2

Overhead Lines

Along streets, alleys, through woods, and in backyards, many of the distribution lines that feed customers are overhead structures. Because overhead lines are exposed to trees and animals, to wind and lightning, and to cars and kites, they are a critical component in the reliability of distribution circuits. This chapter discusses many of the key electrical considerations of overhead lines: conductor characteristics, impedances, ampacity, and other issues.

2.1 Typical Constructions

Overhead constructions come in a variety of configurations (see Figure 2.1). Normally one primary circuit is used per pole, but utilities sometimes run more than one circuit per structure. For a three-phase circuit, the most common structure is a horizontal layout with an 8- or 10-ft wood crossarm on a pole (see Figure 2.2). Armless constructions are also widely found where fiberglass insulator standoffs or post insulators are used in a tighter configuration. Utilities normally use 30- to 45-ft poles, set 6 to 8 ft deep. Vertical construction is also occasionally used. Span lengths vary from 100 to 150 ft in suburban areas to as much as 300 or 400 ft in rural areas.

Distribution circuits normally have an underbuilt neutral — the neutral acts as a safety ground for equipment and provides a return path for unbalanced loads and for line-to-ground faults. The neutral is 3 to 5 ft below the phase conductors. Utilities in very high lightning areas may run the neutral wire above the phase conductors to act as a shield wire. Some utilities also run the neutral on the crossarm. Secondary circuits are often run under the primary. The primary and the secondary may share the neutral, or they may each have their own neutral. Many electric utilities share their space with other utilities; telephone or cable television cables may run under the electric secondary.

(a)

FIGURE 2.1
Example overhead distribution structures. (a) Three-phase 34.5-kV armless construction with covered wire.

(b)

FIGURE 2.1
Continued. (b) Single-phase circuit, 7.2 kV line-to-ground.

(c)

FIGURE 2.1
Continued. (c) Single-phase, 4.8-kV circuit.

(d)

FIGURE 2.1
Continued. (d) 13.2-kV spacer cable.

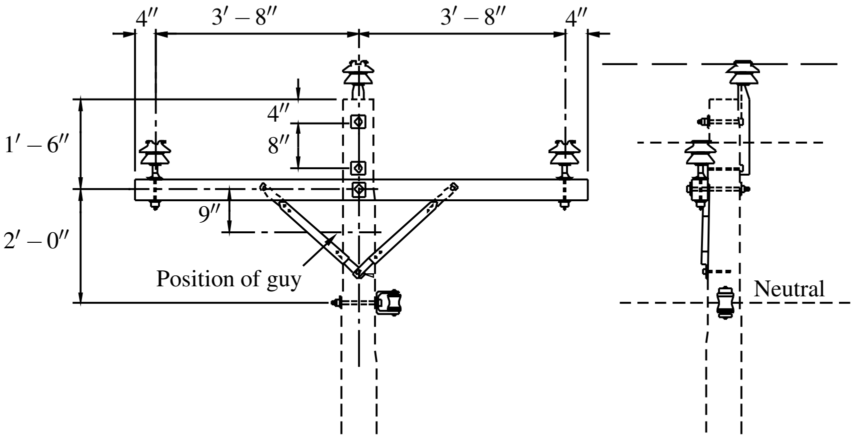

FIGURE 2.2
Example crossarm construction. (From [RUS 1728F-803, 1998].)

Wood is the main pole material, although steel, concrete, and fiberglass are also used. Treated wood lasts a long time, is easy to climb and attach equipment to, and also augments the insulation between the energized conductors and ground. Conductors are primarily aluminum. Insulators are pin type, post type, or suspension, either porcelain or polymer.

The National Electrical Safety Code (IEEE C2-2000) governs many of the safety issues that play important roles in overhead design issues. Poles must have space for crews to climb them and work safely in the air. All equipment must have sufficient strength to stand up to "normal" operations. Conductors must carry their weight, the weight of any accumulated ice, plus withstand the wind pressure exerted on the wire. We are not going to discuss mechanical and structural issues in this book. For more information, see the *Lineman's and Cableman's Handbook* (Kurtz et al., 1997), the *Mechanical Design Manual for Overhead Distribution Lines* (RUS 160-2, 1982), the *NESC* (IEEE C2-2000), and the *NESC Handbook* (Clapp, 1997).

Overhead construction can cost \$10,000/mi to \$250,000/mi, depending on the circumstances. Some of the major variables are labor costs, how developed the land is, natural objects (including rocks in the ground and trees in the way), whether the circuit is single or three phase, and how big the conductors are. Suburban three-phase mains are typically about \$60,000 to \$150,000/mi; single-phase laterals are often in the \$40,000 to \$75,000/mi range. Construction is normally less expensive in rural areas; in urban areas, crews must deal with traffic and set poles in concrete. As Willis (1997) notes, upgrading a circuit normally costs more than building a new line. Typically this work is done live: the old conductor has to be moved to standoff brackets while the new conductor is strung, and the poles may have to be reinforced to handle heavier conductors.

2.2 Conductor Data

A *wire* is metal drawn or rolled to long lengths, normally understood to be a solid wire. Wires may or may not be insulated. A *conductor* is one or more wires suitable for carrying electric current. Often the term *wire* is used to mean conductor. Table 2.1 shows some characteristics of common conductor metals.

Most conductors are either aluminum or copper. Utilities use aluminum for almost all new overhead installations. Aluminum is lighter and less expensive for a given current-carrying capability. Copper was installed more in the past, so significant lengths of copper are still in service on overhead circuits.

Aluminum for power conductors is alloy 1350, which is 99.5% pure and has a minimum conductivity of 61.0% IACS [for more complete characteristics, see the *Aluminum Electrical Conductor Handbook* (Aluminum Association, 1989)]. Pure aluminum melts at 660°C. Aluminum starts to anneal

TABLE 2.1

Nominal or Minimum Properties of Conductor Wire Materials

Property	International Annealed Copper Standard	Commercial Hard-Drawn Copper Wire	Standard 1350-H19 Aluminum Wire	Standard 6201-T81 Aluminum Wire	Galvanized Steel Core Wire	Aluminum Clad Steel
Conductivity,% IACS at 20°C	100.0	97.0	61.2	52.5	8.0	20.3
Resistivity at 20°C, Ω·in.^{2}/1000 ft	0.008145	0.008397	0.013310	0.015515	0.101819	0.04007
Ratio of weight for equal dc resistance and length	1.00	1.03	0.50	0.58	9.1	3.65
Temp. coefficient of resistance, per °C at 20°C	0.00393	0.00381	0.00404	0.00347	0.00327	0.00360
Density at 20°C, lb/in.^{3}	0.3212	0.3212	0.0977	0.0972	0.2811	0.2381
Coefficient of linear expansion, 10^{-6} per °C	16.9	16.9	23.0	23.0	11.5	13.0
Modulus of elasticity, 10^6 psi	17	17	10	10	29	23.5
Specific heat at 20°C, cal/gm-°C	0.0921	0.0921	0.214	0.214	0.107	0.112
Tensile strength, 10^3 psi	62.0	62.0	24.0	46.0	185	175
Minimum elongation,%	1.1	1.1	1.5	3.0	3.5	1.5

Source: Southwire Company, *Overhead Conductor Manual*, 1994.

(soften and lose strength) above 100°C. It has good corrosion resistance; when exposed to the atmosphere, aluminum oxidizes, and this thin, invisible film of aluminum oxide protects against most chemicals, weathering conditions, and even acids. Aluminum can corrode quickly through electrical contact with copper or steel. This galvanic corrosion (dissimilar metals corrosion) accelerates in the presence of salts.

Several variations of aluminum conductors are available:

- *AAC — all-aluminum conductor* — Aluminum grade 1350-H19 AAC has the highest conductivity-to-weight ratio of all overhead conductors. See Table 2.2 for characteristics.
- *ACSR — aluminum conductor, steel reinforced* — Because of its high mechanical strength-to-weight ratio, ACSR has equivalent or higher ampacity for the same size conductor (the kcmil size designation is determined by the cross-sectional area of the aluminum; the steel is neglected). The steel adds extra weight, normally 11 to 18% of the weight of the conductor. Several different strandings are available to provide different strength levels. Common distribution sizes of ACSR have twice the breaking strength of AAC. High strength means the conductor can withstand higher ice and wind loads. Also, trees are less likely to break this conductor. See Table 2.3 for characteristics.
- *AAAC — all-aluminum alloy conductor* — This alloy of aluminum, the 6201-T81 alloy, has high strength and equivalent ampacities of AAC or ACSR. AAAC finds good use in coastal areas where use of ACSR is prohibited because of excessive corrosion.
- *ACAR — aluminum conductor, alloy reinforced* — Strands of aluminum 6201-T81 alloy are used along with standard 1350 aluminum. The alloy strands increase the strength of the conductor. The strands of both are the same diameter, so they can be arranged in a variety of configurations.

For most urban and suburban applications, AAC has sufficient strength and has good thermal characteristics for a given weight. In rural areas, utilities can use smaller conductors and longer pole spans, so ACSR or another of the higher-strength conductors is more appropriate.

Copper has very low resistivity and is widely used as a power conductor, although use as an overhead conductor has become rare because copper is heavier and more expensive than aluminum. It has significantly lower resistance than aluminum by volume — a copper conductor has equivalent ampacity (resistance) of an aluminum conductor that is two AWG sizes larger. Copper has very good resistance to corrosion. It melts at 1083°C, starts to anneal at about 100°C, and anneals most rapidly between 200 and 325°C (this range depends on the presence of impurities and amount of hardening). When copper anneals, it softens and loses tensile strength.

TABLE 2.2

Characteristics of All-Aluminum Conductor (AAC)

					Resistance, Ω/1000 ft					
					dc	60-Hz ac				
AWG	kcmil	Strands	Diameter, in.	GMR, ft	20°C	25°C	50°C	75°C	Breaking. Strength, lb	Weight, lb/1000 ft
6	26.24	7	0.184	0.0056	0.6593	0.6725	0.7392	0.8059	563	24.6
4	41.74	7	0.232	0.0070	0.4144	0.4227	0.4645	0.5064	881	39.1
2	66.36	7	0.292	0.0088	0.2602	0.2655	0.2929	0.3182	1350	62.2
1	83.69	7	0.328	0.0099	0.2066	0.2110	0.2318	0.2527	1640	78.4
1/0	105.6	7	0.368	0.0111	0.1638	0.1671	0.1837	0.2002	1990	98.9
2/0	133.1	7	0.414	0.0125	0.1299	0.1326	0.1456	0.1587	2510	124.8
3/0	167.8	7	0.464	0.0140	0.1031	0.1053	0.1157	0.1259	3040	157.2
4/0	211.6	7	0.522	0.0158	0.0817	0.0835	0.0917	0.1000	3830	198.4
	250	7	0.567	0.0171	0.0691	0.0706	0.0777	0.0847	4520	234.4
	250	19	0.574	0.0181	0.0693	0.0706	0.0777	0.0847	4660	234.3
	266.8	7	0.586	0.0177	0.0647	0.0663	0.0727	0.0794	4830	250.2
	266.8	19	0.593	0.0187	0.0648	0.0663	0.0727	0.0794	4970	250.1
	300	19	0.629	0.0198	0.0575	0.0589	0.0648	0.0705	5480	281.4
	336.4	19	0.666	0.0210	0.0513	0.0527	0.0578	0.0629	6150	315.5
	350	19	0.679	0.0214	0.0494	0.0506	0.0557	0.0606	6390	327.9
	397.5	19	0.724	0.0228	0.0435	0.0445	0.0489	0.0534	7110	372.9
	450	19	0.769	0.0243	0.0384	0.0394	0.0434	0.0472	7890	421.8
	477	19	0.792	0.0250	0.0363	0.0373	0.0409	0.0445	8360	446.8
	477	37	0.795	0.0254	0.0363	0.0373	0.0409	0.0445	8690	446.8
	500	19	0.811	0.0256	0.0346	0.0356	0.0390	0.0426	8760	468.5
	500	37	0.813	0.0260	0.0346	0.0356	0.0390	0.0426	9110	468.3
	556.5	19	0.856	0.0270	0.0311	0.0320	0.0352	0.0383	9750	521.4
	556.5	37	0.858	0.0275	0.0311	0.0320	0.0352	0.0383	9940	521.3
	600	37	0.891	0.0285	0.0288	0.0297	0.0326	0.0356	10700	562.0
	636	37	0.918	0.0294	0.0272	0.0282	0.0309	0.0335	11400	596.0
	650	37	0.928	0.0297	0.0266	0.0275	0.0301	0.0324	11600	609.8
	700	37	0.963	0.0308	0.0247	0.0256	0.0280	0.0305	12500	655.7
	700	61	0.964	0.0310	0.0247	0.0256	0.0280	0.0305	12900	655.8
	715.5	37	0.974	0.0312	0.0242	0.0250	0.0275	0.0299	12800	671.0
	715.5	61	0.975	0.0314	0.0242	0.0252	0.0275	0.0299	13100	671.0
	750	37	0.997	0.0319	0.0230	0.0251	0.0263	0.0286	13100	703.2
	750	61	0.998	0.0321	0.0230	0.0251	0.0263	0.0286	13500	703.2
	795	37	1.026	0.0328	0.0217	0.0227	0.0248	0.0269	13900	745.3
	795	61	1.028	0.0331	0.0217	0.0227	0.0248	0.0269	14300	745.7
	874.5	37	1.077	0.0344	0.0198	0.0206	0.0227	0.0246	15000	820.3
	874.5	61	1.078	0.0347	0.0198	0.0206	0.0227	0.0246	15800	820.6
	900	37	1.092	0.0349	0.0192	0.0201	0.0220	0.0239	15400	844.0
	900	61	1.094	0.0352	0.0192	0.0201	0.0220	0.0239	15900	844.0
	954	37	1.124	0.0360	0.0181	0.0191	0.0208	0.0227	16400	894.5
	954	61	1.126	0.0362	0.0181	0.0191	0.0208	0.0225	16900	894.8
	1000	37	1.151	0.0368	0.0173	0.0182	0.0199	0.0216	17200	937.3
	1000	61	1.152	0.0371	0.0173	0.0182	0.0199	0.0216	17700	936.8

Source: Aluminum Association, *Aluminum Electrical Conductor Handbook*, 1989; Southwire Company, *Overhead Conductor Manual*, 1994.

Different sizes of conductors are specified with gage numbers or area in circular mils. Smaller wires are normally referred to using the American wire gage (AWG) system. The gage is a numbering scheme that progresses geometrically. A number 36 solid wire has a defined diameter of 0.005 in. (0.0127

TABLE 2.3

Characteristics of Aluminum Conductor, Steel Reinforced (ACSR)

					Resistance, Ω/1000 ft					
					dc	60-Hz ac				
AWG	kcmil	Strands	Diameter, in.	GMR, ft	20°C	25°C	50°C	75°C	Breaking. Strength, lb	Weight, lb/1000 ft
6	26.24	6/1	0.198	0.0024	0.6419	0.6553	0.7500	0.8159	1190	36.0
4	41.74	6/1	0.250	0.0033	0.4032	0.4119	0.4794	0.5218	1860	57.4
4	41.74	7/1	0.257	0.0045	0.3989	0.4072	0.4633	0.5165	2360	67.0
2	66.36	6/1	0.316	0.0046	0.2534	0.2591	0.3080	0.3360	2850	91.2
2	66.36	7/1	0.325	0.0060	0.2506	0.2563	0.2966	0.3297	3640	102
1	83.69	6/1	0.355	0.0056	0.2011	0.2059	0.2474	0.2703	3550	115
1/0	105.6	6/1	0.398	0.0071	0.1593	0.1633	0.1972	0.2161	4380	145
2/0	133.1	6/1	0.447	0.0077	0.1265	0.1301	0.1616	0.1760	5300	183
3/0	167.8	6/1	0.502	0.0090	0.1003	0.1034	0.1208	0.1445	6620	230
4/0	211.6	6/1	0.563	0.0105	0.0795	0.0822	0.1066	0.1157	8350	291
	266.8	18/1	0.609	0.0197	0.0644	0.0657	0.0723	0.0788	6880	289
	266.8	26/7	0.642	0.0217	0.0637	0.0652	0.0714	0.0778	11300	366
	336.4	18/1	0.684	0.0221	0.0510	0.0523	0.0574	0.0625	8700	365
	336.4	26/7	0.721	0.0244	0.0506	0.0517	0.0568	0.0619	14100	462
	336.4	30/7	0.741	0.0255	0.0502	0.0513	0.0563	0.0614	17300	526
	397.5	18/1	0.743	0.0240	0.0432	0.0443	0.0487	0.0528	9900	431
	397.5	26/7	0.783	0.0265	0.0428	0.0438	0.0481	0.0525	16300	546
	477	18/1	0.814	0.0263	0.0360	0.0369	0.0405	0.0441	11800	517
	477	24/7	0.846	0.0283	0.0358	0.0367	0.0403	0.0439	17200	614
	477	26/7	0.858	0.0290	0.0357	0.0366	0.0402	0.0438	19500	655
	477	30/7	0.883	0.0304	0.0354	0.0362	0.0389	0.0434	23800	746
	556.5	18/1	0.879	0.0284	0.0309	0.0318	0.0348	0.0379	13700	603
	556.5	24/7	0.914	0.0306	0.0307	0.0314	0.0347	0.0377	19800	716
	556.5	26/7	0.927	0.0313	0.0305	0.0314	0.0345	0.0375	22600	765
	636	24/7	0.977	0.0327	0.0268	0.0277	0.0300	0.0330	22600	818
	636	26/7	0.990	0.0335	0.0267	0.0275	0.0301	0.0328	25200	873
	795	45/7	1.063	0.0352	0.0216	0.0225	0.0246	0.0267	22100	895
	795	26/7	1.108	0.0375	0.0214	0.0222	0.0242	0.0263	31500	1093
	954	45/7	1.165	0.0385	0.0180	0.0188	0.0206	0.0223	25900	1075
	954	54/7	1.196	0.0404	0.0179	0.0186	0.0205	0.0222	33800	1228
	1033.5	45/7	1.213	0.0401	0.0167	0.0175	0.0191	0.0208	27700	1163

Sources: Aluminum Association, *Aluminum Electrical Conductor Handbook*, 1989; Southwire Company, *Overhead Conductor Manual*, 1994.

cm), and the largest size, a number 0000 (referred to as 4/0 and pronounced "four-ought") solid wire has a 0.46-in. (1.17-cm) diameter. The larger gage sizes in sequence of increasing conductor size are: 4, 3, 2, 1, 0 (1/0), 00 (2/0), 000 (3/0), 0000 (4/0). Going to the next bigger size (smaller gage number) increases the diameter by 1.1229. Some other useful rules are:

- An increase of three gage sizes doubles the area and weight and halves the dc resistance.
- An increase of six gage sizes doubles the diameter.

Larger conductors are specified in circular mils of cross-sectional area. One circular mil is the area of a circle with a diameter of one mil (one mil is one-thousandth of an inch). Conductor sizes are often given in kcmil, thousands of circular mils. In the past, the abbreviation MCM was used, which also means thousands of circular mils (M is thousands, not mega, in this case). By definition, a solid 1000-kcmil wire has a diameter of 1 in. The diameter of a solid wire in mils is related to the area in circular mils by $d = \sqrt{A}$.

Outside of America, most conductors are specified in mm^2. Some useful conversion relationships are:

$$1 \text{ kcmil} = 1000 \text{ cmil} = 785.4 \times 10^{-6} \text{ in}^2 = 0.5067 \text{ mm}^2$$

Stranded conductors increase flexibility. A two-layer arrangement has seven wires; a three-layer arrangement has 19 wires, and a four-layer arrangement has 37 wires. The cross-sectional area of a stranded conductor is the cross-sectional area of the metal, so a stranded conductor has a larger diameter than a solid conductor of the same area.

The area of an ACSR conductor is defined by the area of the aluminum in the conductor.

Utilities with heavy tree cover often use covered conductors — conductors with a thin insulation covering. The covering is not rated for full conductor line-to-ground voltage, but it is thick enough to reduce the chance of flashover when a tree branch falls between conductors. Covered conductor is also called *tree wire* or weatherproof wire. Tree wire also helps with animal faults and allows utilities to use armless or candlestick designs or other tight configurations. Tree wire is available with a variety of covering types. The insulation materials polyethylene, XLPE, and EPR are common. Insulation thicknesses typically range from 30 to 150 mils (1 mil = 0.001 in. = 0.00254 cm); see Table 2.4 for typical thicknesses. From a design and operating viewpoint, covered conductors must be treated as bare conductors according to the National Electrical Safety Code (NESC) (IEEE C2-2000), with the only difference that tighter conductor spacings are allowed. It is also used in Australia to reduce the threat of bush fires (Barber, 1999).

While covered wire helps with trees, it has some drawbacks compared with bare conductors. Covered wire is much more susceptible to burndowns caused by fault arcs. Covered-wire systems increase the installed cost somewhat. Covered conductors are heavier and have a larger diameter, so the ice and wind loading is higher than a comparable bare conductor. The covering may be susceptible to degradation due to ultraviolet radiation, tracking, and mechanical effects that cause cracking. Covered conductors are more susceptible to corrosion, primarily from water. If water penetrates the covering, it settles at the low points and causes corrosion (it cannot evaporate). On bare conductors, corrosion is rare; rain washes bare conductors periodically, and evaporation takes care of moisture. The Australian experience has been that complete corrosion can occur with covered wires in 15 to 20 years of operation (Barber, 1999). Water enters the conductor at pinholes caused by lightning strikes, at cover damage caused by abrasion or erosion, and at holes pierced by connectors. Temperature changes then cause water to be

TABLE 2.4

Typical Covering Thicknesses of Covered All-Aluminum Conductor

Size AWG or kcmil	Strands	Cover Thickness, mil	Diameter, in.	
			Bare	Covered
6	7	30	0.184	0.239
4	7	30	0.232	0.285
2	7	45	0.292	0.373
1	7	45	0.328	0.410
1/0	7	60	0.368	0.480
2/0	7	60	0.414	0.524
3/0	7	60	0.464	0.574
4/0	7	60	0.522	0.629
266.8	19	60	0.593	0.695
336.4	19	60	0.666	0.766
397.5	19	80	0.724	0.857
477	37	80	0.795	0.926
556.5	37	80	0.858	0.988
636	61	95	0.918	1.082
795	61	95	1.028	1.187

pumped into the conductor. Because of corrosion concerns, water-blocked conductors are better.

Spacer cables and aerial cables are also alternatives that perform well in treed areas. Spacer cables are a bundled configuration using a messenger wire holding up three phase wires that use covered wire. Because the spacer cable has significantly smaller spacings than normal overhead constructions, its reactive impedance is smaller.

Guy wires, messenger wires, and other wires that require mechanical strength but not current-carrying capability are often made of steel. Steel has high strength (see Table 2.5). Steel corrodes quickly, so most applications use galvanized steel to slow down the corrosion. Because steel is a magnetic material, steel conductors also suffer hysteresis losses. Steel conductors have much higher resistances than copper or aluminum. For some applications requiring strength and conductivity, steel wires coated with copper or aluminum are available. A copperweld conductor has copper-coated steel strands, and an alumoweld conductor aluminum-coated steel strands. Both have better corrosion protection than galvanized steel.

2.3 Line Impedances

Overhead lines have resistance and reactance that impedes the flow of current. These impedance values are necessary for voltage drop, power flow, short circuit, and line-loss calculations.

TABLE 2.5

Characteristics of Steel Conductors

					Resistance, Ω/1000 ft				
						60-Hz ac at the given current level			
Size	Diameter, in.	Conductor Area, in.^{2}	Weight, lb/1000 ft	Strength, lb	dc 25°C	10A	40A	70A	100A
High-Strength Steel — Class A Galvanizing									
5/8	0.621	0.2356	813	29,600	0.41	0.42	0.43	0.46	0.49
1/2	0.495	0.1497	517	18,800	0.65	0.66	0.68	0.73	0.77
7/16	0.435	0.1156	399	14,500	0.84	0.85	0.88	0.94	1.00
3/8	0.360	0.0792	273	10,800	1.23	1.25	1.28	1.38	1.46
Utilities Grade Steel									
7/16	0.435	0.1156	399	18,000	0.87	0.88	0.90	0.95	1.02
3/8	0.380	0.0882	273	11,500	1.23	1.25	1.28	1.38	1.46
Extra-High-Strength Steel — Class A Galvanizing									
5/8	0.621	0.2356	813	42,400	0.43	0.43	0.44	0.47	0.50
1/2	0.495	0.1497	517	26,900	0.67	0.68	0.69	0.73	0.78
7/16	0.435	0.1156	399	20,800	0.87	0.88	0.90	0.95	1.02
3/8	0.360	0.0792	273	15,400	1.28	1.29	1.31	1.39	1.48
Extra-High-Strength Steel — Class C Galvanizing									
7/16	0.435	0.1156	399	20,800		0.70	0.70	0.71	0.71
3/8	0.360	0.0792	273	15,400		1.03	1.03	1.03	1.04
5/16	0.312	0.0595	205	11,200		1.20	1.30	1.30	1.30

Source: EPRI, *Transmission Line Reference Book: 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, CA, 1982.

The dc resistance is inversely proportional to the area of a conductor; doubling the area halves the resistance. Several units are used to describe a conductor's resistance. Conductivity is often given as %IACS, the percent conductivity relative to the International Annealed Copper Standard, which has the following volume resistivities:

$$0.08145\ \Omega\text{-in.}^2/1000\ \text{ft} = 17.241\ \Omega\text{-mm}^2/\text{km} = 10.37\ \Omega\text{-cmil/ft}$$

And with a defined density of 8.89 g/cm^3 at 20°C, the copper standard has the following weight resistivities:

$$875.2\ \Omega\text{-lb/mi}^2 = 0.15328\ \Omega\text{-g/m}^2$$

Hard-drawn copper has 97.3%IACS. Aluminum varies, depending on type; alloy 1350-H19 has 61.2% conductivity.

Temperature and frequency — these change the resistance of a conductor. A hotter conductor provides more resistance to the flow of current. A higher frequency increases the internal magnetic fields. Current has a difficult time flowing in the center of a conductor at high frequency, as it is being opposed by the magnetic field generated by current flowing on all sides of it. Current flows more easily near the edges. This *skin effect* forces the current to flow in a smaller area of the conductor.

Resistance changes with temperature as

$$R_{t2} = R_{t1}\frac{M + t_2}{M + t_1}$$

where

R_{t2} = resistance at temperature t_2 given in °C
R_{t1} = resistance at temperature t_1 given in °C
M = a temperature coefficient for the given material
= 228.1 for aluminum
= 241.5 for annealed hard-drawn copper

For a wide range of temperatures, resistance rises almost linearly with temperature for both aluminum and copper. The effect of temperature is simplified as a linear equation as

$$R_{t2} = R_{t1}[1 + \alpha(t_2 - t_1)]$$

where

α = a temperature coefficient of resistance
= 0.00404 for 61.2% IACS aluminum at 20°C
= 0.00347 for 6201-T81 aluminum alloy at 20°C
= 0.00383 for hard-drawn copper at 20°C
= 0.0036 for aluminum-clad steel at 20°C

So, the resistance of aluminum with a 61.2% conductivity rises 4% for every 10°C rise in temperature.

We can also linearly interpolate using resistances provided at two different temperatures as

$$R(T_c) = R(T_{low}) + \frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}(T_c - T_{low})$$

where

$R(T_c)$ = conductor resistance at temperature T_c
$R(T_{high})$ = resistance at the higher temperature T_{high}
$R(T_{low})$ = resistance at the lower temperature T_{low}

With alternating current, skin effects raise the resistance of a conductor relative to its dc resistance. At 60 Hz, the resistance of a conductor is very close to its dc resistance except for very large conductors. Skin effects are much more important for high-frequency analysis such as switching surges and power-line carrier problems. They play a larger role in larger conductors.

The internal resistance of a solid round conductor including skin effects is [for details, see Stevenson (1962)]:

$$\frac{R_{ac}}{R_{dc}} = \frac{x}{2}\frac{\mathrm{ber}(x)\mathrm{bei}'(x) - \mathrm{bei}(x)\mathrm{ber}'(x)}{(\mathrm{bei}'(x))^2 + (\mathrm{ber}'(x))^2}$$

where

$x = 0.02768\sqrt{\dfrac{f\mu}{R_{dc}}}$

f = frequency in Hz

μ = relative permeability = 1 for nonmagnetic conductors (including aluminum and copper)

R_{dc} = dc resistance of the conductor in ohms/1000 ft

ber, bei, ber′, and bei′ = real and imaginary modified Bessel functions and their derivatives (also called Kelvin functions)

For x greater than 3 (frequencies in the kilohertz range), the resistance increases linearly with x (Clarke, 1950) approximately as

$$\frac{R_{ac}}{R_{dc}} = \frac{x}{2\sqrt{2}} + \frac{1}{4} = 0.009786\sqrt{\frac{f\mu}{R_{dc}}} + 0.25$$

So, for higher frequencies, the ac resistance increases as the square root of the frequency. For most distribution power-frequency applications, we can ignore skin effects (and they are included in ac resistance tables).

For most cases, we can model a stranded conductor as a solid conductor with the same cross-sectional area. ACSR with a steel core is slightly different. Just as in a transformer, the steel center conductor has losses due to hysteresis and eddy currents. If an ACSR conductor has an even number of layers, the axial magnetic field produced by one layer tends to cancel that produced by the next layer. We can model these as a tubular conductor for calculating skin effect. For odd numbers of layers, especially single-layered conductors like 6/1 or 7/1, the 60-Hz/dc ratio is higher than normal, especially at high current densities. These effects are reflected in the resistances included in tables (such as Table 2.3).

The reactance part of the impedance usually dominates the impedances on overhead circuit for larger conductors; below 4/0, resistance plays more of a role. For all-aluminum conductors on a 10-ft crossarm, the resistance approximately equals the reactance for a 2/0 conductor. Reactance is proportional to inductance; and inductance causes a voltage that opposes the change in the flow of current. Alternating current is always changing, so a reactance always creates a voltage due to current flow.

Distance between conductors determines the external component of reactance. Inductance is based on the area enclosed by a loop of current; a larger area (more separation between conductors) has more inductance. On overhead circuits, reactance of the line is primarily based on the separations between conductors — not the size of the conductor, not the type of metal in the conductor, not the stranding of the conductor.

The reactance between two parallel conductors in ohms per mile is:

$$X_{ab} = 0.2794 \frac{f}{60} \log_{10} \frac{d_{ab}}{GMR}$$

where

f = frequency in hertz

d_{ab} = distance between the conductors

GMR = geometric mean radius of both conductors

d_{ab} and GMR must have the same units, normally feet. More separation — a bigger loop — gives larger impedances.

The geometric mean radius (GMR) quantifies a conductor's internal inductance — by definition, the GMR is the radius of an infinitely thin tube having the same internal inductance as the conductor out to a one-foot radius. The GMR is normally given in feet to ease calculations with distances measured in feet. GMR is less than the actual conductor radius. Many conductor tables provide x_a, the inductive reactance due to flux in the conductor and outside the conductor out to a one-foot radius. The GMR in feet at 60 Hz relates to x_a as:

$$x_a = 0.2794 \log_{10} \frac{1}{GMR}$$

where GMR is in feet, and x_a is in ohms/mile.

For a solid, round, nonmagnetic conductor, the relationship between the actual radius and the GMR is

$$\frac{GMR}{r} = e^{-1/4} = 0.779$$

For stranded conductors, the GMR is

$$GMR = k \cdot r$$

TABLE 2.6

GMR Factor

Strands	GMR Factor, k
1 (solid)	0.7788
3	0.6778
7	0.7256
19	0.7577
37	0.7678
61	0.7722

Source: Aluminum Association, *Ampacities for Aluminum and ACSR Overhead Electrical Conductors*, 1986.

where

k = the *GMR* factor from Table 2.6

r = conductor radius

For ACSR conductors (which are layered), the *GMR* factor is more complicated.

Current flowing in a conductor induces a reactive voltage drop on the conductor it is flowing through. By the same induction, current flow in one conductor creates a voltage gradient along parallel conductors (see Figure 2.3). This voltage is of the same polarity as the voltage on the current-carrying conductor. Closer conductors have larger induced voltages. This induction is significant for several reasons:

- *Opposite flow* — Current flows more easily when a parallel conductor has flow in the opposite direction. The magnetic field from the other conductor creates a voltage drop that encourages flow in the opposite direction. Conductors carrying current in opposite directions have lower impedance when they are closer together.
- *Parallel flow* — A conductor carrying current in the same direction as a parallel conductor faces more impedance because of the current in the other conductor. Conductors carrying current in the same direction have higher impedance when they are closer together.
- *Circulating current* — Current flow in the vicinity of a shorted current loop induces currents to circulate in the loop.

For balanced conditions — balanced voltages, balanced loads, and balanced impedances — we can analyze power systems just with positive-sequence voltages, currents, and impedances. This is regularly done in transmission-planning and industrial load-flow studies. Using just positive-sequence quantities simplifies analysis; it's like a single-phase circuit rather than a three-phase circuit. For distribution circuits, unbalanced loading is quite common, so we normally need more than just positive-sequence parameters — we need the zero-sequence parameters as well. We also need unbalanced analysis approaches for phase-to-ground or phase-to-phase faults.

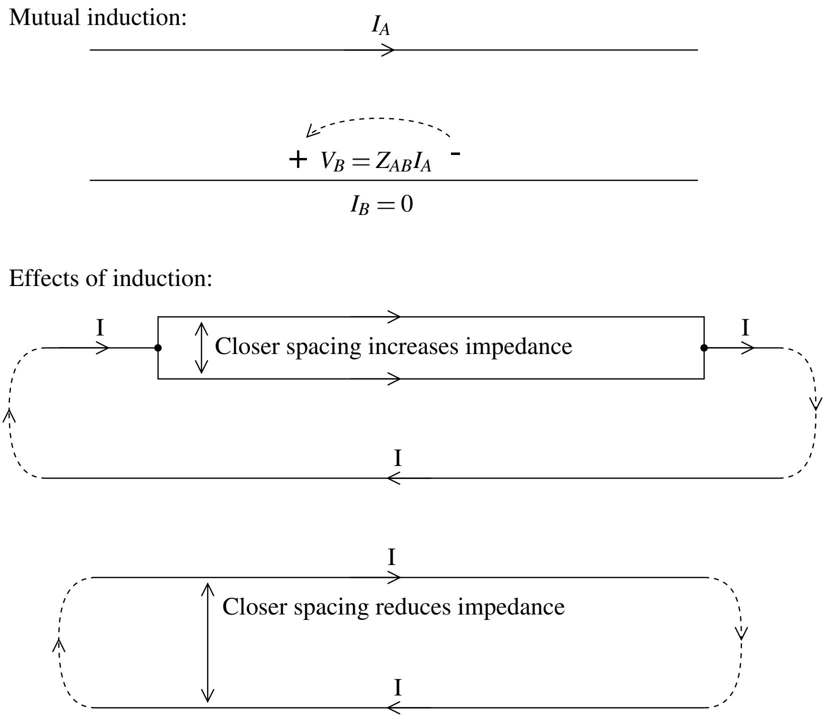

FIGURE 2.3
Mutual induction.

With symmetrical components, the phasors of circuit quantities on each of the three phases resolve to three sets of phasors. For voltage, the symmetrical components relate to the phase voltages as:

$$V_a = V_0 + V_1 + V_2 \qquad V_0 = 1/3\,(V_a + V_b + V_c)$$

$$V_b = V_0 + a^2V_1 + aV_2 \quad \text{and} \quad V_1 = 1/3\,(V_a + aV_b + a^2V_c)$$

$$V_c = V_0 + aV_1 + a^2V_2 \qquad V_2 = 1/3\,(V_a + a^2V_b + aV_c)$$

where $a = 1\angle 120°$ and $a^2 = 1\angle 240°$.

These phase-to-symmetrical conversions apply for phase-to-ground as well as phase-to-phase voltages. The same conversions apply for converting line currents to sequence currents:

$$I_a = I_0 + I_1 + I_2 \qquad I_0 = 1/3\,(I_a + I_b + I_c)$$

$$I_b = I_0 + a^2I_1 + aI_2 \quad \text{and} \quad I_1 = 1/3\,(I_a + aI_b + a^2I_c)$$

$$I_c = I_0 + aI_1 + a^2I_2 \qquad I_2 = 1/3\,(I_a + a^2I_b + aI_c)$$

The voltage drop along each of the phase conductors depends on the currents in each of the phase conductors and the self impedances (such as Z_{aa}) and the mutual impedances (such as Z_{ab}) as

$$V_a = Z_{aa}I_a + Z_{ab}I_b + Z_{ac}I_c$$

$$V_b = Z_{ba}I_a + Z_{bb}I_b + Z_{bc}I_c$$

$$V_c = Z_{ca}I_a + Z_{cb}I_b + Z_{cc}I_c$$

Likewise, when we use sequence components, we have voltage drops of each sequence in terms of the sequence currents and sequence impedances:

$$V_0 = Z_{00}I_0 + Z_{01}I_1 + Z_{02}I_2$$

$$V_1 = Z_{10}I_0 + Z_{11}I_1 + Z_{12}I_2$$

$$V_2 = Z_{20}I_0 + Z_{21}I_1 + Z_{22}I_2$$

This is not much of a simplification until we assume that all of the self-impedance terms are equal ($Z_S = Z_{aa} = Z_{bb} = Z_{cc}$) and all of the mutual impedances are equal ($Z_M = Z_{ab} = Z_{ac} = Z_{bc} = Z_{ba} = Z_{ca} = Z_{cb}$). With this assumption, the sequence impedances decouple; the mutual terms of the zero-sequence matrix (such as Z_{12}) become zero. Zero-sequence current only causes a zero-sequence voltage drop. This is a good enough approximation for many distribution problems and greatly simplifies hand and computer calculations. Now, the sequence voltage drop equations are:

$$V_0 = Z_{00}I_0 = (Z_S + 2Z_M)I_0$$

$$V_1 = Z_{11}I_1 = (Z_S - Z_M)I_1$$

$$V_2 = Z_{22}I_2 = (Z_S - Z_M)I_2$$

Now, we have the sequence terms as

$$Z_0 = Z_S + 2Z_M$$

$$Z_1 = Z_2 = Z_S - Z_M$$

And likewise,

$$Z_S = (Z_0 + 2Z_1)/3$$

$$Z_M = (Z_0 - Z_1)/3$$

Note Z_S, the self-impedance term. Z_S is also the "loop impedance" — the impedance to current through one phase wire and returning through the ground return path. This loop impedance is important because it is the impedance for single-phase lines and the impedance for single line-to-ground faults.

Engineers normally use three methods to find impedances of circuits. In order of least to most accurate, these are:

- Table lookup
- Hand calculations
- Computer calculations

This book provides data necessary for the first two approaches. Table lookups are quite common. Even though table lookup is not the most accurate approach, its accuracy is good enough for analyzing most common distribution problems. Computer calculations are quite accessible and allow easier analysis of more complicated problems.

2.4 Simplified Line Impedance Calculations

The positive-sequence impedance of overhead lines is

$$Z_1 = R_\phi + jk_1 \log_{10} \frac{GMD_\phi}{GMR_\phi}$$

where

R_ϕ = resistance of the phase conductor in Ω/distance
k_1 = $0.2794f/60$ for outputs in Ω/mi
= $0.0529f/60$ for outputs in Ω/1000 ft
f = frequency in hertz
GMR_ϕ = geometric mean radius of the phase conductor in ft
GMD_ϕ = geometric mean distance between the phase conductors in ft
GMD_ϕ = $\sqrt[3]{d_{AB}d_{BC}d_{CA}}$ for three-phase lines
GMD_ϕ = $1.26\, d_{AB}$ for a three-phase line with flat configuration, either horizontal or vertical, where $d_{AB} = d_{BC} = 0.5d_{CA}$
GMD_ϕ = d_{AB} for two-phase lines*

* The two-phase circuit has two out of the three phases; the single-phase circuit has one phase conductor with a neutral return. While it may seem odd to look at the positive-sequence impedance of a one- or two-phase circuit, the analysis approach is useful. This approach uses fictitious conductors for the missing phases to model the one- or two-phase circuit as an equivalent three-phase circuit (no current flows on these fictitious phases).

GMD_ϕ = d_{AN} for single-phase lines*
d_{ij} = distance between the center of conductor i and the center of conductor j, in feet

For 60 Hz and output units of Ω/1000 ft, this is

$$Z_1 = R_\phi + j0.0529\log_{10}\frac{GMD_\phi}{GMR_\phi}$$

Zero-sequence impedance calculations are more complicated than positive-sequence calculations. Carson's equations are the most common way to account for the ground return path in impedance calculations of overhead circuits. Carson (1926) derived an expression including the earth return path. We'll use a simplification of Carson's equations; it includes the following assumptions (Smith, 1980)

- Since distribution lines are relatively short, the height-dependent terms in Carson's full model are small, so we neglect them.
- The multigrounded neutral is perfectly coupled to the earth (this has some drawbacks for certain calculations as discussed in Chapter 13).
- End effects are neglected.
- The current at the sending end equals that at the receiving end (no leakage currents).
- All phase conductors have the same size conductor.
- The ground is infinite and has uniform resistivity.

Consider the circuit in Figure 2.4; current flows in conductor a and returns through the earth. The voltage on conductor a equals the current times Z_{aa}, which is the self-impedance with an earth return path. The current in conductor a induces a voltage drop along conductor b equaling the phase-a current times Z_{ab}, which is the mutual impedance with an earth return path. These two impedances are found (Smith, 1980) with

$$Z_{aa} = R_\phi + R_e + jk_1\log_{10}\frac{D_e}{GMR_\phi}$$

$$Z_{ab} = R_e + jk_1\log_{10}\frac{D_e}{d_{ab}}$$

where
R_e = resistance of the earth return path
= $0.0954f/60$ Ω/mi
= $0.01807f/60$ Ω/1000 ft

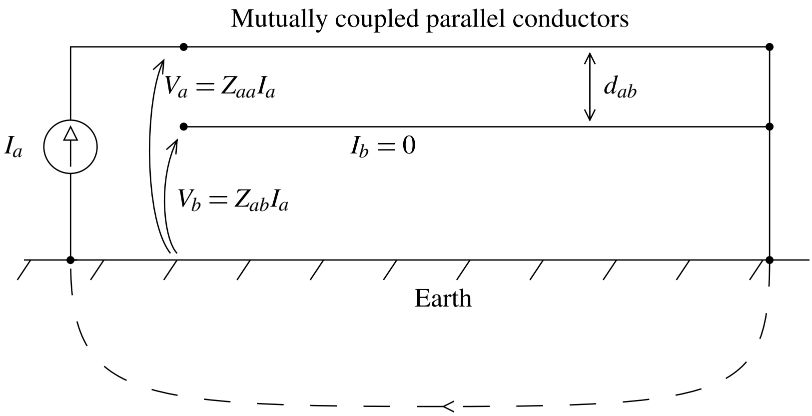

FIGURE 2.4
Depiction of Carson's impedances with earth return.

$D_e = 2160\sqrt{\rho / f}$ = equivalent depth of the earth return current in ft
ρ = earth resistivity in Ω-m
d_{ab} = distance between the centers of conductors *a* and *b*

For 60 Hz and output units of Ω/1000 ft,

$$Z_{aa} = R_\phi + 0.01807 + j0.0529 \log_{10} \frac{278.9\sqrt{\rho}}{GMR_\phi}$$

$$Z_{ab} = \quad 0.01807 + j0.0529 \log_{10} \frac{278.9\sqrt{\rho}}{d_{ab}}$$

These equations lead to different formulations for the zero-sequence impedance of circuits depending on the grounding configuration. They are also useful in their own right in many circumstances. Single-phase circuits with a phase and a neutral are often easier to analyze using these equations rather than using sequence components. Consider a single-phase circuit that is perfectly grounded with a current of I_A in the phase conductor. As Figure 2.5 shows, we can find the neutral current as a function of the mutual impedance between the two conductors divided by the self-impedance of the neutral conductor.

Now, let's look at the zero-sequence impedances — these change depending on grounding configuration. Figure 2.6 shows the configurations that we will consider.

A three-wire overhead line has a zero-sequence impedance of (Smith, 1980):

$$Z_0 = R_\phi + 3R_e + j3k_1 \log_{10} \frac{D_e}{\sqrt[3]{GMR_\phi \cdot GMD_\phi^{\,2}}}$$

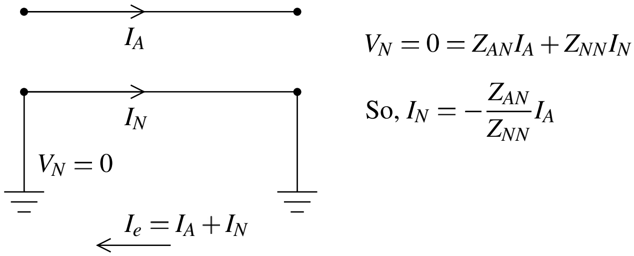

FIGURE 2.5
Current flow in a neutral conductor based on self-impedances and mutual impedances.

For a four-wire multigrounded system, the zero-sequence self-impedance is:

$$Z_0 = R_\phi + 3R_e + j3k_1 \log_{10} \frac{D_e}{\sqrt[3]{GMR_\phi \cdot GMD_\phi{}^2}} - 3\frac{Z_{\phi N}^2}{Z_{NN}}$$

where Z_{NN} is the self-impedance of the neutral conductor with an earth return, and $Z_{\phi N}$ is the mutual impedance between the phase conductors as a group and the neutral. For 60 Hz and output units of Ω/1000 ft, the zero-sequence self-impedance is

$$Z_0 = R_\phi + 0.0542 + j0.1587 \log_{10} \frac{278.9\sqrt{\rho}}{\sqrt[3]{GMR_\phi \cdot GMD_\phi{}^2}} - 3\frac{Z_{\phi N}^2}{Z_{NN}}$$

$$Z_{NN} = R_N + 0.01807 + j0.0529 \log_{10} \frac{278.9\sqrt{\rho}}{GMR_N}$$

$$Z_{\phi N} = 0.01807 + j0.0529 \log_{10} \frac{278.9\sqrt{\rho}}{GMD_{\phi N}}$$

where

GMR_N = geometric mean radius of the neutral conductor in ft

$GMD_{\phi N}$ = geometric mean distance between the phase conductors as a group and the neutral in ft

$GMD_{\phi N} = \sqrt[3]{d_{AN}d_{BN}d_{CN}}$ for three-phase lines

$GMD_{\phi N} = \sqrt{d_{AN}d_{BN}}$ for two-phase lines

$GMD_{\phi N} = d_{AN}$ for single-phase lines

A special case is for a four-wire unigrounded circuit where the return current stays in the neutral, which has a zero-sequence impedance of (Ender et al., 1960)

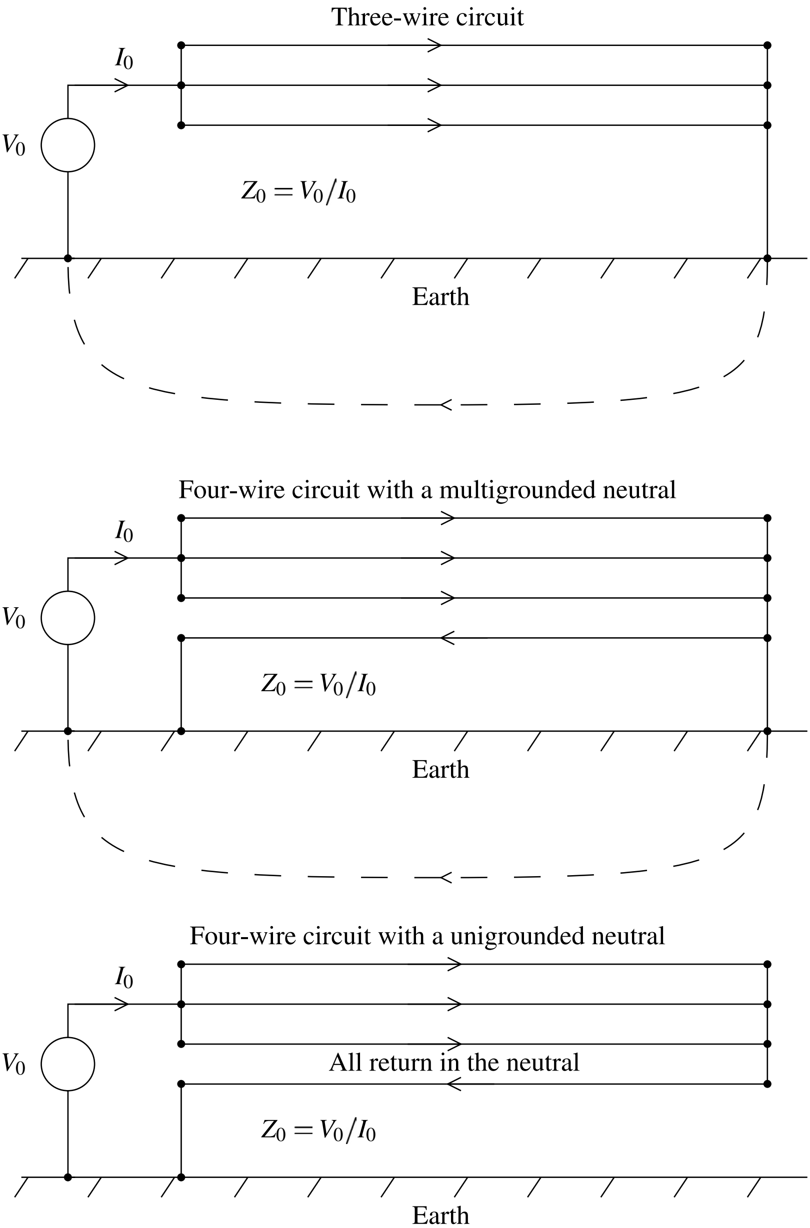

FIGURE 2.6
Different zero-sequence impedances depending on the grounding configuration.

$$Z_0 = R_\phi + 3R_n + jR_n + j3k_1 \log_{10} \frac{GMD_{\phi N^2}}{GMR_N \sqrt[3]{GMR_\phi \cdot GMD_\phi^2}}$$

This is for a four-wire unigrounded circuit where there are no connections between the neutral conductor and earth. We can also use this as an approximation for a multigrounded neutral line that is very poorly grounded. Remember that the equation given above for a multigrounded circuit assumes perfect grounding. For some calculations, that is not accurate. This is the opposite extreme, which is appropriate for some calculations. Lat (1990) used this as one approach to estimating the worst-case overvoltage on unfaulted phases during a line-to-ground fault.

So, what does all of this mean? Some of the major effects are:

- *Conductor size* — Mainly affects resistance — larger conductors have lower positive-sequence resistance. Positive-sequence reactance also lowers with larger conductor size, but since it changes with the logarithm of conductor radius, changes are small.
- *Conductor spacings* — Increasing spacing (higher GMD_ϕ) increases Z_1. Increasing spacing reduces Z_0. Both of these changes with spacing are modest given the logarithmic effect.
- *Neutral* — Adding the neutral always reduces the total zero-sequence impedance, $|Z_0|$. Adding a neutral always reduces the reactive portion of this impedance. But adding a neutral may increase or may decrease the resistive portion of Z_0. Adding a small neutral with high resistance increases the resistance component of Z_0.
- *Neutral spacing* — Moving the neutral closer to the phase conductors reduces the zero-sequence impedance (but may increase the resistive portion, depending on the size of the neutral).
- *Earth resistivity* — The earth resistivity does not change the earth return resistance (R_e only depends on frequency). The current spreads to wider areas of the earth in high-resistivity soil. Earth resistivity does change the reactance. Higher earth resistivities force current deeper into the ground (larger D_e), raising the reactance.
- *Grounding* — The positive-sequence impedance Z_1 stays the same regardless of the grounding, whether four-wire multigrounded, ungrounded, or unigrounded.
- *Negative sequence* — Equals the positive-sequence impedance.

Figure 2.7 and Figure 2.8 show the effects of various parameters on the positive and zero-sequence impedances. Many of the outputs are not particularly sensitive to changes in the inputs. Since many parameters are functions of the logarithm of the variable, major changes induce only small changes in the impedance.

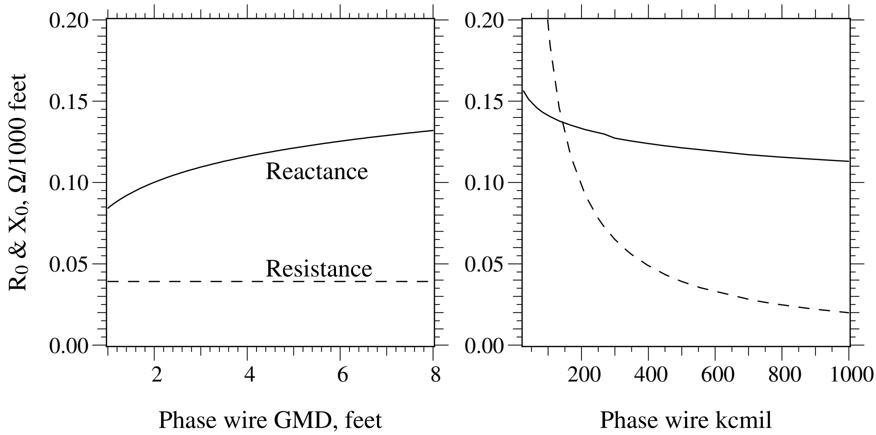

FIGURE 2.7
Effect of spacings and conductor size on the positive-sequence impedance with 500-kcmil AAC phases (GMR = 0.0256 ft) and GMD_ϕ=5 ft.

When do we need more accuracy or more sophistication? For power flows, fault calculations, voltage flicker calculations, and voltage sag analysis, we normally don't need more sophistication. For switching surges, lightning, or other higher frequency transient analysis, we normally need more sophisticated line models.

Most unbalanced calculations can be done with this approach, but some cases require more sophistication. Distribution lines and most lower-voltage subtransmission lines are not transposed. On some long circuits, even with balanced loading, the unbalanced impedances between phases creates voltage unbalance.

2.5 Line Impedance Tables

This section has several tables of impedances for all-aluminum, ACSR, and copper constructions. All are based on the equations in the previous section and assume GMD = 4.8 ft, conductor temperature = 50°C, $GMD_{\phi N}$ = 6.3 ft, and earth resistivity = 100 Ω-m. All zero-sequence values are for a four-wire multigrounded neutral circuit.

2.6 Conductor Sizing

We have an amazing variety of sizes and types of conductors. Several electrical, mechanical, and economic characteristics affect conductor selection:

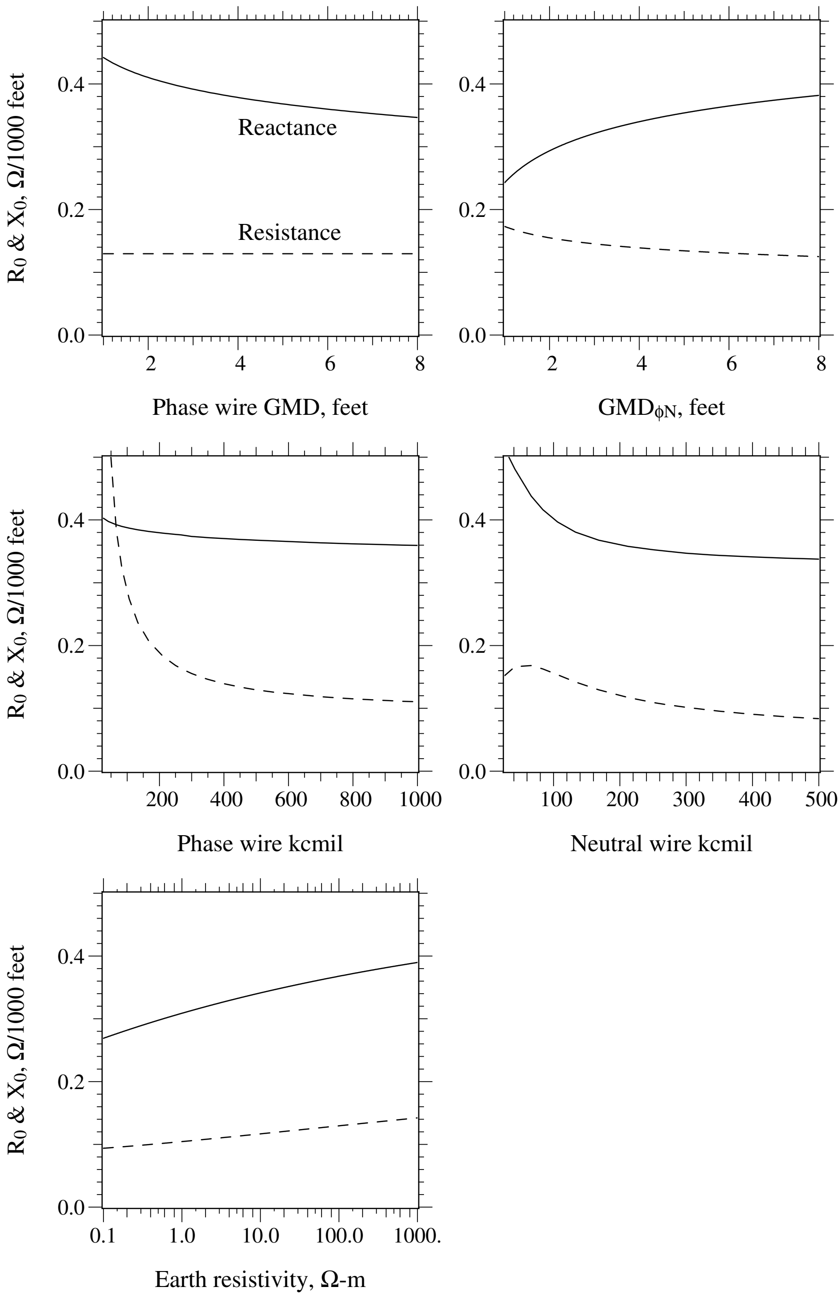

FIGURE 2.8
Effect of various parameters on the zero-sequence impedance with a base case of AAC 500-kcmil phases, 3/0 neutral (168 kcmil), $GMD_{\phi} = 5$ ft, $GMD_{\phi N} = 6.3$ ft, and $\rho = 100$ Ω-m.

TABLE 2.7

Positive-Sequence Impedances of All-Aluminum Conductor

Phase Size	Strands	R_1	X_1	Z_1
6	7	0.7405	0.1553	0.7566
4	7	0.4654	0.1500	0.4890
2	7	0.2923	0.1447	0.3262
1	7	0.2323	0.1420	0.2723
1/0	7	0.1839	0.1394	0.2308
2/0	7	0.1460	0.1367	0.2000
3/0	7	0.1159	0.1341	0.1772
4/0	7	0.0920	0.1314	0.1604
250	7	0.0778	0.1293	0.1509
266.8	7	0.0730	0.1286	0.1478
300	19	0.0649	0.1261	0.1418
336.4	19	0.0580	0.1248	0.1376
350	19	0.0557	0.1242	0.1361
397.5	19	0.0490	0.1229	0.1323
450	19	0.0434	0.1214	0.1289
477	19	0.0411	0.1208	0.1276
500	19	0.0392	0.1202	0.1265
556.5	19	0.0352	0.1189	0.1240
700	37	0.0282	0.1159	0.1192
715.5	37	0.0277	0.1157	0.1190
750	37	0.0265	0.1151	0.1181
795	37	0.0250	0.1146	0.1173
874.5	37	0.0227	0.1134	0.1157
900	37	0.0221	0.1130	0.1152
954	37	0.0211	0.1123	0.1142
1000	37	0.0201	0.1119	0.1137

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). GMD = 4.8 ft, Conductor temp. = 50°C.

- *Ampacity* — The peak current-carrying capability of a conductor limits the current (and power) carrying capability.
- *Economics* — Often we will use a conductor that normally operates well below its ampacity rating. The cost of the extra aluminum pays for itself with lower I^2R losses; the conductor runs cooler. This also leaves room for expansion.
- *Mechanical strength* — Especially on rural lines with long span lengths, mechanical strength plays an important role in size and type of conductor. Stronger conductors like ACSR are used more often. Ice and wind loadings must be considered.
- *Corrosion* — While not usually a problem, corrosion sometimes limits certain types of conductors in certain applications.

As with many aspects of distribution operations, many utilities standardize on a set of conductors. For example, a utility may use 500-kcmil AAC

TABLE 2.8

AAC Zero-Sequence, Z_0, and Ground-Return Loop Impedances, $Z_S = (2Z_1 + Z_0)/3$

Phase Size	Neutral Size	R_0	X_0	Z_0	R_S	X_S	Z_S
6	6	0.8536	0.5507	1.0158	0.7782	0.2871	0.8294
2	6	0.4055	0.5401	0.6754	0.3301	0.2765	0.4306
2	2	0.4213	0.4646	0.6272	0.3353	0.2513	0.4190
1	6	0.3454	0.5374	0.6389	0.2700	0.2738	0.3845
1	1	0.3558	0.4405	0.5662	0.2734	0.2415	0.3648
1/0	6	0.2971	0.5348	0.6117	0.2216	0.2712	0.3502
1/0	1/0	0.2981	0.4183	0.5136	0.2220	0.2323	0.3213
2/0	6	0.2591	0.5321	0.5919	0.1837	0.2685	0.3253
2/0	2/0	0.2487	0.3994	0.4705	0.1802	0.2243	0.2877
3/0	2	0.2449	0.4540	0.5158	0.1589	0.2407	0.2884
3/0	3/0	0.2063	0.3840	0.4359	0.1461	0.2174	0.2619
4/0	1	0.2154	0.4299	0.4809	0.1331	0.2309	0.2665
4/0	4/0	0.1702	0.3716	0.4088	0.1180	0.2115	0.2422
250	2/0	0.1805	0.3920	0.4316	0.1120	0.2169	0.2441
250	250	0.1479	0.3640	0.3929	0.1012	0.2075	0.2309
266.8	2/0	0.1757	0.3913	0.4289	0.1072	0.2161	0.2413
266.8	266.8	0.1402	0.3614	0.3877	0.0954	0.2062	0.2272
300	2/0	0.1675	0.3888	0.4234	0.0991	0.2137	0.2355
300	300	0.1272	0.3552	0.3773	0.0856	0.2025	0.2198
336.4	2/0	0.1607	0.3875	0.4195	0.0922	0.2123	0.2315
336.4	336.4	0.1157	0.3514	0.3699	0.0772	0.2003	0.2147
350	2/0	0.1584	0.3869	0.4181	0.0899	0.2118	0.2301
350	350	0.1119	0.3499	0.3674	0.0744	0.1994	0.2129
397.5	2/0	0.1517	0.3856	0.4143	0.0832	0.2105	0.2263
397.5	397.5	0.1005	0.3463	0.3606	0.0662	0.1974	0.2082
450	2/0	0.1461	0.3841	0.4109	0.0776	0.2089	0.2229
450	450	0.0908	0.3427	0.3545	0.0592	0.1951	0.2039
477	2/0	0.1438	0.3835	0.4096	0.0753	0.2084	0.2216
477	477	0.0868	0.3414	0.3522	0.0563	0.1943	0.2023
500	4/0	0.1175	0.3605	0.3791	0.0653	0.2003	0.2107
500	500	0.0835	0.3401	0.3502	0.0540	0.1935	0.2009
556.5	4/0	0.1135	0.3591	0.3766	0.0613	0.1990	0.2082
556.5	556.5	0.0766	0.3372	0.3458	0.0490	0.1917	0.1978
700	4/0	0.1064	0.3561	0.3717	0.0542	0.1960	0.2033
700	700	0.0639	0.3310	0.3371	0.0401	0.1876	0.1918
715.5	4/0	0.1060	0.3559	0.3714	0.0538	0.1958	0.2030
715.5	715.5	0.0632	0.3306	0.3366	0.0395	0.1873	0.1915
750	4/0	0.1047	0.3553	0.3705	0.0526	0.1952	0.2022
750	750	0.0609	0.3295	0.3351	0.0380	0.1866	0.1904
795	4/0	0.1033	0.3548	0.3695	0.0511	0.1946	0.2012
795	795	0.0582	0.3283	0.3335	0.0361	0.1858	0.1893
874.5	4/0	0.1010	0.3536	0.3678	0.0488	0.1935	0.1996
874.5	874.5	0.0540	0.3261	0.3305	0.0332	0.1843	0.1873
900	4/0	0.1004	0.3533	0.3672	0.0482	0.1931	0.1990
900	900	0.0529	0.3254	0.3296	0.0324	0.1838	0.1866
954	4/0	0.0993	0.3525	0.3662	0.0471	0.1924	0.1981

TABLE 2.8 (Continued)

AAC Zero-Sequence, Z_0, and Ground-Return Loop Impedances, $Z_S = (2Z_1 + Z_0)/3$

Phase Size	Neutral Size	R_0	X_0	Z_0	R_S	X_S	Z_S
954	954	0.0510	0.3239	0.3279	0.0310	0.1828	0.1854
1000	4/0	0.0983	0.3521	0.3656	0.0462	0.1920	0.1975
1000	1000	0.0491	0.3232	0.3269	0.0298	0.1823	0.1847

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). GMD = 4.8 ft, $GMD_{\phi N}$ = 6.3 ft, Conductor temp. = 50°C, Earth resistivity = 100 Ω-m.

TABLE 2.9

Positive-Sequence Impedances of ACSR

Phase Size	Strands	R_1	X_1	Z_1
6	6/1	0.7500	0.1746	0.7700
4	6/1	0.4794	0.1673	0.5077
2	6/1	0.3080	0.1596	0.3469
1	6/1	0.2474	0.1551	0.2920
1/0	6/1	0.1972	0.1496	0.2476
2/0	6/1	0.1616	0.1478	0.2190
3/0	6/1	0.1208	0.1442	0.1881
4/0	6/1	0.1066	0.1407	0.1765
266.8	18/1	0.0723	0.1262	0.1454
336.4	18/1	0.0574	0.1236	0.1362
397.5	18/1	0.0487	0.1217	0.1311
477	18/1	0.0405	0.1196	0.1262
556.5	18/1	0.0348	0.1178	0.1228
636	18/1	0.0306	0.1165	0.1204
795	36/1	0.0247	0.1140	0.1167

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). GMD = 4.8 ft, Conductor temp. = 50°C.

for all mainline spans and 1/0 AAC for all laterals. While many circuit locations are overdesigned, the utility saves from reduced stocking, fewer tools, and standardized connectors. While many utilities have more than just two conductors, most use just a handful of standard conductors; four to six economically covers the needs of most utilities.

2.7 Ampacities

The ampacity is the maximum designed current of a conductor. This current carrying capacity is normally given in amperes. A given conductor has

TABLE 2.10

ACSR Zero-Sequence, Z_0, and Ground-Return Loop Impedances, $Z_S = (2Z_1 + Z_0)/3$

Phase Size	Neutral Size	R_0	X_0	Z_0	R_S	X_S	Z_S
4	4	0.6030	0.5319	0.8040	0.5206	0.2888	0.5953
2	4	0.4316	0.5242	0.6790	0.3492	0.2812	0.4483
2	2	0.4333	0.4853	0.6505	0.3498	0.2682	0.4407
1	4	0.3710	0.5197	0.6385	0.2886	0.2766	0.3998
1	1	0.3684	0.4610	0.5901	0.2877	0.2571	0.3858
1/0	4	0.3208	0.5143	0.6061	0.2384	0.2712	0.3611
1/0	1/0	0.3108	0.4364	0.5357	0.2351	0.2452	0.3397
2/0	2	0.2869	0.4734	0.5536	0.2034	0.2563	0.3272
2/0	2/0	0.2657	0.4205	0.4974	0.1963	0.2387	0.3090
3/0	2	0.2461	0.4698	0.5304	0.1626	0.2527	0.3005
3/0	3/0	0.2099	0.4008	0.4524	0.1505	0.2297	0.2746
4/0	1	0.2276	0.4465	0.5012	0.1469	0.2426	0.2836
4/0	4/0	0.1899	0.3907	0.4344	0.1344	0.2240	0.2612
266.8	2/0	0.1764	0.3990	0.4362	0.1070	0.2171	0.2421
266.8	266.8	0.1397	0.3573	0.3836	0.0948	0.2032	0.2242
336.4	2/0	0.1615	0.3963	0.4280	0.0921	0.2145	0.2334
336.4	336.4	0.1150	0.3492	0.3676	0.0766	0.1988	0.2130
397.5	2/0	0.1528	0.3944	0.4230	0.0834	0.2126	0.2284
397.5	397.5	0.1002	0.3441	0.3584	0.0659	0.1958	0.2066
477	2/0	0.1446	0.3923	0.4181	0.0752	0.2105	0.2235
477	477	0.0860	0.3391	0.3498	0.0557	0.1927	0.2006
556.5	2/0	0.1389	0.3906	0.4145	0.0695	0.2087	0.2200
556.5	556.5	0.0759	0.3351	0.3436	0.0485	0.1902	0.1963

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). GMD = 4.8 ft, $GMD_{\phi N}$ = 6.3 ft, Conductor temp. = 50°C, Earth resistivity = 100 Ω-m.

TABLE 2.11

Positive-Sequence Impedances of Hard-Drawn Copper

Phase Size	Strands	R_1	X_1	Z_1
4	3	0.2875	0.1494	0.3240
2	3	0.1809	0.1441	0.2313
1	7	0.1449	0.1420	0.2029
1/0	7	0.1150	0.1393	0.1807
2/0	7	0.0911	0.1366	0.1642
3/0	12	0.0723	0.1316	0.1501
4/0	12	0.0574	0.1289	0.1411
250	12	0.0487	0.1270	0.1360
300	12	0.0407	0.1250	0.1314
350	19	0.0349	0.1243	0.1291
400	19	0.0307	0.1227	0.1265
450	19	0.0273	0.1214	0.1244
500	19	0.0247	0.1202	0.1227

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). GMD = 4.8 ft, Conductor temp. = 50°C.

TABLE 2.12

Copper Zero-Sequence, Z_0, and Ground-Return Loop Impedances, $Z_S = (2Z_1 + Z_0)/3$

Phase Size	Neutral Size	R_0	X_0	Z_0	R_S	X_S	Z_S
3	3	0.3515	0.4459	0.5678	0.2707	0.2468	0.3663
3	3	0.3515	0.4459	0.5678	0.2707	0.2468	0.3663
6	6	0.5830	0.5157	0.7784	0.4986	0.2751	0.5695
6	6	0.5830	0.5157	0.7784	0.4986	0.2751	0.5695
4	6	0.4141	0.5104	0.6572	0.3297	0.2697	0.4260
4	4	0.4146	0.4681	0.6253	0.3299	0.2556	0.4173
2	6	0.3075	0.5051	0.5913	0.2231	0.2644	0.3460
2	2	0.2924	0.4232	0.5143	0.2181	0.2371	0.3221
1	4	0.2720	0.4606	0.5349	0.1873	0.2482	0.3109
1	1	0.2451	0.4063	0.4745	0.1783	0.2301	0.2911
1/0	4	0.2421	0.4580	0.5180	0.1574	0.2455	0.2916
1/0	1/0	0.2030	0.3915	0.4410	0.1443	0.2234	0.2660
2/0	3	0.2123	0.4352	0.4842	0.1315	0.2362	0.2703
2/0	2/0	0.1672	0.3796	0.4148	0.1165	0.2176	0.2468
3/0	2	0.1838	0.4106	0.4498	0.1095	0.2246	0.2498
3/0	3/0	0.1383	0.3662	0.3915	0.0943	0.2098	0.2300
4/0	2	0.1689	0.4080	0.4415	0.0946	0.2219	0.2412
4/0	4/0	0.1139	0.3584	0.3760	0.0762	0.2054	0.2191
250	1	0.1489	0.3913	0.4187	0.0821	0.2151	0.2303
250	250	0.0993	0.3535	0.3671	0.0656	0.2025	0.2128
300	1	0.1409	0.3893	0.4140	0.0741	0.2131	0.2256
300	300	0.0856	0.3487	0.3590	0.0557	0.1995	0.2071
350	1	0.1351	0.3886	0.4115	0.0683	0.2124	0.2231
350	350	0.0754	0.3468	0.3549	0.0484	0.1985	0.2043
400	1	0.1309	0.3871	0.4086	0.0641	0.2109	0.2204
400	400	0.0680	0.3437	0.3503	0.0431	0.1964	0.2011
450	1/0	0.1153	0.3736	0.3910	0.0566	0.2055	0.2131
450	450	0.0620	0.3410	0.3466	0.0389	0.1946	0.1984
500	1/0	0.1127	0.3724	0.3891	0.0540	0.2043	0.2113
500	500	0.0573	0.3387	0.3435	0.0356	0.1930	0.1963

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). GMD = 4.8 ft, $GMD_{\phi N}$ = 6.3 ft, Conductor temp. = 50°C, Earth resistivity = 100 Ω-m.

several ampacities, depending on its application and the assumptions used. House and Tuttle (1958) derive the ampacity calculations described below, which are used in IEEE Std. 738-1993 and most other published ampacity tables (Aluminum Association, 1986; Southwire Company, 1994).

Sun, wind, and ambient temperature change a conductor's ampacity. A conductor's temperature depends on the thermal balance of heat inputs and losses. Current driven through a conductor's resistance creates heat (I^2R). The sun is another source of heat into the conductor. Heat escapes from the conductor through radiation and from convection. Considering the balance of inputs and outputs, the ampacity of a conductor is

$$I = \sqrt{\frac{q_c + q_r - q_s}{R_{ac}}}$$

where

q_c = convected heat loss, W/ft
q_r = radiated heat loss, W/ft
q_s = solar heat gain, W/ft
R_{ac} = Nominal ac resistance at operating temperature t, Ω/ft

The convected heat loss with no wind is

$$q_c = 0.283\sqrt{\rho_f}D^{0.75}(t_c - t_a)^{1.25}$$

Wind increases convection losses. The losses vary based on wind speed. The IEEE method uses the maximum q_c from the following two equations:

$$q_{c1} = \left[1.01 + 0.371\left(\frac{D\rho_f V}{\mu_f}\right)^{0.52}\right]K_f(t_c - t_a)$$

$$q_{c2} = 0.1695\left(\frac{D\rho_f V}{\mu_f}\right)^{0.6} K_f(t_c - t_a)$$

where

D = conductor diameter, in.
t_c = conductor operating temperature, °C
t_a = ambient temperature, °C
$t_f = (t_c + t_c)/2$
V = air velocity, ft/h
ρ_f = air density at t_f, lb/ft^3
μ_f = absolute viscosity of air at t_f, lb/h-ft
K_f = thermal conductivity of air at t_f, W/ft^2/°C

The density, viscosity, and thermal conductivity of air all depend on temperature (actually the film temperature T_f near the surface of the conductor, which is taken as the average of the conductor and ambient temperatures). Tables of these are available in the references (IEEE Std. 738-1993; Southwire Company, 1994). We may also use the following polynomial approximations (IEEE Std. 738-1993):

$$\rho_f = \frac{0.080695 - (0.2901 \times 10^{-5})H_c + (0.37 \times 10^{-10})H_c^2}{1 + 0.00367T_f}$$

where H_c is the altitude above sea level in feet.

$$k_f = 0.007388 + 2.27889 \times 10^{-5} T_f - 1.34328 \times 10^{-9} T_f^2$$

$$\mu_f = 0.0415 + 1.2034 \times 10^{-4} T_f - 1.1442 \times 10^{-7} T_f^2 + 1.9416 \times 10^{-10} T_f^3$$

A conductor radiates heat as the absolute temperature to the fourth power as

$$q_r = 0.138 D\varepsilon \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right]$$

where
- D = conductor diameter, in.
- ε = emissivity (normally 0.23 to 0.91 for bare wires)
- T_c = conductor temperature, °C
- T_a = ambient temperature, °C

A conductor absorbs heat from the sun as

$$q_s = \alpha Q_s \frac{D}{12} \sin\theta$$

where
- α = solar absorptivity
- Q_s = total solar heat in W/ft²
- θ = effective angle of incidence of the sun's rays
- D = conductor diameter, in.

The angles and total solar heat depend on the time of day and the latitude. Since the solar input term does not change the output significantly, we can use some default values. For a latitude of 30°N at 11 a.m. in clear atmosphere, Q_s = 95.2 W/ft,² and θ = 78.6°.

Emissivity (ε) is the ability of a conductor to radiate heat into the air. Absorptivity (α) quantifies how much heat a conductor can absorb. Emissivity and absorptivity are interrelated; a nice shiny conductor reflects away much of the sun's heat but does not radiate heat well. Commonly, both are assumed to be 0.5 for bare wire. More conservative assumptions, possibly overconservative, are 0.7 for emissivity and 0.9 for absorptivity.

Some of the main factors impacting ampacity are

- *Allowable conductor temperature* — Ampacity increases significantly with higher allowed temperatures.

TABLE 2.13
Ampacities of All-Aluminum Conductor

		Conductor Temp. = 75°C				Conductor Temp. = 100°C			
		Ambient = 25°C		Ambient = 40°C		Ambient = 25°C		Ambient = 40°C	
Conductor	Stranding	No Wind	Wind	No Wind	Wind	No Wind	Wind	No Wind	Wind
6	7	60	103	46	85	77	124	67	111
4	7	83	138	63	114	107	166	92	148
2	7	114	185	86	152	148	223	128	199
1	7	134	214	101	175	174	258	150	230
1/0	7	157	247	118	203	204	299	176	266
2/0	7	184	286	139	234	240	347	207	309
3/0	7	216	331	162	271	283	402	243	358
4/0	7	254	383	190	313	332	466	286	414
250	7	285	425	213	347	373	518	321	460
250	19	286	427	214	348	375	519	322	462
266.8	7	298	443	223	361	390	539	335	479
266.8	19	299	444	224	362	392	541	337	481
300	19	325	479	243	390	426	584	367	519
336.4	19	351	515	262	419	461	628	397	559
350	19	361	527	269	428	474	644	408	572
397.5	19	394	571	293	464	517	697	445	619
450	19	429	617	319	501	564	755	485	671
477	19	447	640	332	519	588	784	506	697
477	37	447	641	333	520	589	785	507	697
500	19	461	658	342	534	606	805	521	716
556.5	19	496	704	368	571	654	864	562	767
556.5	37	496	705	369	571	654	864	563	768
600	37	522	738	388	598	688	905	592	804
636	37	545	767	404	621	720	943	619	838
650	37	556	782	413	633	737	965	634	857
700	37	581	814	431	658	767	1000	660	888
715.5	37	590	825	437	667	779	1014	670	901
715.5	61	590	825	437	667	780	1014	671	901
750	37	609	848	451	686	804	1044	692	927
795	37	634	881	470	712	840	1086	722	964
795	61	635	882	470	713	840	1087	723	965
800	37	636	884	471	714	841	1087	723	965
874.5	61	676	933	500	754	896	1152	770	1023
874.5	61	676	934	500	754	896	1152	771	1023
900	37	689	950	510	767	913	1172	785	1041
954	37	715	983	529	793	946	1210	813	1074
954	61	719	988	532	797	954	1221	821	1084
1000.0	37	740	1014	547	818	981	1252	844	1111

- *Ambient temperature* — Ampacity increases about 1% for each 1°C decrease in ambient temperature.
- *Wind speed* — Even a small wind helps cool conductors significantly. With no wind, ampacities are significantly lower than with a 2-ft/sec crosswind.

Table 2.13 through Table 2.15 show ampacities of all-aluminum, ACSR, and copper conductors. All assume the following:

TABLE 2.14

Ampacities of ACSR

		Conductor Temp. = 75°C				Conductor Temp. = 100°C			
		Ambient = 25°C		Ambient = 40°C		Ambient = 25°C		Ambient = 40°C	
Conductor	Stranding	No Wind	Wind	No Wind	Wind	No Wind	Wind	No Wind	Wind
6	6/1	61	105	47	86	79	126	68	112
4	6/1	84	139	63	114	109	167	94	149
4	7/1	85	141	64	116	109	168	94	149
2	6/1	114	184	86	151	148	222	128	197
2	7/1	117	187	88	153	150	224	129	199
1	6/1	133	211	100	173	173	255	149	227
1/0	6/1	156	243	117	199	202	294	174	261
2/0	6/1	180	277	135	227	235	337	203	300
3/0	6/1	208	315	156	258	262	370	226	329
4/0	6/1	243	363	182	296	319	443	274	394
266.8	18/1	303	449	227	366	398	547	342	487
266.8	26/7	312	458	233	373	409	559	352	497
336.4	18/1	356	520	266	423	468	635	403	564
336.4	26/7	365	530	272	430	480	647	413	575
336.4	30/7	371	536	276	435	487	655	419	582
397.5	18/1	400	578	298	469	527	708	453	629
397.5	26/7	409	588	305	477	538	719	463	639
477	18/1	453	648	337	525	597	793	513	705
477	24/7	461	656	343	532	607	804	523	714
477	26/7	464	659	345	534	611	808	526	718
477	30/7	471	667	350	540	615	810	529	720
556.5	18/1	504	713	374	578	664	874	571	777
556.5	24/7	513	722	380	585	677	887	582	788
556.5	26/7	517	727	383	588	682	893	587	793
636	24/7	562	785	417	635	739	962	636	854
636	26/7	567	791	420	639	748	972	644	863
795	45/7	645	893	478	721	855	1101	735	977
795	26/7	661	910	489	734	875	1122	753	996
954	45/7	732	1001	541	807	971	1238	835	1099
954	54/7	741	1010	547	814	983	1250	846	1109
1033.5	45/7	769	1048	568	844	1019	1294	877	1148

- Emissivity = 0.5, absorptivity = 0.5
- 30°N at 11 a.m. in clear atmosphere
- Wind speed = 2 ft/sec
- Elevation = sea level

The solar heating input has modest impacts on the results. With no sun, the ampacity increases only a few percent.

Some simplifying equations help for evaluating some of the significant impacts on ampacity. We can estimate changes in ambient and allowable temperature variations (Black and Rehberg, 1985; Southwire Company, 1994) with

$$I_{new} = I_{old}\sqrt{\frac{T_{c,new} - T_{a,new}}{T_{c,old} - T_{a,old}}}$$

TABLE 2.15

Ampacities of Copper Conductors

		Conductor Temp. = 75°C				Conductor Temp. = 100°C			
		Ambient = 25°C		Ambient = 40°C		Ambient = 25°C		Ambient = 40°C	
Conductor	Stranding	No Wind	Wind	No Wind	Wind	No Wind	Wind	No Wind	Wind
6	3	83	140	63	116	107	169	92	150
6	1	76	134	58	110	98	160	85	143
5	3	97	162	73	134	125	195	108	174
5	1	90	155	68	127	115	185	99	165
4	3	114	188	86	154	147	226	127	201
4	1	105	179	80	147	136	214	117	191
3	7	128	211	97	174	166	254	143	226
3	3	133	217	101	178	173	262	149	233
3	1	123	206	93	170	159	248	137	221
2	7	150	244	114	201	195	294	168	262
2	3	157	251	118	206	203	303	175	270
2	1	145	239	110	196	187	287	161	256
1	3	184	291	138	238	239	351	206	313
1	7	177	282	133	232	229	340	197	303
1/0	7	207	326	156	267	269	394	232	351
2/0	7	243	378	183	309	317	457	273	407
3/0	12	292	444	219	362	381	539	328	479
3/0	7	285	437	214	357	373	530	321	472
4/0	19	337	507	252	414	440	617	379	549
4/0	12	342	513	256	418	448	624	386	555
4/0	7	335	506	251	413	438	615	377	547
250	19	377	563	282	459	493	684	424	608
250	12	384	569	287	464	502	692	432	615
300	19	427	630	319	513	559	767	481	682
300	12	435	637	324	519	569	776	490	690
350	19	475	694	355	565	624	847	537	753
350	12	484	702	360	571	635	858	546	763
400	19	520	753	387	612	682	920	587	817
450	19	564	811	420	659	742	993	639	883
500	37	606	865	450	702	798	1061	686	942
500	19	605	865	450	701	797	1059	685	941
600	37	685	968	509	784	905	1190	779	1057
700	37	759	1062	563	860	1003	1308	863	1161
750	37	794	1107	588	895	1051	1364	904	1211
800	37	826	1147	612	927	1092	1412	939	1253
900	37	894	1233	662	995	1189	1527	1023	1356
1000	37	973	1333	719	1075	1313	1676	1129	1488

where I_{new} is the new ampacity based on a new conductor limit $T_{c,new}$ and a new ambient temperature $T_{a,new}$. Likewise, I_{old} is the original ampacity based on a conductor limit $T_{c,old}$ and an ambient temperature $T_{a,old}$.

This approach neglects solar heating and the change in conductor resistance with temperature (both have small impacts). Doing this simplifies the ampacity calculation to a constant (dependent on weather and conductor characteristics) times the difference between the conductor temperature and the ambient temperature: $I^2 = K(T_c - T_a)$. We do not use this simplification for the original ampacity calculation, but it helps us evaluate changes in temperatures or currents.

We use this approach in Figure 2.9 to show the variation in ampacity with ambient conductor assumptions along with two conductor operating limits.

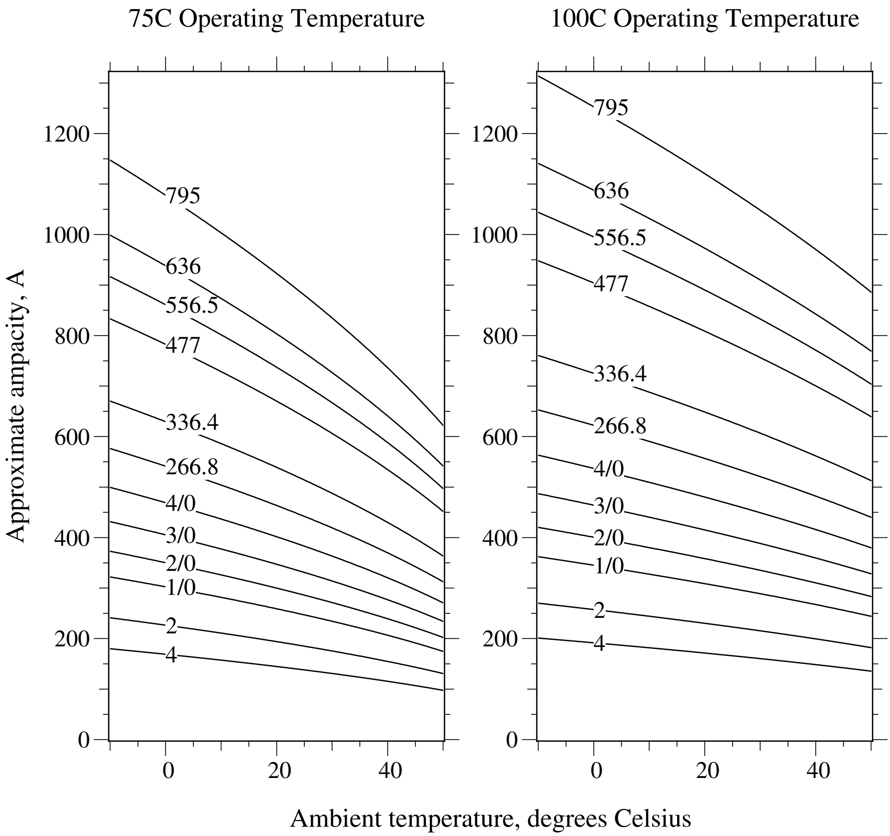

FIGURE 2.9
AAC ampacity with ambient temperature variations, using adjustments from base ampacity data in Table 2.13 (2 ft/sec wind, with sun).

Also, Figure 2.10 shows the conductor temperature vs. loading for several AAC conductors. This graph highlights the major impact of operating temperature on ampacity. If we are overly conservative on a conductor limit, we end up with an overly restrictive ampacity.

We can also use the simplified ampacity equation to estimate the conductor temperature at a current higher or lower than the rated ampacity as (and at a different ambient temperature if we wish):

$$T_{c,new} = T_{a,new} + \left(\frac{I_{new}}{I_{old}}\right)^2 (T_{c,old} - T_{a,old})$$

When examining a line's ampacity, always remember that the overhead wire may not be the weakest link; substation exit cables, terminations, reclosers, or other gear may limit a circuit's current before the conductors do. Also, with currents near a conductor's rating, voltage drop is high.

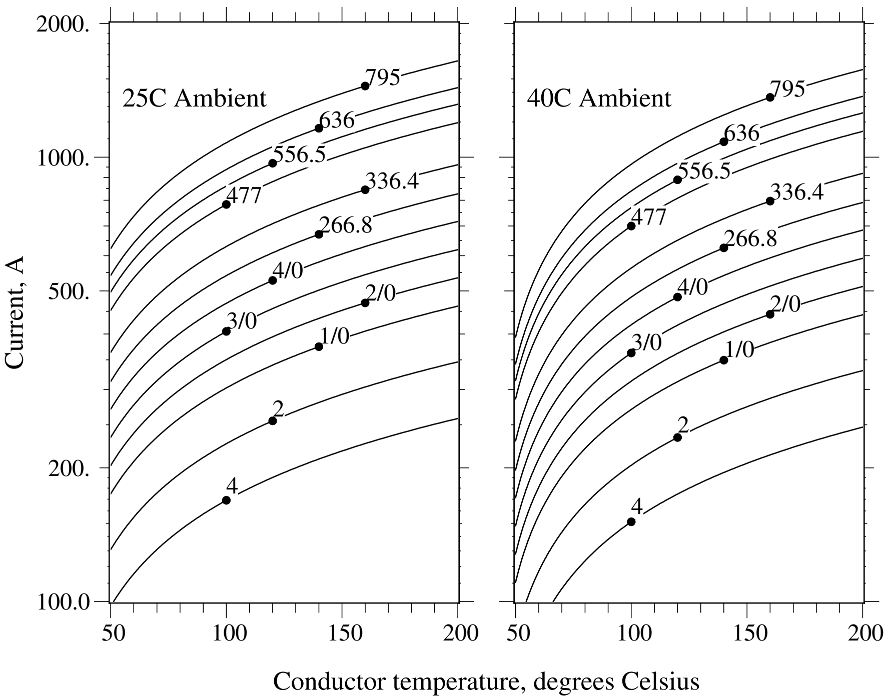

FIGURE 2.10
Conductor temperatures based on the given currents for selected AAC conductors, using adjustments from base ampacity data in Table 2.13 (2 ft/sec wind).

The maximum operating temperature is an important consideration. Higher designed operating temperatures allow higher currents. But at higher temperatures, we have a higher risk of damage to the conductors. Aluminum strands are strain hardened during manufacturing (the H19 in aluminum's 1350-H19 designation means "extra hard"). Heating relaxes the strands — the aluminum elongates and weakens. This damage is called *annealing*. As aluminum anneals, it reverts back to its natural, softer state: fully annealed 1350 aluminum wire elongates by 30% and loses 58% of its strength (10,000 psi vs. 24,000 psi fully hardened). Even fully annealed, failure may not be immediate; the next ice load or heavy winds may break a conductor. Slow annealing begins near 100°C. Aluminum anneals rapidly above 200°C. Annealing damage is permanent and accumulates over time. Remaining strength for AAC conductors varies with conductor temperature and duration of exposure as approximately (Harvey, 1971)

$$R_S = k_1 t^{-\frac{0.1}{d}(0.001T_c - 0.095)}$$

where

R_S = remaining strength, percent of initial strength

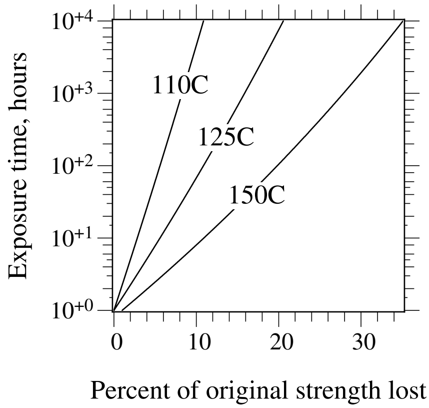

FIGURE 2.11
Loss of strength of all-aluminum conductors due to exposure to high temperatures.

d = strand diameter, in.
t = exposure time, h
T_c = conductor temperature, °C
$k_1 = (-0.24T_c + 135)$, but if $k_1 > 100$, use $k_1 = 100$

Figure 2.11 shows the loss of strength with time for high-temperature operation using this approximation.

ACSR may be loaded higher than the same size AAC conductor. As the aluminum loses strength, the steel carries more of the tension. The steel does not lose strength until reaching higher temperatures.

Covered conductors are darker, so they absorb more heat from the sun but radiate heat better; the Aluminum Association (1986) uses 0.91 for both the emissivity and the absorptivity of covered wire. Table 2.16 shows ampacities of covered wire. Covered conductors have ampacities that are close to bare-conductor ampacities. The most significant difference is that covered conductors have less ability to withstand higher temperatures; the insulation degrades. Polyethylene is especially prone to damage, so it should not be operated above 75°C. EPR and XLPE may be operated up to 90°C.

Some utilities use two ratings, a "normal" ampacity with a 75°C design temperature and an "emergency" ampacity with a 90 or 100°C design. Conductors are selected for the normal rating, but operation is allowed to the emergency rating. Overhead circuits have considerable capability for overload, especially during cooler weather. We do not use relaying to trip "overloaded" circuits. At higher temperatures, conductors age more quickly but do not usually fail immediately.

2.7.1 Neutral Conductor Sizing

Because the neutral conductor carries less current than the phase conductors, utilities can use smaller neutral conductors. On three-phase circuits with

TABLE 2.16

Ampacities of All-Aluminum Conductor Covered with PE, XLPE, or EPR

AWG or kcmil	Stranding	Cover Thickness (mil)	Conductor Temp. = 75°C 25°C Ambient	Conductor Temp. = 75°C 40°C Ambient	Conductor Temp. = 90°C 25°C Ambient	Conductor Temp. = 90°C 40°C Ambient
6	7	30	105	85	120	105
4	7	30	140	110	160	135
2	7	45	185	145	210	180
1	7	45	210	170	245	210
1/0	7	60	240	195	280	240
2/0	7	60	280	225	325	280
3/0	7	60	320	255	375	320
4/0	7	60	370	295	430	370
4/0	19	60	375	295	430	370
266.8	19	60	430	340	500	430
336.4	19	60	500	395	580	495
397.5	19	80	545	430	635	545
477	37	80	615	480	715	610
556.5	37	80	675	530	785	675
636	61	95	725	570	850	725
795	61	95	835	650	980	835
1033.5	61	95	980	760	1150	985

Note: Emissivity = 0.91, absorptivity = 0.91; 30°N at 12 noon in clear atmosphere; wind speed = 2 ft/sec; elevation = sea level.

Source: Aluminum Association, *Ampacities for Aluminum and ACSR Overhead Electrical Conductors*, 1986.

balanced loading, the neutral carries almost no current. On single-phase circuits with a multigrounded neutral, the neutral normally carries 40 to 60% of the current (the earth carries the remainder).

On single-phase circuits, some utilities use fully rated neutrals, where the neutral and the phase are the same size. Some use reduced neutrals. The resistance of the neutral should be no more than twice the resistance of the phase conductor, and we are safer with a resistance less than 1.5 times the phase conductor, which is a conductivity or cross-sectional area of 2/3 the phase conductor. Common practice is to drop one to three gage sizes for the neutral: a 4/0 phase has a 2/0 neutral, or a 1/0 phase has a number 2 neutral. Dropping three gage sizes doubles the resistance, so we do not want to go any smaller than that.

On three-phase circuits, most utilities use reduced neutrals, dropping the area to about 25 to 70% of the phase conductor (and multiplying the resistance by 1.4 to 4).

Several other factors besides ampacity play a role in how small neutral conductors are:

- *Grounding* — A reduced neutral increases the overvoltages on the unfaulted phases during single line-to-ground faults (see Chapter 13). It also increases stray voltages.

- *Faults* — A reduced neutral reduces the fault current for single line-to-ground faults, which makes it more difficult to detect faults at far distances. Also, the reduced neutral is subjected to the same fault current as the phase, so impacts on burning down the neutral should be considered for smaller neutrals.
- *Secondary* — If the primary and secondary neutral are shared, the neutral must handle the primary and secondary unbalanced current (and have the mechanical strength to hold up the secondary phase conductors in triplex or quadraplex construction).
- *Mechanical* — On longer spans, the sag of the neutral should coordinate with the sag of the phases and the minimum ground clearances to ensure that spacing rules are not violated.

2.8 Secondaries

Utilities most commonly install *triplex* secondaries for overhead service to single-phase customers, where two insulated phase conductors are wrapped around the neutral. The neutral supports the weight of the conductors. Phase conductors are normally all-aluminum, and the neutral is all-aluminum, aluminum-alloy, or ACSR, depending on strength needs. Insulation is normally polyethylene, high-molecular weight polyethylene, or cross-linked polyethylene with thickness ranging from 30 to 80 mils (1.1 to 2 mm) rated for 600 V. Similarly for three-phase customers, quadraplex has three insulated phase conductors wrapped around a bare neutral. Table 2.17 shows characteristics of polyethylene triplex with an AAC neutral.

Triplex secondary ampacities depend on the temperature capability of the insulation. Polyethylene can operate up to 75°C. Cross-linked polyethylene and EPR can operate higher, up to 90°C. Table 2.18 shows ampacities for triplex when operated to each of these maximum temperatures. Quadraplex has ampacities that are 10 to 15% less than triplex of the same size conductor. Ampacities for open-wire secondary are the same as that for bare primary conductors.

Table 2.19 shows impedances of triplex. Two impedances are given: one for the 120-V loop and another for a 240-V loop. The 240-V loop impedance is the impedance to current flowing down one hot conductor and returning on the other. The 120-V loop impedance is the impedance to current down one hot conductor and returning in the neutral (and assuming no current returns through the earth). If the phase conductor and the neutral conductor are the same size, these impedances are the same. With a reduced neutral, the 120-V loop impedance is higher. Table 2.19 shows impedances for the reduced neutral size given; for a fully-rated neutral, use the 240-V impedance for the 120-V impedance.

TABLE 2.17

Typical Characteristics of Polyethylene-Covered AAC Triplex

Phase Conductor		Neutral Options (Bare)					
		ACSR Neutral Messenger		Reduced ACSR Neutral Messenger		AAC Neutral Messenger	
Size (Stranding)	Insulation Thickness, mil	Size (Stranding)	Rated Strength, lb	Size (Stranding)	Rated Strength, lb	Size (Stranding)	Rated Strength, lb
6 (1)	45	6 (6/1)	1190				
6 (7)	45	6 (6/1)	1190				
4 (1)	45	4 (6/1)	1860	6 (6/1)	1190	6 (7)	563
4 (7)	45	4 (6/1)	1860	6 (6/1)	1190	4 (7)	881
2 (7)	45	2 (6/1)	2850	4 (6/1)	1860	2 (7)	1350
1/0 (7)	60	1/0 (6/1)	4380	2 (6/1)	2853	1/0 (7)	1990
1/0 (19)	60	1/0 (6/1)	4380	2 (6/1)	2853	1/0 (7)	1990
2/0 (7)	60	2/0 (6/1)	5310	1 (6/1)	3550	2/0 (7)	2510
2/0 (19)	60	2/0 (6/1)	5310	1 (6/1)	3550		
3/0 (19)	60	3/0 (6/1)	6620	1/0 (6/1)	4380	3/0 (19)	3310
4/0 (19)	60	4/1 (6/1)	8350	2/0 (6/1)	5310	4/0 (19)	4020
336.4 (19)	80	336.4 (18/1)	8680	4/0 (6/1)	8350	336.4 (19)	6146

TABLE 2.18

Ampacities of All-Aluminum Triplex

		Conductor temp = 75°C		Conductor temp = 90°C	
Phase Conductor AWG	Strands	25°C Ambient	40°C Ambient	25°C Ambient	40°C Ambient
6	7	85	70	100	85
4	7	115	90	130	115
2	7	150	120	175	150
1/0	7	200	160	235	200
2/0	7	230	180	270	230
3/0	7	265	210	310	265
4/0	7	310	240	360	310

Note: Emissivity = 0.91, absorptivity = 0.91; 30°N at 12 noon in clear atmosphere; wind speed = 2 ft/sec; elevation = sea level.

Source: Aluminum Association, *Ampacities for Aluminum and ACSR Overhead Electrical Conductors*, 1986.

2.9 Fault Withstand Capability

When a distribution line short circuits, very large currents can flow for a short time until a fuse or breaker or other interrupter breaks the circuit. One important aspect of overcurrent protection is to ensure that the fault arc and fault currents do not cause further, possibly more permanent, damage. The two main considerations are:

TABLE 2.19

Typical Impedances of All-Aluminum Triplex Secondaries, **Ω**/1000 ft

Phase		Neutral		120-V Loop Impedance*		240-V Loop Impedance	
Size	Strands	Size	Strands	R_{S1}	X_{S1}	R_S	X_S
2	7	4	7	0.691	0.0652	0.534	0.0633
1	19	3	7	0.547	0.0659	0.424	0.0659
1/0	19	2	7	0.435	0.0628	0.335	0.0616
2/0	19	1	19	0.345	0.0629	0.266	0.0596
3/0	19	1/0	19	0.273	0.0604	0.211	0.0589
4/0	19	2/0	19	0.217	0.0588	0.167	0.0576
250	37	3/0	19	0.177	0.0583	0.142	0.0574
350	37	4/0	19	0.134	0.0570	0.102	0.0558
500	37	300	37	0.095	0.0547	0.072	0.0530

* With a full-sized neutral, the 120-V loop impedance is equal to the 240-V loop impedance.

Source: ABB Inc., *Distribution Transformer Guide*, 1995.

- *Conductor annealing* — From the substation to the fault location, all conductors in the fault-current path must withstand the heat generated by the short-circuit current. If the relaying or fuse does not clear the fault in time, the conductor anneals and loses strength.
- *Burndowns* — Right at the fault location, the hot fault arc can burn the conductor. If a circuit interrupter does not clear the fault in time, the arc will melt the conductor until it breaks apart.

For both annealing and arcing damage, we should design protection to clear faults before more damage is done. To do this, make sure that the time-current characteristics of the relay or fuse are faster than the time-current damage characteristics. Characteristics of annealing and arcing damage are included in the next two sections.

2.9.1 Conductor Annealing

During high currents from faults, conductors can withstand significant temperatures for a few seconds without losing strength. For all-aluminum conductors, assuming a maximum temperature of 340°C during faults is common. ACSR conductors can withstand even higher temperatures because short-duration high temperature does not affect the steel core. An upper limit of 645°C, the melting temperature of aluminum, is often assumed. For short-duration events, we ignore convection and radiation heat losses and assume that all heat stays in the conductor. With all heat staying in the conductor, the temperature is a function of the specific heat of the conductor material. Specific heat is the heat per unit mass required to raise the temperature by one degree Celsius (the specific heat of aluminum is 0.214 cal/g-°C). Considering the heat inputs and the conductor characteristics, the

TABLE 2.20

Conductor Thermal Data for Short-Circuit Limits

Conductor Material	λ, °C	*K*
Copper (97%)	234.0	0.0289
Aluminum (61.2%)	228.1	0.0126
6201 (52.5%)	228.1	0.0107
Steel	180.0	0.00327

Source: Southwire Company, *Overhead Conductor Manual*, 1994.

conductor temperature during a fault is related to the current (Southwire Company, 1994) as

$$\left(\frac{I}{1000A}\right)^2 t = K\log_{10}\left(\frac{T_2+\lambda}{T_1+\lambda}\right)$$

where

I = fault current, A
t = fault duration, sec
A = cross-sectional area of the conductor, kcmil
T_2 = conductor temperature from the fault, °C
T_1 = conductor temperature before the fault, °C
K = constant depending on the conductor, which includes the conductor's resistivity, density, and specific heat (see Table 2.20)
λ = inferred temperature of zero resistance, °C below zero (see Table 2.20)

If we set T_2 to the maximum allowable conductor temperature, we can find the maximum allowable I^2t characteristic for a given conductor. For all-aluminum conductors, with a maximum temperature, T_2 = 340°C, and an ambient of 40°C, the maximum allowable time-current characteristic for a given conductor size (Southwire Company, 1994) is

$$I^2t = (67.1A)^2$$

For ACSR with a maximum temperature of 640˚C, the maximum allowable time-current characteristic for a given conductor size (Southwire Company, 1994) is

$$I^2t = (86.2A)^2$$

Covered conductors have more limited short-circuit capability because the insulation is damaged at lower temperatures. Thermoplastic insulations like polyethylene have a maximum short-duration temperature of 150°C. The thermoset insulations EPR and XLPE have a maximum short-duration tem-

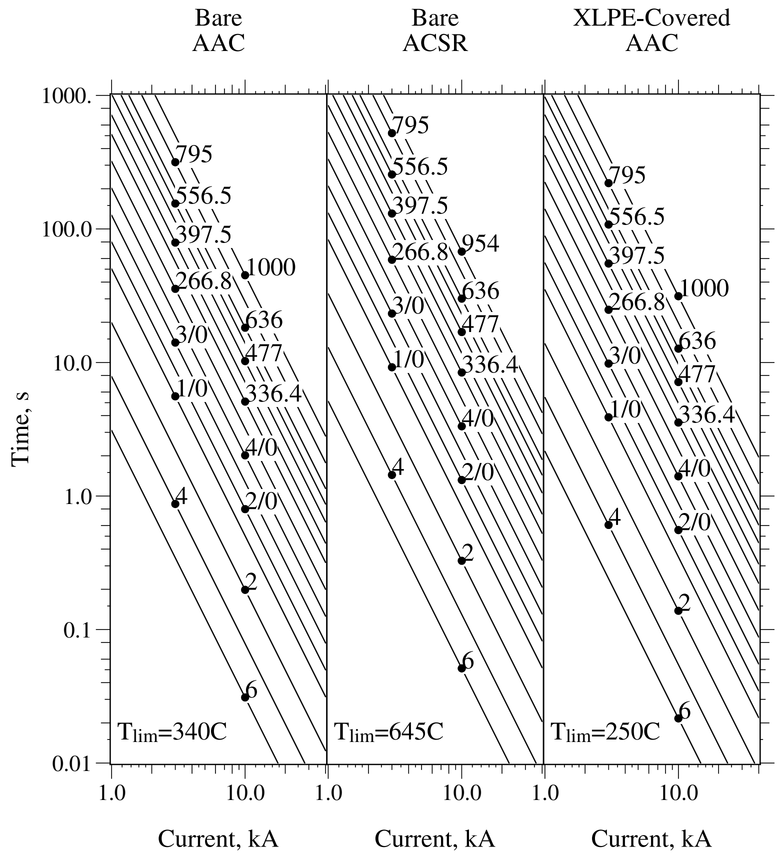

FIGURE 2.12
Annealing curves of bare AAC, ACSR, and covered AAC.

perature of 250°C. With these upper temperature limits (and $T_1 = 40$°C), the allowable time-current characteristics of aluminum conductors are:

$$\text{Polyethylene:} \quad I^2 t = (43A)^2$$

$$\text{XLPE or EPR:} \quad I^2 t = (56A)^2$$

Figure 2.12 compares short-circuit damage curves for various conductors.

2.9.2 Burndowns

Fault-current arcs can damage overhead conductors. The arc itself generates tremendous heat, and where an arc attaches to a conductor, it can weaken or burn conductor strands. On distribution circuits, two problem areas stand out:

1. *Covered conductor* — Covered conductor (also called tree wire or weatherproof wire) holds an arc stationary. Because the arc cannot move, burndowns happen faster than with bare conductors.
2. *Small bare wire on the mains* — Small bare wire (less than 2/0) is also susceptible to wire burndowns, especially if laterals are not fused.

Covered conductors are widely used to limit tree faults. Several utilities have had burndowns of covered conductor circuits when the instantaneous trip was not used or was improperly applied (Barker and Short, 1996; Short and Ammon, 1997). If a burndown on the main line occurs, all customers on the circuit will have a long interruption. In addition, it is a safety hazard. After the conductor breaks and falls to the ground, the substation breaker may reclose. After the reclosure, the conductor on the ground will probably not draw enough fault current to trip the station breaker again. This is a high-impedance fault that is difficult to detect.

A covered conductor is susceptible to burndowns because when a fault current arc develops, the covering prevents the arc from moving. The heat from the arc is what causes the damage. Although ionized air is a fairly good conductor, it is not as good as the conductor itself, so the arc gets very hot. On bare conductors, the arc is free to move, and the magnetic forces from the fault cause the arc to move (in the direction away from the substation; this is called *motoring*). The covering constricts the arc to one location, so the heating and melting is concentrated on one part of the conductor. If the covering is stripped at the insulators and a fault arcs across an insulator, the arc motors until it reaches the covering, stops, and burns the conductor apart at the junction. A party balloon, lightning, a tree branch, a squirrel — any of these can initiate the arc that burns the conductor down. Burndowns are most associated with lightning-caused faults, but it is the fault current arc, not the lightning, that burns most of the conductor.

Conductor damage is a function of the duration of the fault and the current magnitude. Burndown damage occurs much more quickly than conductor annealing that was analyzed in the previous section.

Although they are not as susceptible as covered conductors, bare conductors can also have burndowns. In tests of smaller bare conductors, Florida Power & Light Co. (FP&L) found that the hot gases from the arc anneal the conductor (Lasseter, 1956). They found surprisingly little burning from the arc; in fact, arcs could seriously degrade conductor strength even when there is no visible damage. Objects like insulators or tie wires absorb heat from the ionized gases and reduce the heat to the conductor.

What we would like to do is plot the arc damage characteristic as a function of time and current along with the time-current characteristics of the protective device (whether it be a fuse or a recloser or a breaker). Doing this, we can check that the protective device will clear the fault before the conductor is damaged. Figure 2.13 shows burndown damage characteristics for small bare ACSR conductors along with a 100 K lateral fuse element and a typical ground relay element. The fuse protects the conductors shown, but

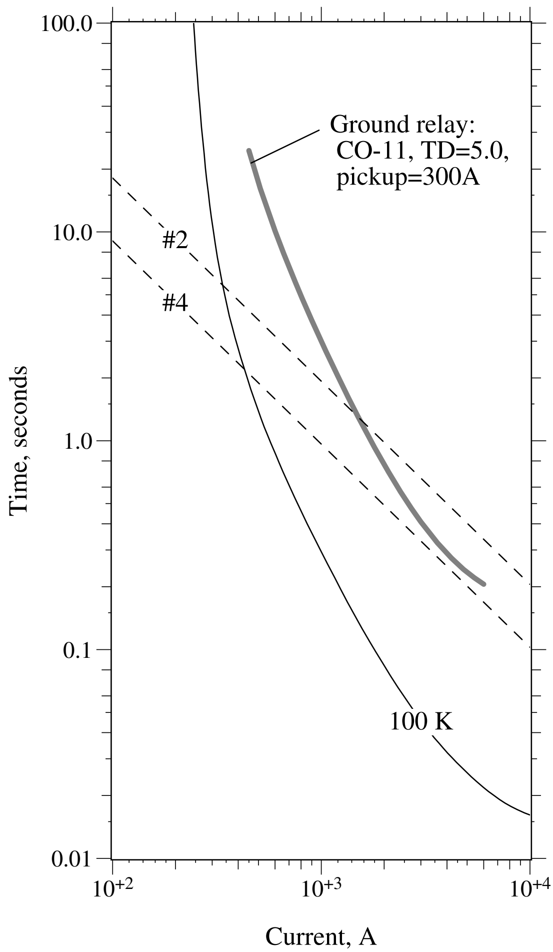

FIGURE 2.13
Bare-conductor ACSR threshold-of-damage curves along with the 100-K lateral fuse total clearing time and a ground relay characteristic. (Damage curves from [Lasseter, 1956].)

the ground relay does not provide adequate protection against damage for these conductors. These damage curves are based on FP&L's tests, where Lasseter reported that the threshold-of-damage was 25 to 50% of the average burndown time (see Table 2.21).

Such arc damage data for different conductor sizes as a function of time and current is limited. Table 2.22 summarizes burndown characteristics of some bare and covered conductors based on tests by Baltimore Gas & Electric (Goode and Gaertner, 1965). Figure 2.14 shows this same data on time-current plots along with a 100 K fuse total clearing characteristic. For conductor sizes not given, take the closest size given in Table 2.22, and scale the burndown time by the ratio of the given conductor area to the area of the desired conductor.

TABLE 2.21

The Burndown Characteristics of Several Small Bare Conductors

Conductor	Threshold of Damage	Average Burndown Time
#4 AAAC	$t = \dfrac{4375}{I^{1.235}}$	$t = \dfrac{17500}{I^{1.235}}$
#4 ACSR	$t = \dfrac{800}{I^{0.973}}$	$t = \dfrac{3350}{I^{0.973}}$
#2 ACSR	$t = \dfrac{1600}{I^{0.973}}$	$t = \dfrac{3550}{I^{0.973}}$
#6 Cu	$t = \dfrac{410}{I^{0.909}}$	$t = \dfrac{1440}{I^{0.909}}$
#4 Cu	$t = \dfrac{500}{I^{0.909}}$	$t = \dfrac{1960}{I^{0.909}}$

Note: I = rms fault current, A; t = fault duration, sec.

Source: Lasseter, J.A., "Burndown Tests on Bare Conductor," *Electric Light and Power*, pp. 94–100, December 1956.

If covered conductor is used, consider the following options to limit burndowns:

- *Fuse saving* — Using a fuse blowing scheme can increase burndowns because the fault duration is much longer on the time-delay relay elements than on the instantaneous element. With fuse saving, the instantaneous relay element trips the circuit faster and reduces conductor damage.
- *Arc protective devices* (APDs) — These sacrificial masses of metal attach to the ends where the covering is stripped (Lee et al., 1980). The arc end attaches to the mass of metal, which has a large enough volume to withstand much more arcing than the conductor itself.
- *Fuse all taps* — Leaving smaller covered conductors unprotected is a sure way of burning down conductors.
- *Tighter fusing* — Not all fuses protect some of the conductor sizes used on taps. Faster fuses reduce the chance of burndowns.
- *Bigger conductors* — Bigger conductors take longer to burn down. Doubling the conductor cross-sectional area approximately doubles the time it takes to burn the conductor down.

Larger bare conductors are fairly immune to burndown. Smaller conductors used on taps are normally safe if protected by a fuse. The solutions for small bare conductors are

- *Fuse all taps* — This is the best option.

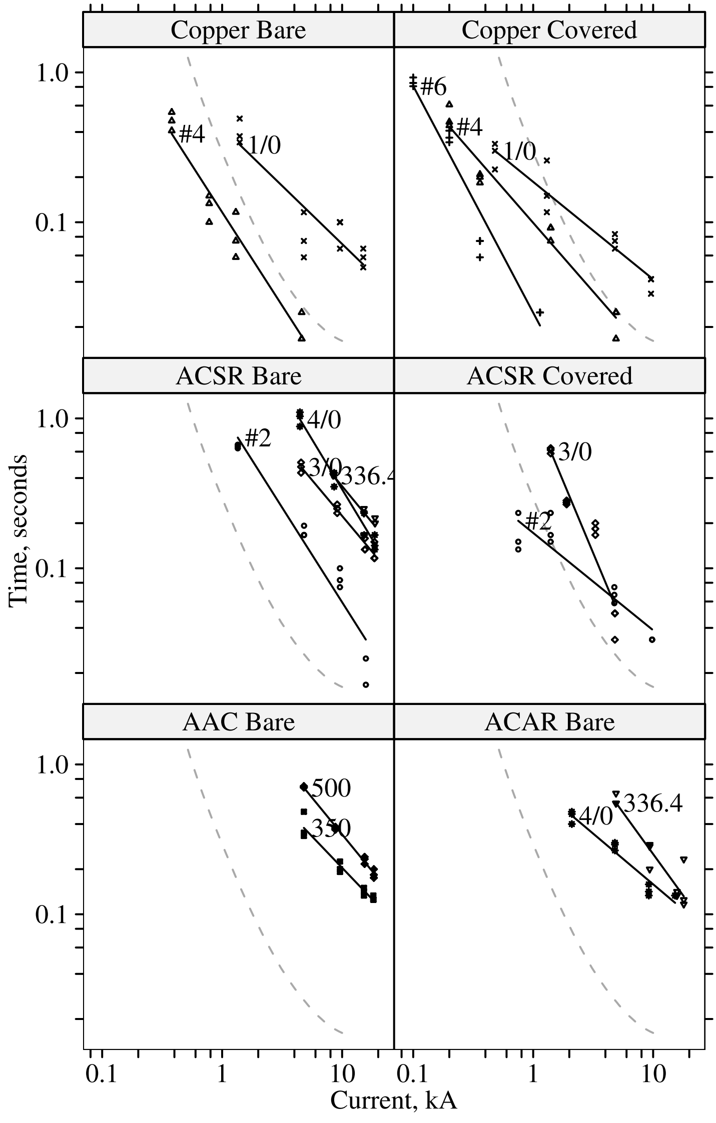

FIGURE 2.14
Burndown characteristics of various conductors. The dashed line is the total clearing time for a 100-K fuse. (Data from [Goode and Gaertner, 1965].)

- *Fuse saving* — The time-delay relay element may not protect smaller tap conductors. Faults cleared by an instantaneous element with fuse saving will not damage bare conductors. If fuse blowing is used, consider an alternative such as a high-set instantaneous or a delayed instantaneous (see Chapter 8 for more information).

TABLE 2.22

Burndown Characteristics of Various Conductors

		Duration, 60-Hz Cycles			
	Current, A	Min	Max	Other	Curvefit
#6 Cu covered	100	48.5	55.5	51	$t = 858/I^{1.51}$
	200	20.5	24.5	22	
	360	3.5	4.5	4.5	
	1140	1.5	1.5	1.5	
#4 Cu covered	200	26.5	36.5	28	$t = 56.4/I^{0.92}$
	360	11	12.5	12	
	1400	4.5	5.5	5.5	
	4900	1	1.5	1.5	
#4 Cu bare	380	24.5	32.5	28.5	$t = 641/I^{1.25}$
	780	6	9	8	
	1300	3.5	7	4.5	
	4600	1	1.5	1	
#2 ACSR covered	750	8	9	14	$t = 15.3/I^{0.65}$
	1400	10	9	14	
	4750	3.5	4.5	4	
	9800	2	2	NA	
#2 ACSR bare	1350	38	39	40	$t = 6718/I^{1.26}$
	4800	10	11.5	10	
	9600	4.5	5	6	
	15750	1	1.5	NA	
1/0 Cu covered	480	13.5	20	18	$t = 16.6/I^{0.65}$
	1300	7	15.5	9	
	4800	4	5	4.5	
	9600	2	2.5	2.5	
1/0 Cu bare	1400	20.5	29.5	22.5	$t = 91/I^{0.78}$
	4800	3.5	7	4.5	
	9600	4	6	6	
	15000	3	4	3.5	
3/0 ACSR covered	1400	35	38	37	$t = 642600/I^{1.92}$
	1900	16	17	16.5	
	3300	10	12	11	
	4800	2	3	3	
3/0 ACSR bare	4550	26	30.5	28.5	$t = 1460/I^{0.95}$
	9100	14	16	15	
	15500	8	9.5	8	
	18600	7	9	7	
4/0 ACAR bare	2100	24	29	28	$t = 80.3/I^{0.68}$
	4800	16	18	17.5	
	9200	8	9.5	8.5	
	15250	8	8	NA	
4/0 ACSR bare	4450	53	66	62	$t = 68810/I^{1.33}$
	8580	21	26	25	
	15250	10	14	NA	
	18700	8	10	8.5	
336.4-kcmil ACAR bare	4900	33	38.5	33	$t = 6610/I^{1.10}$
	9360	12	17.5	17	
	15800	8	8.5	8	
	18000	7	14	7.5	

TABLE 2.22 (Continued)

Burndown Characteristics of Various Conductors

	Current, A	Duration, 60-Hz Cycles Min	Max	Other	Curvefit
336.4-kcmil ACSR bare	8425	25	26	26	$t = 2690/I^{0.97}$
	15200	10	15	14	
	18800	12	13	12	
350-kcmil AAC bare	4800	29	21	20	$t = 448/I^{0.84}$
	9600	11.5	13.5	12	
	15200	8	9	8.5	
	18200	8	7.5	7.5	
500-kcmil AAC bare	4800	42	43	42.5	$t = 2776/I^{0.98}$
	8800	22.5	23	22	
	15400	13	14.5	14	
	18400	11	12	10.5	

Source: Goode, W.B. and Gaertner, G.H., "Burndown Tests and Their Effect on Distribution Design," EEI T&D Meeting, Clearwater, FL, Oct. 14–15, 1965.

2.10 Other Overhead Issues

2.10.1 Connectors and Splices

Connectors and splices are often weak links in the overhead system, either due to hostile environment or bad designs or, most commonly, poor installation. Utilities have had problems with connectors, especially with higher loadings (Jondahl et al., 1991).

Most primary connectors use some sort of compression to join conductors (see Figure 2.15 for common connectors). Compression splices join two conductors together — two conductors are inserted in each end of the sleeve, and a compression tool is used to tighten the sleeve around the conductors. For conductors under tension, automatic splices are also available. Crews just insert the conductors in each end, and serrated clamps within the splice grip the conductor; with higher tension, the wedging action holds tighter.

For tapping a smaller conductor off of a larger conductor, many options are available. Hot-line clamps use a threaded bolt to hold the conductors together. Wedge connectors have a wedge driven between conductors held by a C-shaped body. Compression connectors (commonly called *squeeze-ons*) use dies and compression tools to squeeze together two conductors and the connector.

Good cleaning is essential to making a good contact between connector surfaces. Both copper and aluminum develop a hard oxide layer on the surface when exposed to air. While very beneficial in preventing corrosion, the oxide layer has high electrical resistance. Copper is relatively easy to brush clean. Aluminum is tougher; crews need to work at it harder, and a

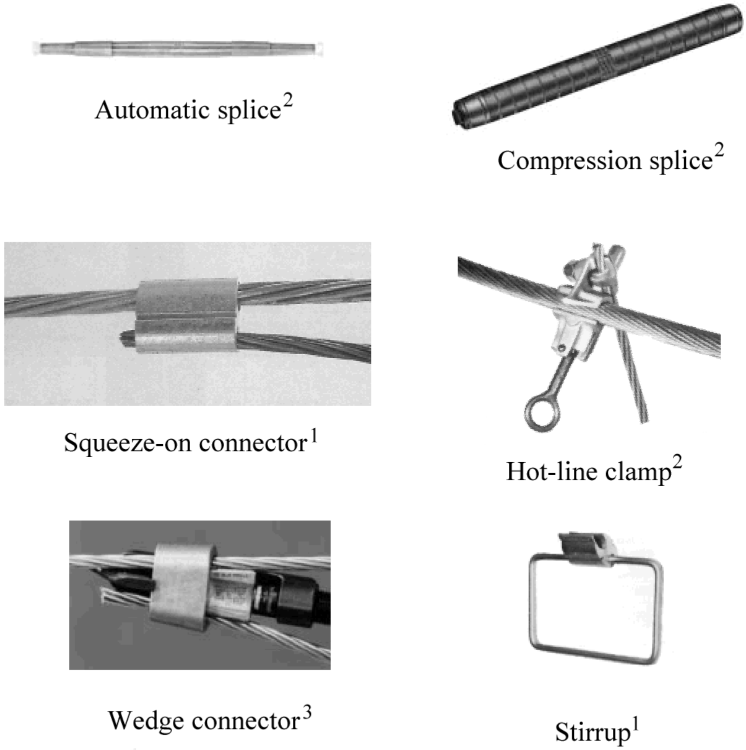

FIGURE 2.15
Common distribution connectors. [1] Reprinted with the permission of Cooper Industries, Inc. [2] Reprinted with the permission of Hubbell Power Systems, Inc. [3] Reprinted with the permission of Tyco Electronics Corporation.

shiny surface is no guarantee of a good contact. Aluminum oxidizes quickly, so crews should clean conductors just before attaching the connector. Without good cleaning, the temperatures developed at the hotspot can anneal the conductor, possibly leading to failure. Joint compounds are important; they inhibit oxidation and help maintain a good contact between joint surfaces.

Corrosion at interfaces can prematurely fail connectors and splices. Galvanic corrosion can occur quickly between dissimilar metals. For this reason, aluminum connectors are used to join aluminum conductors. Waterproof joint compounds protect conductors and joints from corrosion.

Aluminum expands and contracts with temperature, so swings in conductor temperature cause the conductor to creep with respect to the connector. This can loosen connectors and allow oxidation to develop between the connector and conductor. ANSI specifies a standard for connectors to withstand thermal cycling and mechanical stress (ANSI C119.4-1998).

Poor quality work leads to failures. Not using joint compound (or not using enough), inadequate conductor cleaning, misalignments, not fully inserting the conductor prior to compression, or using the wrong dies — any of these mistakes can cause a joint to fail prematurely.

Infrared thermography is the primary way utilities spot bad connectors. A bad connection with a high contact resistance operates at significantly higher temperatures than the surrounding conductor. While infrared inspections are easy for crews to do, they are not foolproof; they can miss bad connectors and falsely target good conductors. Infrared measurements are very sensitive to sunlight, line currents, and background colors. Temperature differences are most useful (but still not perfect indicators). Experience and visual checks of the connector can help identify false readings (such as glare due to sunlight reflection). A bad connector can become hot enough to melt the conductor, but often the conductor can resolidify, temporarily at a lower resistance. Infrared inspections can miss these bad connectors if they are in the resolidified stage. For compression splices, EPRI laboratory tests and field inspections found high success rates using hotstick-mounted resistance measuring devices that measure the resistance across a short section of the conductor (EPRI 1001913, 2001).

Short-circuit current can also damage inline connectors. Mechanical stresses and high currents can damage some splices and connectors. If an inline connector does not make solid contact at its interfaces to the conductor, hotspots can weaken and possibly break the connector or conductor. If the contact is poor enough to cause arcing, the arcing can quickly eat the connection away. Mechanical forces can also break an already weakened or corroded connector.

Hot-line clamps are popular connectors that crews can easily apply with hot-line tools. Threaded bolts provide compression between conductors. Hot-line clamps can become loose, especially if not installed correctly. Utilities have had problems with hot-line clamps attached directly to primary conductors, especially in series with the circuit (rather than tapped for a jumper to equipment) where they are subjected to the heat and mechanical forces of fault currents. Loose or high-resistance hot-line clamps can arc across the interface, quickly burning away the primary conductor.

Stirrups are widely used between the main conductor and a jumper to a transformer or capacitor bank. A stirrup is a bail or loop of wire attached to the main conductor with one or two compression connectors or hot-line connectors. Crews can quickly make a connection to the stirrup with hot-line clamps. The main reason for using the stirrup is to protect the main conductor from burndown. If tied directly to the main conductor, arcing across a poor connection can burn the main conductor down. If a poor hot-line clamp is connected to a stirrup, the stirrup may burn down, but the main line is protected. Also, any arcing when crews attach or detach the connector does not damage the main conductor, so stirrups are especially useful where jumpers may be put on and taken off several times. Using stirrups is reliable; a survey by the National Rural Electric Cooperative Association (NRECA) found that less than 10% of utilities have annual failure rates between 1 and 5%, and almost all of the remainder have failure rates less than 1% (RUS, 1996).

2.10.2 Radio Frequency Interference

Distribution line hardware can generate radio-frequency interference (RFI). Such interference can impact the AM and FM bands as well as VHF television broadcasts. Ham radio frequencies are also affected.

Most power-line noise is from arcs — arcs across gaps on the order of 1 mm, usually at poor contacts. These arcs can occur between many metallic junctions on power-line equipment. Consider two metal objects in close proximity but not quite touching. The capacitive voltage divider between the conducting parts determines the voltage differences between them. The voltage difference between two metallic pieces can cause an arc across a small gap. After arcing across, the gap can clear easily, and after the capacitive voltage builds back up, it can spark over again. These sparkovers radiate radio-frequency noise. Stronger radio-frequency interference is more likely from hardware closer to the primary conductors.

Arcing generates broadband radio-frequency noise from several kilohertz to over 1000 MHz. Above about 50 MHz, the magnitude of arcing RFI drops off. Power-line interference affects lower frequency broadcasts more than higher frequencies. The most common from low to high frequency are: AM radio (0.54 to 1.71 MHz), low-band VHF TV (channels 2 to 6, 54 to 88 MHz), FM radio (88.1 to 107.9 MHz), and high-band VHF TV (channels 7 to 13, 174 to 216 MHz). UHF (ultra-high frequencies, about 500 MHz) are only created right near the sparking source.

On an oscilloscope, arcing interference looks like a series of noise spikes clustered around the peaks of the sinusoidal power-frequency driving voltage (see Figure 2.16). Often power-line noise causes a raspy sound, usually with a 120-Hz characteristic. The "sound" of power-line noise varies depending on the length of the arcing gap, so interference cannot always be identified by a specific characteristic sound (Loftness, 1997).

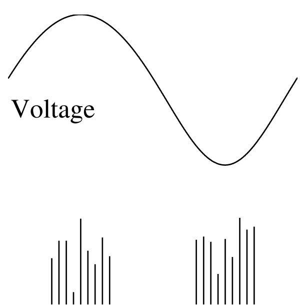

FIGURE 2.16
Arcing source creating radio-frequency interference.

Arcing across small gaps accounts for almost all radio-frequency interference created by utility equipment on distribution circuits. Arcing from corona can also cause interference, but distribution circuit voltages are too low for corona to cause significant interference. Radio interference is more common at higher distribution voltages.

Some common sources and solutions include [for more detail, see (Loftness, 1996; NRECA 90-30, 1992)]:

- *Loose or corroded hot-line clamps* — Replace the connector. After cleaning the conductor and applying fresh inhibitor replace the clamp with a new hot-line clamp or a wedge connector or a squeeze-on connector.
- *Loose nut and washer on a through bolt* — Commonly a problem on double-arming bolts between two crossarms; use lock washers and tighten.
- *Loose or broken insulator tie wire or incorrect tie wire* — Loose tie wires can cause arcing, and conducting ties on covered conductors generate interference; in either case, replace the tie wire.
- *Loose dead-end insulator units* — Replace, preferably with single-unit types. Semiconductive grease provides a short-term solution.
- *Loose metal staples on bonding or ground wires, especially near the top* — Replace with insulated staples (hammering in existing staples may only help for the short term).
- *Loose crossarm lag screw* — Replace with a larger lag screw or with a through bolt and lock washers.
- *Bonding conductors touching or nearly touching other metal hardware* — Separate by at least 1 in. (2.54 cm).
- *Broken or contaminated insulators* — Clean or replace.
- *Defective lightning arresters, especially gapped units* — Replace.

Most of these problems have a common characteristic: gaps between metals, often from loose hardware. Crews can fix most problems by tightening connections, separating metal hardware by at least 1 in., or bonding hardware together. Metal-to-wood interfaces are less likely to cause interference; a tree branch touching a conductor usually does not generate radio-frequency interference.

While interference is often associated with overhead circuits, underground lines can also generate interference. Again, look for loose connections, either primary or secondary such as in load-break elbows.

Interference from an arcing source can propagate in several ways: radiation, induction, and conduction. RFI can radiate from the arcing source just like a radio transmitter. It can conduct along a conductor and also couple inductively from one conductor to parallel conductors. Lower frequencies propagate farther; AM radio is affected over larger distances. Interference is roughly in inverse proportion to frequency at more than a few poles from the source.

Many different interference detectors are available; most are radios with directional antennas. Closer to the source, instruments can detect radio-frequency noise at higher and higher frequencies, so higher frequencies can help pinpoint sources. As you get closer to the source, follow the highest frequency that you can receive. (If you cannot detect interference at higher and higher frequencies as you drive along the line, you are probably going in the wrong direction.) Once a problem pole is identified, an ultrasonic detector with a parabolic dish can zero in on problem areas to identify where the arcing is coming from. Ultrasonic detectors measure ultra-high frequency sound waves (about 20 to 100 kHz) and give accurate direction to the source. Ultrasonic detectors almost require line-of-sight to the arcing source, so they do not help if the arcing is hidden. In such cases, the sparking may be internal to an enclosed device, or the RF could be conducted to the pole by a secondary conductor or riser pole. For even more precise location, crews can use hot-stick mounted detectors to identify exactly what's arcing.

Note that many other nonutility sources of radio-frequency interference exist. Many of these also involve intermittent arcing. Common power-frequency type sources include fans, light dimmers, fluorescent lights, loose wiring within the home or facility, and electrical tools such as drills. Other sources include defective antennas, amateur or CB radios, spark-plug ignitions from vehicles or lawn mowers, home computers, and garage door openers.

References

ABB, *Distribution Transformer Guide*, 1995.

Aluminum Association, *Ampacities for Aluminum and ACSR Overhead Electrical Conductors*, 1986.

Aluminum Association, *Aluminum Electrical Conductor Handbook*, 1989.

ANSI C119.4-1998, *Electric Connectors for Use Between Aluminum-to-Aluminum or Aluminum-to-Copper Bare Overhead Conductors*.

Barber, K., "Improvements in the Performance and Reliability of Covered Conductor Distribution Systems," International Covered Conductor Conference, Cheshire, U.K., January 1999.

Barker, P.P. and Short, T.A., "Findings of Recent Experiments Involving Natural and Triggered Lightning," IEEE/PES Transmission and Distribution Conference, Los Angeles, CA, 1996.

Black, W.Z. and Rehberg, R.L., "Simplified Model for Steady State and Real-Time Ampacity of Overhead Conductors," *IEEE Transactions on Power Apparatus and Systems*, vol. 104, pp. 29–42, October 1985.

Carson, J.R., "Wave Propagation in Overhead Wires with Ground Return," Bell System Technical Journal, vol. 5, pp. 539–54, 1926.

Clapp, A.L., *National Electrical Safety Code Handbook*, The Institute of Electrical and Electronics Engineers, Inc., 1997.

Clarke, E., *Circuit Analysis of AC Power Systems, II,* General Electric Company, 1950.
Ender, R.C., Auer, G.G., and Wylie, R.A., "Digital Calculation of Sequence Impedances and Fault Currents for Radial Primary Distribution Circuits," *AIEE Transactions on Power Apparatus and Systems*, vol. 79, pp. 1264–77, 1960.
EPRI 1001913, *Electrical, Mechanical, and Thermal Performance of Conductor Connections*, Electric Power Research Institute, Palo Alto, CA, 2001.
EPRI, *Transmission Line Reference Book: 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, CA, 1982.
Goode, W.B. and Gaertner, G.H., "Burndown Tests and Their Effect on Distribution Design," EEI T&D Meeting, Clearwater, FL, Oct. 14–15, 1965.
Harvey, J.R., "Effect of Elevated Temperature Operation on the Strength of Aluminum Conductors," IEEE/PES Winter Power Meeting Paper T 72 189–4, 1971. As cited by Southwire (1994).
House, H.E. and Tuttle, P.D., "Current Carrying Capacity of ACSR," *IEEE Transactions on Power Apparatus and Systems*, pp. 1169–78, February 1958.
IEEE C2-2000, *National Electrical Safety Code Handbook*, The Institute of Electrical and Electronics Engineers, Inc.
IEEE Std. 738-1993, *IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors*.
Jondahl, D.W., Rockfield, L.M., and Cupp, G.M., "Connector Performance of New vs. Service Aged Conductor," IEEE/PES Transmission and Distribution Conference, 1991.
Kurtz, E.B., Shoemaker, T.M., and Mack, J.E., *The Lineman's and Cableman's Handbook*, McGraw Hill, New York, 1997.
Lasseter, J.A., "Burndown Tests on Bare Conductor," *Electric Light & Power*, pp. 94–100, December 1956.
Lat, M.V., "Determining Temporary Overvoltage Levels for Application of Metal Oxide Surge Arresters on Multigrounded Distribution Systems," *IEEE Transactions on Power Delivery*, vol. 5, no. 2, pp. 936–46, April 1990.
Lee, R.E., Fritz, D.E., Stiller, P.H., Kilar, L.A., and Shankle, D.F., "Prevention of Covered Conductor Burndown on Distribution Circuits," American Power Conference, 1980.
Loftness, M.O., *AC Power Interference Field Manual*, Percival Publishing, Tumwater, WA, 1996.
Loftness, M.O., "Power Line RF Interference — Sounds, Patterns, and Myths," *IEEE Transactions on Power Delivery*, vol. 12, no. 2, pp. 934–40, April 1997.
NRECA 90-30, *Power Line Interference: A Practical Handbook*, National Rural Electric Cooperative Association, 1992.
RUS 160-2, *Mechanical Design Manual for Overhead Distribution Lines*, United States Department of Agriculture, Rural Utilities Service, 1982.
RUS 1728F-803, *Specifications and Drawings for 24.9/14.4 kV Line Construction*, United States Department of Agriculture, Rural Utilities Service, 1998.
RUS, "Summary of Items of Engineering Interest," United States Department of Agriculture, Rural Utilities Service, 1996.
Short, T.A. and Ammon, R.A., "Instantaneous Trip Relay: Examining Its Role," *Transmission and Distribution World*, vol. 49, no. 2, 1997.
Smith, D.R., "System Considerations — Impedance and Fault Current Calculations," *IEEE Tutorial Course on Application and Coordination of Reclosers, Sectionalizers, and Fuses*, 1980. Publication 80 EHO157-8-PWR.
Southwire Company, *Overhead Conductor Manual*, 1994.

Stevenson, W.D., *Elements of Power System Analysis*, 2nd ed., McGraw Hill, New York, 1962.
Willis, H.L., *Power Distribution Planning Reference Book*, Marcel Dekker, New York, 1997.

Saying "You can't do that" to a Lineman is the same as saying "Hey, how about a contest?"

Powerlineman law #23, By CD Thayer and other Power Linemen, http://www.cdthayer.com/lineman.htm