UNDERGROUND DISTRIBUTION SYSTEMS

Underground distribution systems are used where overhead (aerial) construction is impractical, unsafe, costly, or environmentally unacceptable; these areas include airport approaches, station and substation exits, long water crossings, and areas of unusual scenic value or with extreme vulnerability to damage by natural forces. The increasing public interest in improving the appearance of residential areas, local government mandates, and the declining costs of underground construction are all contributing to the rapid growth of underground distribution systems.

The function of distribution networks is to receive electric power from large, bulk sources and to distribute it to consumers at lower voltage levels (subtransmission, primary distribution, and secondary distribution) via different network topologies (radial, loop, multiple loop and network configurations) that are appropriate to the various types of users. In addition, today's increasing emphasis on reliability requires a higher degree of distribution automation that is becoming more practical as the necessary equipment and communication channels are developed. Among other applications, underground cables are used to transport electric energy in underground distribution systems.

Compared with overhead lines, which utilize the insulating characteristics of air, insulating materials for underground cables have always faced the problems of: (1) humidity in the insulating layers; (2) air trapped in the insulating layers; (3) impurities in the insulating materials; and (4) aging of insulating material as a result of thermal and voltage effects. For these reasons, adequate tests are required to assure both the proper design and quality of cable systems.

Electric discharges that do not completely bridge the electrodes or other metallic surfaces of dissimilar electric potentials are called partial discharges (PDs). Historically, when older paper-based insulating materials were dominantly used, detection of partial discharges was not needed. After World War II, newer insulating materials such as polyethylene and epoxy resin were introduced and the requirements for HV cables called for smaller dimensions and greater utilization of insulating properties. Production techniques of the new insulating materials were not perfect and could easily leave a single cavity or a void in the insulation system. Such a cavity can be detrimental to cable operation and could cause partial breakdowns under high ac voltage, thereby leading to complete insulation failure. For these reasons measuring techniques that can detect minute discharges in a single cavity are needed.

Although stringent tests are performed in the factory to find cable defects after production, failures may still occur during the normal operating life of the cable. The failures can be caused by either one or a combination of: (1) poor quality of work during installation; (2) accelerated aging due to cable overloading; (3) abnormal temperature stresses; (4) erosion due to unusual environment; (5) mechanical damage due to false digging; and (6) normal aging. A failure in the cable is called a “cable fault,” and to locate a fault means to "pinpoint" it to the extent that no further tests are required before repairs are started (for example, in duct-line construction, locating a fault between two maintenance holes is sufficient).

UNDERGROUND POWER DISTRIBUTION NETWORKS

Broadly speaking, “distribution” includes all parts of an electric power delivery system between bulk power sources and the consumers' service-entrance equipment. Figure 1 shows a typical distribution system, where both overhead and underground networks are used. Underground distribution systems are used where overhead construction is impractical, unsafe, costly, or environmental unacceptable. Depending on the con-

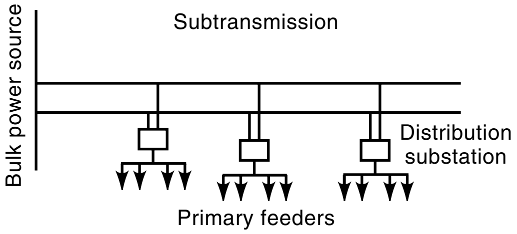

Figure 1. Typical distribution system that includes subtransmission circuit that delivers energy from bulk power sources to the distribution substations; distribution substations that convert the energy to a lower "primary system" voltage; and primary feeders that supply the load to a defined area.

sumers' requirements of voltage levels and degrees of reliability, underground power distribution systems are generally classified into four types: (1) primary distribution system; (2) low-voltage secondary network; (3) service to large commercial loads; and (4) underground residential distribution (URD). All types of underground power distribution systems consist of similar construction components with similar names and generally share the common application practices.

Types of Underground Distribution System

Primary Distribution System. Figure 2 shows a typical underground primary distribution system supplying basically residential and small commercial loads. Note that the main feeders operate as radial circuits but with normally open ties to adjacent feeders. Because it is difficult to perform many maintenance and operating functions on an underground system while it is energized, special sectionalizing switches must be incorporated. The main feeder switches are usually 3 phase, manually operated load-break switches rated at several hundred amperes of continuous current. The lateral circuits are single phase or 3 phase, operated as normally open loops with a current rating of a few hundred amperes; either load-break switches or separable insulated cable connectors are used. Overcurrent protection of the system is provided in two stages depending on the location of the fault: (1) a primary cable fault is cleared by operation of the feeder circuit breaker at the substation; and (2) fuses cut out faults in the lateral circuits.

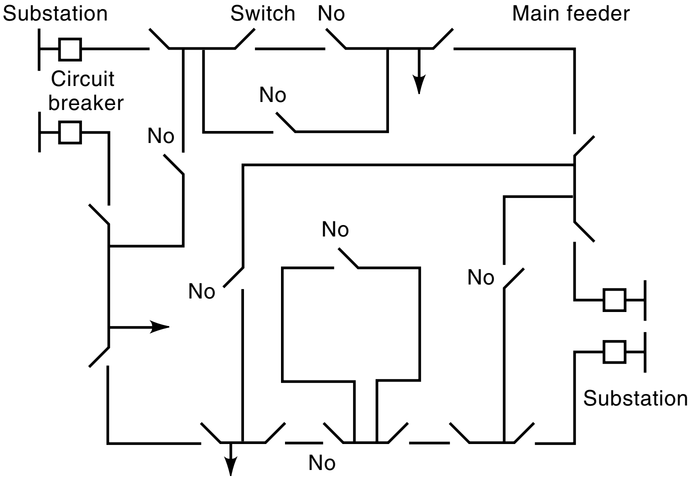

Figure 2. A typical primary feeder underground circuit that supplies residential and small commercial loads. Note that the primary feeders are operated in radial, but with normally open (NO) ties to adjacent feeders. The lateral circuits are also operated as normally open loops. All switches shown in "open state" are normally closed except NO tie switches.

The voltage levels of primary feeders are found in the range of 5 kV to 35 kV. At 15 kV a typical feeder serves a normal peak load on the order of 6000 kVA to 7000 kVA. A fully developed 35 kV feeder could serve 18,000 kVA to 20,000 kVA.

Low-Voltage Secondary Network. In metropolitan areas, the primary feeders are usually radial circuits placed in underground duct lines. They supply power through distribution transformers to numerous points of a grid of interconnected low voltage cables (secondary network). Figure 3 shows a schematic diagram of a small segment of a secondary network system, which is supplied by several primary feeders (usually connected to the same substation bus) suitably interlaced through the area in order to (1) provide high service reliability; and (2) achieve uniform loading of each network transformer under overload conditions. The number of primary feeders is usually based on the assumption that the loss of one (first contingency) or two feeders (second contingency) will not cause a service interruption. For example, under the first contingency a secondary network supplied by five feeders will keep each of the network transformers loading at 125% or less during the outage of one primary feeder. Overcurrent protection of the network system can be accomplished as follows: (1) primary cable faults are cleared by operating the feeder circuit breaker at the substation and opening of all network protectors on the low voltage side of all transformers supplied by that feeder; and (2) secondary cable faults are allowed to burn clear or are cleared by low voltage current limiters.

The service voltage level of the secondary network is of the order of a few hundred volts supplying loads to stores, hotels, restaurants, office buildings, apartment houses and, in some cases, individual residences with an averaged load density of 40,000 kVA per square kilometer.

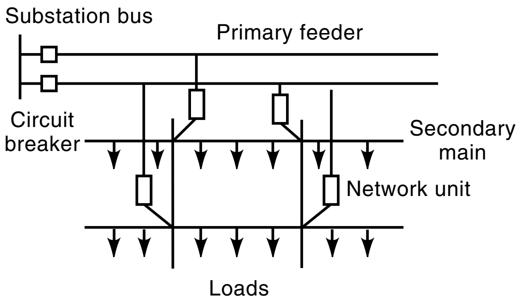

Figure 3. A typical secondary network that is supplied by several feeders through network units and secondary mains interlaced through the area in order to achieve acceptable loading of the transformers under emergency conditions and high service reliability. The network unit in a vault consists of network transformer, network protector, and current limiting fuse.

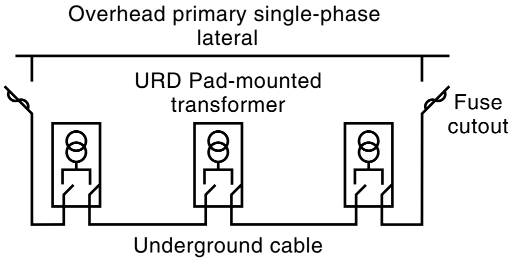

Figure 4. An underground system supplying residential areas derived from an existing overhead primary lateral feeder (single-phase). The transformer locations in the system are the key components; the primary cable connections, switches, and protective equipment are housed in the transformer enclosure.

Service to Large Commercial Loads. In heavily developed areas large commercial loads are often serviced by an underground supply network. Several basic arrangements can be found for these loads: (1) radial; (2) primary loop; (3) primary selective; (4) secondary selective; and (5) spot network. Although the radial system is the least complex and least expensive failures either in the primary cable or the transformer will result in an immediate and lengthy outage, normally lasting 10 h to 12 h. A primary loop, which provides two-way feed to each transformer, is a great improvement over the radial system. The primary selective system uses the same basic components as in the primary loop, but each transformer can select its source in a dual scheme. The secondary selective system, common in industrial plants and on other institutional properties, uses two transformers and low-voltage switching. The secondary spot network uses two or more transformer/network protector units in parallel, which can provide required redundancy for maximum service reliability and operating flexibility.

The service voltage is typically in the range of a few hundred volts for loads in the range of 3000 kVA–4000 kVA. Service quality such as voltage regulation and service continuity is high.

Underground Residential Distribution (URD). Figure 4 shows a single-phase system servicing residential areas. Its primary circuit operates as a normally open loop and the primary lateral loops are connected at each transformer; that is, there are two primary cable connections to each transformer. In the case of a cable fault in this configuration, locating and isolating the failure can be accomplished easily to restore service rapidly to all customers on the nonfaulted portions of the primary loop. The heart of the URD system is the single-phase transformer and its housing, where both the primary cable connections with their necessary switching equipment and overcurrent protective equipment are usually installed. These URD systems can be found along the residential streets in front of houses (“front-lot” types), or in the back (“rear-lot” types). Many utilities prefer rear-lot placement.

The service voltage is similar to that of primary/secondary systems. Typically, four to eight houses are supplied by each transformer.

Construction Components

Modern underground distribution system construction components can be sorted into eight categories:

1. Primary cable
2. Secondary cable
3. Conductor connections
4. Terminations and splices
5. Transformers
6. Switchgear
7. Capacitor banks
8. Structures

Common practices of each category are described in the following.

1. Primary cable
    - A. Type of insulation: thermoset crosslinked polyethylene (XLPE), thermoplastic polyethylene (PE) or ethylene propylene rubber (EPR)
    - B. Insulation thickness for different voltage levels: 175 mil–220 mil for 15 kV; 220 mil–345 mil for 25 kV and 345 mil–420 mil for 35 kV
    - C. Nonjacketed and jacketed cable: jacketed by extrusion or tubular
    - D. Conductor material and stranding: aluminum or copper, solid or stranded
    - E. Shield: semiconducting tape and nonmagnetizing metal tape
    - F. Cable installation: duct system or direct buried
    - G. Depth of burial: 60 cm–150 cm
    - H. Circuit design: normally open loop or radial
    - I. Lightning arrester location: riser pole, normally open point, internal under oil inside each transformer or external to each transformer
2. Secondary cable
    - A. Type of insulation: XLPE, PE or EPR
    - B. Conductor material and stranding: aluminum or copper, solid or stranded
    - C. Neutral: bare or insulated
    - D. Depth of burial: 60 cm–120 cm
3. Conductor connection
    - A. Type of connection: compression, bolted, setscrew, or welded
    - B. Secondary connection made in: pedestal, handhole, or direct buried
4. Termination and splice
    - A. Primary termination location: pole top, at transformer or at switchgear
    - B. Type of primary termination: porcelain, molded (stress cone, loadbreak, deadbreak), heat shrink, cold shrink, or taped
    - C. Type of primary splice: taped, factory-molded, or field-molded
    - D. Type of secondary splice: taped, heat shrink, cold shrink, factory molded or encapsulated
5. Transformer
    - A. Type of transformer: pad mounted, subsurface, dry type, and direct burial
    - B. Transformer location: front lot or rear lot

   C. Type of protection: current limiting fuse, external expulsion fuse, internal weak link, bayonet, or pressure relief valve
6. Switchgear
   A. Type of switchgear: padmounted, subsurface, or load-break elbow
   B. Interruption medium: air, oil, vacuum, or SF_6
   C. Interruption rating: 200/600 A continuous current for load interruption
7. Capacitor bank
   A. Type of capacitor bank: padmounted or subsurface
   B. Operation: switched or fixed
   C. Protection: current limiting fuse or expulsion fuse
   D. Size: typically 100, 300, 600, 900,1200, and 1800 kVA
8. Structures
   A. Maintenance, handhole and pad material: precast concrete, poured in place concrete, fiberglass, polymer concrete, or plastic
   B. Vault material: same as item 8A, excluding plastic
   C. Duct system material: PVC, ABS, HDPE, steel, concrete, or fiberglass
   D. Duct installation: concrete encased or direct buried

TESTING AND DIAGNOSTICS OF CABLES

Cable tests fall into three categories: (1) type approval tests; (2) routine tests and sample tests; and (3) site commissioning tests. The first category is typically carried out in the manufacturing plant, the last category, on site.

Aside from paper-based insulation, polymer-based insulating materials such as: (1) EPR, (2) PE, and (3) XLPE constitute the majority of extruded cables. Traditionally, the utility industry determined the integrity of extruded cables by using such electrical testing techniques as measurements of ac and impulse breakdown strength, dissipation factor, and volume resistivity. Results of breakdown strength tests have been used to infer loss of life by aging. "Aging" is understood as the change in the electrical, mechanical, or thermal properties of the material with time. Other industries use nonelectrical, physical, and chemical diagnostic techniques to characterize aged cable materials.

Various nondestructive techniques exist to measure the quality of either a small specimen of an insulating material or complete equipment. Because the extrusion process can leave small cavities or voids in the insulation material of the polymer-based cables, partial discharge measurement is an important and effective way to quantify cavity problems. The PD detection methods have been endorsed by the international standards (IEC-270).

Testing of Cables

Type approval tests are made to demonstrate that the cable performance characteristics are satisfactory for the intended application. Only when the material or design changes will the tests have to be repeated.

Routine tests are made on the full length of every reel (drum) of cable and on every high voltage accessory. Sample tests are performed on short lengths of a cable or randomly selected accessory or component.

Site commissioning tests vary in specifications among utilities. As an illustration a brief summary of similar type approval testing terms is documented in Table 1. Testing terms of the type tests usually cover every term of routine tests and sample tests.

Table 1. Summary of Type Approval Tests on XLPE Cable

Testing Terms	Cable Length
Appearance check	Reel
Construction and dimension measurement	Sample
Structural stability test	Sample
Dimension stability test	Sample
Moisture test	Reel
Conductor resistance test	Reel
Insulation resistance test	Reel
Dc high voltage on jacket	Reel
Capacitance and power factor tests	Sample
Partial discharge test	Sample
Dc high voltage test	Sample
Cyclic aging test	Sample
Ac high voltage time test	Sample
Impulse voltage test	Sample
Testing of insulation (component):	Sample
1. Tensile strength and elongation tests	—
2. Degree of crosslinking test	—
3. Void and contaminant determination	—
4. Protrusion test	—
Testing of jacket (component):	Sample
1. Tensile strength and elongation tests	—
2. Heat distortion test	—
3. Cold bend test	—
4. Heat shock test	—
5. Flame resisting test	—
6. Abrasing test	—
Testing of inner and outer semiconductive layers (component):	Sample
1. Aged elongation test	—
2. Brittle temperature test	—
3. Volume resistivity test	—
4. Solvent extraction test	—
5. Void and contaminant determination	—
6. Protrusion test	—

Characterizations of Cable Materials Using Nonelectrical Techniques

Insulating Materials of Cables. Cable insulation can consist of oil-impregnated paper, natural rubber, or synthetic materials (polymers). As a result of recent advanced technology developments, polymers can now be produced with various electrical, thermal and mechanical properties according to utility industry requirements.

A polymer is a macromolecule composed of a large number of basic units, or monomers. Technically important polymers are classified according to their physical properties as:

1. Thermoplastics: plastically formable and reversibly plastifiable at higher temperatures, that is, they harden on cooling but become plastifiable when reheated; typical examples are PE, XLPE, and PVC.

2. Thermosetting: hardens when heated above a critical temperature and no longer reversibly formable, a typical example is epoxy resin (EP).
3. Elastomers: develop elastic characteristics after vulcanizing, typical examples are natural rubber (NR), and EPR.

Applications of Nonelectrical Techniques. Traditionally, the remaining life of a cable and the condition of its components have been indirectly assessed by destructive high voltage, thermal, and mechanical tests under artificially elevated stress conditions. For example:

1. As the insulating material of the cable degrades, so does the breakdown strength; relationship between lifetime (t) and breakdown stress (E_b) of an insulating material is expressed in terms of Eq. (1):

   $$tE_b^n = \text{constant} \tag{1}$$

   where the exponent n depends on the material.
2. The rate at which the thermal aging process takes place in the insulating materials can be expressed in terms of the Arrhenius equation (2):

   $$t_E = \exp(A + B/T) \tag{2}$$

   where, t_E is the service life, representing the time to reach the end criterion; T is the absolute temperature in kelvin; and A,B are constants for a given insulation material.

There are other nonelectrical, diagnostic techniques used to evaluate nonaged, laboratory-aged, and field-aged cables insulated with EPR, PE and XLPE materials. The following techniques are briefly depicted here and the interested reader may refer to Ref. 1 for further details.

1. Volatile analysis: to characterize volatile materials contained within the cable insulation.
2. Nonvolatile analysis: to detect and identify the nonvolatile compounds extracted from cable insulation in order to understand the changes that occurred on aging.
3. Automated microscopic examination: to examine under a microscope the insulation cavities, contaminants, and treeing. Statistical information on tree sizes and spatial distributions may be collected.
4. Microchemical analysis: to analyze the chemical nature of insulating materials in small, localized regions and characterize the changes that occurred on aging.
5. Ion chromatography: to assess the presence and concentration of ionic contaminants in the insulation of nonaged and aged cables.
6. Measurement of moisture concentration: to determine moisture concentration within cable insulation.
7. Dynamic mechanical analysis: to identify those microstructural changes that may occur in aged cables.
8. Detection of contaminant sites susceptible to degradation: to detect the existence of traces of transition metals and other contaminants susceptible to oxidation in extruded PE and XLPE insulation.

Types of Results of Cable Material Testing. When identical nonaged and aged cable materials are compared by using a variety of the diagnostic techniques the observed results reveal the following conclusions. (1)

1. The amount and nature of volatile compounds change in a nonsystematic fashion.
2. Electrically aged cables exhibit treeing; the type, size and population density of trees is affected by aging.
3. The population density and location of voids change significantly with aging.
4. Oxidation and the presence of water are associated with water treeing.
5. Oxidation and an absence of water are associated with electrical treeing.
6. Significant changes in ion concentration in the insulation near the semiconducting shields can occur in aged cables, but only when moisture is present.
7. Significant depletion of ions in the semiconducting shields occurs in cables aged in the presence of moisture.
8. Ions, including silicon, aluminum and others are associated with water tree initiation.
9. Moisture content can vary significantly in concentration and location.
10. Aged XLPE insulation maintains well its structural properties.

Partial Discharge in Cables

Partial Discharge (PD) Measurement. Failures caused by PD in high voltage insulation have been known for a long time. Chemical and thermal effects associated with this pulse current flow can lead to a complete breakdown. In simplified form, the physical process of PDs can be envisioned as short-duration, electrical breakdowns of a small section of the insulation path. The detection of PDs is based on energy exchanges, which take place during the breakdown events. Figure 5 shows a PD electrical energy exchange process simulated by using an equivalent circuit of capacitors, which rep-

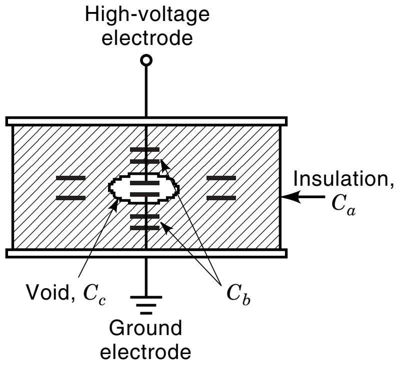

Figure 5. The equivalent circuit for the partial discharge (PD) representation. Capacitance C_c represents the void, C_a represents bulk of the healthy insulation, and C_b represents insulation material just above and below the void. The void originates PD when the applied voltage is increased. By comparing the system before and after the PD event the voltage drop between the electrodes can be estimated.

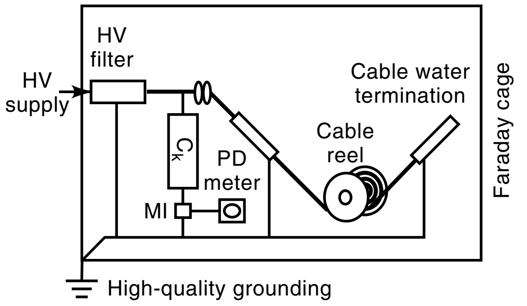

Figure 6. Apparent charge is a measure of the cable insulation quality. By using the coupling capacitor (C_k) with sufficient capacitance compared with the cable capacitance PD currents can be generated through the matching impedance (MI). The PD meter can read charge in picocoulombs. A *Faraday* cage is used to screen electrical noises from the outside of the PD test system. An HV filter suppresses noises from the HV supply. The HV supply is a discharge-free HV transformer fed through a low-voltage (LV) filter and a regulating transformer (not shown in the figure).

resent the insulation layers between the two electrodes and a void in the insulation. Electrical measurements of PD activity are made on the basis of the momentary change in the voltage at the electrodes under test (i.e., terminals of the equipment). By a suitable calibration such a change may be recalculated to obtain an "apparent charge" of PD.

The voltage measurement of PD level is specified by National Electrical Manufacturers Association standards, NEMA 107-1940, as "Radio Influence Voltage" readings in microvolts (μV) on a quasi-peak basis at or near 1.0 MHz frequency. The apparent charge measurement of PD level is described by the International Electrical Commission standards, IEC 270-1981. A "calibration charge" in picocoulombs (pC) is injected instantaneously between the terminals of the test object and the momentary change in the voltage between the equipment terminals is compared to the voltage change due to the actual PD. The calibration charge that causes the same voltage change corresponds to the apparent charge of the PD.

Partial Discharge Tests on Cables. Partial discharge (PD) tests on cables are required to ensure that voids in cables are detected. Because the possible PD levels are low at rated voltages, higher voltages are required to induce a detectable level of PD. In most specifications, this requirement is met by admitting the PD magnitude to ~5 pC for long cables for test voltage of twice the rated voltage (phase to ground).

Figure 6 shows a sample PD test system with PD measurement of the apparent discharge made between the conductor and the sheath. This system can detect the presence of voids but is not able to identify either the void shape or the influence of aging. The PD measurements are unable to detect impurities in the insulating material or water-filled voids.

Sensitive PD tests can be aggravated by different noise sources. Generally, a screened test laboratory (*Faraday cage*) should be used to keep outside noise signals away from the test circuit. If a PD measurement has to be conducted in an open or insufficiently screened test site, a balanced bridge circuit and two parallel cables should be used. In the balanced bridge configuration the two cables make up the upper two arms of the bridge. When the test voltage is applied to both cables, two impedances (the two lower arms of the bridge) are varied to obtain balance. Discharges inside the two cables are detected by the bridge but the noise signals from outside the cables are suppressed.

OPERATION AND MAINTENANCE OF CABLES

Current-Carrying Capacity

Basic Thermal Calculation. A cable is heated by losses generated by current in the conductors (I^2R) and, in case of ac, by losses generated in the metal sheathing as well as by dielectric losses. The dielectric losses can be ignored for cables in low and medium voltage ratings. Under steady-state conditions the dissipated heat is equal to the sum of all losses in the cable. Heat losses are conducted to the surface of the cable and, if the cable is installed in the ground, conducted from the cable surface through the surrounding soil to the atmosphere.

As the difference between conductor temperature and ambient temperature is approximately proportional to total losses, the heat flow in cables is analogous to Ohm's law. The flow of heat corresponds to the flow of electric current, the temperature difference to voltage difference, and the thermal resistance to electrical resistance. The analogous equivalent circuit diagram can be drawn for the thermal system as shown in Fig. 7.

Cable Capacity Ratings. Current-carrying capacity of a cable is governed by the maximum allowable conductor temperature (permissible operating temperature). Temperature rise of a cable is dependent on construction, characteristics of materials, and operating conditions (normal and emergency operation). An additional temperature rise must be considered when grouping cables together or when heat input from heating pipes, solar radiation, and so on, can occur. A detailed calculation of temperature rise of cables is beyond the scope of this article. Interested readers may refer to Ref. 2.

Normal operation of cables includes continuous operation, short-time operation, intermittent operation, cyclic operation,

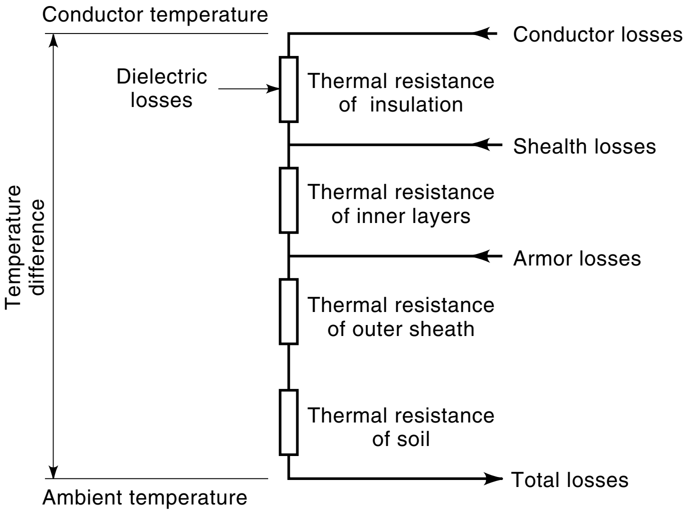

Figure 7. Analogous equivalent electrical circuit for the heat flow in a cable. Heat loss, temperature, and thermal resistance are analogous to current, voltage, and resistance, respectively.

Table 2. Permissible Conductor Temperature for Cable Insulation

Cable Insulation	Permissible Conductor Temperature	
	Normal	*Emergency*
PE	75	90
XLPE	90	130

and utility supply operation. In all cases the permissible operating temperature should not be exceeded. Emergency operation is quite common in the United States and some other countries. The conductor emergency operating temperature (high temperature peak) may, on some occasions, significantly exceed the permissible operating temperature for a certain length of time (100 h, 300 h, or no-specific-time-length) by recognizing that such operation reduces insulation service life. Table 2 lists the typical permissible conductor temperatures for different insulation under normal operation and "no-specific-time-length" emergency operation.

Cable Fault Location

Cables are generally laid directly in the ground or in ducts in the underground distribution system. They are not easily accessible for periodic routine inspection. When the cable fails one or more of the following can happen: a substation circuit breaker operates; circuit reclosers operate; or customers report an outage. In order to restore energy supply as quickly as possible, a systematic approach to locate the fault has to be followed. Special fault indicators, often equipped with a glowing neon light indicating that fault current passed through the cable, preinstalled at strategic points, aid in locating the fault. On-line fault location techniques using artificial intelligence and "smart" microprocessor-based relays designed for interconnected cable systems have recently gained more popularity and acceptance. The preliminary results are positive.

A Systematic Approach of Fault Location. A systematic approach to fault location in cables includes three steps:

1. Preliminary measurements allow a judgment to be made as to the type of fault: (1) short-circuited conductor cores, (2) damaged conductor core (open circuit), and (3) ground fault (conductor core-earthed). The most common type of fault is the ground fault. Unfortunately it also varies the most in its physical and electrical characteristics. Figure 8 shows a typical equivalent circuit of ground fault in a cable.

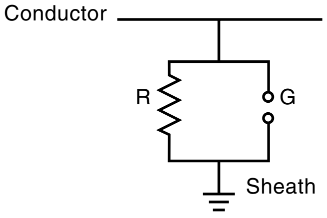

Figure 8. A ground fault equivalent circuit. The fault resistance may be any fixed value from zero to infinity, or it may be a variable within certain limits. The fault gap geometry may or may not be symmetrical and its spacing may range from zero to a distance greater than the insulation thickness. The gap space may be filled with gas, water, oil, or arc byproducts (e.g., carbonized compounds).

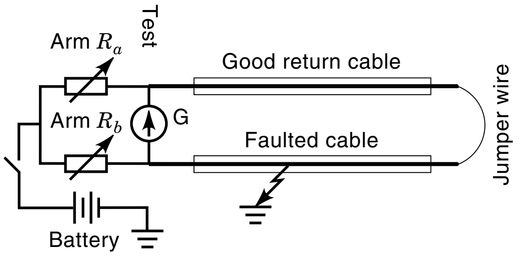

Figure 9. A schematic bridge circuit for pre-locating faults in cables. Balance is achieved by adjusting the left two arms until galvanometer indicates zero. The distance from the test terminal to the fault (x) can be calculated: $x = 2l/(1 + r)$, where $2l$ is the length of cable plus the same length of return cable, and r is ratio of left two arms (R_a/R_b).

2. A suitable localization technique is selected and coarse localization measurement is conducted.
3. Further measurements are performed to locate (pinpoint) the fault. Pinpoint measurement means that no further tests are required before repairs can be initiated. In duct-line construction, the positive location between two maintenance holes is sufficient because the whole length between two maintenance holes must be removed for either repairs or replacement. In the case of direct buried cable, more precise pinpointing is needed because digging the faulted cable is time consuming and expensive and should always be minimized.

Fault Location Techniques. The available fault location techniques can be summarized as follows:

1. Terminal techniques: where the entire test, and determination of fault location is made at one or more accessible terminals of the cable, usually by electrical bridge circuits as in the example shown in Fig. 9.
2. Tracer techniques: where some form of electrical signal is injected into the cable at one of its terminations, the signal then being traced to the fault by patrolling the cable route with a sensor/detector as shown in Fig. 10.

A wide variety of measuring equipment and procedures are available to suit the type of fault and site conditions. A brief example of a three-step procedure to locate a fault is outlined here.

1. Ascertaining the type of fault: insulation tester (equipment used: meggar).

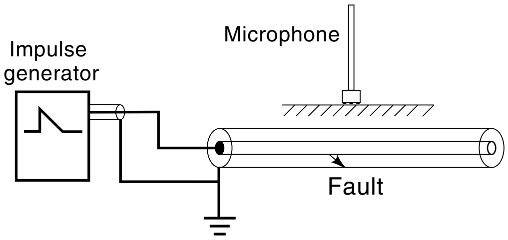

Figure 10. A sound tracer method for pinpointing faults in cables. An impulse generator feeds impulse energy to the faulted cable. At the point of fault flashover occurs, producing a loud sound (bang). This sound can be detected by use of a special microphone.

2. Localizing the fault: bridge and pulse reflection methods
  - 2.1. Bridge methods:
    - 2.1.1. For ground or short-circuit faults with low or medium resistance (0 Ω to 50 kΩ):
      - (a) if two auxiliary wires are available: use voltage ratio measurement or GRAF three-point measurement.
      - (b) if the return cable is available: use MURRAY bridge measurement.
      - (c) if only one auxiliary wire (another parallel cable or overhead line) is available: use MURRAY bridge measurement with conversion calculation for the auxiliary wire.
      - (d) if no return cable or auxiliary wire is available: use WURMBACH current direction method.
    - 2.1.2. For ground faults with high resistance (greater than 50 kΩ): use high voltage measuring bridge or burn the fault through and then measure with low voltage bridge. Burning through the insulation at the point of fault carbonizes the cable material and lowers resistance of the fault.
    - 2.1.3. For damaged conductor at point of fault (cut or open wire):
      - (a) for ground faults on one or several cores: use WURMBACH current direction method.
      - (b) if cores have good insulation: use capacitance comparison measurement.
  - 2.2. Pulse reflection method: connect impulse generator to the cable, measure the impulse travel time; the estimated distance to the fault location can be read from the apparatus as half the travel time times the traveling speed.
3. Locating the fault: the cable is connected to an audio frequency (tone) transmitter and the route is patrolled with the tone frequency receiver.

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