3

Underground Distribution

Much new distribution is underground. Underground distribution is much more hidden from view than overhead circuits, and is more reliable. Cables, connectors, and installation equipment have advanced considerably in the last quarter of the 20th century, making underground distribution installations faster and less expensive.

3.1 Applications

One of the main applications of underground circuits is for underground residential distribution (URD), underground branches or loops supplying residential neighborhoods. Utilities also use underground construction for substation exits and drops to padmounted transformers serving industrial or commercial customers. Other uses are crossings: river crossings, highway crossings, or transmission line crossings. All-underground construction — widely used for decades in cities — now appears in more places.

Underground construction is expensive, and costs vary widely. Table 3.1 shows extracts from one survey of costs done by the CEA; the two utilities highlighted differ by a factor of ten. The main factors that influence underground costs are:

- *Degree of development* — Roads, driveways, sidewalks, and water pipes — these and other obstacles slow construction and increase costs.
- *Soil condition* — Rocks and frozen ground increase overtime pay for cable crews.
- *Urban, suburban, or rural* — Urban construction is more difficult not only because of concrete, but also because of traffic. Rural construction is generally the least expensive per length, but lengths are long.
- *Conduit* — Concrete-encased ducts cost more than direct-buried conduits, which cost more than preassembled flexible conduit, which cost more than directly buried cable with no conduits.

TABLE 3.1

Comparison of Costs of Different Underground Constructions at Different Utilities

Utility	Construction	$/ft[a]
TAU	Rural or urban, 1 phase, #2 Al, 25 kV, trenched, direct buried	6.7
	Rural, 3 phase, #2 Al, 25 kV, trenched, direct buried	13.4
	Urban commercial, 3 phase, #2 Al, 25 kV, trenched, direct buried	13.4
	Urban express, 3 phase, 500-kcmil Al, 25 kV, trenched, direct buried	23.5
WH	Urban, 1 phase, 1/0 Al, 12.5 kV, trenched, conduit	84.1
	Urban commercial, 3 phase, 1/0 Al, 12.5 kV, trenched, conduit	117.7
	Urban express, 3 phase, 500-kcmil Cu, 12.5 kV, trenched, conduit	277.4

[a] Converted assuming that one 1991 Canadian dollar equals 1.1 U.S. dollars in 2000.

Source: CEA 274 D 723, *Underground Versus Overhead Distribution Systems*, Canadian Electrical Association, 1992.

- *Cable size and materials* — The actual cable cost is a relatively small part of many underground applications. A 1/0 aluminum full-neutral 220-mil TR-XLPE cable costs just under $2 per ft; with a 500-kcmil conductor and a one-third neutral, the cable costs just under $4 per ft.
- *Installation equipment* — Bigger machines and machines more appropriate for the surface and soil conditions ease installations.

3.1.1 Underground Residential Distribution (URD)

A classic underground residential distribution circuit is an underground circuit in a loop arrangement fed at each end from an overhead circuit (see Figure 3.1). The loop arrangement allows utilities to restore customers more quickly; after crews find the faulted section, they can reconfigure the loop and isolate any failed section of cable. This returns power to all customers. Crews can delay replacing or fixing the cable until a more convenient time or when suitable equipment arrives. Not all URD is configured in a loop. Utilities sometimes use purely radial circuits or circuits with radial taps or branches.

Padmounted transformers step voltage down for delivery to customers and provide a sectionalizing point. The elbow connectors on the cables (pistol grips) attach to bushings on the transformer to maintain a dead-front — no exposed, energized conductors. To open a section of cable, crews can simply pull an elbow off of the transformer bushing and place it on a parking stand, which is an elbow bushing meant for holding an energized elbow connector.

Elbows and other terminations are available with continuous-current ratings of 200 or 600 A (IEEE Std. 386-1995). Load-break elbows are designed to break load; these are only available in 200-A ratings. Without load-break capability, crews should of course only disconnect the elbow if the cable is deenergized. Elbows normally have a test point where crews can check if

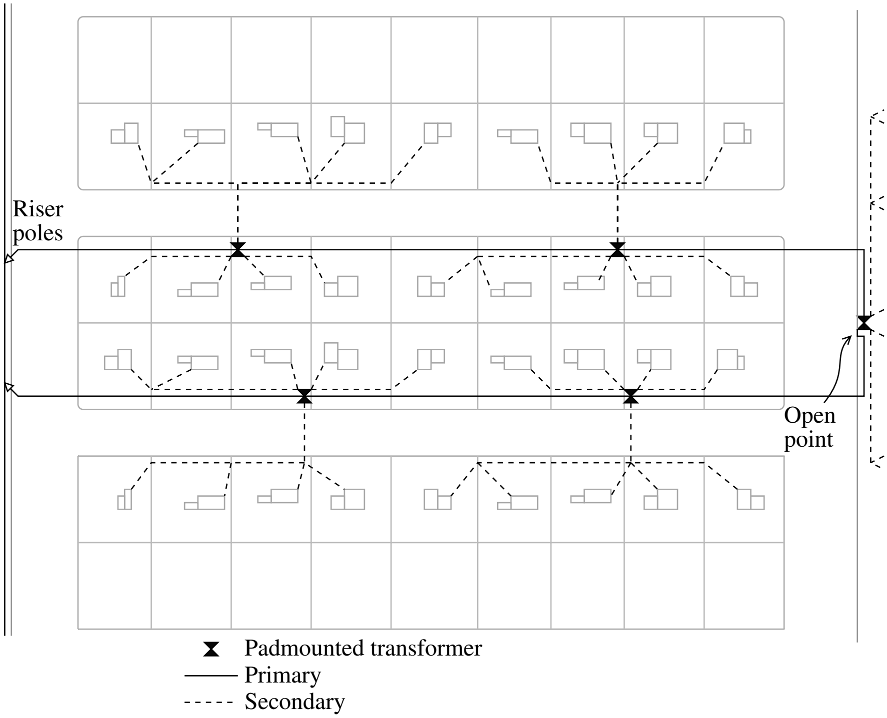

FIGURE 3.1
An example front-lot underground residential distribution (URD) system.

the cable is live. Elbows are also tested to withstand ten cycles of fault current, with 200-A elbows tested at 10 kA and 600-A elbows tested at 25 kA (IEEE Std. 386-1995).

The interface between the overhead circuit and the URD circuit is the riser pole. At the riser pole (or a dip pole or simply a dip), cable terminations provide the interface between the insulated cable and the bare overhead conductors. These pothead terminations grade the insulation to prevent excessive electrical stress on the insulation. Potheads also keep water from entering the cable, which is critical for cable reliability. Also at the riser pole are expulsion fuses, normally in cutouts. Areas with high short-circuit current may also have current-limiting fuses. To keep lightning surges from damaging the cable, the riser pole should have arresters right across the pothead with as little lead length as possible.

Underground designs for residential developments expanded dramatically in the 1970s. Political pressure coupled with technology improvements were the driving forces behind underground distribution. The main developments — direct-buried cables and padmounted transformers having load-break elbows — dramatically reduced the cost of underground distribution to close to that of overhead construction. In addition to improving the visual landscape, underground construction improves reliability. Underground residential distribution has had difficulties, especially high cable failure rates. In the late 1960s and early 1970s, given the durability of plastics, the polyethylene cables installed at that time were thought to have a life of at least 50 years. In practice, cables failed at a much higher rate than expected, enough so that many utilities had to replace large amounts of this cable.

According to Boucher (1991), 72% of utilities use front-lot designs for URD. With easier access and fewer trees and brush to clear, crews can more easily install cables along streets in the front of yards. Customers prefer rear-lot service, which hides padmounted transformers from view. Back-lot placement can ease siting issues and may be more economical if lots share rear property lines. But with rear-lot design, utility crews have more difficulty accessing cables and transformers for fault location, sectionalizing, and repair.

Of those utilities surveyed by Boucher (1991), 85% charge for underground residential service, ranging from $200 to $1200 per lot (1991 dollars). Some utilities charge by length, which ranges from $5.80 to $35.00 per ft.

3.1.2 Main Feeders

Whether urban, suburban, or even rural, all parts of a distribution circuit can be underground, including the main feeder. For reliability, utilities often configure an underground main feeder as a looped system with one or more tie points to other sources. Switching cabinets or junction boxes serve as tie points for tapping off lateral taps or branches to customers. These can be in handholes, padmounted enclosures, or pedestals above ground. Three-phase circuits can also be arranged much like URD with sections of cable run between three-phase padmounted transformers. As with URD, the padmounted transformers serve as switching stations.

Although short, many feeders have an important underground section — the substation exit. Underground substation exits make substations easier to design and improve the aesthetics of the substation. Because they are at the substation, the source of a radial circuit, substation exits are critical for reliability. In addition, the loading on the circuit is higher at the substation exit than anywhere else; the substation exit may limit the entire circuit's ampacity. Substation exits are not the place to cut corners. Some strategies to reduce the risks of failures or to speed recovery are: concrete-enclosed ducts to help protect cables, spare cables, overrated cables, and good surge protection.

While not as critical as substation exits, utilities use similar three-phase underground dips to cross large highways or rivers or other obstacles. These are designed in much the same way as substation exits.

3.1.3 Urban Systems

Underground distribution has reliably supplied urban systems since the early 1900s. Cables are normally installed in concrete-encased duct banks beneath streets, sidewalks, or alleys. A duct bank is a group of parallel ducts, usually with four to nine ducts but often many more. Ducts may be precast concrete sections or PVC encased in concrete. Duct banks carry both primary and secondary cables. Manholes every few hundred feet provide access to cables. Transformers are in vaults or in the basements of large buildings.

Paper-insulated lead-covered (PILC) cables dominated urban applications until the late 20th century. Although a few utilities still install PILC, most use extruded cable for underground applications. In urban applications, copper is more widely used than in suburban applications. Whether feeding secondary networks or other distribution configurations, urban circuits may be subjected to heavy loads.

"Vertical" distribution systems are necessary in very tall buildings. Medium-voltage cable strung up many floors feed transformers within a building. Submarine cables are good for this application since their protective armor wire provides support when a cable is suspended for hundreds of feet.

3.1.4 Overhead vs. Underground

Overhead or underground? The debate continues. Both designs have advantages (see Table 3.2). The major advantage of overhead circuits is cost; an underground circuit typically costs anywhere from 1 to 2.5 times the equivalent overhead circuit (see Table 3.3). But the cost differences vary wildly, and it's often difficult to define "equivalent" systems in terms of performance. Under the right conditions, some estimates of cost report that cable installations can be less expensive than overhead lines. If the soil is easy to dig, if the soil has few rocks, if the ground has no other obstacles like water pipes or telephone wires, then crews may be able to plow in cable faster and for less cost than an overhead circuit. In urban areas, underground is almost the only choice; too many circuits are needed, and above-ground space is too expensive or just not available. But urban duct-bank construction is expensive on a per-length basis (fortunately, circuits are short in urban appli-

TABLE 3.2

Overhead vs. Underground: Advantages of Each

Overhead	Underground
Cost — Overhead's number one advantage. Significantly less cost, especially initial cost.	*Aesthetics* — Underground's number one advantage. Much less visual clutter.
Longer life — 30 to 50 years vs. 20 to 40 for new underground works.	*Safety* — Less chance for public contact.
Reliability — Shorter outage durations because of faster fault finding and faster repair.	*Reliability* — Significantly fewer short and long-duration interruptions.
Loading — Overhead circuits can more readily withstand overloads.	*O&M* — Notably lower maintenance costs (no tree trimming).
	Longer reach — Less voltage drop because reactance is lower.

TABLE 3.3

Comparison of Underground Construction Costs with Overhead Costs

Utility		Construction	$/ft[a]	Underground to overhead ratio
Single-Phase Lateral Comparisons				
NP	Overhead	1/0 AA, 12.5 kV, phase and neutral	8.4	
NP	Underground	1/0 AA, 12.5 kV, trenched, in conduit	10.9	1.3
APL	Overhead	Urban, #4 ACSR, 14.4 kV	2.8	
APL	Underground	Urban, #1 AA, 14.4 kV, trenched, direct buried	6.6	2.4
Three-Phase Mainline Comparisons				
NP	Overhead	Rural, 4/0 AA, 12.5 kV	10.3	
NP	Underground	Rural, 1/0 AA, 12.5 kV, trenched, in conduit	17.8	1.7
NP	Overhead	Urban, 4/0 AA, 12.5 kV	10.9	
NP	Underground	Urban, 4/0 AA, 12.5 kV, trenched, in conduit	17.8	1.6
APL	Overhead	Urban, 25 kV, 1/0 ACSR	8.5	
APL	Underground	Urban, 25 kV, #1 AA, trenched, direct buried	18.8	2.2
EP	Overhead	Urban, 336 ACSR, 13.8 kV	8.7	
EP	Underground	Urban residential, 350 AA, 13.8 kV, trenched, direct buried	53.2	6.1
EP	Underground	Urban commercial, 350 AA, 13.8 kV, trenched, direct buried	66.8	7.6

[a] Converted assuming that one 1991 Canadian dollar equals 1.1 U.S. dollars in 2000.

Source: CEA 274 D 723, *Underground Versus Overhead Distribution Systems*, Canadian Electrical Association, 1992.

cations). On many rural applications, the cost of underground circuits is difficult to justify, especially on long, lightly loaded circuits, given the small number of customers that these circuits feed.

Aesthetics is the main driver towards underground circuits. Especially in residential areas, parks, wildlife areas, and scenic areas, visual impact is important. Undergrounding removes a significant amount of visual clutter. Overhead circuits are ugly. It is possible to make overhead circuits less ugly with tidy construction practices, fiberglass poles instead of wood, keeping poles straight, tight conductor configurations, joint use of poles to reduce the number of poles, and so on. Even the best though, are still ugly, and many older circuits look awful (weathered poles tipped at odd angles, crooked crossarms, rusted transformer tanks, etc.).

Underground circuits get rid of all that mess, with no visual impacts in the air. Trees replace wires, and trees don't have to be trimmed. At ground level, instead of poles every 150 ft (many having one or more guy wires) urban construction has no obstacles, and URD-style construction has just padmounted transformers spaced much less frequently. Of course, for maximum benefit, all utilities must be underground. There is little improvement to undergrounding electric circuits if phone and cable television are still strung on poles (i.e., if the telephone wires are overhead, you might as well have the electric lines there, too).

While underground circuits are certainly more appealing when finished, during installation construction is messier than overhead installation. Lawns, gardens, sidewalks, and driveways are dug up; construction lasts longer; and the installation "wounds" take time to heal. These factors don't matter much when installing circuits into land that is being developed, but it can be upsetting to customers in an existing, settled community.

Underground circuits are more reliable. Overhead circuits typically fault about 90 times/100 mi/year; underground circuits fail less than 10 times/100 mi/year. Because overhead circuits have more faults, they cause more voltage sags, more momentary interruptions, and more long-duration interruptions. Even accounting for the fact that most overhead faults are temporary, overhead circuits have more permanent faults that lead to long-duration circuit interruptions. The one disadvantage of underground circuits is that when they do fail, finding the failure is harder, and fixing the damage or replacing the equipment takes longer. This can partially be avoided by using loops capable of serving customers from two directions, by using conduits for faster replacement, and by using better fault location techniques. Underground circuits are much less prone to the elements. A major hurricane may drain an overhead utility's resources, crews are completely tied up, customer outages become very long, and cleanup costs are a major cost to utilities. However, underground circuits are not totally immune from the elements. In "heat storms," underground circuits are prone to rashes of failures. Underground circuits have less overload capability than overhead circuits; failures increase with operating temperature.

In addition to less storm cleanup, underground circuits require less periodic maintenance. Underground circuits don't require tree trimming, easily the largest fraction of most distribution operations and maintenance budgets. The CEA (1992) estimated that underground system maintenance averaged 2% of system plant investment whereas overhead systems averaged 3 to 4%, or as much as twice that of underground systems.

Underground circuits are safer to the public than overhead circuits. Overhead circuits are more exposed to the public. Kites, ladders, downed wires, truck booms — despite the best public awareness campaigns, these still expose the public to electrocution from overhead lines. Don't misunderstand; underground circuits still have dangers, but they're much less than on overhead circuits. For the public, dig-ins are the most likely source of contact. For utility crews, both overhead and underground circuits offer dangers that proper work practices must address to minimize risks.

We cannot assume that underground infrastructure will last as long as overhead circuits. Early URD systems failed at a much higher rate than expected. While most experts believe that modern underground equipment is more reliable, it is still prudent to believe that an overhead circuit will last 40 years, while an underground circuit will only last 30 years.

Overhead vs. underground is not an all or nothing proposition. Many systems are hybrids; some schemes are:

- *Overhead mainline with underground taps* — The larger, high-current conductors are overhead. If the mains are routed along major roads, they have less visual impact. Lateral taps down side roads and into residential areas, parks, and shopping areas are underground. Larger primary equipment like regulators, reclosers, capacitor banks, and automated switches are installed where they are more economical — on the overhead mains. Because the mainline is a major contributor to reliability, this system is still less reliable than an all-underground system.
- *Overhead primary with underground secondary* — Underground secondary eliminates some of the clutter associated with overhead construction. Eliminating much of the street and yard crossings keeps the clutter to the pole-line corridor. Costs are reasonable because the primary-level equipment is still all overhead.

Converting from overhead to underground is costly, yet there are locations and situations where it is appropriate for utilities and their customers. Circuit extensions, circuit enhancements to carry more load, and road-rebuilding projects — all are opportunities for utilities and communities to upgrade to underground service.

3.2 Cables

At the center of a cable is the phase conductor, then comes a semiconducting conductor shield, the insulation, a semiconducting insulation shield, the neutral or shield, and finally a covering jacket. Most distribution cables are single conductor. Two main types of cable are available: concentric-neutral cable and power cable. Concentric-neutral cable normally has an aluminum conductor, an extruded insulation, and a concentric neutral (Figure 3.2 shows a typical construction). A concentric neutral is made from several copper wires wound concentrically around the insulation; the concentric neutral is a true neutral, meaning it can carry return current on a grounded system. Underground residential distribution normally has concentric-neutral cables; concentric-neutral cables are also used for three-phase mainline applications and three-phase power delivery to commercial and industrial customers. Because of their widespread use in URD, concentric-neutral cables are often called URD cables. Power cable has a copper or aluminum phase

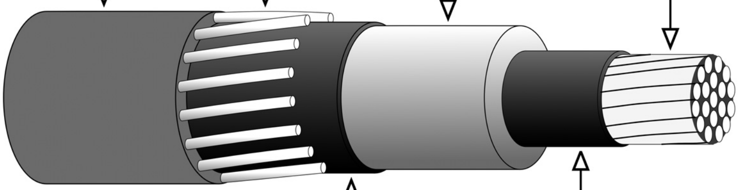

FIGURE 3.2
A concentric neutral cable, typically used for underground residential power delivery.

conductor, an extruded insulation, and normally a thin copper tape shield. On utility distribution circuits, power cables are typically used for mainline feeder applications, network feeders, and other high current, three-phase applications. Many other types of medium-voltage cable are available. These are sometimes appropriate for distribution circuit application: three-conductor power cables, armored cables, aerial cables, fire-resistant cables, extra flexible cables, and submarine cables.

3.2.1 Cable Insulation

A cable's insulation holds back the electrons; the insulation allows cables with a small overall diameter to support a conductor at significant voltage. A 0.175-in. (4.5-mm) thick polymer cable is designed to support just over 8 kV continuously; that's an average stress of just under 50 kV per in. (20 kV/cm). In addition to handling significant voltage stress, insulation must withstand high temperatures during heavy loading and during short circuits and must be flexible enough to work with. For much of the 20th century, paper insulation dominated underground application, particularly PILC cables. The last 30 years of the 20th century saw the rise of polymer-insulated cables, polyethylene-based insulations starting with high-molecular weight polyethylene (HMWPE), then cross-linked polyethylene (XLPE), then tree-retardant XLPE and also ethylene-propylene rubber (EPR) compounds.

Table 3.4 compares properties of TR-XLPE, EPR, and other insulation materials. Some of the key properties of cable insulation are:

- *Dielectric constant* (ε, also called permittivity) — This determines the cable's capacitance: the dielectric constant is the ratio of the capacitance with the insulation material to the capacitance of the same

TABLE 3.4

Properties of Cable Insulations

	Dielectric Constant 20°C	Loss Angle Tan δ at 20°C	Volume Resistivity Ω-m	Annual Dielectric Loss[a] W/1000 ft	Unaged Impulse Strength V/mil	Water Absorption ppm
PILC	3.6	0.003	10^{11}	N/A	1000–2000	25
PE	2.3	0.0002	10^{14}	N/A		100
XLPE	2.3	0.0003	10^{14}	8	3300	350
TR-XLPE	2.4	0.001	10^{14}	10	3000	<300
EPR	2.7–3.3	0.005–0.008	10^{13}–10^{14}	28–599	1200–2000	1150–3200

[a] For a typical 1/0 15-kV cable.

configuration in free space. Cables with higher capacitance draw more charging current.

- *Volume resistivity* — Current leakage through the insulation is a function of the insulation's dc resistivity. Resistivity decreases as temperature increases. Modern insulation has such high resistivity that very little resistive current passes from the conductor through the insulation.
- *Dielectric losses* — Like a capacitor, a cable has dielectric losses. These losses are due to dipole movements within the polymer or by the movement of charge carriers within the insulation. Dielectric losses contribute to a cable's resistive leakage current. Dielectric losses increase with frequency and temperature and with operating voltage.
- *Dissipation factor* (also referred to as the loss angle, loss tangent, tan δ, and approximate power factor) — The dissipation factor is the ratio of the resistive current drawn by the cable to the capacitive current drawn (I_R/I_X). Because the leakage current is normally low, the dissipation factor is approximately the same as the power factor:

$$\text{pf} = I_R / |I| = I_R / \sqrt{I_R^2 + I_X^2} \approx I_R / I_X = \text{dissipation factor}$$

Paper-Insulated Lead-Covered (PILC) Cables. Paper-insulated cables have provided reliable underground power delivery for decades. Paper-insulated lead-sheathed cable has been the dominant cable configuration, used mainly in urban areas. PILC cables have kraft-paper tapes wound around the conductor that are dried and impregnated with insulating oil. A lead sheath is one of the best moisture blocks: it keeps the oil in and keeps water out. Paper cables are normally rated to 85°C with an emergency rating up to 105°C (EPRI TR-105502, 1995). PILC cables have held up astonishingly well; many 50-year-old cables are still in service with almost new insulation capability. While PILC has had very good reliability, some utilities are concerned about its present day failure, not because of bad design or application, but because the in-service stock is so old. Moisture ingress, loss of oil, and thermal stresses — these are the three main causes of PILC failure (EPRI 1000741, 2000). Water decreases the dielectric strength (especially when the cable is hot) and increases the dielectric losses (further heating the cable). Heat degrades the insulating capability of the paper, and if oil is lost, the paper's insulating capability declines. PILC use has declined but still not disappeared. Some utilities continue to use it, especially to supply urban networks. Utilities use less PILC because of its high cost, work difficulties, and environmental concerns. Splicing also requires significant skill, and working with the lead sheath requires environmental and health precautions.

Polyethylene (PE). Most modern cables have polymer insulation extruded around the conductor — either polyethylene derivatives or ethylene-propylene properties. Polyethylene is a tough, inexpensive polymer with good electrical properties. Most distribution cables made since 1970 are based on some variation of polyethylene. Polyethylene is an ethylene polymer, a long string or chain of connected molecules. In polyethylene, some of the polymer chains align in crystalline regions, which give strength and moisture resistance to the material. Other regions have nonaligned polymer chains — these amorphous regions give the material flexibility but are permeable to gas and moisture and are where impurities locate. Polyethylene is a thermoplastic. When heated and softened, the polymer chains break apart (becoming completely amorphous); as it cools, the crystalline regions reform, and the material returns to its original state. Polyethylene naturally has high density and excellent electrical properties with a volume resistivity of greater than 10^{14} Ω-m and an impulse insulation strength of over 2700 V/mil.

High-Molecular Weight Polyethylene (HMWPE). High-molecular weight polyethylene is polyethylene that is stiffer, stronger, and more resistant to chemical attack than standard polyethylene. Insulations with higher molecular weights (longer polymer chains) generally have better electrical properties. As with standard polyethylene, HMWPE insulation is a thermoplastic rated to 75°C. Polyethylene softens considerably as temperature increases. Since plastics are stable and seem to last forever, when utilities first installed HMWPE in the late 1960s and early 1970s, utilities and manufacturers expected long life for polyethylene cables. In practice, failure rates increased dramatically after as little as 5 years of service. The electrical insulating strength (the dielectric strength) of HMWPE was degraded by water treeing, an electrochemical degradation driven by the presence of water and voltage. Polyethylene also degrades quickly under partial discharges; once partial discharges start, they can quickly eat away the insulation. Because of high failure rates, HMWPE insulation is off the market now, but utilities still have many miles of this cable in the ground.

Cross-Linked Polyethylene (XLPE). Cross-linking agents are added that form bonds between polymer chains. The cross-linking bonds interconnect the chains and make XLPE semi-crystalline and add stiffness. XLPE is a thermoset: the material is vulcanized (also called "cured"), irreversibly creating the cross-linking that sets when the insulation cools. XLPE has about the same insulation strengths as polyethylene, is more rigid, and resists water treeing better than polyethylene. Although not as bad as HMWPE, pre-1980s XLPE has proven susceptible to premature failures because of water treeing. XLPE has higher temperature ratings than HWMPE; cables are rated to 90°C under normal conditions and 130°C for emergency conditions.

Tree-Retardant Cross-Linked Polyethylene (TR-XLPE). This has adders to XLPE that slow the growth of water trees. Tree-retardant versions of XLPE have almost totally displaced XLPE in medium-voltage cables. Various compounds when added to XLPE reduce its tendency to grow water trees under voltage. These additives tend to slightly reduce XLPE's electrical properties, slightly increase dielectric losses, and slightly lower initial insulation strength (but much better insulation strength when aged). While there is no standard industry definition of TR-XLPE, different manufacturers offer XLPE compounds with various adders that reduce tree growth. The oldest and most widely used formulation was developed by Union Carbide (now Dow); their HFDA 4202 tree-retardant XLPE maintains its insulation strength better in accelerated aging tests (EPRI TR-108405-V1, 1997) and in field service (Katz and Walker, 1998) than standard XLPE.

Ethylene-Propylene Rubber (EPR). EPR compounds are polymers made from ethylene and propylene. Manufacturers offer different ethylene-propylene formulations, which collectively are referred to as EPR. EPR compounds are thermoset, normally with a high-temperature steam curing process that sets cross-linking agents. EPR compounds have high concentrations of clay fillers that provide its stiffness. EPR is very flexible and rubbery. When new, EPR only has half of the insulation strength as XLPE, but as it ages, its insulation strength does not decrease nearly as much as that of XLPE. EPR is naturally quite resistant to water trees, and EPR has a proven reliable record in the field. EPR has very good high-temperature performance. Although soft, it deforms less at high temperature than XLPE and maintains its insulation strength well at high temperature (Brown, 1983). Most new EPR cables are rated to 105°C under normal conditions and to 140°C for emergency conditions, the MV-105 designation per UL Standard 1072. (Historically, both XLPE and EPR cables were rated to 90°C normal and 130°C emergency.) In addition to its use as cable insulation, most splices and joints are made of EPR compounds. EPR has higher dielectric losses than XLPE; depending on the particular formulation, EPR can have two to three times the losses of XLPE to over ten times the losses of XLPE. These losses increase the cost of operation over its lifetime. While not as common or as widely used as XLPE in the utility market, EPR dominates for medium-voltage industrial applications.

TR-XLPE vs. EPR: which to use? Of the largest investor-owned utilities 56% specify TR-XLPE cables, 24% specify EPR, and the remainder specify a mix (Dudas and Cochran, 1999). Trends are similar at rural cooperatives. In a survey of the co-ops with the largest installed base of underground cable, 42% specify TR-XLPE, 34% specify EPR, and the rest specify both (Dudas and Rodgers, 1999). When utilities specify both EPR and TR-XLPE, commonly EPR is used for 600-A three-phase circuits, and TR-XLPE is used for 200-A applications like URD. Each cable type has advocates. TR-XLPE is less expensive and has lower losses. EPR's main feature is its long history of reliability and water-tree resistance. EPR is also softer (easier to handle) and has a higher temperature rating (higher ampacity). Boggs and Xu (2001) show how EPR and TR-XLPE are becoming more similar: EPR compounds are being designed that have fewer losses; tree-retardant additives to XLPE make the cable more tree resistant at the expense of increasing its water absorption and slightly increasing losses.

Cables have a voltage rating based on the line-to-line voltage. Standard voltage ratings are 5, 8, 15, 25, and 35 kV. A single-phase circuit with a nominal voltage of 7.2 kV from line to ground must use a 15-kV cable, not an 8-kV cable (because the line-to-line voltage is 12.47 kV).

Within each voltage rating, more than one insulation thickness is available. Standards specify three levels of cable insulation based on how the cables are applied. The main factor is grounding and ability to clear line-to-ground faults in order to limit the overvoltage on the unfaulted phases. The standard levels are (AEIC CS5-94, 1994):

- *100 percent level* — Allowed where line-to-ground faults can be cleared quickly (at least within one minute); normally appropriate for grounded circuits
- *133 percent level* — Where line-to-ground faults can be cleared within one hour; normally can be used on ungrounded circuits

Standards also define a 173% level for situations where faults cannot be cleared within one hour, but manufacturers typically offer the 100 and 133% levels as standard cables; higher insulation needs can be met by a custom order or going to a higher voltage rating. Table 3.5 shows standard insulation thicknesses for XLPE and EPR for each voltage level. In addition to protecting against temporary overvoltages, thicker insulations provide higher insulation to lightning and other overvoltages and reduce the chance of failure from water tree growth. For 15-kV class cables, Boucher (1991) reported that 59% of utilities surveyed in North America use 100% insulation (175-mil).

TABLE 3.5

Usual Insulation Thicknesses for XLPE or EPR Cables Based on Voltage and Insulation Level

Voltage Rating, kV	Insulation Thickness, Mil (1 mil = 0.001 in. = 0.00254 cm) 100% Level	133% Level
8	115	140
15	175	220
25	260	320
35	345	420

At 25 and 35 kV, the surveyed utilities more universally use 100% insulation (88 and 99%, respectively). Dudas and Cochran (1999) report similar trends in a survey of practices of the 45 largest investor-owned utilities: at 15 kV, 69% of utilities specified 100% insulation; at 25 and 35 kV, over 99% of utilities specified 100% insulation.

3.2.2 Conductors

For underground residential distribution (URD) applications, utilities normally use aluminum conductors; Boucher (1991) reported that 80% of utilities use aluminum (alloy 1350); the remainder, copper (annealed, soft). Copper is more prevalent in urban duct construction and in industrial applications. Copper has lower resistivity and higher ampacity for a given size; aluminum is less expensive and lighter. Cables are often stranded to increase their flexibility (solid conductor cables are available for less than 2/0). ASTM class B stranding is the standard stranding. Class C has more strands for applications requiring more flexibility. Each layer of strands is wound in an opposite direction. Table 3.6 shows diameters of available conductors.

3.2.3 Neutral or Shield

A cable's shield, the metallic barrier that surrounds the cable insulation, holds the outside of the cable at (or near) ground potential. It also provides a path for return current and for fault current. The shield also protects the cable from lightning strikes and from current from other fault sources. The metallic shield is also called the *sheath*.

A concentric neutral — a shield capable of carrying unbalanced current — has copper wires wound helically around the insulation shield. The concentric neutral is expected to carry much of the unbalanced load current, with the earth carrying the rest. For single-phase cables, utilities normally use a "full neutral," meaning that the resistance of the neutral equals that of the phase conductor. Also common is a "one-third neutral," which has a resistance that is three times that of the phase conductor. In a survey of underground distribution practices, Boucher (1991) reported that full neutrals dominated for residential application, and reduced neutrals are used more for commercial and feeder applications (see Figure 3.3).

Power cables commonly have 5-mil thick copper tape shields. These are wrapped helically around the cable with some overlap. In a tape-shield cable, the shield is not normally expected to carry unbalanced load current. As we will see, there is an advantage to having a higher resistance shield: the cable ampacity can be higher because there is less circulating current. Shields are also available that are helically wound wires (like a concentric neutral but with smaller wires).

Whether wires or tapes, cable shields and neutrals are copper. Aluminum corrodes too quickly to perform well in this function. Early unjacketed cables

TABLE 3.6

Conductor Diameters

	Solid	Class B stranding	
Size	**Diameter, in.**	**Strands**	**Diameter, in.**
24	0.0201	7	0.023
22	0.0253	7	0.029
20	0.032	7	0.036
19	0.035	7	0.041
18	0.0403	7	0.046
16	0.0508	7	0.058
14	0.0641	7	0.073
12	0.0808	7	0.092
10	0.1019	7	0.116
9	0.1144	7	0.13
8	0.1285	7	0.146
7	0.1443	7	0.164
6	0.162	7	0.184
5	0.1819	7	0.206
4	0.2043	7	0.232
3	0.2294	7	0.26
2	0.2576	7	0.292
1	0.2893	19	0.332
1/0	0.3249	19	0.373
2/0	0.3648	19	0.419
3/0	0.4096	19	0.47
4/0	0.46	19	0.528
250		37	0.575
300		37	0.63
350		37	0.681
400		37	0.728
500		37	0.813
600		61	0.893
750		61	0.998
1000		61	1.152
1250		91	1.289
1500		91	1.412
1750		127	1.526
2000		127	1.632
2500		127	1.824

normally had a coating of lead-tin alloy to prevent corrosion. Cable neutrals still corroded. Dudas (1994) reports that in 1993, 84% of utilities specified a bare copper neutral rather than a coated neutral.

The longitudinally corrugated (LC) shield improves performance for fault currents and slows down water entry. The folds of a corrugated copper tape are overlapped over the cable core. The overlapping design allows movement and shifting while also slowing down water entry. The design performs better for faults because it is thicker than a tape shield, so it has less resistance, and it tends to distribute current throughout the shield rather than keeping it in a few strands.

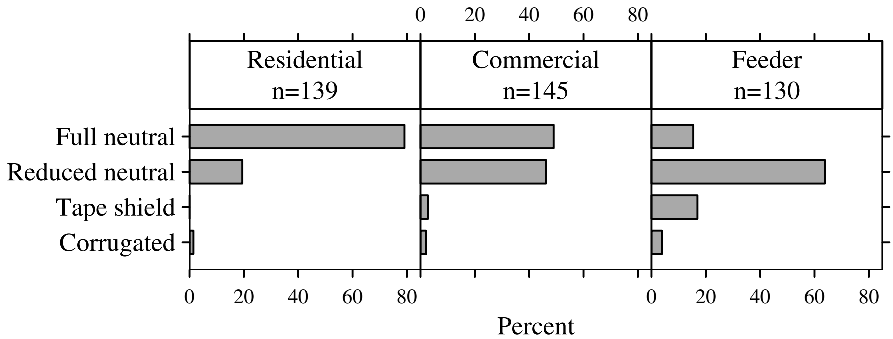

FIGURE 3.3
Surveyed utility use of cable neutral configurations for residential, commercial, and feeder applications. (Data from [Boucher, 1991].)

3.2.4 Semiconducting Shields

In this application, semiconducting means "somewhat conducting": the material has some resistance (limited to a volume resistivity of 500 Ω-m [ANSI/ICEA S-94-649-2000, 2000; ANSI/ICEA S-97-682-2000, 2000]), more than the conductor and less than the insulation. Semiconducting does not refer to nonlinear resistive materials like silicon or metal oxide; the resistance is fixed; it does not vary with voltage. Also called screens or semicons, these semiconducting shields are normally less than 80 mil. The resistive material evens out the electric field at the interface between the phase conductor and the insulation and between the insulation and the neutral or shield. Without the shields, the electric field gradient would concentrate at the closest interfaces between a wire and the insulation; the increased localized stress could break down the insulation. The shields are made by adding carbon to a normally insulating polymer like EPR or polyethylene or cross-linked polyethylene. The conductor shield is normally about 20 to 40 mil thick; the insulation shield is normally about 40 to 80 mil thick. Thicker shields are used on larger diameter cables.

Semiconducting shields are important for smoothing out the electric field, but they also play a critical role in the formation of water trees. The most dangerous water trees are vented trees, those that start at the interface between the insulation and the semiconducting shield. Treeing starts at voids and impurities at this boundary. "Supersmooth" shield formulations have been developed to reduce vented trees (Burns, 1990). These mixtures use finer carbon particles to smooth out the interface. Under accelerated aging tests, cables with supersmooth semiconducting shields outperformed cables with standard semiconducting shields.

Modern manufacturing techniques can extrude the semiconducting conductor shield, the insulation, and the semiconducting insulation shield in one pass. Using this *triple* extrusion provides cleaner, smoother contact between layers than extruding each layer in a separate pass.

A note on terminology: a *shield* is the conductive layer surrounding another part of the cable. The conductor shield surrounds the conductor; the insulation shield surrounds the insulation. Used generically, shield refers to the metallic shield (the sheath). Commonly, the metallic shield is called the neutral, the shield, or the sheath. Sometimes, the sheath is used to mean the outer part of the cable, whether conducting or not conducting.

3.2.5 Jacket

Almost all new cables are jacketed, and the most common jacket is an encapsulating jacket (it is extruded between and over the neutral wires). The jacket provides some (but not complete) protection against water entry. It also provides mechanical protection for the neutral. Common LLDPE jackets are 50 to 80 mil thick.

Bare cable, used frequently in the 1970s, had a relatively high failure rate (Dedman and Bowles, 1990). Neutral corrosion was often cited as the main reason for the higher failure rate. At sections with a corroded neutral, the ground return current can heat spots missing neutral strands. Dielectric failure, not neutral corrosion, is still the dominant failure mode (Gurniak, 1996). Without the jacket, water enters easily and accelerates water treeing, which leads to premature dielectric failure.

Several materials are used for jackets. Polyvinyl chloride (PVC) was one of the earliest jacketing materials and is still common. The most common jacket material is made from linear low-density polyethylene (LLDPE). PVC has good jacketing properties, but LLDPE is even better in most regards: mechanical properties, temperature limits, and water entry. Moisture passes through PVC jacketing more than ten times faster than it passes through LLDPE. LLDPE starts to melt at 100°C; PVC is usually more limited, depending on composition. Low-density polyethylene resists abrasion better and also has a lower coefficient of friction, which makes it easier to pull through conduit.

Semiconducting jackets are also available. Semiconducting jackets provide the grounding advantages of unjacketed cable, while also blocking moisture and physically protecting the cable. When direct buried, an exposed neutral provides an excellent grounding conductor. The neutral in contact with the soil helps improve equipment grounding and improves protection against surges. A semiconducting jacket has a resistivity equivalent to most soils (less than 100 Ω-m), so it transfers current to the ground the same as an unjacketed cable. NRECA (1993) recommends not using a semiconducting jacket for two reasons. First, semiconducting jackets let more water pass through than LLDPE jackets. Second, the semiconducting jacket could contribute to corrosion. The carbon in the jacket (which makes the jacket semiconducting) is galvanic to the neutral and other nearby metals; especially with water in the cable, the carbon accelerates neutral corrosion. Other nearby objects in the ground such as ground rods or pipes can also corrode more rapidly from the carbon in the jacket.

3.3 Installations and Configurations

Just as there are many different soil types and underground applications, utilities have many ways to install underground cable. Some common installation methods include [see NRECA RER Project 90-8 (1993) for more details]:

- *Trenching* — This is the most common way to install cables, either direct-buried or cables in conduit. After a trench is dug, cable is installed, backfill is added and tamped, and the surface is restored. A trenching machine with different cutting chains is available for use on different soils. Backhoes also help with trenching.
- *Plowing* — A cable plow blade breaks up and lifts the earth as it feeds a cable into the furrow. Plowing eliminates backfilling and disturbs the surface less than trenching. NRECA reports that plowing is 30 to 50% less expensive than trenching (NRECA RER Project 90-8, 1993). Plowed cables may have lower ampacity because of air pockets between the cable and the loose soil around the cable. Heat cannot transfer as effectively from the cable to the surrounding earth.
- *Boring* — A number of tunneling technologies are available to drill under roads or even over much longer distances with guided, fluid-assisted drill heads.

Utilities also have a number of installation options, each with tradeoffs:

- *Direct buried* — Cables are buried directly in the earth. This is the fastest and least expensive installation option. Its major disadvantage is that cable replacement or repair is difficult.
- *Conduit* — Using conduit allows for quicker replacement or repair. Rigid PVC conduit is the most common conduit material; steel and HDPE and fiberglass are also used. Cables in conduit have less ampacity than direct-buried cables.
- *Direct buried with a spare conduit* — Burying a cable with a spare conduit provides provisions for repair or upgrades. Crews can pull another cable through the spare conduit to increase capacity or, if the cable fails, run a replacement cable through the spare conduit and abandon the failed cable. Normally, when the cable is plowed in, the conduit is coilable polyethylene.
- *Concrete-encased conduit* — Most often used in urban construction, conduit is encased in concrete. Concrete protects the conduit, resisting collapse due to shifting earth. The concrete also helps prevent dig-ins.
- *Preassembled cable in conduit* — Cable with flexible conduit can be purchased on reels, which crews can plow into the ground together.

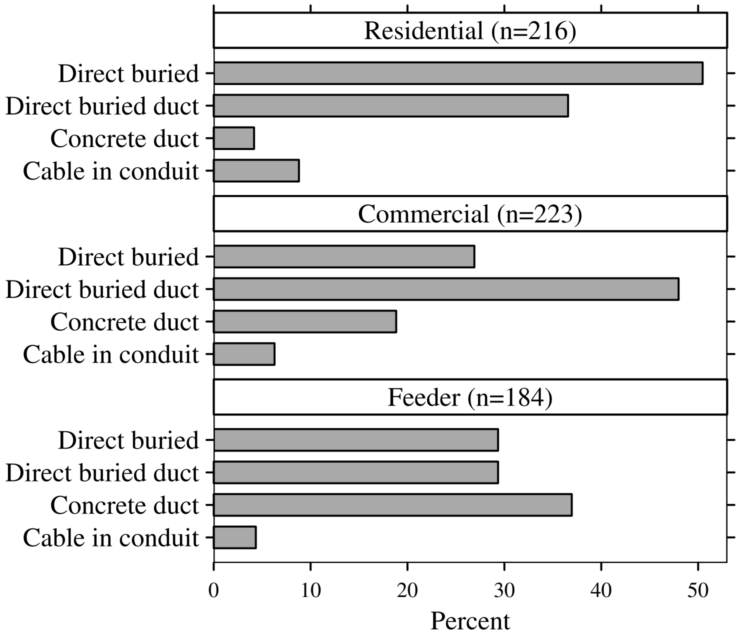

FIGURE 3.4
Surveyed utility cable installation configurations for residential, commercial, and feeder applications. (Data from [Boucher, 1991].)

> The flexible conduit is likely to be more difficult to pull cable through, especially if the conduit is not straight. Flexible conduit is also not as strong as rigid conduit; the conduit can collapse due to rocks or other external forces.

Utilities are split between using direct-buried cable and conduits or ducts for underground residential applications. Conduits are used more for three-phase circuits, for commercial service, and for main feeder applications (see Figure 3.4). Conduit use is rising as shown by a more recent survey in Table 3.7. In a survey of the rural cooperatives with the most underground distribution, Dudas and Rodgers (1999) reported that 80% directly bury cable.

With conduits, customers have less outage time because cables can be replaced or repaired more quickly. In addition, replacement causes much less trouble for customers. Replacement doesn't disturb driveways, streets, or lawns; crews can concentrate their work at padmounted gear, rather than spread out along entire cable runs; and crews are less likely to tie up traffic. Conduit costs more than direct buried cable initially, typically from 25 to 50% more for PVC conduit (but this ranges widely depending on soil conditions and obstacles in or on the ground). Cable in flexible conduit may be slightly less than cable in rigid conduit. While directly buried cable has lower initial costs, lifetime costs can be higher than conduit depending on economic

TABLE 3.7

Surveyed Utility Use of Cable Duct Installations

	Percent of Cable Miles with Each Configuration	
	1998 Installed	Planned for the Future
Direct buried	64.6	46.9
Installed in conduit sections	25.5	37.9
Preassembled cable in conduit	7.1	11.7
Direct buried with a spare conduit	1.1	0.5
Continuous lengths of PE tubing	1.7	3.0

Source: Tyner, J. T., "Getting to the Bottom of UG Practices," *Transmission & Distribution World*, vol. 50, no. 7, pp. 44–56, July 1998.

assumptions and assumptions on how long cables will last or if they will need to be upgraded. Some utilities use a combination approach; most cable is direct buried, but ducts are used for road crossings and other obstacles.

The National Electrical Safety Code requires that direct-buried cable have at least 30 in. (0.75 m) of cover (IEEE C2-1997). Typically, trench depths are at least 36 in.

If communication cables are buried with primary power cables, extra rules apply. For direct-buried cable with an insulating jacket, the NESC requires that the neutral must have at least one half of the conductivity of the phase conductor (IEEE C2-1997) (it must be a one-half neutral or a full neutral).

Some urban applications are constrained by small ducts: 3, 3.5, or 4-in. diameters. These ducts were designed to hold three-conductor paper-insulated lead-sheathed cables which have conductors squashed in a sector shape for a more compact arrangement. Insulation cannot be extruded over these shapes, so obtaining an equivalent replacement cable with extruded insulation is difficult. Manufacturers offer thinner cables to meet these applications. For triplex cable, the equivalent outside diameter is 2.155 times the diameter of an individual cable. So, to fit in a 3-in. duct, an individual cable must be less than 1.16 in. in diameter to leave a 1/2-in. space (see Table 3.8 for other duct sizes). Some cable offered as "thin-wall" cable has slightly reduced insulation. For 15-kV cable, the smallest insulation thicknesses range between 150 and 165 mil as compared to the standard 175 mil (EPRI 1001734, 2002) (the ICEA allows 100% 15-kV cable insulation to range from 165 to 205

TABLE 3.8

Maximum Cable Diameters for Small Conduits Using PILC or Triplexed Cables that Leave 1/2-in. Pulling Room

Duct Size, in.	Largest Three-Conductor 15-kV PILC	Maximum Cable Diameter for Triplex Construction, in.	Largest Standard Construction Triplexed 15-kV Copper Cable
3.0	350 kcmil	1.16	3/0
3.5	750 kcmil	1.39	350 kcmil
4.0	1000 kcmil	1.62	500 kcmil

mil (ANSI/ICEA S-97-682-2000, 2000)). One manufacturer has proposed reduced insulation thicknesses based on the fact that larger conductors have lower peak voltage stress on the insulation than smaller conductors (Cinquemani et al., 1997), for example, 110-mil insulation at 15 kV for 4/0 through 750 kcmil. The maximum electric field (EPRI 1001734, 2002) is given by

$$E_{max} = \frac{2V}{d\ln(D/d)}$$

where

E_{max} = maximum electric field, V/mil (or other distance unit)
V = operating or rated voltage to neutral, V
d = inside diameter of the insulation, mil (or other distance unit)
D = outside diameter of the insulation in the same units as d

So, a 750-kcmil cable with 140-mil insulation has about the same maximum voltage stress as a 1/0 cable with 175-mil insulation at the same voltage. Nevertheless, most manufacturers are reluctant to trim the primary insulation too much, fearing premature failure due to water treeing. In addition to slightly reduced insulation, thin-wall cables are normally compressed copper and have thinner jackets and thinner semiconducting shields around the conductor and insulation. EPRI has also investigated other polymers for use in thin-wall cables (EPRI TR-111888, 2000). Their investigations found promising results with novel polymer blends that could achieve insulation strengths that are 30 to 40% higher than XLPE. These tests suggest promise, but more work must be done to improve the extrusion of these materials.

3.4 Impedances

3.4.1 Resistance

Cable conductor resistance is an important part of impedance that is used for fault studies and load flow studies. Resistance also greatly impacts a cable's ampacity. The major variable that affects resistance is the conductor's temperature; resistance rises with temperature. Magnetic fields from alternating currents also reduce a conductor's resistance relative to its dc resistance. At power frequencies, skin effect is only apparent for large conductors and proximity effect only occurs for conductors in very tight configurations. The starting point for resistance calculations is the dc resistance. From there, we can adjust for temperature and for frequency effects. Table 3.9 shows the dc resistances of several common conductors used for cables.

Resistance increases with temperature as

TABLE 3.9

dc Resistance at 25°C in Ω/1000 ft

	Aluminum		Uncoated Copper		Coated Copper	
Size	Solid	Class-B Stranded	Solid	Class-B Stranded	Solid	Class-B Stranded
24			26.2		27.3	
22			16.5		17.2	
20			10.3	10.5	10.7	11.2
19			8.21		8.53	
18			6.51	6.64	6.77	7.05
16			4.1	4.18	4.26	4.44
14	4.22		2.57	2.62	2.68	2.73
12	2.66	2.7	1.62	1.65	1.68	1.72
10	1.67	1.7	1.02	1.04	1.06	1.08
9	1.32	1.35	0.808	0.824	0.831	0.857
8	1.05	1.07	0.641	0.654	0.659	0.679
7	0.833	0.85	0.508	0.518	0.523	0.539
6	0.661	0.674	0.403	0.41	0.415	0.427
5	0.524	0.535	0.319	0.326	0.329	0.339
4	0.415	0.424	0.253	0.259	0.261	0.269
3	0.33	0.336	0.201	0.205	0.207	0.213
2	0.261	0.267	0.159	0.162	0.164	0.169
1	0.207	0.211	0.126	0.129	0.13	0.134
1/0	0.164	0.168	0.1	0.102	0.103	0.106
2/0	0.13	0.133	0.0795	0.0811	0.0814	0.0843
3/0	0.103	0.105	0.063	0.0642	0.0645	0.0668
4/0	0.082	0.0836	0.05	0.0509	0.0512	0.0525
250		0.0708		0.0431		0.0449
300		0.059		0.036		0.0374
350		0.0505		0.0308		0.032
400		0.0442		0.027		0.0278
500		0.0354		0.0216		0.0222
600		0.0295		0.018		0.0187
750		0.0236		0.0144		0.0148
1000		0.0177		0.0108		0.0111
1250		0.0142		0.00863		0.00888
1500		0.0118		0.00719		0.0074
1750		0.0101		0.00616		0.00634
2000		0.00885		0.00539		0.00555
2500		0.00715		0.00436		0.00448

Note: × 5.28 for Ω/mi or × 3.28 for Ω/km.

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

where

R_{t2} = resistance at temperature t_2 given, °C
R_{t1} = resistance at temperature t_1 given, °C
M = a temperature coefficient for the given material
= 228.1 for aluminum
= 234.5 for soft-drawn copper

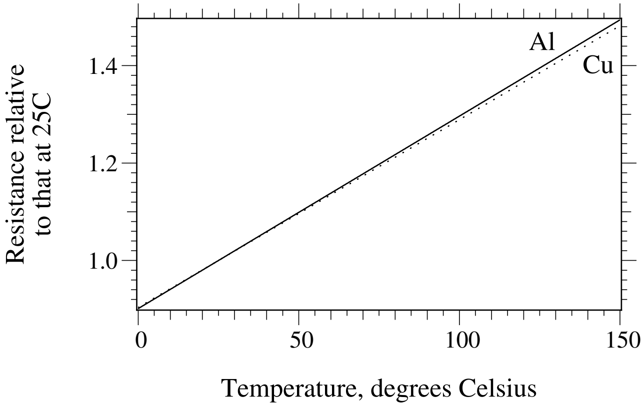

FIGURE 3.5
Resistance change with temperature.

Both copper and aluminum change resistivity at about the same rate as shown in Figure 3.5.

The ac resistance of a conductor is the dc resistance increased by a skin effect factor and a proximity effect factor

$$R = R_{dc}(1 + Y_{cs} + Y_{cp})$$

where

R_{dc} = dc resistance at the desired operating temperature, Ω/1000 ft
Y_{cs} = skin-effect factor
Y_{cp} = proximity effect factor

The skin-effect factor is a complex function involving Bessel function solutions. The following polynomial approximates the skin-effect factor (Anders, 1998):

$$Y_{cs} = \frac{x_s^4}{192 + 0.8x_s^4} \qquad \text{for } x_s \le 2.8$$

$$Y_{cs} = -0.136 - 0.0177x_s + 0.0563x_s^2 \qquad \text{for } 2.8 < x_s \le 3.8$$

$$Y_{cs} = \frac{x_s}{2\sqrt{2}} - \frac{11}{15} \qquad \text{for } 3.8 < x_s$$

where

$$x_s = 0.02768\sqrt{\frac{f \cdot k_s}{R_{dc}}}$$

f = frequency, Hz

k_s = skin effect constant = 1 for typical conductors in extruded cables, may be less than one for paper cables that are dried and impregnated and especially those with round segmental conductors [see Neher and McGrath (1957) or IEC (1982)].

R_{dc} = dc resistance at the desired operating temperature, Ω/1000 ft

For virtually all applications at power frequency, x_s is < 2.8.

With a conductor in close proximity to another current-carrying conductor, the magnetic fields from the adjacent conductor force current to flow in the portions of the conductor most distant from the adjacent conductor (with both conductors carrying current in the same direction). This magnetic field effect increases the effective ac resistance. The proximity effect factor is approximately (Anders, 1998; IEC 287, 1982):

$$Y_{cp} = ay^2\left(0.312y^2 + \frac{1.18}{a + 0.27}\right)$$

where

$$a = \frac{x_p^4}{192 + 0.8x_p^4}, \quad y = \frac{d_c}{s}$$

$$x_p = 0.02768\sqrt{\frac{f \cdot k_p}{R_{dc}}}$$

d_c = conductor diameter

s = distance between conductor centers

k_p = proximity effect constant = 1 for typical conductors in extruded cables; may be < 1 for paper cables that are dried and impregnated and especially those with round segmental conductors [see Neher and McGrath (1957) or IEC (1982)].

At power frequencies, we can ignore proximity effect if the spacing exceeds ten times the conductor diameter (the effect is less than 1%).

Table 3.10 and Table 3.11 show characteristics of common cable conductors.

3.4.2 Impedance Formulas

Smith and Barger (1972) showed that we can treat a multi-wire concentric neutral as a uniform sheath; further work by Lewis and Allen (1978) and by Lewis, Allen, and Wang (1978) simplified the calculation of the representation of the concentric neutral. Following the procedure and nomenclature of Smith (1980) and Lewis and Allen (1978), we can find a cable's sequence impedances from the self and mutual impedances of the cable phase and neutral conductors as

TABLE 3.10

Characteristics of Aluminum Cable Conductors

Conductor	Stranding	GMR, in.	ac/dc Resistance Ratio	Resistances, Ω/1000 ft		
				dc at 25°C	ac at 25°C	ac at 90°C
2	7	0.105	1	0.2660	0.2660	0.3328
1	19	0.124	1	0.2110	0.2110	0.2640
1/0	19	0.139	1	0.1680	0.1680	0.2102
2/0	19	0.156	1	0.1330	0.1330	0.1664
3/0	19	0.175	1	0.1050	0.1050	0.1314
4/0	19	0.197	1	0.0836	0.0836	0.1046
250	37	0.216	1.01	0.0707	0.0714	0.0893
350	37	0.256	1.01	0.0505	0.0510	0.0638
500	37	0.305	1.02	0.0354	0.0361	0.0452
750	61	0.377	1.05	0.0236	0.0248	0.0310
1000	61	0.435	1.09	0.0177	0.0193	0.0241

TABLE 3.11

Characteristics of Copper Cable Conductors

Conductor	Stranding	GMR, in.	ac/dc Resistance Ratio	Resistances, Ω/1000 ft		
				dc at 25°C	ac at 25°C	ac at 90°C
2	7	0.105	1	0.1620	0.1620	0.2027
1	19	0.124	1	0.1290	0.1290	0.1614
1/0	19	0.139	1	0.1020	0.1020	0.1276
2/0	19	0.156	1.01	0.0810	0.0818	0.1023
3/0	19	0.175	1.01	0.0642	0.0648	0.0811
4/0	19	0.197	1.01	0.0510	0.0515	0.0644
250	37	0.216	1.01	0.0431	0.0435	0.0545
350	37	0.256	1.03	0.0308	0.0317	0.0397
500	37	0.305	1.06	0.0216	0.0229	0.0286
750	61	0.377	1.13	0.0144	0.0163	0.0204
1000	61	0.435	1.22	0.0108	0.0132	0.0165

$$Z_{11} = Z_{aa} - Z_{ab} - \frac{(Z_{ax} - Z_{ab})^2}{Z_{xx} - Z_{ab}}$$

$$Z_{00} = Z_{aa} + 2Z_{ab} - \frac{(Z_{ax} + 2Z_{ab})^2}{Z_{xx} + 2Z_{ab}}$$

The self and mutual impedances in the sequence equations are found with

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

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

$$Z_{xx} = R_N + R_e + jk_1 \log_{10} \frac{D_e}{GMR_N}$$

$$Z_{ax} = R_e + jk_1 \log_{10} \frac{D_e}{DN2}$$

where the self and mutual impedances with earth return are:

Z_{aa} = self impedance of each phase conductor
Z_{ab} = the mutual impedance between two conductors (between two phases, between two neutral, or between a phase and a neutral)
Z_{ax} = the mutual impedance between a phase conductor and its concentric neutral (or sheath)
Z_{xx} = self impedance of each concentric neutral (or shield)

and

R_ϕ = resistance of the phase conductor, Ω/distance
R_N = resistance of the neutral (or shield), Ω/distance
k_1 = $0.2794f/60$ for outputs in Ω/mi
= $0.0529f/60$ for outputs in Ω/1000 ft
f = frequency, Hz
GMR_ϕ = geometric mean radius of the phase conductor, in. (see Table 3.12)
GMD_ϕ = geometric mean distance between the phase conductors, in.
= $\sqrt[3]{d_{AB}d_{BC}d_{CA}}$
= 1.26 d_{AB} for a three-phase line with flat configuration, either horizontal or vertical, when $d_{AB} = d_{BC} = 0.5d_{CA}$
= the cable's outside diameter for triplex cables
= 1.15 times the cable's outside diameter for cables cradled in a duct
d_{ij} = distance between the center of conductor i and the center of conductor j, in. (see Figure 3.6)
R_e = resistance of the earth return path
= $0.0954(f/60)$Ω/mi
= $0.01807(f/60)$Ω/1000 ft
D_e = $25920\sqrt{\rho/f}$ = equivalent depth of the earth return current, in.
ρ = earth resistivity, Ω-m
GMR_N = geometric mean radius of the sheath or neutral. For single-conductor cables with tape or lead sheaths, set GMR_N equal to the average radius of the sheath. For cables with a multi-wire concentric neutral, use $GMR_N = \sqrt[n]{0.7788nDN2^{(n-1)}r_n}$ where n is the number of neutrals and r_n is the radius of each neutral, in.

TABLE 3.12

Geometric Mean Radius (GMR) of Class B Stranded Copper and Aluminum Conductors

		GMR, in.		
Size	**Stranding**	**Round**	**Compressed**	**Compact**
8	7	0.053		
6	7	0.067		
4	7	0.084		
2	7	0.106	0.105	
1	19	0.126	0.124	0.117
1/0	19	0.141	0.139	0.131
2/0	19	0.159	0.156	0.146
3/0	19	0.178	0.175	0.165
4/0	19	0.200	0.197	0.185
250	37	0.221	0.216	0.203
350	37	0.261	0.256	0.240
500	37	0.312	0.305	0.287
750	61	0.383	0.377	0.353
1000	61	0.442	0.435	0.413

Source: Southwire Company, *Power Cable Manual*, 2nd ed., 1997.

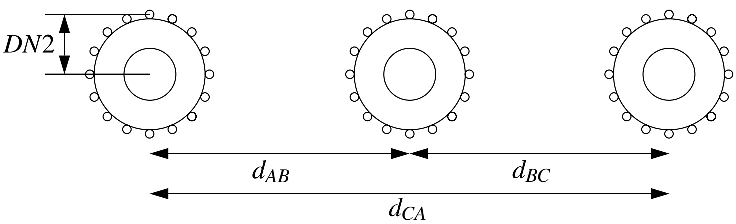

FIGURE 3.6
Cable dimensions for calculating impedances.

$DN2$ = effective radius of the neutral = the distance from the center of the phase conductor to the center of a neutral strand, in.

Smith (1980) reported that assuming equal GMR_N and $DN2$ for cables from 1/0 to 1000 kcmil with one-third neutrals is accurate to 1%.

For single-phase circuits, the zero and positive-sequence impedances are the same:

$$Z_{11} = Z_{00} = Z_{aa} - \frac{Z_{ax}^2}{Z_{xx}}$$

This is the loop impedance, the impedance to current flow through the phase conductor that returns in the neutral and earth. The impedances of two-phase circuits are more difficult to calculate (see Smith, 1980).

The sheath resistances depend on whether it is a concentric neutral, a tape shield, or some other configuration. For a concentric neutral, the resistance is approximately (ignoring the lay of the neutral):

$$R_{neutral} = \frac{R_{strand}}{n}$$

where
R_{strand} = resistance of one strand, in Ω/unit distance
n = number of strands

A tape shield's resistance (Southwire Company, 1997) is

$$R_{shield} = \frac{\rho_c}{A_s}$$

where
ρ_c = resistivity of the tape shield, Ω-cmil/ft = 10.575 for uncoated copper at 25°C
A_s = effective area of the shield in circular mil

$$A_s = 4b \cdot d_m \cdot \sqrt{\frac{50}{100 - L}}$$

b = thickness of the tape, mil
d_m = mean diameter outside of the metallic shield, mil
L = lap of the tape shield in percent (normally 10 to 25%)

Normally, we can use dc resistance as the ac resistance for tape shields or concentric neutrals. The skin effect is very small because the shield conductors are thin (skin effect just impacts larger conductors). We should adjust the sheath resistance for temperature; for copper conductors, the adjustment is:

$$R_{t2} = R_{t1} \frac{234.5 + t_2}{234.5 + t_1}$$

where
R_{t2} = resistance at temperature t_2 given in °C
R_{t1} = resistance at temperature t_1 given in °C

These calculations are simplifications. More advanced models, normally requiring a computer, can accurately find each element in the full impedance matrix. For most load-flow calculations, this accuracy is not needed, though access to user-friendly computer models allows quicker results than calculating the equations shown here. For evaluating switching transients and some ampacity problems or configurations with several cables, we sometimes need more sophisticated models [see Amateni (1980) or Dommel (1986) for analytical details].

In a cable, the neutral tightly couples with the phase. Phase current induces neutral voltages that force circulating current in the neutrals. With balanced, positive-sequence current in the three phases and with symmetrical conductors, the neutral current (Lewis and Allen, 1978; Smith and Barger, 1972) is

$$I_{X1} = -\frac{Z_{ax} - Z_{ab}}{Z_{xx} - Z_{ab}} I_a$$

which is

$$I_{X1} = -\frac{j0.0529 \log_{10} \dfrac{d_{ab}}{DN2}}{R_N + j0.0529 \log_{10} \dfrac{d_{ab}}{GMR_N}} I_a$$

Since $DN2$ and GMR_N are almost equal, if R_N is near zero, the neutral (or shield) current (I_{X1}) almost equals the phase current (I_a). Higher neutral resistances actually reduce positive-sequence resistances.

Significant effects on positive and zero-sequence impedances include:

- *Cable separation* — Larger separations increase Z_1; spacing does not affect Z_0. Triplex cables have the lowest positive-sequence impedance.
- *Conductor size* — Larger conductors have much less resistance; reactance drops somewhat with increasing size.
- *Neutral/shield resistance* — Increasing the neutral resistance increases the reactive portion of the positive and zero-sequence impedances. Beyond a certain point, increasing neutral resistances decreases the resistive portion of Z_1 and Z_0.
- *Other cables or ground wires* — Adding another grounded wire nearby has similar impacts to lowering sheath resistances. Zero-sequence resistance and reactance usually drop. Positive-sequence reactance is likely to decrease, but positive-sequence resistance may increase.

Figure 3.7 and Figure 3.8 show the impact of the most significant variables on impedances for three-phase and single-phase circuits. None of the following significantly impacts either the positive or zero-sequence impedances: insulation thickness, insulation type, depth of burial, and earth resistivity.

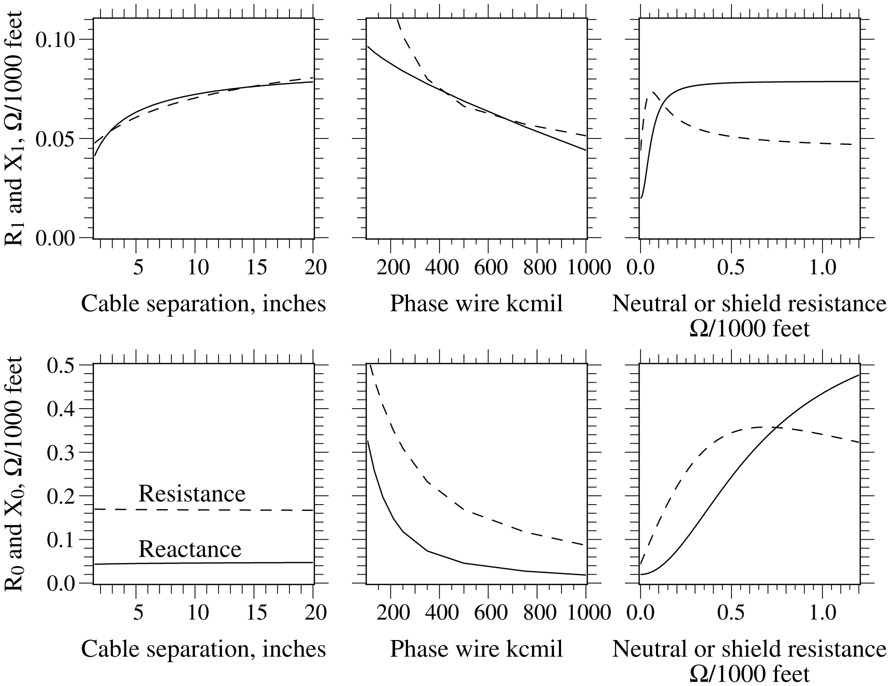

FIGURE 3.7
Effect of various parameters on the positive-sequence (top row) and zero-sequence impedances (bottom row) with a base case having 500-kcmil aluminum cables with 1/3 neutrals, 220-mil insulation, a horizontal configuration with 7.5 in. between cables, and ρ = 100 Ω-m.

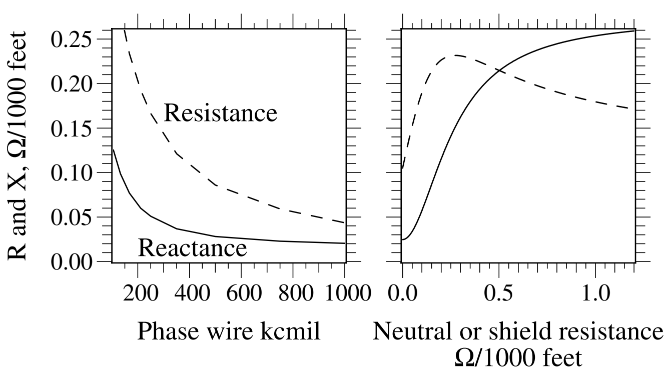

FIGURE 3.8
Resistance and reactance of a single-phase cable ($R = R_0 = R_1$ and $X = X_0 = X_1$) as the size of the cable and neutral varies with a base case having a 4/0 aluminum cable with a full neutral, 220-mil insulation, and ρ = 100 Ω-m.

TABLE 3.13

Loop Impedances of Single-Phase Concentric-Neutral Aluminum Cables

Conductor	Full Neutral			1/3 Neutral		
Size	Neutral	R	X	Neutral	R	X
2	10#14	0.4608	0.1857			
1	13#14	0.3932	0.1517			
1/0	16#14	0.3342	0.1259	6#14	0.3154	0.2295
2/0	13#12	0.2793	0.0974	7#14	0.2784	0.2148
3/0	16#12	0.2342	0.0779	9#14	0.2537	0.1884
4/0	13#10	0.1931	0.0613	11#14	0.2305	0.1645
250	16#10	0.1638	0.0493	13#14	0.2143	0.1444
350	20#10	0.1245	0.0387	18#14	0.1818	0.1092
500				16#12	0.1447	0.0726
750				15#10	0.1067	0.0462
1000				20#10	0.0831	0.0343

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). Conductor temperature = 90°C, neutral temperature = 80°C, 15-kV class, 220-mil insulation, ρ = 100 Ω-m. For the neutral, 10#14 means 10 strands of 14-gage wire.

3.4.3 Impedance Tables

This section contains tables of several common cable configurations found on distribution circuits. All values are for a multigrounded circuit. Many other cable configurations are possible, with widely varying impedances. For PILC cables, refer to impedances in the Westinghouse (1950) T&D book. For additional three-phase power cable configurations, refer to the IEEE Red Book (IEEE Std. 141-1993), St. Pierre (2001), or Southwire Company (1997).

3.4.4 Capacitance

Cables have significant capacitance, much more than overhead lines. A single-conductor cable has a capacitance given by:

$$C = \frac{0.00736\varepsilon}{\log_{10}\left(\frac{D}{d}\right)}$$

where

C = capacitance, μF/1000 ft

ε = dielectric constant (2.3 for XLPE, 3 for EPR, see Table 3.4 for others)

d = inside diameter of the insulation, mil (or other distance unit)

D = outside diameter of the insulation in the same units as d

TABLE 3.14

Impedances of Three-Phase Circuits Made of Three Single-Conductor Concentric-Neutral Aluminum Cables

Conductor Size	Neutral Size	R_1	X_1	R_0	X_0	R_S	X_S
Full Neutral							
2	10#14	0.3478	0.1005	0.5899	0.1642	0.4285	0.1217
1	13#14	0.2820	0.0950	0.4814	0.1166	0.3484	0.1022
1/0	16#14	0.2297	0.0906	0.3956	0.0895	0.2850	0.0902
2/0	13#12	0.1891	0.0848	0.3158	0.0660	0.2314	0.0785
3/0	16#12	0.1578	0.0789	0.2573	0.0523	0.1910	0.0701
4/0	13#10	0.1331	0.0720	0.2066	0.0423	0.1576	0.0621
250	16#10	0.1186	0.0651	0.1716	0.0356	0.1363	0.0553
350	20#10	0.0930	0.0560	0.1287	0.0294	0.1049	0.0471
1/3 Neutral							
1/0	6#14	0.2180	0.0959	0.5193	0.2854	0.3185	0.1591
2/0	7#14	0.1751	0.0930	0.4638	0.2415	0.2713	0.1425
3/0	9#14	0.1432	0.0896	0.4012	0.1787	0.2292	0.1193
4/0	11#14	0.1180	0.0861	0.3457	0.1375	0.1939	0.1032
250	13#14	0.1034	0.0833	0.3045	0.1103	0.1704	0.0923
350	18#14	0.0805	0.0774	0.2353	0.0740	0.1321	0.0762
500	16#12	0.0656	0.0693	0.1689	0.0468	0.1000	0.0618
750	15#10	0.0547	0.0584	0.1160	0.0312	0.0752	0.0494
1000	20#10	0.0478	0.0502	0.0876	0.0248	0.0611	0.0417

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). Resistances for a conductor temperature = 90°C and a neutral temperature = 80°C, 220-mil insulation (15 kV), ρ = 100 Ω-m. Flat spacing with a 7.5-in. separation between cables. For the neutral, 10#14 means 10 strands of 14-gage wire.

The vars provided by cable are

$$Q_{var} = 2\pi \cdot f \cdot C \cdot V_{LG,kV}^2$$

where

Q_{var} = var/1000 ft/phase

f = frequency, Hz

C = capacitance, μF/1000 ft

$V_{LG,kV}$ = line-to-ground voltage, kV

Table 3.17 shows capacitance values and reactive power produced by cables for typical cables. The table results are for XLPE cable with a dielectric constant (ε) of 2.3. For other insulation, both the capacitance and the reactive power scale linearly. For example, for EPR with ε = 3, multiply the values in Table 3.17 by 1.3 (3/2.3 = 1.3).

TABLE 3.15

Impedances of Single-Conductor Aluminum Power Cables with Copper Tape Shields

Conductor Size	R_1	X_1	R_0	X_0	R_S	X_S
Flat spacing with a 7.5-in. separation						
2	0.3399	0.1029	0.6484	0.4088	0.4427	0.2049
1	0.2710	0.0990	0.5808	0.3931	0.3743	0.1971
1/0	0.2161	0.0964	0.5268	0.3790	0.3196	0.1906
2/0	0.1721	0.0937	0.4833	0.3653	0.2759	0.1842
3/0	0.1382	0.0911	0.4494	0.3493	0.2419	0.1771
4/0	0.1113	0.0883	0.4217	0.3314	0.2148	0.1693
250	0.0955	0.0861	0.4037	0.3103	0.1982	0.1609
350	0.0696	0.0822	0.3734	0.2827	0.1709	0.1490
500	0.0508	0.0781	0.3483	0.2557	0.1499	0.1373
750	0.0369	0.0732	0.3220	0.2185	0.1319	0.1216
1000	0.0290	0.0698	0.3018	0.1915	0.1200	0.1104
Triplex						
2	0.3345	0.0531	0.7027	0.4244	0.4573	0.1769
1	0.2655	0.0501	0.6330	0.4060	0.3880	0.1687
1/0	0.2105	0.0483	0.5767	0.3893	0.3326	0.1620
2/0	0.1666	0.0465	0.5310	0.3734	0.2880	0.1554
3/0	0.1326	0.0448	0.4944	0.3550	0.2532	0.1482
4/0	0.1056	0.0432	0.4636	0.3346	0.2249	0.1403
250	0.0896	0.0424	0.4418	0.3109	0.2070	0.1319
350	0.0637	0.0403	0.4067	0.2807	0.1780	0.1204
500	0.0447	0.0381	0.3769	0.2518	0.1554	0.1093
750	0.0308	0.0359	0.3443	0.2129	0.1353	0.0949
1000	0.0228	0.0348	0.3197	0.1853	0.1218	0.0850

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). Resistances for a conductor temperature = 90°C and a shield temperature = 50°C, 220-mil insulation (15 kV), ρ = 100 Ω-m, 5-mil copper tape shield with a lap of 20%.

3.5 Ampacity

A cable's ampacity is the maximum continuous current rating of the cable. We should realize that while we may derive one number, say 480 A, for ampacity during normal operations for a given conductor, there is nothing magic about 480 A. The cable will not burst into flames at 481 A; the 480 A is simply a design number. We don't want to exceed that current during normal operations.

The insulation temperature is normally the limiting factor. By operating below the ampacity of a given cable, we keep the cable insulation below its

TABLE 3.16

Impedances of Single-Conductor Copper Power Cables

Conductor Size	R_1	X_1	R_0	X_0	R_S	X_S
Flat spacing with a 7.5-in. separation						
2	0.2083	0.1029	0.5108	0.4401	0.3092	0.2153
1	0.1671	0.0991	0.4718	0.4267	0.2687	0.2083
1/0	0.1334	0.0965	0.4405	0.4115	0.2358	0.2015
2/0	0.1082	0.0938	0.4171	0.3967	0.2112	0.1948
3/0	0.0871	0.0911	0.3975	0.3794	0.1906	0.1872
4/0	0.0705	0.0884	0.3816	0.3626	0.1742	0.1798
250	0.0607	0.0862	0.3719	0.3471	0.1644	0.1732
350	0.0461	0.0823	0.3558	0.3181	0.1493	0.1609
500	0.0352	0.0782	0.3411	0.2891	0.1372	0.1485
750	0.0272	0.0732	0.3241	0.2490	0.1261	0.1318
1000	0.0234	0.0699	0.3104	0.2196	0.1191	0.1198
Triplex						
2	0.2032	0.0508	0.5707	0.4642	0.3257	0.1886
1	0.1619	0.0477	0.5301	0.4480	0.2846	0.1811
1/0	0.1281	0.0460	0.4966	0.4295	0.2509	0.1738
2/0	0.1028	0.0442	0.4709	0.4116	0.2255	0.1667
3/0	0.0816	0.0426	0.4485	0.3910	0.2039	0.1587
4/0	0.0649	0.0409	0.4299	0.3713	0.1866	0.1510
250	0.0551	0.0398	0.4175	0.3532	0.1759	0.1442
350	0.0403	0.0377	0.3962	0.3202	0.1589	0.1319
500	0.0292	0.0355	0.3765	0.2882	0.1450	0.1197
750	0.0211	0.0333	0.3524	0.2450	0.1315	0.1039
1000	0.0173	0.0322	0.3336	0.2142	0.1227	0.0929

Note: Impedances, Ω/1000 ft (× 5.28 for Ω/mi or × 3.28 for Ω/km). Resistances for a conductor temperature = 90°C and a shield temperature = 50°C, 220-mil insulation (15 kV), ρ = 100 Ω-m, 5-mil copper tape shield with a lap of 20%.

TABLE 3.17

Cable Capacitance for Common Cable Sizes and Voltages

	Capacitance, μF/1000 ft				Reactive power, kvar/1000 ft			
Size	175 mil	220 mil	260 mil	345 mil	12.5 kV 175 mil	12.5 kV 220 mil	25 kV 260 mil	34.5 kV 345 mil
2	0.0516	0.0441	0.0396	0.0333	1.01	0.862	3.09	4.98
1	0.0562	0.0479	0.0428	0.0358	1.1	0.936	3.35	5.35
1/0	0.0609	0.0516	0.046	0.0383	1.19	1.01	3.6	5.72
2/0	0.0655	0.0553	0.0492	0.0407	1.28	1.08	3.84	6.09
3/0	0.0712	0.0599	0.0531	0.0437	1.39	1.17	4.15	6.54
4/0	0.078	0.0654	0.0578	0.0473	1.52	1.28	4.52	7.08
250	0.0871	0.0727	0.064	0.0521	1.7	1.42	5.00	7.79
350	0.0995	0.0826	0.0725	0.0586	1.94	1.61	5.67	8.76
500	0.113	0.0934	0.0817	0.0656	2.21	1.83	6.38	9.81
750	0.135	0.111	0.0969	0.0772	2.65	2.18	7.57	11.5
1000	0.156	0.127	0.111	0.0875	3.04	2.49	8.64	13.1

Note: For XLPE cable with ε = 2.3.

recommended maximum temperature. Cross-linked polyethylene cables are rated for a maximum operating temperature of 90°C during normal operations. Operating cables above their ampacity increases the likelihood of premature failures: water trees may grow faster, thermal runaway-failures are more likely, and insulation strength may decrease. In addition to absolute temperature, thermal cycling also ages cable more quickly.

Ampacity most often limits the loading on a cable; rarely, voltage drop or flicker limits loadings. Relative to overhead lines, cables of a given size have lower impedance and lower ampacities. So cable circuits are much less likely than overhead circuits to be voltage-drop limited. Only very long cable runs on circuits with low primary voltages are voltage-drop limited. Ampacity is not the only consideration for cable selection; losses and stocking considerations should also factor into cable selection. Choosing the smallest cable that meets ampacity requirements has the lowest initial cost, but since the cable is running hotter, the cost over its life may not be optimal because of the losses. Also allow for load growth when selecting cables.

Ampacity calculations follow simple principles: the temperature at the conductor is a function of the heat generated in a cable (I^2R) and the amount of heat conducted away from the cable. We can model the thermal performance with a thermal circuit analogous to an electric circuit: heat is analogous to current; temperature to voltage; and thermal resistance to electrical resistance. Heat flow through a thermal resistance raises the temperature between the two sides of the thermal material. Higher resistance soils or insulations trap the heat and cause higher temperatures. Using the thermal equivalent of Ohm's law, the temperature difference is:

$$\Delta T = T_C - T_A = R_{TH}H = R_{TH}(I^2R)$$

where

T_C = conductor temperature, °C
T_A = ambient earth temperature, °C
R_{TH} = total thermal resistance between the cable conductor and the air, thermal Ω-ft
H = heat generated in the cable, W (= I^2R)
I = electric current in the conductor, A
R = electric resistance of the conductor, Ω/ft

Most ampacity tables and computer calculation routines are based on the classic paper by Neher and McGrath (1957). The original paper is an excellent reference. Ander's book (1998) provides a detailed discussion of cable ampacity calculations, including the Neher–McGrath method along with IEC's method that is very similar (IEC 287, 1982). Hand calculations or spreadsheet calculations of the Neher–McGrath equations are possible, but tiresome; while straightforward in principle, the calculations are very detailed. A review of the Neher–McGrath procedure — the inputs, the tech-

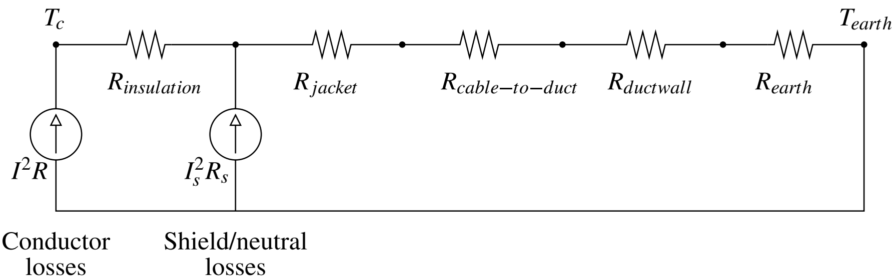

FIGURE 3.9
Thermal circuit model of a cable for ampacity calculations.

niques, the assumptions — provides a better understanding of ampacity calculations to better use computer ampacity calculations.

The Neher–McGrath procedure solves for the current in the equation above. Figure 3.9 shows a simplified model of the thermal circuit. The two main sources of heat within the cable are the I^2R losses in the phase conductor and the I^2R losses in the neutral or shield. The cable also has dielectric losses, but for distribution-class voltages, these are small enough that we can neglect them. The major thermal resistances are the insulation, the jacket, and the earth. If the cable system is in a duct, the air space within the duct and the duct walls adds thermal resistance. These thermal resistances are calculated from the thermal resistivities of the materials involved. For example, the thermal resistance of the insulation, jacket, and duct wall are all calculated with an equation of the following form:

$$R = 0.012\rho \log_{10}(D / d)$$

where

R = thermal resistance of the component, thermal Ω-ft
ρ = thermal resistivity of the component material, °C-cm/W
D = outside diameter of the component
d = inside diameter of the component

Thermal resistivity quantifies the insulating characteristics of a material. A material with ρ = 1°C-cm/W has a temperature rise of 1°C across two sides of a 1-cm^3 cube for a flow of one watt of heat through the cube. As with electrical resistivity, the inverse of thermal resistivity is thermal conductivity. Table 3.18 shows resistivities commonly used for cable system components. The thermal resistance of a material quantifies the radial temperature rise from the center outward. One thermal Ω-ft has a radial temperature rise of 1°C for a heat flow of 1 W per ft of length (length along the conductor). Mixing of metric (SI) units with English units comes about for historical reasons.

TABLE 3.18

Thermal Resistivities of Common Components

Component	Thermal Resistivity, °C-cm/W
XLPE insulation	350
EPR insulation	500
Paper insulation	700
PE jackets	350
PVC jackets	500
Plastic ducts	480
Concrete	85
Thermal fill	60
Soil	90
Water	160
Air	4000

Sources: IEC 287, *Calculation of the Continuous Current Rating of Cables (100% Load Factor)*, 2nd ed., International Electrical Commission (IEC), 1982; Neher, J. H. and McGrath, M. H., "The Calculation of the Temperature Rise and Load Capability of Cable Systems," *AIEE Transactions*, vol. 76, pp. 752–64, October 1957.

TABLE 3.19

Ampacities of Single-Phase Circuits of Full-Neutral Aluminum Conductor Cables

	Direct Buried Load Factor		In Conduit Load Factor	
Size	100%	75%	100%	75%
2	187	201	146	153
1	209	225	162	170
1/0	233	252	180	188
2/0	260	282	200	210
3/0	290	316	223	234
4/0	325	356	249	262
250	359	395	276	291
350	424	469	326	345

Note: 90°C conductor temperature, 25°C ambient earth temperature, ρ = 90°C-cm/W.

The Neher–McGrath calculations also account for multiple cables, cables with cyclic daily load cycles, external heat sources, duct arrangements, and shield resistance and grounding variations.

Often, the easiest way to find ampacities for a given application is with ampacity tables. Table 3.19 and Table 3.20 show ampacities for common distribution configurations. Of the many sources of ampacity tables, the IEEE publishes the most exhaustive set of tables (IEEE Std. 835-1994). The National Electrical Code (NFPA 70, 1999) and manufacturer's publications (Okonite, 1990; Southwire Company, 1997) are also useful. Ampacity tables provide a

TABLE 3.20

Ampacities of Three-Phase Circuits Made of Single-Conductor, One-Third Neutral Aluminum Cables

	Direct Buried Load factor		In Conduit Load factor	
Size	**100%**	**75%**	**100%**	**75%**
Flat spacing (7.5-in. separation)				
1/0	216	244	183	199
2/0	244	277	207	226
3/0	274	312	233	255
4/0	308	352	262	287
250	336	386	285	315
350	392	455	334	370
500	448	525	382	426
750	508	601	435	489
1000	556	664	478	541
Triplex				
1/0	193	224	158	173
2/0	220	255	180	197
3/0	249	290	204	225
4/0	283	330	232	256
250	312	365	257	284
350	375	442	310	345
500	452	535	375	419
750	547	653	457	514
1000	630	756	529	598

Note: 90°C conductor temperature, 25°C ambient earth temperature, ρ = 90°C-cm/W.

good starting point for determining the ampacity of a specific cable application. When using tables, be careful that the assumptions match your particular situation; if not, ampacity results can be much different than expected.

Conductor temperature limits, sheath resistance, thermal resistivity of the soil — these are some of the variables that most impact ampacity (see Figure 3.10). These and other effects are discussed in the next few paragraphs [see also (CEA, 1982; NRECA RER Project 90-8, 1993) for more discussions].

Sheath resistance — On a three-phase circuit, the resistance of the sheath (or shield or neutral) plays an important role in ampacity calculations. Because a cable's phase conductor and sheath couple so tightly, current through the phase induces a large voltage along the sheath. With the cable sheath grounded periodically, circulating current flows to counter the induced voltage. The circulating current is a function of the resistance of the sheath. This circulating current leads to something counterintuitive: sheaths with higher resistance have more ampacity. Higher resistance sheaths reduce the circulating current and reduce the I^2R losses in the sheath. This effect is

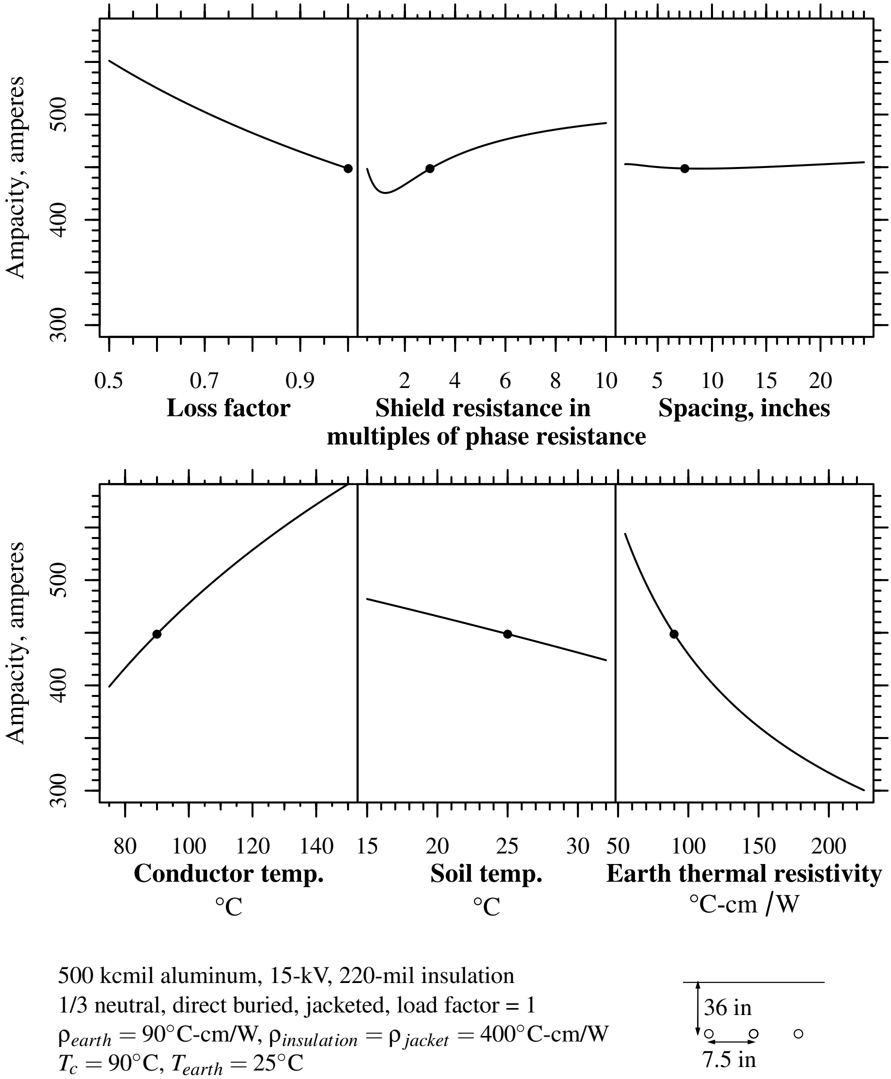

FIGURE 3.10
Effect of variables on ampacity for an example cable.

most pronounced in larger conductors. Many ampacity tables assume that cable sheaths are open circuited, this eliminates the sheath losses and increases the ampacity. The open-circuit sheath values can be approximately corrected to account for circulating currents (Okonite, 1990) by

$$k = \sqrt{\frac{I^2 R}{I_S^2 R_S + I^2 R}}$$

where

k = ampacity multiplier to account for sheath losses, i.e., $I_{grounded\ sheath} = k \cdot I_{open\ sheath}$

I = phase conductor current, A

I_S = sheath current, A

I^2R = phase conductor losses, W/unit of length

$I_S{}^2R_S$ = sheath losses, W/unit of length

The sheath losses are a function of the resistance of the sheath and the mutual inductance between the sheath and other conductors. For a triangular configuration like triplex, the shield losses are

$$I_S^2 R_S = I^2 R_S \frac{X_M^2}{R_S^2 + X_M^2}$$

where

$$X_M = 2\pi f(0.1404)\log_{10}(2S/d_S)$$

and

X_M = mutual inductance of the sheath and another conductor, mΩ/1000 ft

R_S = resistance of the sheath, mΩ/1000 ft

f = frequency, Hz

S = spacing between the phase conductors, in.

d_S = mean diameter of the sheath, in.

For configurations other than triplex, see Southwire Company (1997) or Okonite (1990). Figure 3.11 shows how sheath losses vary with conductor size and with spacing. Spacing has a pronounced effect. Steel ducts can significantly increase heating from circulating currents. In fact, even nearby steel pipes can significantly reduce ampacity.

Spacings — Separating cables separates the heat sources. But at larger spacings, circulating currents are higher. Optimal spacings involve balancing these effects. For smaller cables, separating cables provides the best ampacity. For larger cables (with larger circulating currents), triplex or other tight spacing improves ampacity. For one-third neutral, aluminum cables, NRECA (1993) shows that a flat spacing with 7.5 in. between cables has better ampacity than triplex for conductors 500 kcmil and smaller. For copper cables, the threshold is lower: conductors larger than 4/0 have better ampacity with a triplex configuration.

Conductor temperature — If we allow a higher conductor temperature, we can operate a cable at higher current. If we know the ampacity for a given conductor temperature, at a different conductor temperature we can find the ampacity with the following approximation:

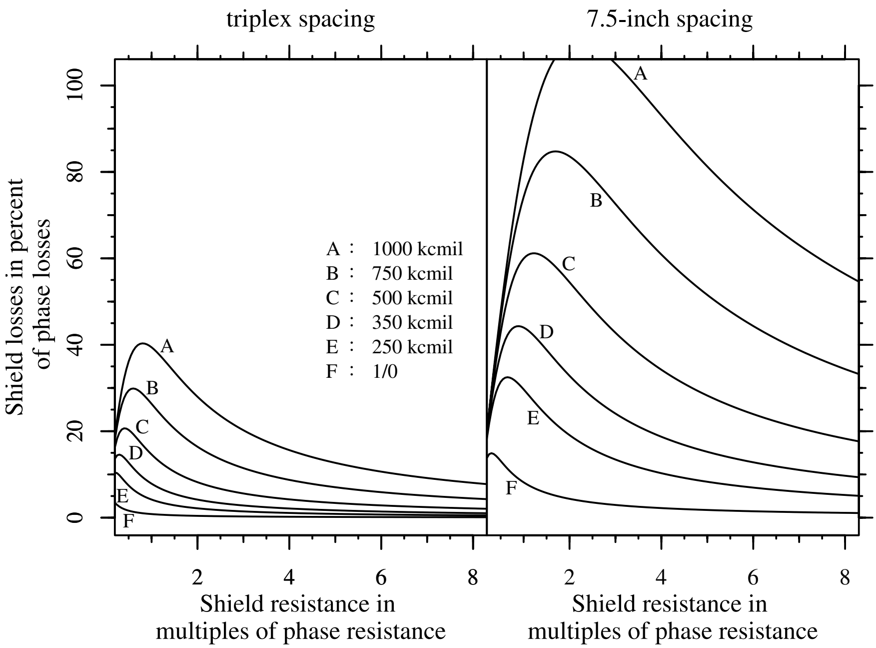

FIGURE 3.11
Shield losses as a function of shield resistance for aluminum cables (triplex configuration).

$$I' = I\sqrt{\frac{T_C' - T_A'}{T_C - T_A}\,\frac{228.1 + T_C}{228.1 + T_C'}} \qquad \text{(Aluminum conductor)}$$

$$I' = I\sqrt{\frac{T_C' - T_A'}{T_C - T_A}\,\frac{234.5 + T_C}{234.5 + T_C'}} \qquad \text{(Copper conductor)}$$

where

I' = ampacity at a conductor temperature of T_C' and an ambient earth temperature T_A'

I = ampacity at a conductor temperature of T_C and an ambient earth temperature T_A (all temperatures are in °C)

We can use these equations to find emergency ampacity ratings of cables. In an emergency, XLPE can be operated to 130°C. Some EPR cables can be operated to 140°C (MV-105 cables). ICEA standards allow emergency overload for 100 hours per year with five such periods over the life of the cable. Polyethylene cables, including HMWPE, have little overload capability. Their maximum recommended emergency temperature is 95°C. Table 3.21 shows common ampacity multipliers; these are valid for both copper and aluminum conductors within the accuracy shown. We can also use the

TABLE 3.21

Common Ampacity Rating Conversions (with $T_A = 25°C$)

Original Temperature, °C	New Temperature, °C	Ampacity Multiplier
75	95	1.15
90	75	0.90
90	105	1.08
90	130	1.20
105	140	1.14

appropriate temperature-adjustment equation to adjust for different ambient earth temperatures.

Loss factor — The earth has a high thermal storage capability; it takes considerable time to heat (or cool) the soil surrounding the cable. Close to the cable, the peak heat generated in the cable determines the temperature drop; farther out, the average heat generated in the cable determines the temperature drop. As discussed in Chapter 5, we normally account for losses using the loss factor, which is the average losses divided by the peak losses. Since this number is not normally available, we find the loss factor from the load factor (the load factor is the average load divided by the peak load). Assuming a 100% load factor (continuous current) is most conservative but can lead to a cable that is larger than necessary. We should try to err on the high side when estimating the load factor. A 75% load factor is commonly used.

Conduits — The air space in conduits or ducts significantly reduces ampacity. The air insulation barrier traps more heat in the cable. Direct-buried cables may have 10 to 25% higher ampacities. Although the less air the better, there is little practical difference in the thermal performance between the sizes of ducts commonly used. Concrete duct banks have roughly the same thermal performance as direct-buried conduits (concrete is more consistent and less prone to moisture fluctuations).

Soil thermal resistivity and temperature — Soils with lower thermal resistivity more readily conduct heat away from cables. Moisture is an important component, moist soil has lower thermal resistivity (see Figure 3.12). Dense soil normally has better conductivity. More so than any other single factor, soil resistivity impacts the conductor's temperature and the cable's ampacity. A resistivity of 90°C-cm/W is often assumed for ampacity calculations. This number is conservative enough for many areas, but if soil resistivities are higher, cable temperatures can be much higher than expected. For common soils, Table 3.22 shows typical ranges of thermal resistivities. At typical installation depths, resistivity varies significantly with season as moisture content changes. Unfortunately in many locations, just when we need ampacity the most — during peak load in the summer — the soil is close to its hottest and driest. Seasonal changes can be significant, but daily

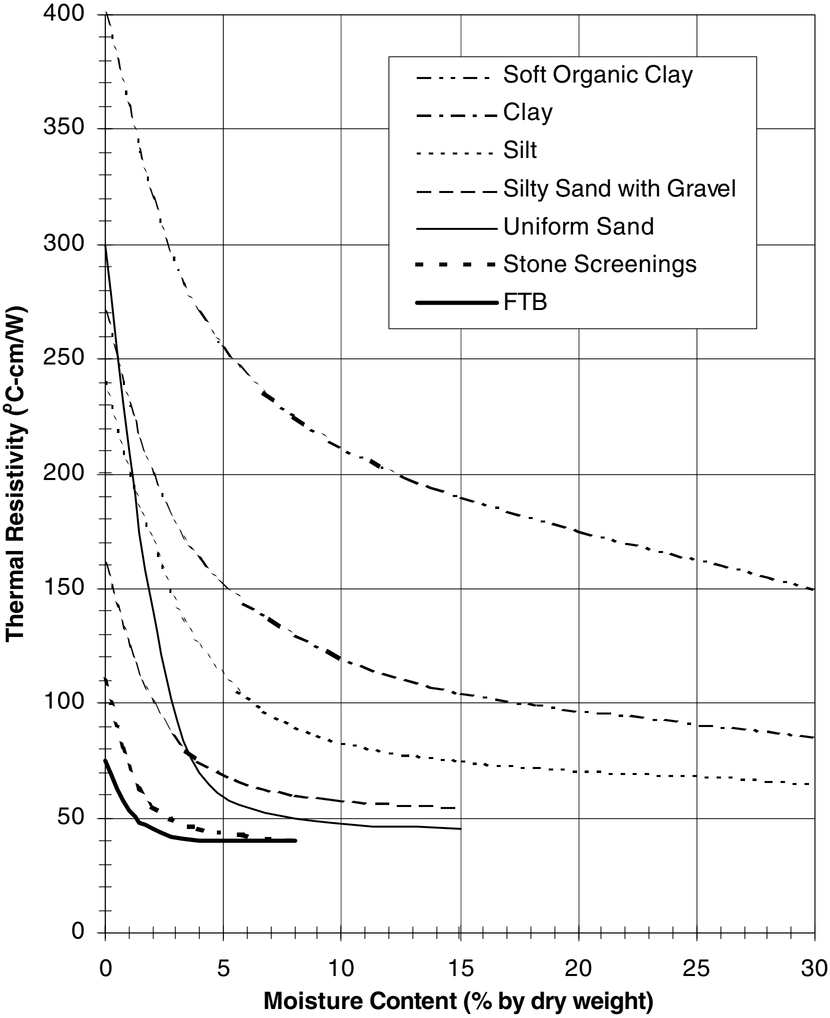

FIGURE 3.12
Effect of moisture on the thermal resistivity of various soils. (Copyright © 1997. Electric Power Research Institute. TR-108919. *Soil Thermal Properties Manual for Underground Power Transmission.* Reprinted with permission.)

changes are not; soil temperature changes lag air temperature changes by 2 to 4 weeks.

The depth of burial can affect ampacity. With a constant resistivity and soil temperature, deeper burial decreases ampacity. But deeper, the soil tends to have lower temperature, more moisture, and soil is more stable seasonally. To go deep enough to take advantage of this is not cost effective though.

For areas with poor soil (high clay content in a dry area, for example), one of several thermal backfills can give good performance, with stable

TABLE 3.22

Typical Thermal Resistivities of Common Soils

USCS	Soil	Dry Density (g/cm^3)	Range of Moisture Contents (%) Above Water Table	Saturated Moisture Content (%)	Thermal Resistivity (°C-cm/W) Wet–Dry
GW	well graded gravel	2.1	3–8	10	40–120
GP	poor graded gravel	1.9	2–6	15	45–190
GM	silty gravel	2.0	4–9	12	50–140
GC	clayey gravel	1.9	5–12	15	55–150
SW	well graded sand	1.8	4–12	18	40–130
SP	uniform sand	1.6	2–8	25	45–300
SM	silty sand	1.7	6–16	20	55–170
SC	clayey sand	1.6	8–18	25	60–180
ML	Silt	1.5	8–24	30	65–240
CL	silty clay	1.6	10–22	25	70–210
OL	organic silt	1.2	15–35	45	90–350
MH	micaceous silt	1.3	12–30	40	75–300
CH	clay	1.3	20–35	40	85–270
OH	soft organic clay	0.9	30–70	75	110–400
Pt	silty peat	0.4			150–600+

resistivities below 60°C-cm/W even when moisture content drops below one percent.

Earth interface temperature — Because soil conductivity depends on moisture, the temperature at the interface between the cable or duct and the soil is important. Unfortunately, heat tends to push moisture away. High interface temperatures can dry out the surrounding soil, which further increases the soil's thermal resistivity. Soil drying can lead to a runaway situation; hotter cable temperatures dry the soil more, raising the cable temperature more and so on. Some soils, especially clay, shrink significantly as it dries; the soil can pull away from the cable, leaving an insulating air layer. Thermal runaway can lead to immediate failure. Direct-buried cables are the most susceptible; ducts provide enough of a barrier that temperature is reduced by the time it reaches the soil.

Depending on the soil drying characteristics in an area, we may decide to limit earth interface temperatures. Limiting earth interface temperatures to 50 to 60°C reduces the risk of thermal runaway. But doing this also significantly decreases the ampacity of direct-buried cable to about that of cables in conduit. In fact, using the conduit ampacity values is a good approximation for the limits needed to keep interface temperatures in the 50 to 60°C range.

Current unbalance — Almost every ampacity table (including those in this section) assumes balanced, three-phase currents. On multigrounded distribution systems, this assumption is rarely true. An ampacity of 100 A means a limit of 100 A on each conductor. Unbalance restricts the power a three-

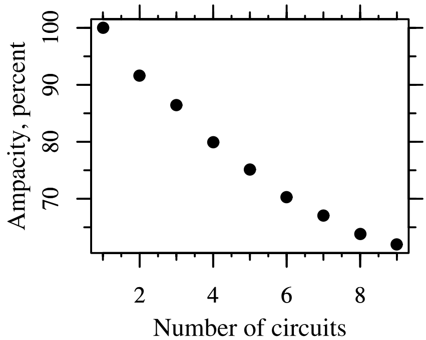

FIGURE 3.13
Ampacity reduction with multiple cable circuits in a duct bank (15 kV, aluminum, 500 kcmil, tape shield power cables, triplex configuration).

phase cable circuit can carry ($I_A = I_B = I_C = 100$ A carries more power than $I_A = 100$ A, $I_B = I_C = 70$ A). In addition, the unbalanced return current may increase the heating in the cable carrying the highest current. It may or it may not; it depends on phase relationships and the phase angle of the unbalanced current. If the unbalances are just right, the unbalanced return current can significantly increase the neutral current on the most heavily loaded phases. Unbalance also depends on the placement of the cables. In a flat configuration, the middle cable is the most limiting because the outer two cables heat the middle cable.

Just as higher sheath resistances reduce circulating currents, higher sheath resistances reduce unbalance currents in the sheath. Higher sheath resistances force more of the unbalanced current to return in the earth. The heat generated in the sheath from unbalance current also decreases with increasing sheath resistance (except for very low sheath resistances, where the sheath has less resistance than the phase conductor).

System voltage and insulation thickness — Neither significantly impacts the ampacity of distribution cables. Ampacity stays constant with voltage; 5-kV cables have roughly the same ampacity as 35-kV cables. At higher voltages, insulation is thicker, but this rise in the thermal resistance of the insulation reduces the ampacity just slightly. Higher operating voltages also cause higher dielectric losses, but again, the effect is small (it is more noticeable with EPR cable).

Number of cables — Cables in parallel heat each other, which restricts ampacity. Figure 3.13 shows an example for triplex power cables in duct banks.

Cable crossings and other hotspots — Tests have found that cable crossings can produce significant hotspots (Koch, 2001). Other hotspots can occur in locations where cables are paralleled for a short distance like taps to padmounted transformers or other gear. Differences in surface covering (such as asphalt roads) can also produce hot spots. Anders and Brakelmann (1999a, 1999b) provide an extension to the Neher–McGrath model that includes the effects of cable crossings at different angles. They conclude: "the derating of

3 to 5% used by some utilities may be insufficient, especially for cables with smaller conductors."

Riser poles — Cables on a riser pole require special attention. The protective vertical conduit traps air, and the sun adds external heating. Hartlein and Black (1983) tested a specific riser configuration and developed an analytical model. They concluded that the size of the riser and the amount of venting were important. Large diameter risers vented at both ends are the best. With three cables in one riser, they found that the riser portion of the circuit limits the ampacity. This is especially important in substation exit cables and their riser poles. In a riser pole application, ampacity does not increase for lower load factors; a cable heats up much faster in the air than when buried in the ground (the air has little thermal storage). NRECA (1993) concluded that properly vented risers do not need to be derated, given that venting can increase ampacity between 10 and 25%. If risers are not vented, then the riser becomes the limiting factor. Additional work in this area has been done by Cress (1991) (tests and modeling for submarine cables in riser poles) and Anders (1996) (an updated analytical model).

3.6 Fault Withstand Capability

Short-circuit currents through a conductor's resistance generates tremendous heat. All cable between the source and the fault is subjected to the same phase current. For cables, the weakest link is the insulation; both XLPE and EPR have a short-duration upper temperature limit of 250°C. The short-circuit current injects energy as a function of the fault duration multiplied by the square of the current.

For aluminum conductors and XLPE or EPR insulation, the maximum allowable time-current characteristic is given by

$$I^2t = (48.4A)^2$$

where

I = fault current, A
t = fault duration, sec
A = cross-sectional area of the conductor, kcmil

This assumes an upper temperature limit of 250°C and a 90°C starting temperature. For copper, the upper limit is defined by

$$I^2t = (72.2A)^2$$

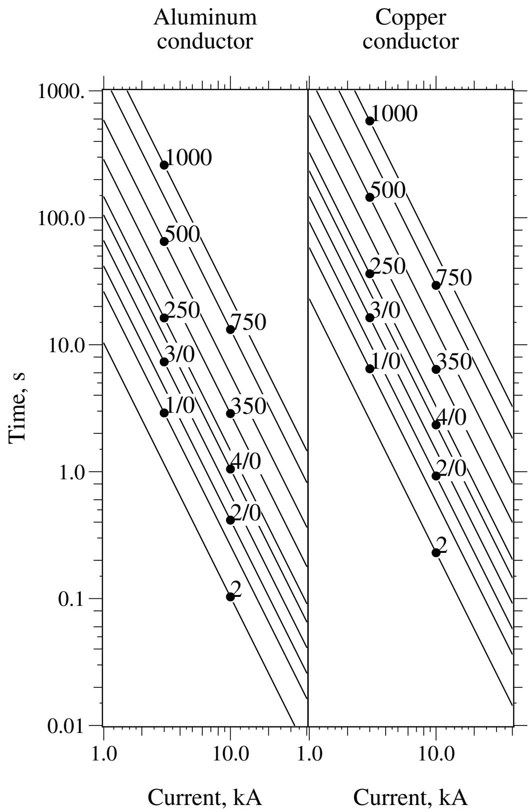

FIGURE 3.14
Short-circuit limit of cables with EPR or XLPE insulation.

We can plot these curves along with the time-current characteristics of the protecting relay, fuse, or recloser to ensure that the protective devices protect our cables.

Damage to the shield or the neutral is more likely than damage to the phase conductor. During a ground fault, the sheath may conduct almost as much current as the phase conductor, and the sheath is normally smaller. With a one-third neutral, the cable neutral's I^2t withstand is approximately 2.5 times less than the values for the phase conductor indicated in Figure 3.14 (this assumes a 65°C starting temperature). Having more resistance, a tape shield is even more vulnerable. A tape shield has a limiting time-current characteristic of

$$I^2t = (z \cdot A)^2$$

where z is 79.1 for sheaths of copper, 58.2 for bronze, 39.2 for zinc, 23.7 for copper-nickel, and 15 for lead [with a 65°C starting temperature and an

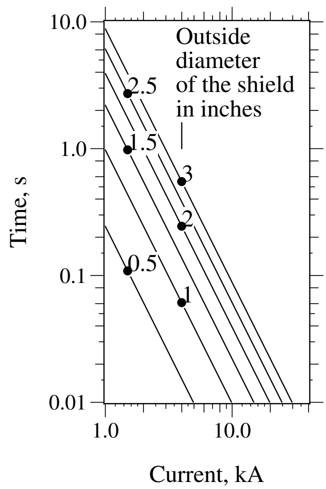

FIGURE 3.15
Short-circuit insulation limit of copper tape shields based on outside diameter (starting temperature is 65°C, final temperature is 250°C, 20% lap on the shield).

upper limit of 250°C; using data from (Kerite Company)]. Figure 3.15 shows withstand characteristics for a 5-mil copper tape shield. The characteristic changes with cable size because larger diameter cables have a shield with a larger circumference and more cross-sectional area. If a given fault current lasts longer than five times the insulation withstand characteristic (at 250°C), the shield reaches its melting point.

In the vicinity of the fault, the fault current can cause considerably more damage to the shield or neutral. With a concentric neutral, the fault current may only flow on a few strands of the conductor until the cable has a grounding point where the strands are tied together. Excessive temperatures can damage the insulation shield, the insulation, and the jacket. In addition, the temperature may reach levels that melt the neutral strands. A tape shield can suffer similar effects: where tape layers overlap, oxidation can build up between tape layers, which insulate the layers from each other. This can restrict the fault current to a smaller portion of the shield. Additionally, where the fault arc attaches, the arc injects considerable heat into the shield or neutral, causing further damage at the failure point. Some additional damage at the fault location must be tolerated, but the arc can burn one or more neutral strands several feet back toward the source.

Martin et al. (1974) reported that longitudinally corrugated sheaths perform better than wire or tape shields for high fault currents. They also reported that a semiconducting jacket helped spread the fault current to the sheaths of other cables (the semiconducting material breaks down).

Pay special attention to substation exit cables in areas with high fault currents (especially since exit cables are critical for circuit reliability). During a close fault, where currents are high, a reduced neutral or tape shield is most prone to damage.

3.7 Cable Reliability

3.7.1 Water Trees

The most common failure cause of solid-dielectric cables has been *water treeing*. Water trees develop over a period of many years and accelerate the failure of solid dielectric cables. Excessive treeing has led to the premature failure of many polyethylene cables. Cable insulation can tree two ways:

- *Electrical trees* — These hollow tubes develop from high electrical stress; this stress creates partial discharges that eat away at the insulation. Once initiated, electrical trees can grow fast, failing cable within hours or days.
- *Water trees* — Water trees are small discrete voids separated by insulation. Water trees develop slowly, growing over a period of months or years. Much less electrical stress is needed to cause water trees. Water trees actually look more like fans, blooms, or bushes whereas electrical trees look more like jagged branched trees. As its name indicates, water trees need moisture to grow; water that enters the dielectric accumulates in specific areas (noncrystalline regions) and causes localized degradation. Voids, contaminants, temperature, and voltage stress — all influence the rate of growth.

The formation of water trees does not necessarily mean the cable will fail. A water tree can even bridge the entire dielectric without immediate failure. Failure occurs when a water tree converts to an electrical tree. One explanation of the initiation of electrical trees is from charges trapped in the cable insulation. In Thue's words (1999), "they can literally bore a tunnel from one void or contaminant to the next." Impulses and dc voltage (in a hi-pot test) can trigger electrical treeing in a cable that is heavily water treed.

The growth rate of water trees tends to reduce with time; as trees fan out, the electrical stress on the tree reduces. Trees that grow from contaminants near the boundary of the conductor shield are most likely to keep growing. These are "vented" trees. Bow-tie trees (those that originate inside the cable) tend to grow to a critical length and then stop growing.

The electrical breakdown strength of aged cable has variation, a variation that has a skewed probability distribution. Weibull or lognormal distributions are often used to characterize this probability and predict future failure probabilities.

Polyethylene insulation systems have been plagued by early failures caused by water trees. Early XLPE and especially HMWPE had increasing failure rates that have led utilities to replace large quantities of cable. By most accounts, polyethylene-based insulation systems have become much more resistant to water treeing and more reliable for many reasons (Dudas, 1994; EPRI 1001894, 2001; Thue, 1999):

- *Extruded semiconducting shields* — Rather than taped conductor and insulation shields, manufacturers extrude both semiconducting shields as they are extruding the insulation. This one-pass extrusion provides a continuous, smooth interface. The most dangerous water trees are those that initiate from imperfections at the interface between the insulation and the semiconducting shield. Reducing these imperfections reduces treeing.
- *Cleaner insulation* — AEIC specifications for the allowable number and size of contaminants and protrusions have steadily improved. Both XLPE compound manufacturers and cable manufacturers have reduced contaminants by improving their production and handling processes.
- *Fewer voids* — Dry curing reduces the number and size of voids in the cable. Steam-cured cables pass through a long vulcanizing tube filled with 205°C steam pressurized at 20 atm. Cables cured with steam have sizeable voids in the insulation. Instead of steam, dry curing uses nitrogen gas pressurized to 10 atm; an electrically heated tube radiates infrared energy that heats the cable. Dry curing has voids, but these voids have volumes 10 to 100 times less than with steam curing.
- *Tree-retardant formulations* — Tree-retardant formulations of XLPE perform much better in accelerated aging tests, tests of field-aged cables, and also in field experience.

EPR insulation has proven to be naturally water tree resistant; EPR cables have performed well in service since the 1970s. EPR insulation can and does have water trees, but they tend to be smaller. EPR cable systems have also improved by having cleaner insulation compounds, jackets, and extruded semiconductor shields.

Several accelerated aging tests have been devised to predict the performance of insulation systems. The tests use one of two main methods to quantify performance: (1) loss of insulation strength or (2) time to failure. In accelerated aging, testers normally submerge cables in water, operate the cables at a continuous overvoltage, and possibly subject the cables to thermal cycling. The accelerated water treeing test (AWTT) is a protocol that measures the loss of insulation strength of a set of samples during one year of testing (ANSI/ICEA S-94-649-2000, 2000). The wet aging as part of this test includes application of three times rated voltage and current sufficient to heat the water to 60°C. In another common test protocol, the accelerated cable life test (ACLT), cables are submerged in water, water is injected into the conductor strands, cables are operated to (commonly) four times nominal voltage, and cables are brought to 90°C for eight hours each day. The cables are operated to failure. Brown (1991) reported that under such a test, XLPE and TR-XLPE cables had geometric mean failure times of 53 and 161 days, respectively. Two EPR constructions did not fail after 597 days of testing. Because EPR and XLPE age differently depending on the type of stress, EPR can come out better or worse than TR-XLPE, depending on the test conditions. There is no consensus on the best accelerated-aging test. Normally such tests are used to compare two types of cable constructions. Bernstein concludes, "… there is still no acceptable means of relating service and laboratory aging to 'remaining life' " (EPRI 1000273, 2000).

Even without voltage, XLPE cable left outdoors can age. EPRI found that XLPE cables left in the Texas sun for 10 years lost over 25% of their ac insulation strength (EPRI 1001389, 2002). These researchers speculate that heating from the sun led to a loss of peroxide decomposition by-products, which is known to result in loss of insulation strength.

Since water promotes water treeing, a few utilities use different forms of water blocking (Powers, 1993). Water trees grow faster when water enters the insulation from both sides: into the conductor strands and through the cable sheath. The most common water-protection method is a filled strand conductor; moisture movement or migration is minimized by the filling, which can be a semiconducting or an insulating filler. Another variation uses water absorbing powders; as the powder absorbs water it turns to a gel that blocks further water movement. An industry standard water blocking test is provided (ICEA Publication T-31-610, 1994; ICEA Publication T-34-664, 1996). In addition to reducing the growth and initiation of water trees, a strand-blocked conductor reduces corrosion of aluminum phase conductors. We can also use solid conductors to achieve the same effect (on smaller cables).

Another approach to dealing with water entry and treeing in existing cable is to use a silicone injection treatment (Nannery et al., 1989). After injection into the stranded conductor, the silicone diffuses out through the conductor shield and into the insulation. The silicone fills water-tree voids and reacts with water such that it dries the cable. This increases the dielectric strength and helps prevent further treeing and loss of life.

Another way to increase the reliability is to increase the insulation thickness. As an example, the maximum electrical stress in a cable with an insulation thickness of 220 mil (1 mil = 0.001 in. = 0.00254 cm) is 14% lower than a 175-mil cable (Mackevich, 1988).

Utilities and manufacturers have taken steps to reduce the likelihood of cable degradation. Table 3.23 shows trends in cable specifications for underground residential cable. Tree-retardant insulation and smooth semiconductor shields, jackets and filled conductors, and dry curing and triple extrusion are features specified by utilities to improve reliability.

TABLE 3.23

Trends in URD Cable Specifications

Characteristic	1983	1988	1993	1998
XLPE insulation	84	52	20	0
TR-XLPE insulation		36	52	68
EPR insulation	12	12	28	32
Protective jacket	64	80	92	93[a]
Filled strand conductor	4	32	60	68
Dry cure for XLPE and TR-XLPE		24	56	52
Triple extrusion		44	64	67[a]
Supersmooth semicon shields		0	44	56
Bare copper neutrals		72	84	

Note: Percentage of the 25 largest investor-owned utilities in the U.S. that specify the given characteristic.

[a] Somewhat different data set: percentages from the top 45 largest investor-owned utilities.

Sources: Dudas, J. H., "Technical Trends in Medium Voltage URD Cable Specifications," *IEEE Electrical Insulation Magazine*, vol. 10, no. 2, pp. 7–16, March/April 1994; Dudas, J. H. and Cochran, W. H., "Technical Advances in the Underground Medium-Voltage Cable Specification of the Largest Investor-Owned Utilities in the U.S.," *IEEE Electrical Insulation Magazine*, vol. 15, no. 6, pp. 29–36, November/December 1999.

Good lightning protection also reduces cable faults. This requires surge arresters at the riser pole and possibly arresters at the cable open point (depending on the voltage). Keep arrester lead lengths as short as possible. Surges are a known cause of dielectric failures. Surges that do not fail the insulation may cause aging. Accelerated aging tests have found that 15-kV XLPE cables tested with periodic surges applied with magnitudes of 40, 70, and 120 kV failed more often and earlier than samples that were not surged (EPRI EL-6902, 1990; EPRI TR-108405-V1, 1997; Hartlein et al., 1989; Hartlein et al., 1994). Very few of the failures occurred during the application of a surge; this follows industry observations that cables often fail after a thunderstorm, not during the storm.

Rather than continue patching, many utilities regularly replace cable. Program policies are done based on the number of failures (the most common approach), cable inspection, customer complaints, or cable testing. High-molecular weight polyethylene and older XLPE are the most likely candidates for replacement. Most commonly, utilities replace cable after two or three electrical failures within a given time period (see Table 3.24).

3.7.2 Other Failure Modes

Cable faults can be caused by several events including:

TABLE 3.24

Typical Cable Replacement Criteria

Replacement Criteria	Responses (n = 51)
One failure	2%
Two failures	31%
Three failures	41%
Four failures	4%
Five failures	6%
Based on evaluation procedures	16%

Source: Tyner, J. T., "Getting to the Bottom of UG Practices," *Transmission & Distribution World*, vol. 50, no. 7, pp. 44–56, July 1998.

- Dig-ins
- Cable failures
- Cable equipment failures — splices, elbows, terminations

Better public communications reduces dig-ins into cables. The most common way is with one phone number that can be used to coordinate marking of underground facilities before digging is done. Physical methods of reducing dig-ins include marker tape, surface markings, or concrete covers. Marker tape identifies cable. A few utilities use surface marking to permanently identify the location of underground facilities. Concrete covers above underground facilities physically block dig-ins.

Temporary faults are unusual in underground facilities. Faults are normally bolted, permanent short circuits. Reclosing will just do additional damage to the cable. Occasionally, animals or water will temporarily fault a piece of live-front equipment. Recurring temporary faults like these can be very difficult to find.

Another type of temporary, self-clearing fault can occur on a cable splice (Stringer and Kojovic, 2001). Figure 3.16 shows a typical waveform of an impending splice failure. This type of fault has some distinguishing characteristics: it self-clears in 1/4 cycle, the frequency of occurrence increases with time, and faults occur near the peak of the voltage. The author has observed this type of fault during monitoring (but never identified the culprit). This type of fault can occur in a cable splice following penetration of water into the splice. The water breaks down the insulation, then the arc energy melts the water and creates vapor at high pressure. Finally, the high-pressure vapor extinguishes the arc. The process can repeat when enough water accumulates again until the failure is permanent. This type of self-clearing fault can go unnoticed until it finally fails. The downside is that it causes a short-duration voltage sag that may affect sensitive equipment. Another problem, the fault may have enough current to blow a fuse; but since the fault self-clears, it can be much harder to find. Crews may just replace the fuse (successfully) and leave without replacing the damaged equipment.

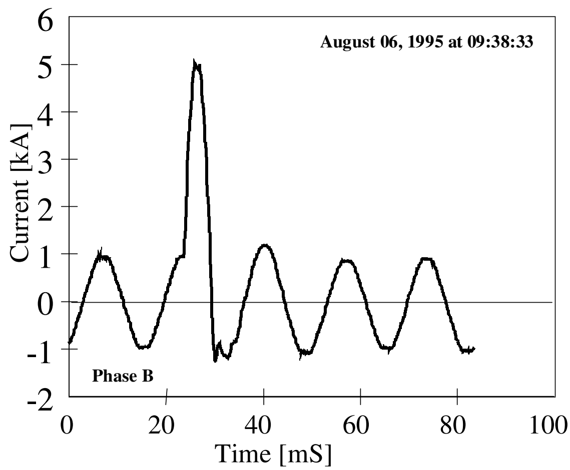

FIGURE 3.16
Self-clearing fault signature on an incipient cable-splice failure. (From Stringer, N. T. and Kojovic, L. A., "Prevention of Underground Cable Splice Failures," *IEEE Trans. Industry App.*, 37(1), 230-9, Jan./Feb. 2001. With permission. ©2001 IEEE.)

3.7.3 Failure Statistics

The annual failures of cables is on the order of 6 to 7 failures per 100 mi per year (3.7 to 4.3 failures per 100 km per year) according to survey data from the Association of Edison Illuminating Companies from 1965 through 1991 (Thue, 1999). Figure 3.17 shows cable failure data from a variety of sources; experience varies widely. Application, age, and type of cable markedly change the results. Utilities have experienced high failures of HMWPE, especially those that installed in the early 1970s. An EPRI database of 15 utilities showed a marked increase in failure rates for HMWPE cables with time (Stember et al., 1985). XLPE also shows a rise in failure rates with time, but not as dramatic (see Figure 3.18). The EPRI data showed failure rates increased faster with a higher voltage gradient on the dielectric for both HMWPE and XLPE.

Much of the failure data in Figure 3.17 is dominated by earlier polyethylene-based cable insulation technologies. Not as much data is available on the most commonly used insulation materials: TR-XLPE and EPR. The AEIC survey reported results in 1991 — both had fewer than 0.5 failures per 100 cable mi during that year. TR-XLPE results were better (0.2 vs. 0.4 failures/100 mi/year for EPR), but the installed base of TR-XLPE would have been newer than EPR at that time. Jacketed cable has had fewer failures than unjacketed cable as shown in Table 3.25.

Another consideration for underground circuits is the performance of connectors and other cable accessories. 200-A elbows have failed at high rates (and they tend to fail when switching under load) (Champion, 1986).

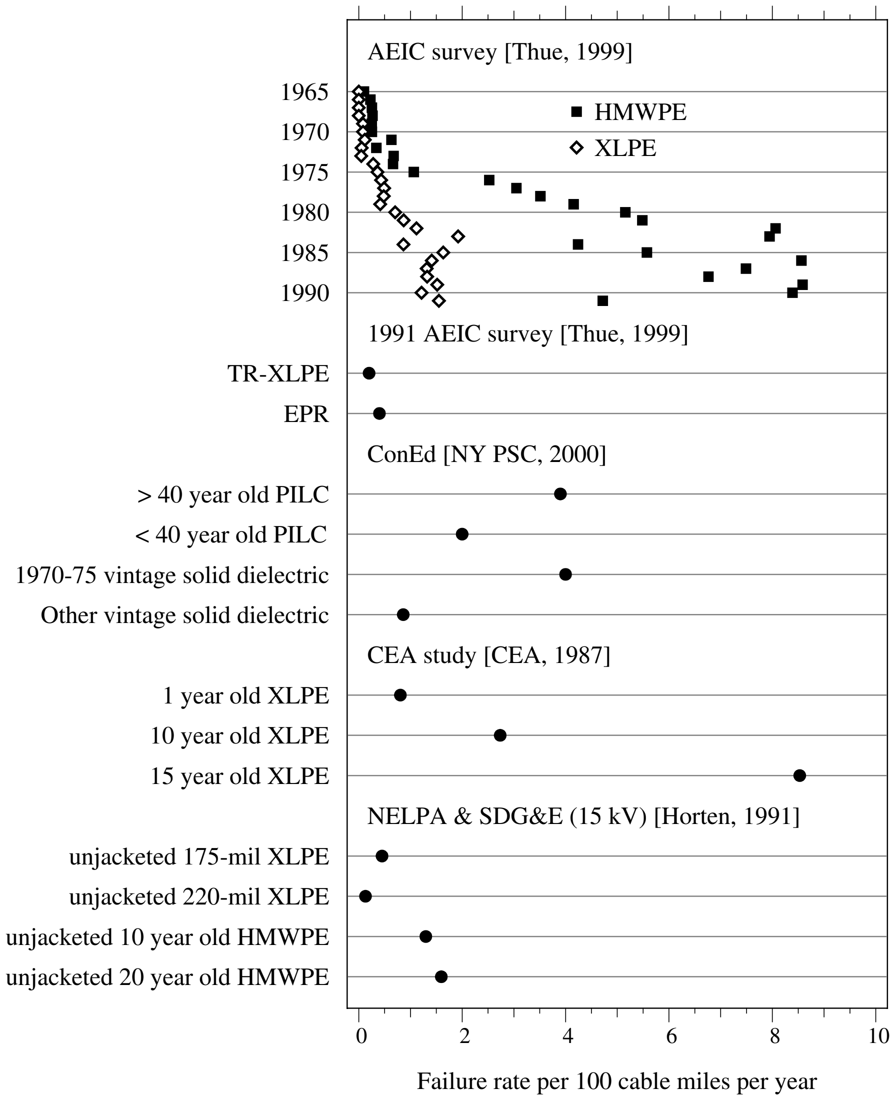

FIGURE 3.17
Cable failure rates found in different studies and surveys (in cable miles, not circuit miles). (Data from [CEA 117 D 295, 1987; Horton and Golberg, 1991; State of New York Department of Public Service, 2000; Thue, 1999].)

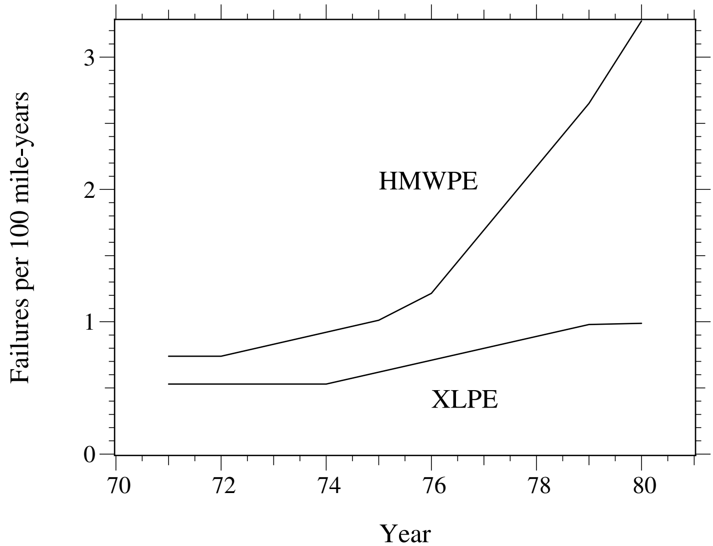

FIGURE 3.18
Cumulative service-time failure rates for HMWPE and XLPE cable. (From Stember, L. H., Epstein, M. M., Gaines, G. V., Derringer, G. C., and Thomas, R. E., "Analysis of Field Failure Data on HMWPE- and XLPE-Insulated High-Voltage Distribution Cable," *IEEE Trans. Power Apparatus Sy.*, PAS-104(8), 1979-85, August 1985. With permission. ©1985 IEEE.)

TABLE 3.25

Comparison of the Median of the Average Yearly Failure Rates of XLPE Found by AEIC from 1983 to 1991

Configuration	Failures per 100 Cable miles/year
No jacket	3.1
Jacketed	0.2
Direct buried	2.6
Duct	0.2

Source: Thue, W. A., *Electrical Power Cable Engineering*, Marcel Dekker, New York, 1999.

One important factor is that the type of splice should be correctly matched with the type of cable (Mackevich, 1988). Table 3.26 shows annual failure rates for some common underground components that were developed based on data from the Northwest Underground Distribution Committee of the Northwest Electric Light and Power Association (Horton and Golberg, 1990; Horton and Golberg, 1991). Table 3.27 shows failure rates of splices for New York City.

An EPRI review of separable connector reliability found mixed results (EPRI 1001732, 2002). Most utilities do not track these failures. One utility that did keep records found that failure rates of separable connectors ranged

TABLE 3.26

Annual Underground-Component Failure Rates

Component	Annual Failure Rate, %
Load-break elbows	0.009t
15-kV molded rubber splices	0.31
25-kV molded rubber splices	0.18
35-kV molded rubber splices	0.25
Single-phase padmounted transformers	0.3

Note: t is the age of the elbow in years.

Sources: Horton, W. F. and Golberg, S., "The Failure Rates of Underground Distribution System Components," Proceedings of the Twenty-Second Annual North American Power Symposium, 1990; Horton, W. F. and Golberg, S., "Determination of Failure Rates of Underground Distribution System Components from Historical Data," IEEE/PES Transmission and Distribution Conference, 1991.

TABLE 3.27

Underground Network Component Failure Rates in New York City (Con Edison)

Component	Annual Failure Rate, %
Splices connecting paper to solid cables (stop joints)	1.20
Splices connecting similar cables (straight joints)	0.51
Network transformers	0.58

Source: State of New York Department of Public Service, "A Report on Consolidated Edison's July 1999 System Outages," March 2000.

from 0.1 to 0.4% annually. Of these failures, an estimated 3 to 20% are from overheating. They also suggested that thermal monitoring is a good practice, but effectiveness is limited because the monitoring is often done when the loadings and temperatures are well below their peak.

3.8 Cable Testing

A common approach to test cable and determine insulation integrity is to use a hi-pot test. In a hi-pot test, a dc voltage is applied for 5 to 15 min. IEEE-400 specifies that the hi-pot voltage for a 15-kV class cable is 56 kV for an acceptance test and 46 kV for a maintenance test (ANSI/IEEE Std. 400-1980). Other industry standard tests are given in (AEIC CS5-94, 1994; AEIC CS6-96, 1996; ICEA S-66-524, 1988). High-pot testing is a brute-force test; imminent failures are detected, but the amount of deterioration due to aging is not quantified (it is a go/no–go test).

The dc test is controversial — some evidence has shown that hi-pot testing may damage XLPE cable (Mercier and Ticker, 1998). EPRI work has shown that dc testing accelerates treeing (EPRI TR-101245, 1993; EPRI TR-101245-V2, 1995). For hi-pot testing of 15-kV, 100% insulation (175-mil, 4.445-mm) XLPE cable, EPRI recommended:

- Do not do testing at 40 kV (228 V/mil) on cables that are aged (especially those that failed once in service and then are spliced). Above 300 V/mil, deterioration was predominant.
- New cable can be tested at the factory at 70 kV. No effect on cable life was observed for testing of new cable.
- New cable can be tested at 55 kV in the field prior to energization if aged cable has not been spliced in.
- Testing at lower dc voltages (such as 200 V/mil) will not pick out bad sections of cable.

Another option for testing cable integrity: ac testing does not degrade solid dielectric insulation (or at least degrades it more slowly). The use of very low frequency ac testing (at about 0.1 Hz) may cause less damage to aged cable than dc testing (Eager et al., 1997) (but utilities have reported that it is not totally benign, and ac testing has not gained widespread usage). The low frequency has the advantage that the equipment is much smaller than 60-Hz ac testing equipment.

3.9 Fault Location

Utilities use a variety of tools and techniques to locate underground faults. Several are described in the next few paragraphs [see also EPRI TR-105502 (1995)].

Divide and conquer — On a radial tap where the fuse has blown, crews narrow down the faulted section by opening the cable at locations. Crews start by opening the cable near the center, then they replace the fuse. If the fuse blows, the fault is upstream; if it doesn't blow, the fault is downstream. Crews then open the cable near the center of the remaining portion and continue bisecting the circuit at appropriate sectionalizing points (usually padmounted transformers). Of course, each time the cable faults, more damage is done at the fault location, and the rest of the system has the stress of carrying the fault currents. Using current-limiting fuses reduces the fault-current stress but increases the cost.

Fault indicators — Faulted circuit indicators (FCIs) are small devices clamped around a cable that measure current and signal the passage of fault current. Normally, these are applied at padmounted transformers. Faulted circuit indicators do not pinpoint the fault; they identify the fault to a cable section. After identifying the failed section, crews must use another method

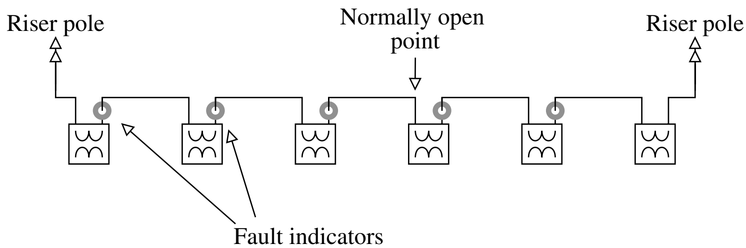

FIGURE 3.19
Typical URD fault indicator application.

such as the thumper to precisely identify the fault. If the entire section is in conduit, crews don't need to pinpoint the location; they can just pull the cable and replace it (or repair it if the faulted portion is visible from the outside). Cables in conduit require less precise fault location; a crew only needs to identify the fault to a given conduit section.

Utilities' main justification for faulted circuit indicators is reducing the length of customer interruptions. Faulted circuit indicators can significantly decrease the fault-finding stage relative to the divide-and-conquer method. Models that make an audible noise or have an external indicator decrease the time needed to open cabinets.

Utilities use most fault indicators on URD loops. With one fault indicator per transformer (see Figure 3.19), a crew can identify the failed section and immediately reconfigure the loop to restore power to all customers. The crew can then proceed to pinpoint the fault and repair it (or even delay the repair for a more convenient time). For larger residential subdivisions or for circuits through commercial areas, location is more complicated. In addition to transformers, fault indicators should be placed at each sectionalizing or junction box. On three-phase circuits, either a three-phase fault indicator or three single-phase indicators are available; single-phase indicators identify the faulted phase (a significant advantage). Other useful locations for fault indicators are on either end of cable sections of overhead circuits, which are common at river crossings or under major highways. These sections are not fused, but fault indicators will show patrolling crews whether the cable section has failed.

Fault indicators may be reset in a variety of ways. On manual reset units, crews must reset the devices once they trip. These units are less likely to reliably indicate faults. Self-resetting devices are more likely to be accurate as they automatically reset based on current, voltage, or time. Current-reset is most common; after tripping, if the unit senses current above a threshold, it resets [standard values are 3, 1.5, and 0.1 A (NRECA RER Project 90-8, 1993)]. With current reset, the minimum circuit load at that point must be above the threshold, or the unit will never reset. On URD loops, when applying current-reset indicators, consider that the open point might change. This changes the current that the fault indicator sees. Again, make sure the circuit load is enough to reset the fault indicator. Voltage reset models provide a voltage sensor; when the voltage exceeds some value (the voltage sensor senses at secondary voltage or at an elbow's capacitive test point). Time-reset units simply reset after a given length of time.

Fault indicators should only operate for faults — not for load, not for inrush, not for lightning, and not for backfeed currents. False readings can send crews on wild chases looking for faults. Reclose operations also cause loads and transformers to draw inrush, which can falsely trip a fault indicator. An inrush restraint feature disables tripping for up to one second following energization. On single-phase taps, inrush restraint is really only needed for manually-reset fault indicators (the faulted phase with the blown fuse will not have inrush that affects downstream fault indicators). Faults in adjacent cables can also falsely trip indicators; the magnetic fields couple into the pickup coil. Shielding can help prevent this. Several scenarios cause backfeed that can trip fault indicators. Downstream of a fault, the stored charge in the cable will rush into the fault, possibly tripping fault indicators. McNulty (1994) reported that 2000 ft of 15-kV cable created an oscillatory current transient that peaked at 100 A and decayed in 0.15 msec. Nearby capacitor banks on the overhead system can make outrush worse. Motors and other rotating equipment can also backfeed faults. To avoid false trips, use a high set point. Equipment with filtering that reduces the indicator's sensitivity to transient currents also helps, but too much filtering may leave the faulted-circuit indicator unable to detect faults cleared rapidly by current-limiting fuses.

Self-resetting fault indicators can also falsely reset. Backfeed currents and voltages can reset fault indicators. On a three-phase circuit with one phase tripped, the faulted phase can backfeed through three-phase transformer connections (see Chapter 4), providing enough current or enough voltage to reset faulted-circuit indicators. On single-phase circuits, these are not a problem. In general, single-phase application is much easier; we do not have backfeed problems or problems with indicators tripping from faults on nearby cables. For single-phase application guidelines, see (IEEE Std 1216-2000).

Fault indicators may have a threshold-type trip characteristic like an instantaneous relay (any current above the set point trips the flag), or they may have a time-overcurrent characteristic which trips faster for higher currents. Those units with time-overcurrent characteristics should be coordinated with minimum clearing curves of current-limiting fuses to ensure that they operate. Another type of fault indicator uses an adaptive setting that trips based on a sudden increase in current followed by a loss of current.

Set the trip level on fault indicators to less than 50% of the available fault current or 500 A, whichever is less (IEEE P1610/D03, 2002). This trip threshold should be at least two to three times the load on the circuit to minimize false indications. These two conditions will almost never conflict, only at the end of a very long feeder (low fault currents) on a cable that is heavily loaded.

Normally, fault indicators are fixed equipment, but they can be used for targeted fault location. When crews arrive at a faulted and isolated section, they first apply fault indicators between sections (normally at padmounted transformers). Crews reenergize the failed portion and then check the fault indicators to identify the faulted section. Only one extra fault is applied to the circuit, not multiple faults as with the divide and conquer method.

Section testing — Crews isolate a section of cable and apply a dc hi-pot voltage. If the cable holds the hi-pot voltage, crews proceed to the next section and repeat until finding a cable that cannot hold the hi-pot voltage. Because the voltage is dc, the cable must be isolated from the transformer. In a faster variation of this, high-voltage sticks are available that use the ac line voltage to apply a dc voltage to the isolated cable section.

Thumper — The thumper applies a pulsed dc voltage to the cable. As its name implies, at the fault the thumper discharges sound like a thumping noise as the gap at the failure point repeatedly sparks over. The thumper charges a capacitor and uses a triggered gap to discharge the capacitor's charge into the cable. Crews can find the fault by listening for the thumping noise. Acoustic enhancement devices can help crews locate weak thumping noises; antennas that pick up the radio-frequency interference from the arc discharge also help pinpoint the fault. Thumpers are good for finding the exact fault location so that crews can start digging. On a 15-kV class system, utilities typically thump with voltages from 10 to 15 kV, but utilities sometimes use voltages to 25 kV.

While pulsed discharges are thought to be less damaging to cable than a steady dc voltage, utilities have concern that thumping can damage the unfailed sections of cable. When a thumper pulse breaks down the cable, the incoming surge shoots past the fault. When it reaches the open point, the voltage doubles, then the voltage pulse bounces back and forth between the open point and the fault, switching from +2 to $-2E$ (where E is the thumper pulse voltage). In tests, EPRI research found that thumping can reduce the life of aged cable (EPRI EL-6902, 1990; EPRI TR-108405-V1, 1997; Hartlein et al., 1989; Hartlein et al., 1994). The thumping discharges at the failure point can also increase the damage at the fault point. Most utilities try to limit the voltage or discharge energy, and a few don't use a thumper for fear of additional damage to cables and components (Tyner, 1998). A few utilities also disconnect transformers from the system during thumping to protect the transformer and prevent surges from propagating through the transformer (these surges should be small). If the fault has no gap, and if the fault is a solid short circuit, then no arc forms, and the thumper will not create its characteristic thump (fortunately, solid short circuits are rare in cable faults). Some crews keep thumping in an effort to burn the short circuit apart enough to start arcing. With cable in conduit, the thumping may be louder near the conduit ends than at the fault location. Generally, crews should start with the voltage low and increase as needed. A dc hi-pot voltage can help determine how much voltage the thumper needs.

Radar — Also called time-domain reflectometry (TDR), a radar set injects a very short-duration current pulse into the cable. At discontinuities, a portion of the pulse will reflect back to the set; knowing the velocity of wave propagation along cable gives us an estimate of the distance to the fault. Depending on the test set and settings, radar pulses can be from 5 ns to 5 μs wide. Narrower pulses give higher resolution, so users can better differentiate between faults and reflections from splices and other discontinuities (Banker et al., 1994).

Radar does not give pinpoint accuracy; its main use is to narrow the fault to a certain section. Then, crews can use a thumper or other pinpoint technique to find the failure. Taking a radar pulse from either end of a cable and averaging the results can lead to an improved estimate of the location. Radar location on circuits with taps can be complicated, especially those with multiple taps; the pulse will reflect off the taps, and the reflection from the actual fault will be less than it otherwise would be. Technology has been developed to use above-ground antennas to sense and pinpoint faults based on the radar signals.

Radar and thumper — After a fuse or other circuit interrupter clears a fault in a cable, the area around the fault point recovers some insulation strength. Checking the cable with an ohm meter would show an open circuit. Likewise, the radar pulse passes right by the fault, so the radar set alone cannot detect the fault. Using radar with a thumper solves this problem. A thumper pulse breaks down the gap, and the radar superimposes a pulse that reflects off the fault arc. The risetime of the thumper waveshape is on the order of a few microseconds; the radar pulse total width may be less than 0.05 μsec. Another less attractive approach is to use a thumper to continually burn the cable until the fault resistance becomes low enough to get a reading on a radar set (this is less attractive because it subjects the cable to many more thumps, especially if crews use high voltages).

Boucher (1991) reported that fault indicators were the most popular fault locating approach, but most utilities use a variety of techniques (see Figure 3.20). Depending on the type of circuit, the circuit layout, and the equipment available, different approaches are sometimes better.

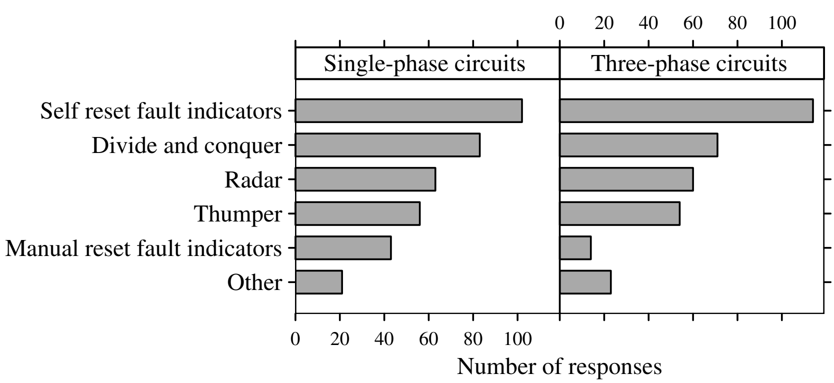

FIGURE 3.20
Utility use of fault-locating techniques (204 utilities surveyed, multiple responses allowed). (Data from [Boucher, 1991].)

When applying test voltages to cables, crews must be mindful that cables can hold significant charge. Cables have significant capacitance, and cables can maintain charge for days.

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I was down in the hole and pulled on one of the splices thinking that I might find the faulted one by pulling it apart, well you can only guess what happens next! KA-BOOOM, I was really pissed off at that point and still am. BUT YOU KNOW SOMETHING, IT'S MY FAULT FOR TAKING SOME OTHER HALF ASS LINEMAN'S WORD FOR IT BEING DEAD AND NOT CHECKING IT OUT FOR MY SELF!

Anonymous poster, about beginning work after another lineman told him that the cables were disconnected at the source end.

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