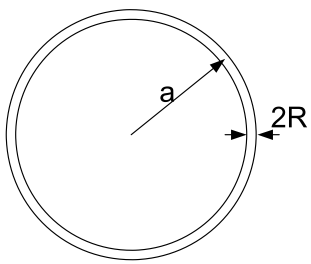
- In multiple-layer windings in inductors and transformers, the proximity effect can also greatly increase the winding resistance
- Field from one wire affects the current profile in another



Cable Inductance

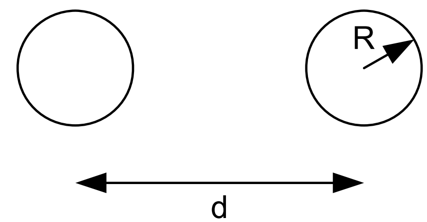
- Inductance is defined by the geometry of the wire loop
- Included in the calculation is wire radius, and loop length and shape

- Circular loop of wire



$$L = \mu_o a \left[\ln\left(\frac{8a}{R} \right) - 1.75 \right]$$

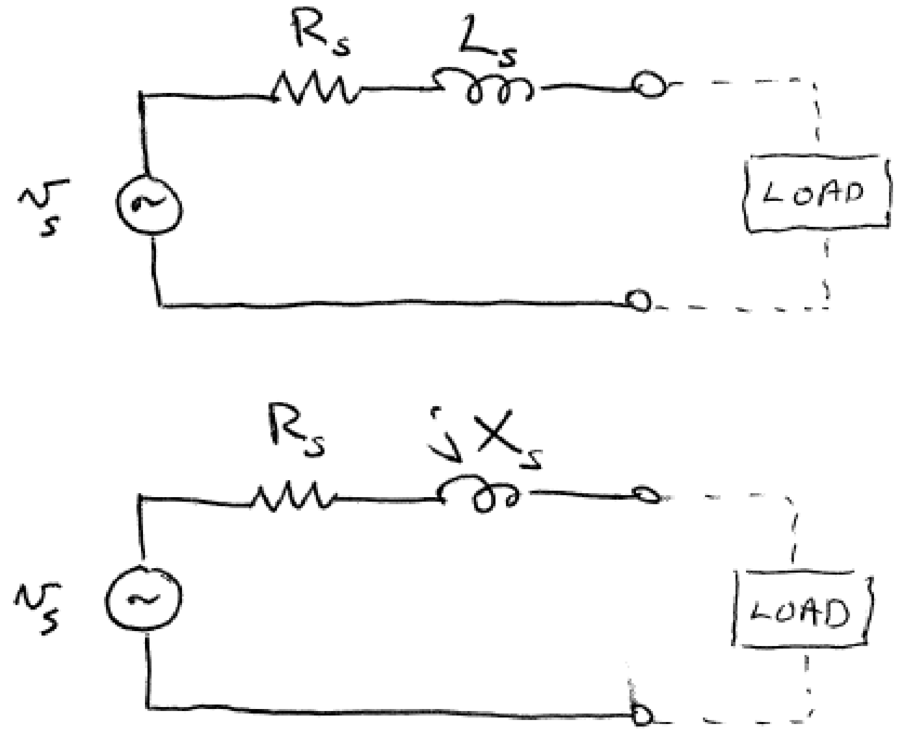
- Parallel-wire line



$$L = \frac{\mu_o l}{\pi} \ln\left[\frac{d}{R} + \frac{1}{4} - \frac{d}{l} \right]$$

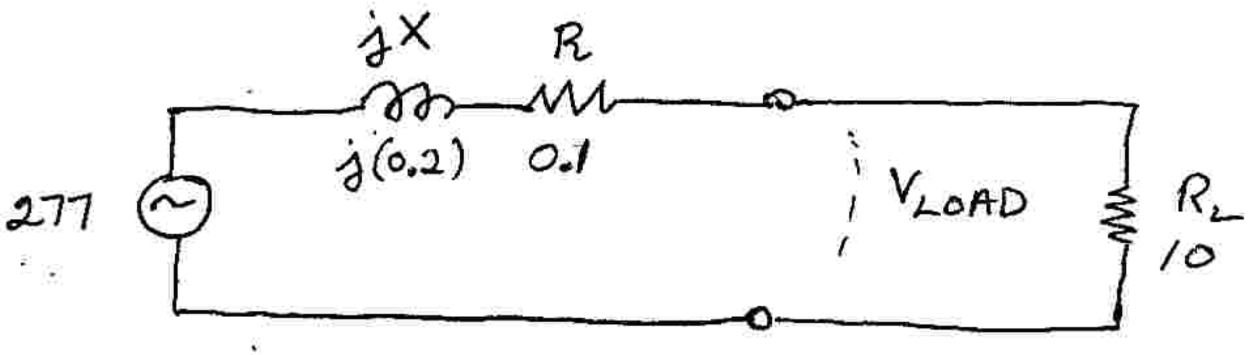
AC Service with Real-World Impedance

- All electrical services have finite impedance; shown here the impedance is $R_s + j\omega L_s$
- These types of power distribution drawings rarely show inductance explicitly; rather the inductive reactance jX_s is used.
- L_s is the sum of wiring inductance, transformer leakage, etc.



Example 3: Line Voltage Drop

- Find load voltage and load current
- Note that line resistance is 0.1Ω and line reactance is 0.2Ω



$$I_L = \frac{277}{0.2j + 0.1 + 10} = 27.4 - 0.54j$$

$$V_{LOAD} = I_L R_L = 274 - 5.4j$$

- Note voltage drop across line impedance of a few Volts

National Electrical Code Impedance Estimates

- NEC Table 9 Note conduit type affects resistance and reactance

TABLE 16–1

Table 9 Alternating-Current Resistance and Reactance for 600-Volt Cables, 3-Phase, 60 Hz, 75°C (167°F)— Three Single Conductors in Conduit

Ohms to Neutral per Kilometer / Ohms to Neutral per 1000 Feet

Size (AWG or kcmil)	X_L (Reactance) for All Wires		Alternating-Current Resistance for Uncoated Copper Wires			Alternating-Current Resistance for Aluminum Wires			Effective Z at 0.85 PF for Uncoated Copper Wires			Effective Z at 0.85 PF for Aluminum Wires			Size (AWG or kcmil)
	PVC, Aluminum Conduits	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	PVC Conduit	Aluminum Conduit	Steel Conduit	
14	0.190 0.058	0.240 0.073	10.2 3.1	10.2 3.1	10.2 3.1	— —	— —	— —	8.9 2.7	8.9 2.7	8.9 2.7	— —	— —	— —	14
12	0.177 0.054	0.223 0.068	6.6 2.0	6.6 2.0	6.6 2.0	10.5 3.2	10.5 3.2	10.5 3.2	5.6 1.7	5.6 1.7	5.6 1.7	9.2 2.8	9.2 2.8	9.2 2.8	12
10	0.164 0.050	0.207 0.063	3.9 1.2	3.9 1.2	3.9 1.2	6.6 2.0	6.6 2.0	6.6 2.0	3.6 1.1	3.6 1.1	3.6 1.1	5.9 1.8	5.9 1.8	5.9 1.8	10
8	0.171 0.052	0.213 0.065	2.56 0.78	2.56 0.78	2.56 0.78	4.3 1.3	4.3 1.3	4.3 1.3	2.26 0.69	2.26 0.69	2.30 0.70	3.6 1.1	3.6 1.1	3.6 1.1	8
6	0.167 0.051	0.210 0.064	1.61 0.49	1.61 0.49	1.61 0.49	2.66 0.81	2.66 0.81	2.66 0.81	1.44 0.44	1.48 0.45	1.48 0.45	2.33 0.71	2.36 0.72	2.36 0.72	6
4	0.157 0.048	0.197 0.060	1.02 0.31	1.02 0.31	1.02 0.31	1.67 0.51	1.67 0.51	1.67 0.51	0.95 0.29	0.95 0.29	0.98 0.30	1.51 0.46	1.51 0.46	1.51 0.46	4
3	0.154 0.047	0.194 0.059	0.82 0.25	0.82 0.25	0.82 0.25	1.31 0.40	1.35 0.41	1.31 0.40	0.75 0.23	0.79 0.24	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Derived Wire Chart

- Uses NEC Table 9 and estimates weight and cost per length

WIRE CHART --- MTT 11/20/08

Data taken from NEC 2005 Table 9, using alternating current (60 Hz) resistance and reactance for 600V, 3-phase 60 Hz, 75C, 3 single conductors in conduit

Est. copper wire cost per kg: $10.00

AWG r kcmil	XL Ohm-neutral per km	L (microH/meter)	R (ohms-neutral per km)	Wire diam. (mm)	Weight (kg/km)	Est. cost (per km)
14	0.190	0.50	10.2	1.63	18.416	$184
12	0.177	0.47	6.6	2.05	29.283	$293
10	0.164	0.44	3.9	2.59	46.561	$466
8	0.171	0.45	2.56	3.26	74.035	$740
6	0.167	0.44	1.61	4.12	117.721	$1,177
4	0.157	0.42	1.02	5.19	187.183	$1,872
3	0.154	0.41	0.82	5.83	236.034	$2,360
2	0.148	0.39	0.62	6.54	297.633	$2,976
1	0.151	0.40	0.49	7.35	375.308	$3,753
1/0	0.144	0.38	0.39	8.25	473.255	$4,733
2/0	0.141	0.37	0.33	9.27	596.763	$5,968
3/0	0.138	0.37	0.253	10.40	752.505	$7,525
4/0	0.135	0.36	0.203	11.68	948.891	$9,489
250	0.135	0.36	0.171	12.70	1121.090	$11,211
300	0.135	0.36	0.144	13.91	1345.308	$13,453
350	0.131	0.35	0.125	15.03	1569.526	$15,695
400	0.131	0.35	0.108	16.06	1793.744	$17,937
500	0.128	0.34	0.089	17.96	2242.181	$22,422
600	0.128	0.34	0.075	19.67	2690.617	$26,906
750	0.125	0.33	0.062	22.00	3363.271	$33,633
1000	0.121	0.32	0.049	25.40	4484.361	$44,844

Types of Power Cable

TABLE 6–1
Cable Insulation Types

THW-2	Thermoplastic insulation (usually PVC), Heat resistant (90°C rating), suitable for Wet locations.
THWN-2	Same as THW except Nylon jacket over reduced insulation thickness. Also rated THHN.
THHN	Thermoplastic insulation (usually PVC), High Heat resistant (90°C rating), dry locations only, Nylon jacket. Also rated THWN.
XHHW-2	Cross-linked polyethylene insulation (X), High Heat resistant (90°C rating), for wet and dry locations.
RHH	Rubber insulation. Most manufacturers use cross-linked polyethylene because it has the same properties as rubber. High Heat resistant (90°C rating), for dry locations only.
RHW-2	Rubber insulation (cross-linked polyethylene). Heat resistant (90°C rating), suitable for Wet locations.
USE-2	Underground Service Entrance. Most utilize XLP for 90°C in direct burial applications. Product is usually triple rated: RHH-RHW-USE.
NM-B	NonMetallic sheathed cable. The "B" denotes that individual conductor insulation is rated 90°C; however, ampacity is limited to that of a 60°C conductor. Thermoplastic (PVC) conductor insulation, nylon jacketed, with overall PVC cable jacket.
SEU	Service Entrance Cable, Unarmored. Usually type XHHW insulated conductors with overall PVC jacket. As such, the cable is rated for 90°C dry, 75°C wet locations.
SER	Service Entrance Cable, Round. Same material construction as SEU but round construction.

Source: Southwire Power Cable Manual and Product Catalog. © Southwire Company.

Wire Sizes

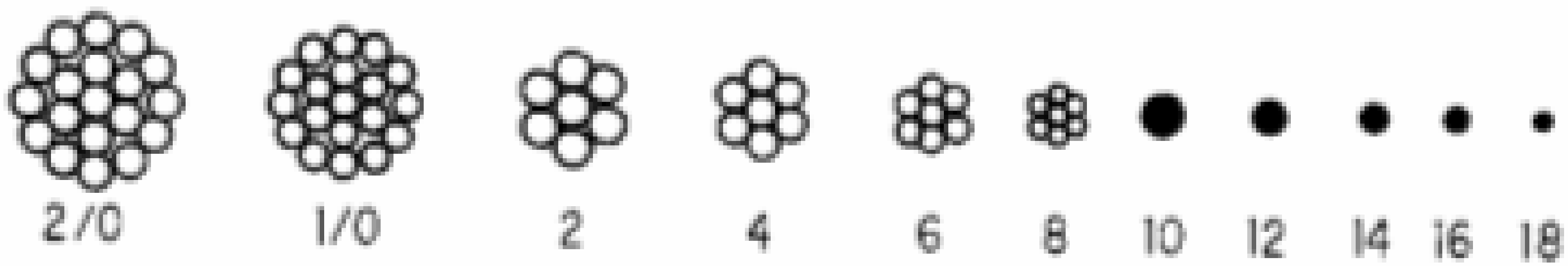
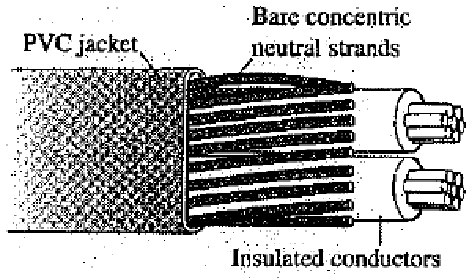


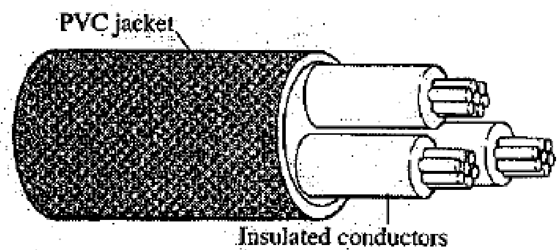
Fig. 6-1 Actual diameters of typical sizes of electric wires, without the insulation.

Reference: Richter and Schwan, *Practical Electrical Wiring (16th edition)*, McGraw-Hill, 1993

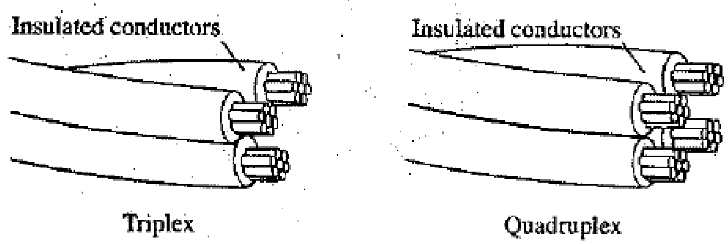
Types of Power Cable



SEU

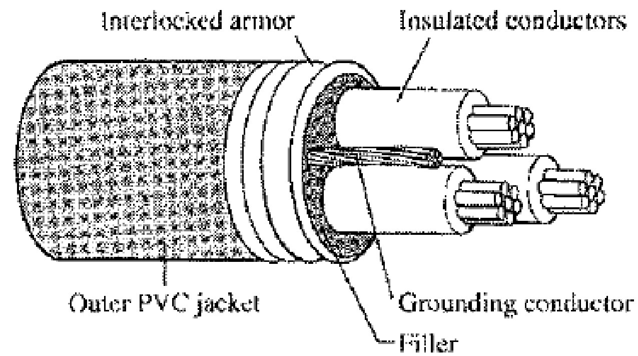


SER

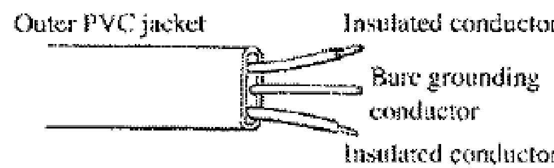


USE

A. Armored Cable (AC)



B. Metal-Clad Cable (MC)



C. Nonmetallic Sheathed Cable (NM)

Type NM

- Residential, non wet
- NEC Article 334

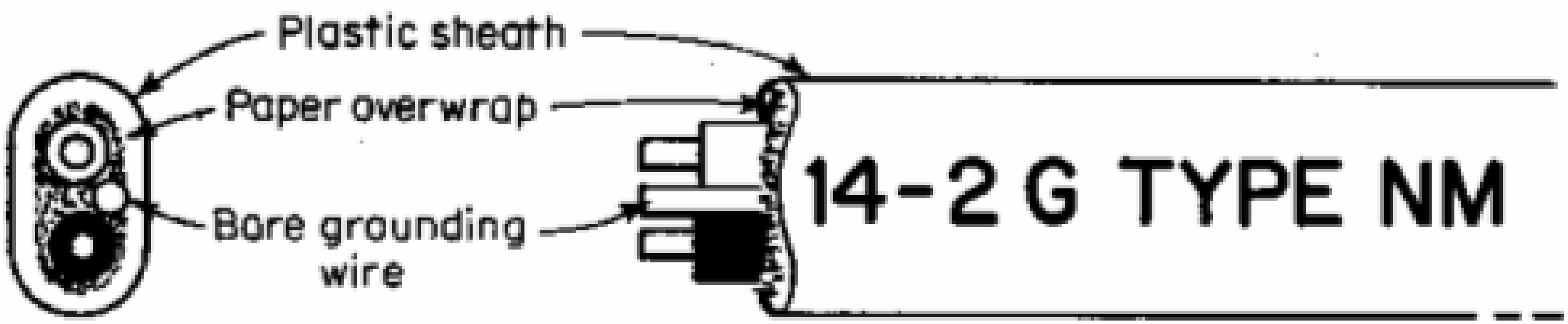


Fig. 6-5 Nonmetallic-sheathed cable is popular for ordinary wiring. This is NEC Type NM and may be used only in dry locations.

Reference: Richter and Schwan, *Practical Electrical Wiring (16th edition)*, McGraw-Hill, 1993

Type NMC

- Residential, dry or damp
- NEC Article 334

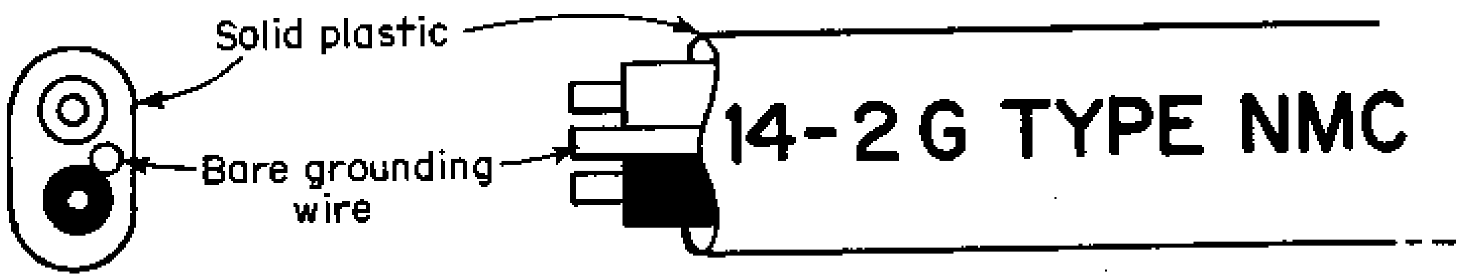


Fig. 6-6 Type NMC nonmetallic-sheathed cable may be used in dry or damp locations.

Reference: Richter and Schwan, *Practical Electrical Wiring (16th edition)*, McGraw-Hill, 1993

Type "BX" Armored

- Light industrial
- NEC calls it AC
- Armored cable covered in NEC Article 320

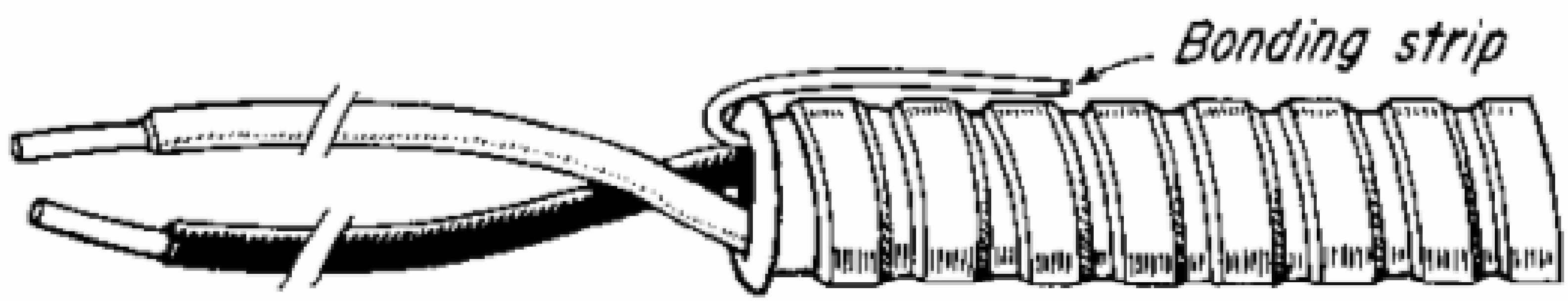


Fig. 6-7 Armored cable has metal armor for its final protection.

Reference: Richter and Schwan, *Practical Electrical Wiring (16th edition)*, McGraw-Hill, 1993

National Elec. Code Ampacity Estimates

- Table 310.16, ampacity table

ARTICLE 310: Conductors for General Wiring
NEC Table 310.16

Table 310.16 Allowable Ampacities of Insulated Conductors Rated 0 Through 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

	Temperature Rating of Conductor						
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	
or kcmil	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			or kcmil
18	–	–	14	–	–	–	–
16	–	–	18	–	–	–	–
14*	20	20	25	–	–	–	–
12*	25	25	30	20	20	25	12*
10*	30	35	40	25	30	35	10*
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	150	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	190	230	255	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	355	420	475	285	340	385	600
700	385	460	520	310	375	420	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	450	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	520	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	560	665	750	470	560	630	2000

CORRECTION FACTORS

Ambient Temp. (°C)	For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below.						Ambient Temp. (°F)
21-25	1.08	1.05	1.04	1.08	1.05	1.04	70-77
26-30	1.00	1.00	1.00	1.00	1.00	1.00	78-86
31-35	0.91	0.94	0.96	0.91	0.94	0.96	87-95
36-40	0.82	0.88	0.91	0.82	0.88	0.91	96-104
41-45	0.71	0.82	0.87	0.71	0.82	0.87	105-113
46-50	0.58	0.75	0.82	0.58	0.75	0.82	114-122
51-55	0.41	0.67	0.76	0.41	0.67	0.76	123-131
56-60	—	0.58	0.71	—	0.58	0.71	132-140
61-70	—	0.33	0.58	—	0.33	0.58	141-158
71-80	—	—	0.41	—	—	0.41	159-176

* **Small Condutors.** Unless specifically permitted in 240.4(E) through (G), the overcurrent protection shall not exceed 15 amperes for 14 AWG, 20 amperes for 12 AWG, and 30 amperes for 10 AWG copper; or 15 amperes for 12 AWG and 25 amperes for 10 AWG aluminum and copper-clad aluminum after any correction factors for ambient temperature and number of conductors have been applied.

National Elec. Code Ampacity Estimates

- Correction factor for ambient temperature, Table 310.16

	CORRECTION FACTORS					
Ambient Temp. (°C)	For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below					
21–25	1.08	1.05	1.04	1.08	1.05	1.04
26–30	1.00	1.00	1.00	1.00	1.00	1.00
31–35	0.91	0.94	0.96	0.91	0.94	0.96
36–40	0.82	0.88	0.91	0.82	0.88	0.91
41–45	0.71	0.82	0.87	0.71	0.82	0.87
46–50	0.58	0.75	0.82	0.58	0.75	0.82
51–55	0.41	0.67	0.76	0.41	0.67	0.76
56–60	—	0.58	0.71	—	0.58	0.71
61–70	—	0.33	0.58	—	0.33	0.58
71–80	—	—	0.41	—	—	0.41

*See 240.4(D).