



**KINGDOM OF SAUDI ARABIA**

Ministry Of High Education

**Umm Al-Qura University**

College of Engineering & Islamic Architecture

**Department Of Electrical Engineering**

# Transmission and Distribution of Electrical Power

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## 1.1 INTRODUCTION

Overhead or underground? The debate continues. Both designs have advantages (see Table 1).

The major advantage of overhead circuits is cost; underground lines are typically ten times more expensive to install than overhead lines. An underground circuit typically costs anywhere from 1 to 2.5 times the equivalent overhead circuit. But the cost differences vary wildly, and it's often difficult to define "equivalent" systems in terms of performance. However, 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.

Table 1: Overhead vs. Underground: Advantages of Each

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

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 applications). 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).



**Figure 1: Before and After: Left, part of the Yonge Street hill, Toronto, August, 1947; and Right, the same location as it looked 44 years later in August, 1991.**

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:

1. 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.
2. 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.

## 1.2 CABLES CONSTRUCTION

Cables are used for the transmission and distribution of electrical energy in public and industrial power systems. Cables are generally classified as underground, submarine or aerial.

The permissible loading of the cables is determined by different parameters such as environmental conditions, type of laying (in ground or in air), cable design and type of insulation, operating conditions and so on.

Conductors are made of aluminum or copper.

The insulation is of various materials; PVC (polyvinyl chloride) and PE (polyethylene) are used as standard used in LV and MV cables; oil - insulation and gas - pressure cables can still be found in HV systems ( $U_n > 110$  kV), whereas XLPE (cross - linked polyethylene) - insulated cables are today standard in power systems with nominal voltages of 110 kV and above. Mass -impregnated paper - insulated cables are still in use in the medium - voltage range, but are found only on older cable routes; this type will no longer be installed.

Cable abbreviation codes are used that indicate the material of the cable from the inner layer to outer layers. Copper conductors, mass - impregnated paper – insulated cables, and internal protection shields are not specially indicated. In addition to the coding of the inner construction, the number of conductors, the cross - section and the shape of the conduct as well as the nominal voltage (line - to - ground / line - to - line) is indicated.

### 1.2.1 CONDUCTORS

The fundamental concern of power cable engineering is to transmit current (power) economically and efficiently. The choice of the conductor material, size, and design must take into consideration such items as:

- Ampacity (current carrying capacity)
- Voltage stress at the conductor
- Voltage regulation
- Conductor losses
- Bending radius and flexibility
- Overall economics
- Material considerations
- Mechanical properties

The conductors used in underground cables can be copper or aluminum. Aluminum dictates larger conductor sizes to carry the same current as copper. The need for mechanical flexibility requires stranded conductors to be used. The equivalent aluminum cable is lighter in weight and larger in diameter in comparison to copper cable. Stranded conductors can be in various configurations, for example:

1. Concentric round
2. Compressed round (97% of the diameter of concentric)
3. Compact round (90–91% of the diameter of concentric)
4. Rope
5. Abbreviation

The metal type and size determines the ampacity and losses ( $I^2R$ ). Copper having a higher intrinsic conductivity will have a greater ampacity and lower resistance than an equivalent size aluminum conductor. Aluminum 1350 alloy medium hardness is typical for power cable use.

### 1.2.2 INSULATION

Within the low voltage range, PVC or PE insulated cables with an outer protective covering or sheath of PVC are used.

For increased protection against touch voltages, concentric copper screens of round wires are applied to the insulation. If waveform screens are applied, the screen must not be cut for connecting coupling T - joints (cable type NYCWY). For higher tensile strength, cables with longitudinal galvanized steel wires as outer armoring are used (cable type NYFGY). To protect cables against penetration of aromatic hydrocarbons, a lead alloy sheath is used covered by the outer sheath of PVC (cable type NYKY).



Within the medium - voltage range (3.6/6 kV to 18/30 kV), cables without electric field limiting screens can still be used, as the inhomogeneous field causes relatively low electric field strength in the tangential direction in the insulation.

For higher voltages, only cables with homogeneous electric field are used. An electric field - limiting screen or foil ensures a homogeneous electric field in the dielectricum; the electric field strength is only effective in the radial direction.

Each cable core is covered with its own sheath of lead alloy. To protect the sheath against mechanical damage, additional armoring by steel tapes or wires is used (cable type NEKEBA).

Today cables with plastic insulation (PVC, PE or XLPE) are used in the medium - voltage range, whereas PVC insulations are used only for voltages up to 10 kV due to the high dissipation factor (cable type NYSEY).

XLPE insulation (cable type N2XS2Y) is used for higher voltages (110 kV and above). The main electrical parameters of cable insulation materials are shown in Table 8.3 .

Cables with oil insulation and XLPE insulation are installed in MV and HV systems ( $U_n > 30$  kV). A typical cable used in 110 kV systems is the gas – pressure type cable. The cable is placed in a hermetically sealed steel pipe field with nitrogen (pressure 1.6 MPa).

The steel pipes are either constructed as seamless pipe or as lengthwise - welded pipe. Gas - pressure cables are suitable because of their mechanical withstand capability, the low inductive interference and the possibility of laying the steel pipe in short segments, which is an outstanding advantage in crowded urban areas. In practice, the importance of oil - insulated cables and gas - pressure cables has decreased and XLPE - insulated cables are installed even in EHV systems.

Table 2: Properties of Cable Insulations

	Oil	PVC	XLPE	Impregnated paper
Dissipation factor $\tan \delta$	3	100	0.55	10
Max. temperature $\vartheta_{\max}$ (°C)	85	70	90	65–85
Specific resistance $\rho_i$ ( $\Omega\text{m}$ )	$5 \times 10^{12}$	$7 \times 10^{11}$	$10^{14}$	$5 \times 10^{14}$
Maximum electric field strength $E_D$ (kV mm <sup>-1</sup> )	15–25	40	95	15–40
Permittivity $\varepsilon_r$ at 20 °C	2.2–2.8	3–4	2.4	3.3–4.2



Some of the key properties of cable insulation are:

1. **Dielectric constant (e, 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 configuration in free space. **Cables with higher capacitance draw more charging current.**
2. **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.
3. **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.**
4. **Dissipation factor** (also referred to as the loss angle, loss tangent,  $\tan \delta$ , 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:**

### **1.3 TYPES OF CABLES**

In the field of underground wiring, by the time that the polyphase AC system was conceived in 1886, several major steps had been taken towards making possible a practical underground power transmission system. One was Borel's invention of an efficient lead press in 1879, and another was MacCracken's concept of helically applied paper insulating tapes in 1884. Finally, in 1890, Vincent de Ferranti produced his famous 10,000-volt concentric cable, which was installed in London, England.

Continuous progress in the development of underground power transmission has taken place since that time. The first 3-conductor 25 kV cables were installed in Montreal in 1902, and they operated successfully for over 50 years. Then, in 1917, Emanuelli conceived a design for hollow-core oil-filled cables, a breakthrough which permitted eventual transmission of power at high and extra-high voltages.

Gradually, the voltage levels of underground power cables increased, to 66 kV in 1926 in Montreal and Philadelphia, 220 kV in 1936 in Paris, and in recent years, reaching 525 kV in Canada and 535 kV in the United States. Current technology permits underground transmission cable systems as high as 1,100 kV.






Figure 2: An historic photo of downtown Toronto in 1883, at the peak of overhead chaos.

### 1.3.1 TRANSMISSION CABLES

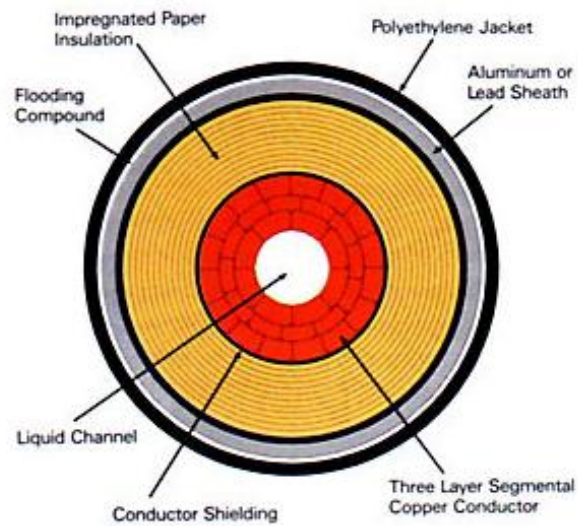
#### 1.3.1.1 Self Contained Liquid-Filled (SCLF) Cables

 Impregnated paper insulation was first used by Ferranti in a 10 kV cable. Impregnated paper does not give the impression of being a suitable insulation material. However, the combination of its excellent electrical and mechanical characteristics has resulted in a reliable and economic insulation unsurpassed for many decades, and it now claims a history of almost 100 years. Many paper-insulated circuits dating back to the early part of this century are still in service. Others that have been replaced by larger cables after decades of operation, have exhibited excellent insulation integrity when examined in the laboratory.

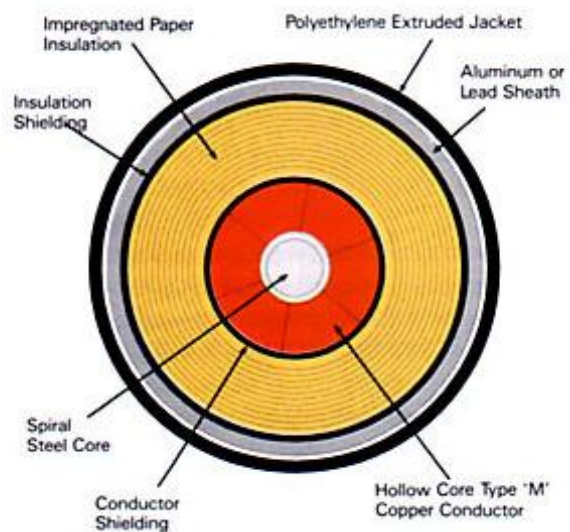
The drying and impregnating process for solid and non-pressure type paper cables, leads to the formation of dielectric (air) voids which ionize under electrical stress. The ionic bombardment of the liquid and paper can ultimately result in failure. This led Emanuelli to develop the self-contained oil-filled cable which was actually implemented in 1924. The basic principle of a liquid-filled cable is that all the spaces inside the cable sheath are completely filled, thus preventing voids in the insulation.



**1.3.1.1 Figure 3: Self Contained Liquid-Filled (SCLF) Cables**



**Figure 4: Copper segment conductor.**



**Figure 5: Copper type 'M' conductor.**

Two typical self-contained, single-conductor, liquid-filled cables are shown in Figure 4 and Figure 5. The first has a copper segmented conductor and a hollow core, while the second has a Milliken, or Type 'M', copper conductor with a spiral steel core.

The manufacturing process starts with the production of the conductor. Segmented copper conductors, as in Figure 4, may comprise one, two or more layers of segments, applied one layer at a time from the smallest diameter to the largest. Due to the shape of the segments, this type of conductor, while having a hollow core, is usually self-supporting and does not require a central helix to prevent it from collapsing.

With very large conductors, as shown in Figure 5, the Type 'M' construction is used. This conductor consists of six segments. Each segment is made up of wires stranded and shaped in the stranding machine, the segments being lightly insulated from one another by paper tapes. The six segments are cabled over a spiral steel core.

The paper insulation is stored and applied under constant temperature and low relative humidity conditions in one pass. For a cable of about 220 kV and over, this requires a machine with many taping heads maintained under uniform temperature, constant relative humidity and extreme cleanliness conditions.

The insulated cable is placed in a horizontal pan, which in turn, is placed inside the impregnating tank. The insulation is dried under vacuum, then completely immersed and impregnated with insulating liquid under pressure. After cooling, the metallic sheath is applied. Metal sheaths are either a lead alloy or aluminum. They are seamless, and their integrity is essential.

The sheathed and impregnated cable is provided with a polyethylene (PE) or polyvinyl chloride (PVC) jacket. From the time the cable is impregnated, it is always connected to a liquid supply under positive pressure, and as a result, during shipment, installation, and operation the cable is never permitted to develop voids.

#### **1.3.1.2 High Pressure Liquid-Filled Pipe-Type Cables (HPLF)**

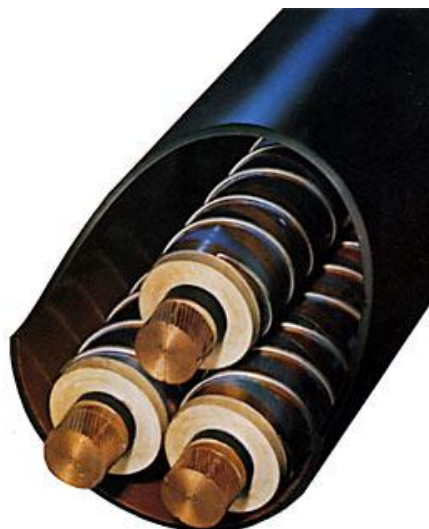
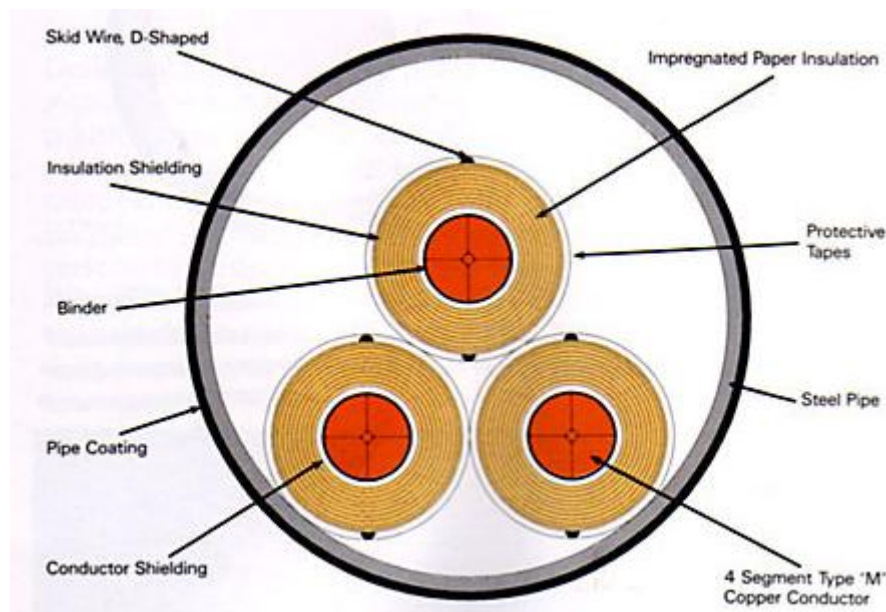


Figure 6: High Pressure Liquid-Filled Pipe-Type Cable (HPLF)

For bulk power transmission in liquid-filled pipe-type cables, three single paper-insulated liquid-impregnated cores are arranged in an equilateral configuration inside a buried steel pipe, as shown in Figure 7.



**Figure 7: High Pressure Liquid-Filled Pipe-Type Cable**

The pipe is filled with insulating liquid, and the cables are designed to operate without individual metallic sheaths while under a nominal hydraulic pressure of about **200 psi**. The maximum electrical operating levels, are the same as those of the Self-Contained Liquid-Filled (SCLF) cable.

In the case of SCLF cables, with a normal operating pressure of over 10 psi, it is the impermeability of the metallic sheath that retains the liquid under pressure. However, in the case of high pressure liquid-filled pipe-type cable, with an operating pressure of over 200 psi, the entire pipe is filled with liquid, including the cables. All are under the same liquid pressure, and the steel pipe provides the impermeability.

The cable manufacturing process begins with the production of the copper conductors. Up to cross sections of 500 mm<sup>2</sup>, they are usually stranded compact round shapes, with compact segmented Type 'M' conductors being used for larger sizes. The advantage of the compact segmented design is its low AC resistance.

After application of the paper insulation, mass impregnation takes place. A seal prevents excessive loss of impregnating liquid and exposure of the impregnated paper to the moist atmosphere. The cable is finally wound on to special reels which are sealed under a blanket of nitrogen at low pressure until the time of installation.

The steel pipe is in 40- to 50-foot (12- to 15-metre) random lengths, with a wall thickness of 1/4 inch (6mm).

Typical nominal pipe sizes for various systems, are as follows:

Internal Diameter	System
5" (127 mm)	72 kV
6" (152 mm)	138 kV
8" (203 mm)	230 kV
10" (254 mm)	345 kV

The pipe size chosen is usually the nearest standard size which has an internal area 2.5 or 2.8 times that of the three cables. This amounts to about a 50% fill, which allows ample installation space without jamming and permits lateral movement of conductors during electrical load cycles.

### 1.3.1.3 Solid Dielectric Cables



Figure 8: Solid Dielectric Cable.

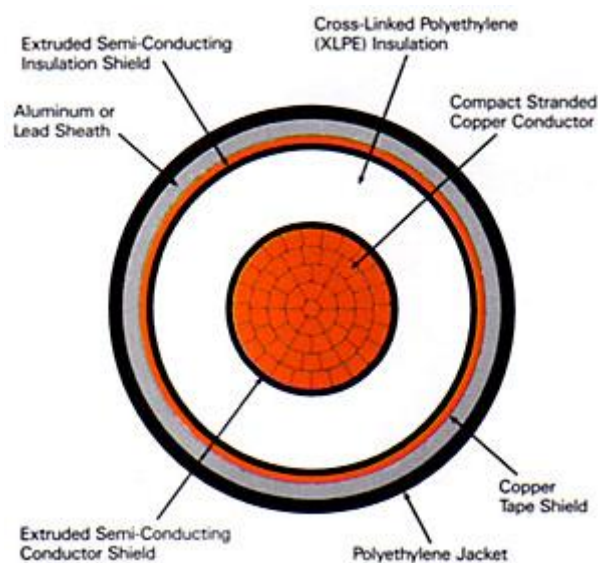


Figure 9: Solid Dielectric Cable.



In Solid Dielectric Cables, the insulation is usually cross-linked polythethylene (XLPE), or ethylene-propylene rubber (EPR). This cable design, Figure 4, has a copper compacted strand single conductor. These cables are normally rated for installations with a maximum nominal electrical loading of 138 kV.

The basic manufacturing process starts with extrusion of the conductor shield, the insulation and the insulation shield in a single operation. This triple extrusion operation ensures the smoothness of the interface between the three layers, which has a vital influence on the electrical strength of the cable. The core then passes into a curing tube where the temperature of the extrudate is raised to initiate the chemical cross-linking reaction. It then passes into a cooling zone where the temperature is reduced nearly to ambient. Both the curing and the cooling, are conducted under pressure to avoid the formation of micro-voids which could considerably reduce the electrical strength and endurance of the cable. A copper tape shielding is then wrapped on, usually followed by a sheath and finally, a polyethylene (PE) or polyvinyl chloride (PVC) jacket.

For high-voltage cables (over 69 kV) such as are required in underground transmission systems, a lead-alloy or an aluminum sheath is always specified. Its purpose is to protect the insulated core against the ingress of moisture. This sheath ensures the absence of moisture, and enhances the reliability and service life of the transmission circuits. When cables are intended for underground installations in the vicinity of oil refineries or other petro-chemical complexes, a lead-alloy sheath is often specified to protect against the detrimental effects of petroleum by-products.

#### **1.3.1.4 Submarine Cables**

Although all three types of high-voltage cable may be considered for a submarine cable (fresh or sea water), either the Self-Contained Liquid-Filled Cable or the Solid Dielectric Cable is usually chosen. Most frequently it is the SCLF cable, which is capable of handling higher voltages.


Because of the severe environmental demands placed on a submarine cable, a lead-alloy sheath is often chosen, because of its compressibility, flexibility and corrosion resistance. The sheath is usually covered by a number of outer layers, comprising polyethylene jackets, metal wire armouring, and bitumized jute.

### **1.3.2 MEDIUM VOLTAGE POWER CABLE**

Medium-voltage distribution systems begin at substations and supply electricity to a wide spectrum of power consumers. When selecting a cable, the basic aim is to safely provide adequate electrical power, with continuous, trouble-free operation, in a system that is able to withstand unexpected demands and overload conditions. Each installation has particular requirements that must be considered. There are distinct benefits from specifying a copper-conductor cable that has been manufactured under rigid specification and quality control procedures. It will provide maximum performance with minimum maintenance.

There are several types of medium-voltage power cables in the 5 kV to 46 kV range, the "type" referring to the cable construction. Most are available in one-and three-conductor configurations. There are ranges of sizes and design variations for each type.

### 1.3.2.1 Teck Cables

 Teck Cables were originally developed for use in mines, but they are now widely used in primary and secondary industries, chemical plants, refineries and general factory environments. They are also used in multi-storey and commercial buildings. They are flexible, resistant to mechanical abuse, corrosion resistant, compact and reliable. A modified Teck Cable construction may be used for vertical installations, such as in mine shafts and multi-storey buildings, where the armour is locked-in-place to prevent slippage of the inner core.

There are many different combinations of conductor size, voltage rating, armour type and so forth, available in Teck Cables to meet the requirements of particular installations.

Annealed, bare, copper is used for the conductor (s), and they are usually compact stranded to reduce diameter. In multi-conductor cables, the insulated conductors are cabled together, including the bare copper bonding (grounding) conductor. In shielded multi-conductor cables, the bonding (grounding) conductor is positioned to contact the copper shields. A PVC outer jacket which may be colour-coded depending on the rating of the cable is applied.



**Figure 10: Teck Cable.**



### 1.3.2.2 Shielded Cables



Shielded Power Cable may be single- or three-conductor. The basic construction begins with a conductor of annealed, bare, solid or concentric-stranded copper, which may be compact or compressed. This is followed by a semi-conducting conductor shield, insulation, and then a semi-conducting insulation shield.

Metallic shielding follows, which is usually either gapped or lapped copper tape. Other types of metallic shielding are available, including concentric wires and longitudinally corrugated copper tape. The outer jacket is either PVC or PE.

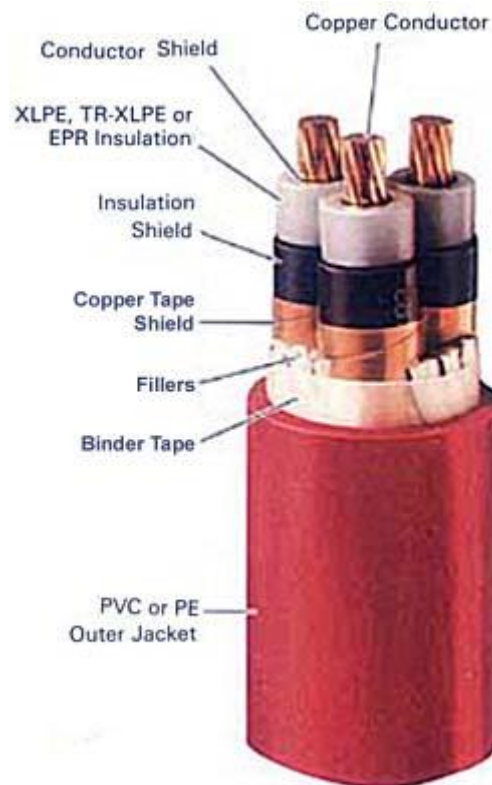


Figure 11: Shielded Cables.

### 1.3.2.3 Concentric Neutral Cables

These power cables may be used in dry or wet locations, for a wide variety of types of installations, and may be single- or three-conductor. The two standard constructions are Unjacketed and Jacketed, the latter being most frequently used.

The conductor is typically annealed, bare, stranded copper, but tin-coated wire and solid conductors are also available.

The concentric neutral conductor, from which the cable derives its name, is bare or tin-coated copper wire, applied helically over the insulation shield. These wires act as the metallic component of the shield and the neutral, at the same time.

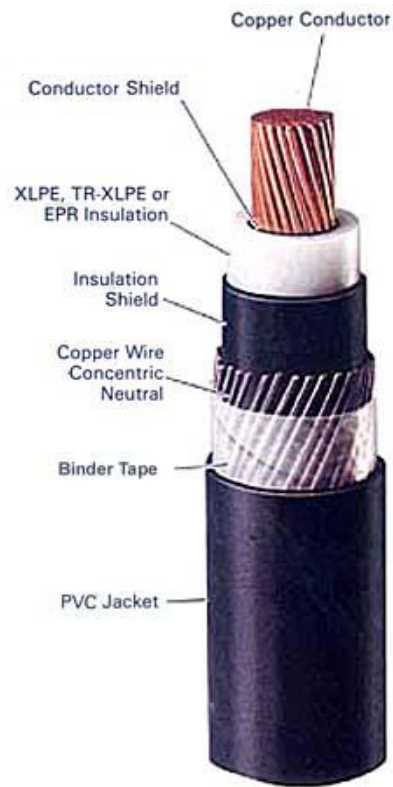


Figure 12: Concentric Neutral Cables.

#### 1.3.2.4 Paper-Insulated Lead-Covered Cables (PILC)

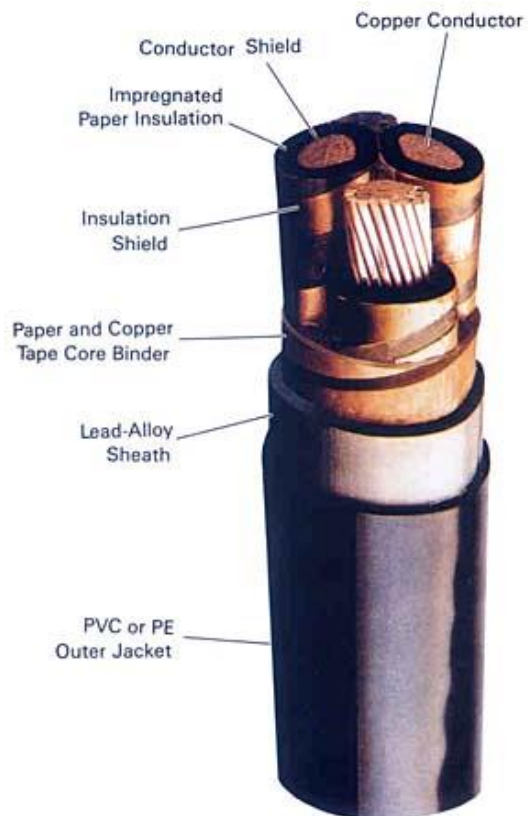


Figure 13: Paper-Insulated Lead-Covered Cables (PILC).

PILC cables are used in power distribution and industrial applications, and they may be installed exposed, in underground ducts or directly buried. Their design begins with annealed, bare copper conductor(s) which may be round, concentric, compressed or compact stranded, compact sector, and in larger sizes ... Type M segmental stranded. An example of compact sector conductors is shown in the illustration. The insulated cable core is impregnated with a medium viscosity polybutene-based compound. The combination of the excellent electrical and mechanical characteristics of the liquid and the paper has resulted in a reliable and economic insulation, which now claims a history of almost 100 years. It is little wonder why so many utilities and power-consuming industries, still continue to specify PILC.

To prevent the ingress of moisture, a seamless lead-alloy sheath is applied. The outer jacket may be PVC or PE, and if required by the application, armour is available.

### 1.3.2.5 Submarine Cables

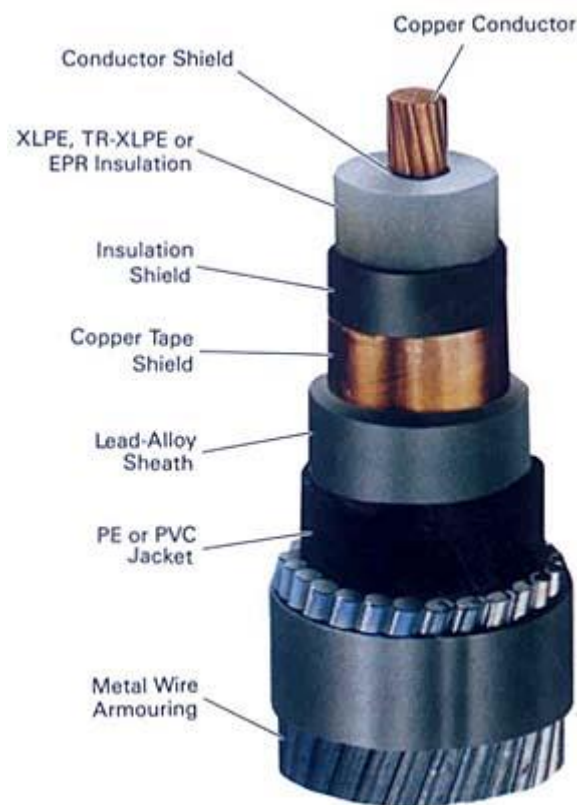


Figure 14: Submarine Cables.

For submarine installations, usually Self-Contained Liquid-Filled Cables (SCLF), or Solid Dielectric Cables are selected, depending on voltage and power load. SCLF Cables are capable of handling very high voltages. However, for medium-voltage installations, a Solid Dielectric Cable can easily fulfil the electrical demands of the system.

A submarine Solid Dielectric Cable is shown in the illustration. Its construction begins with a compact stranded, annealed, bare copper conductor, followed by a semi-conducting conductor shield. A copper tape shield is helically applied, followed by a lead-alloy sheath. Due to the severe environmental demands placed on submarine cables, a lead-alloy sheath

is often specified because of its compressibility, flexibility and resistance to moisture and corrosion. The sheath is usually covered by a number of outer layers, comprising a PE or PVC jacket and metal wire armouring.

#### 1.3.2.6 Mining Cables

A number of different types of cables are used in mines. There are fixed mining cables and portable mining cables, the latter being described here. The key requirements of portable cables are flexibility, and resistance to mechanical abrasion and damage. Due to the additional demands put on portable mining cables used for reeling and dereeling applications, special design may be required.

There are many types of portable mining cables. They are available in ratings up to 25 kV, and may have as many as five conductors.

An example of SHD-GC Cable, is shown in the illustration. It has three insulated, shielded conductors, two bare ground wires, a ground check wire, and an overall jacket. The conductors for this cable are annealed, bare or tinned copper wires.

The braided shield may be tin-coated wires, or a tin-coated copper wire/textile composite. The grounding conductor(s) annealed, bare or tinned, stranded copper wires, and the ground check conductor is annealed, bare, stranded copper wires with EPR insulation and nylon braid, elastomeric jacket holds the conductor assembly firmly in place, to minimize snaking and cork-screwing during reeling and dereeling.

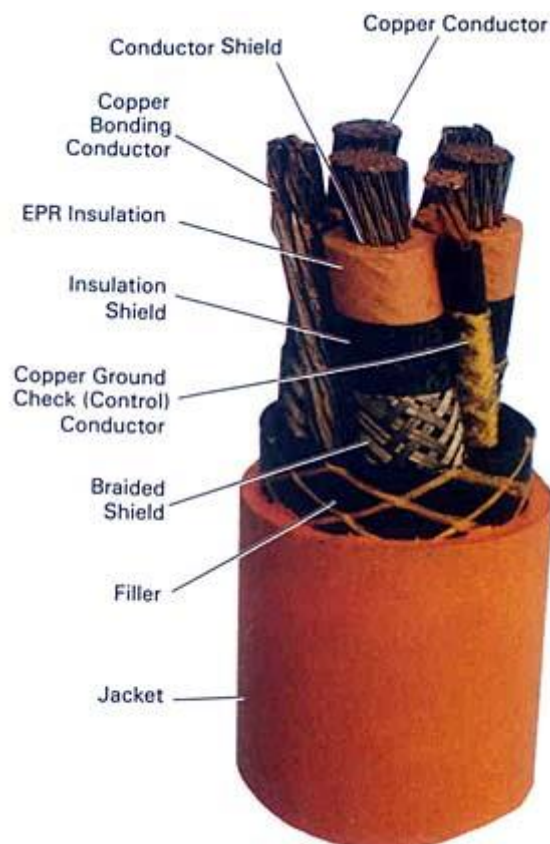


Figure 15: Mining Cables.

#### 1.3.2.7 Aluminum-Sheathed Cables

These power cables are used for exposed and concealed wiring, in wet and dry locations, and where exposed to the weather. They may be installed in ventilated, unventilated and ladder-type cable-troughs, and ventilated flexible cableways.

Aluminum-Sheathed Power Cables may be single-,two-,three- or four-conductor, the conductor(s) being annealed, bare, compressed-round stranded copper. The insulated core is enclosed in a liquid- and vapour-tight solid corrugated aluminum sheath, covered by a PVC jacket.

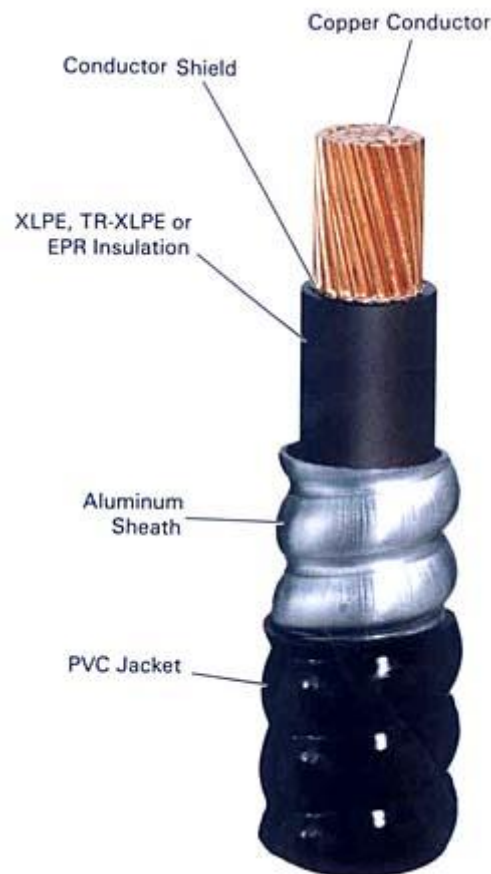


Figure 16: Aluminum-Sheathed Cables.

### 1.3.3 DIRECT CURRENT CABLES

### 1.3.4 SUPERCONDUCTION

## 1.4 ELECTRICAL CHARACTERISTICS OF INSULATED CABLES

### 1.4.1 ELECTRIC STRESS IN SINGLE CONDUCTOR CABLE

Figure 17 shows a cross section of a single conductor cable. Assume that the length of the cable is 1m.

Let the charge on the conductor surface be  $q$  coulomb per meter of length. Assume that the cable has perfectly homogeneous dielectric and perfect symmetry between conductor and insulation. Therefore, according to Coulomb's law, the electric flux density at a radius of  $x$  is

$D = \frac{q}{2\pi x} \text{ C/m}^2$	(1)
--------------------------------------	-----

Where

$D$ = electric flux density at radius  $x$  in Coulombs per square meter

$q$ = charge on conductor surface in Coulombs per square meter

$x$ = the radius from the center of the conductor in meter, where  $r < x < R$

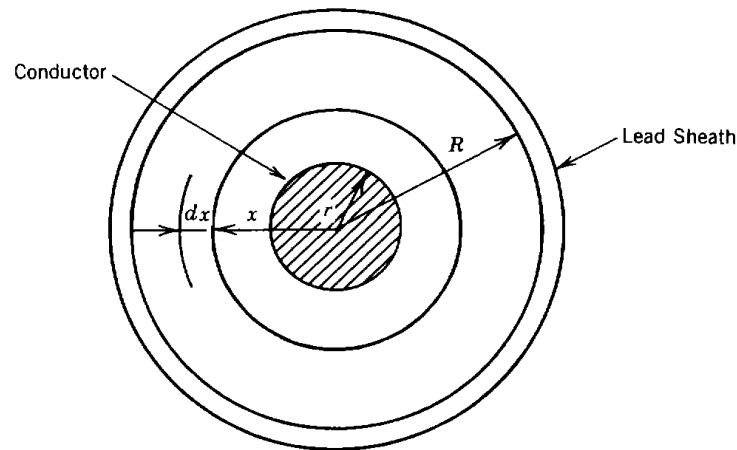


Figure 17: Cross section of single conductor cable.

Since the absolute permittivity of the insulation is

$\epsilon = \frac{D}{E}$	(2)
--------------------------	-----

The electric field or potential gradient or electric stress or so called dielectric stress  $E$  at radius  $x$  is

$E = \frac{q}{2\pi\epsilon x} \text{ V/m}$	(3)
--	-----

If the potential gradient at radius  $x$  is  $dV/dx$ , the potential difference  $V$  between conductor and lead sheath is

$V = \int_r^R E dx$	(4)
---------------------	-----

Or

$V = \int_r^R \frac{q}{2\pi\epsilon x} dx$	(5)
--	-----

So

$V = \frac{q}{2\pi\epsilon} \ln \frac{R}{r} \quad V$	(6)
--	-----

Therefore,

$E = \frac{V}{x \ln \frac{R}{r}} \quad V/m$	(7)
---	-----

Where

E= electric stress of cable in volts per meter

V= potential difference between conductor and lead sheath in volts

x= distance from center of conductor in meter

R= outside radius of insulation or inside radius of lead sheath in meters

r= radius of conductor in meter

Dielectric strength is the maximum voltage that a dielectric can stand in a uniform field before it breaks down. It represents the permissible voltage gradient through the dielectric.

Average stress is the amount of voltage across the insulation material divided by the thickness of the insulation.

Maximum stress in a cable usually occurs at the surface of the conductor, while the minimum stress occurs at the outer surface of the insulation. Average stress is the amount of voltage across the insulation material divided by the thickness of the insulation.

Therefore, the maximum electric stress in the cable shown in Figure 17 occurs at  $x = r$ ; thus

$E_{max} = \frac{V}{r \ln \frac{R}{r}} \quad V/m$	(8)
---	-----

And the minimum electric stress occurs at  $x = R$ ; hence,

$E_{min} = \frac{V}{R \ln \frac{R}{r}} \quad V/m$	(9)
---	-----

Thus for a given V and R, there is one particular radius that gives the minimum stress at the conductor surface. In order to get the smallest value of  $E_{max}$ , let

$\frac{dE_{max}}{dr} = 0$	(10)
---------------------------	------

From which



$\ln \frac{R}{r} = 1$	( 11)
-----------------------	-------

Thus,

$R = er = 2.718r$	( 12)
-------------------	-------

And the insulation thickness is

$R - r = 1.718$	( 13)
-----------------	-------

And the actual stress at the conductor is

$E_{max} = \frac{V}{r}$	( 14)
-------------------------	-------

Where r is the optimum conductor radius that satisfies ( 12).

#### Example 1:

A single conductor belted cable of 5km long has a conductor diameter of 2cm and an inside diameter of lead sheath of 5cm. the cable is used at 24.9 kV line to neutral voltage and 60Hz frequency. Calculate the following:

- Maximum and minimum values of electric stress.
- Optimum value of conductor radius that results in smallest (minimum) value of maximum stress.

#### Solution:

(a)

$$E_{max} = \frac{V}{r \ln \frac{R}{r}} = \frac{24.9}{1 \ln 2.5} = 27.17 \text{ kV/cm}$$

$$E_{min} = \frac{V}{R \ln \frac{R}{r}} = \frac{24.9}{2.5 \ln 2.5} = 10.87 \text{ kV/cm}$$

(b) From equation (4.15), the optimum conductor radius is

$$r = \frac{R}{2.718} = \frac{2.5}{2.718} = 0.92 \text{ cm}$$

Therefore, the minimum value of the maximum stress is

$$E_{max} = \frac{24.9}{0.92 \ln(2.5/0.92)} = 27.07 \text{ kV/cm}$$

#### Example 2:

Assume that a single conductor belted cable has a conductor diameter of 2cm and has insulation of two layers of different materials each 2 cm thick, as shown in Figure 18. The dielectric constants for the inner and the outer layers are 4 and 3, respectively. If the potential difference between the conductor and the outer lead sheath is 19.94 kV, calculate the potential gradient at the surface of the conductor.

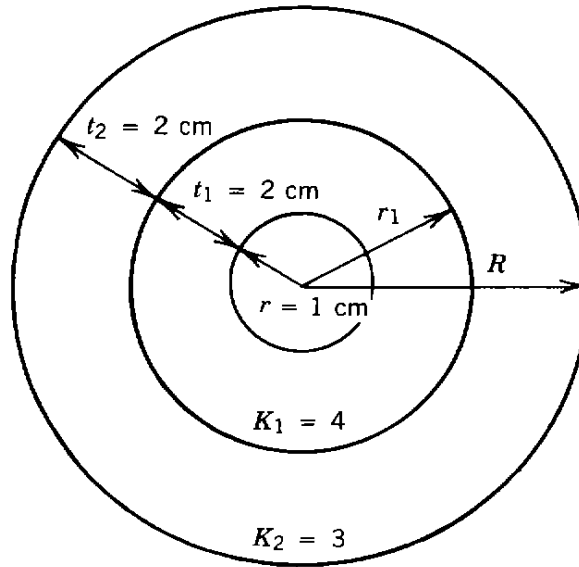


Figure 18: for this example.

**Solution:**

$$r = 1 \text{ cm}$$

$$r_1 = r + t_1 = 3 \text{ cm}$$

$$R = r_1 + r_2 = 5 \text{ cm}$$

Since

$$E_1 = \frac{2q}{rK_1} \quad \text{and} \quad E_2 = \frac{2q}{r_1K_2}$$

their division gives

$$\begin{aligned} \frac{E_1}{E_2} &= \frac{r_1 t_2}{r t_1} \\ &= \frac{3 \times 3}{1 \times 4} = 2.25 \end{aligned}$$

In addition,

$$\begin{aligned} E_1 &= \frac{V_1}{r \ln(r_1/r)} \\ &= \frac{V_1}{1 \ln(3/1)} \end{aligned}$$

and

$$\begin{aligned} E_2 &= \frac{V_2}{r_1 \ln(R/r_1)} \\ &= \frac{19.94 - V_1}{3 \ln(5/3)} \end{aligned}$$

or

$$\frac{E_1}{E_2} = \frac{V_1}{1 \ln(3/1)} \cdot \frac{3 \ln(5/3)}{19.94 - V_1}$$

or

$$\frac{E_1}{E_2} = \frac{1.532V_1}{21.906 - 1.099V_1}$$

but it was found previously that

$$\frac{E_1}{E_2} = 2.25$$

Therefore,

$$\frac{1.532V_1}{21.906 - 1.099V_1} = 2.25$$

from which

$$V_1 = 12.308 \text{ kV}$$

Hence,

$$\begin{aligned} E_1 &= \frac{V_1}{1 \ln 3} \\ &= \frac{12.308}{1 \ln 3} \\ &= 11.20 \text{ kV/cm} \end{aligned}$$

#### 1.4.2 CAPACITANCE OF SINGLE CONDUCTOR CABLE

Assume that the potential difference is  $V$  between the conductor and the lead sheath of single conductor cable shown in Figure 17. Let the charge on the conductor and sheath be  $+q$  and  $-q$  C/m of length. From the equation of the voltage given by

$V = \frac{q}{2\pi\epsilon} \ln \frac{R}{r} \text{ V}$	( 15 )
--	--------

Where

$V$ = potential difference between conductor and lead sheath in volts

$\epsilon$ = absolute permittivity of insulation

$R$ = outside radius of insulation in meters

$r$ = radius of conductor in meter

Therefore, the capacitance between the conductor and the sheath is

$C = \frac{q}{V}$	( 16 )
-------------------	--------

Or

$C = \frac{2\pi\epsilon}{\ln \left( \frac{R}{r} \right)} \text{ F/m}$	( 17 )
---	--------

Since

$\epsilon = \epsilon_0 K$	( 18 )
---------------------------	--------

Therefore

$C = \frac{2\pi\epsilon_0 K}{\ln \left( \frac{R}{r} \right)} \text{ F/m}$	( 19 )
---	--------

Where

$\epsilon_0 = \frac{1}{36\pi \times 10^9} \text{ for air}$ $= 8.85 \times 10^{-12} \text{ F/m}$	<b>( 20 )</b>
---	---------------

And

K= dielectric constant of cable insulation

Therefore,

$C = \frac{10^{-9}K}{18 \ln \left( \frac{R}{r} \right)} \text{ F/m}$	<b>( 21 )</b>
--	---------------

Or

$C = \frac{K}{18 \ln \left( \frac{R}{r} \right)} \mu\text{F/km}$	<b>( 22 )</b>
--	---------------

### 1.4.3 DIELECTRIC CONSTANT OF CABLE INSULATION

The dielectric constant of any material is defined as the ratio of the capacitance of a conductor with the material as the dielectric to the capacitance of a similar condenser with air as the dielectric. It is also called the relative permittivity of specific inductive capacity. It is usually denoted by K. (it is also represented by  $\epsilon_r$  or SIC) Table 3 gives the typical values of the dielectric constants for various dielectric materials.

Using the symbol K, the formula for calculating the capacitance of a shielded or concentric neutral single conductor cable becomes:

$C = \frac{K}{18 \ln \left( \frac{D}{d} \right)} \mu\text{F/km}$	<b>( 23 )</b>
--	---------------

Where

C is the capacitance in farads per km

K is the dielectric constant of cable insulation

D is the diameter over insulation in unit length

d is the diameter over conductor shield in unit length

**Table 3: Typical Values of Various Dielectric Materials.**

Dielectric Material	K
Air	1
Impregnated paper	3.3
Polyvinyl chloride (PVC)	3.5–8.0
Ethylene propylene insulation	2.8–3.5
Polyethylene insulation	2.3
Cross-Linked polyethylene	2.3–6.0

#### 1.4.4 CHARGING CURRENT

By definition of susceptance,

$B = \omega C \text{ S}$	( 24)
--------------------------	-------

Or

$B = 2\pi f C \text{ S}$	( 25)
--------------------------	-------

Then the admittance Y corresponding to C is

$Y = jB$	( 26)
----------	-------

Or

$Y = j2\pi f C \text{ S}$	( 27)
---------------------------	-------

Therefore, the charging current is

$I_C = YV_{L-N}$	( 28)
------------------	-------

Or

$I_C = 2\pi f C V_{L-N}$	( 29)
--------------------------	-------

So we can write

$I_C = \frac{2\pi f K V_{L-N}}{18 \ln\left(\frac{D}{d}\right)} 10^{-9} \text{ A}$	( 30)
---	-------

Where,

$f$  is the frequency in hertz

$D$  is the diameter over insulation in unit length

$d$  is the diameter over conductor shield in unit length

$K$  is the dielectric constant of cable insulation

$V$  line to neutral voltage

The charging current and the capacitance are relatively greater for insulated cables than in overhead circuits because of closer spacing and the higher dielectric constant of the insulation of the cable. In general, the charging current is negligible for overhead circuits at distribution voltages, contrary to high voltage transmission circuits.

#### 1.4.5 DETERMINATION OF INSULATION RESISTANCE OF SINGLE CONDUCTOR CABLE

Assume that the cable shown in Figure 19 has a length of 1m.

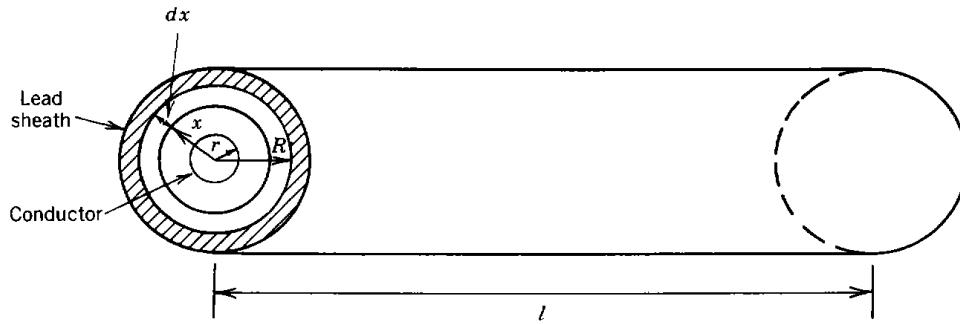


Figure 19: cross section of single conductor cable.

Then the incremental insulation resistance of the cylindrical element in the radial direction is

$$\Delta R_i = \frac{\rho}{2\pi x l} dx \quad (31)$$

Therefore, the total insulation resistance between the conductor and the lead sheath is

$$R_i = \int_r^R \frac{\rho}{2\pi x l} dx \quad (32)$$

Or

$$R_i = \frac{\rho}{2\pi l} \ln \frac{R}{r} \quad (33)$$

Where

$R_i$  is the total insulation resistance in ohms

$\rho$  is the insulation (dielectric) resistivity in ohm meters

$l$  is the total length of cable in meter

$R$  is the outside radius of insulation or inside radius of lead sheath in meters

$r$  is the radius of conductor in meters

A more practical version of this equation is given by

$$R_i = r_{si} \log \frac{D}{d} \text{ M}\Omega/1000\text{ft} \quad (34)$$

Where

$R_i$  is the total insulation resistance in mega-ohms per ft for particular cable construction.

$r_{si}$  is the specific insulation resistance in mega-ohms per 1000 ft at 60°F

$D$  is the inside diameter of sheath

$d$  is the outside the diameter of conductor

Table 4 gives typical  $r_{si}$  values of various insulation materials.

Table 4: Typical values of  $r_{si}$

Insulation Material	$r_{si}$ (MΩ/1000 ft)
Synthetic rubber	2,000
Ethylene propylene insulation	20,000
Polyethylene	50,000
PVC	2,000
Cross-linked polyethylene	20,000

The equation giving the insulation resistance indicates that the insulation resistance is inversely proportional to the length of the insulated cable. An increase in insulation thickness increases the disruptive critical voltage of the insulation but does not give a proportional decrease in voltage gradient at the conductor surface. Therefore, it does not permit a proportional increase in voltage rating.

**Example 3:**

A 250 kcmil, single conductor, synthetic rubber, belted cable has a conductor diameter of 0.575 inches, and an inside diameter of sheath of 1.235 inches. The cable has a length of 6000 ft and is going to be used at 60 Hz and 115 kV. Calculate the following

- The total insulation resistance in mega-ohms at 60°F.
- Power loss due to leakage current flowing through insulation resistance.

**Solution:**

- By using equation (4.42),

$$R_i = r_{si} \log \frac{D}{d}$$

From Table 4.2, specific insulation resistance  $r_{si}$  is 2000 MΩ/1000 ft. Therefore, the total insulation resistance is

$$\begin{aligned} R_i &= 6 \times 2000 \log \frac{1.235}{0.575} \\ &= 3.984 \text{ M}\Omega \end{aligned}$$

- The power loss due to leakage current is

$$\begin{aligned} \frac{V^2}{R_i} &= \frac{115,000^2}{3984 \times 10^6} \\ &= 3.3195 \text{ W} \end{aligned}$$

#### 1.4.6 DIELECTRIC POWER FACTOR AND DIELECTRIC LOSS

When a voltage is applied across a perfect dielectric, there is no dielectric loss because of the existence of an induced capacitance current  $I_C$ , located 90° ahead of the voltage  $V$ . however, in practices, since a perfect dielectric cannot be achieved, there is a small current component  $I_V$  that is in phase with voltage  $V$ . therefore, the summation of these two current vectors gives the current vector  $I$  that leads the voltage  $V$  by less than 90°,



as shown in Figure 20. The cosine of the angle  $\phi_d$  is the power factor of the dielectric, which provides a useful measure of the quality of the cable dielectric. The power factor of a dielectric is

$\cos \phi_d = \frac{\text{losses in dielectric W}}{\text{apparent power (VA)}}$	( 35)
--	-------

The power factor of an impregnated- paper dielectric is very small, approximately 0.003. the dielectric power factor should not be confused with the regular (supply) power factor. The dielectric power factor represents loss and therefore, an attempt to reduce it should be made. Whereas an attempt should be made to increase the supply power factor toward unity.

Since for a good dielectric insulation,  $\phi_d$  is close to  $90^\circ$ ,  $\delta$  is sometimes called the dielectric loss angle, therefore,  $\delta$  is in radians,

$\delta \cong \tan \delta \cong \sin \delta \cong \cos \phi_d$	( 36)
--	-------

Since  $\delta = 90 - \phi_d$  and  $\delta < 0.5^\circ$  for most cables.

Here  $\cos \phi_d$  should be held very small under all operating conditions. If it is large, the power loss is large, and the insulation temperature T rises considerably. The rise in temperature causes a rise in power loss in the dielectric, which again results in additional temperature rise. If the cable to operate under conditions where  $\delta(\cos \phi_d)/\delta T$  is significantly large, the temperature continues to increase until the insulation of the cable is damaged.

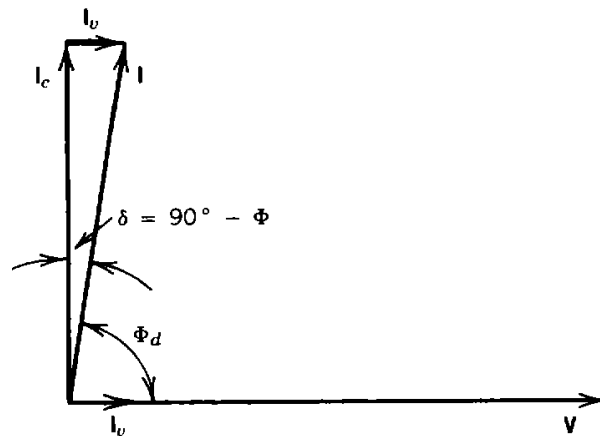


Figure 20: phasor diagram for cable dielectric.

When an ac  $V_{L-N}$  voltage is applied across the effective cable capacitance C, the power loss in dielectric,  $P_{dl}$ , is

$P_{dl} = \omega C V_{L-N}^2$	( 37)
-------------------------------	-------

This is larger than the dielectric power loss if the applied voltage is dc. The increase in the power loss is due to dielectric hysteresis, and it usually is much greater than leakage loss. The dielectric hysteresis loss cannot be measured separately. The total dielectric loss, consisting of dielectric hysteresis loss and the power loss due to leakage current flowing

through the insulation resistance can be measured by means of the Schering bridge. These losses depend on voltage, frequency, and the stat of the cable dielectric. Therefore, the test has to be made at rated voltage and frequency for a given cable.

For a balanced three phase circuit, the dielectric loss at rated voltage and temperature is

$P_{dl} = 3\omega CV_{L-N}^2 \cos \phi_d \text{ W/1000ft}$	<b>( 38 )</b>
--	---------------

where  $P_{dl}$  = cable dielectric loss in watts per 1000 ft

$$\omega = 2\pi f$$

$C$  = positive-sequence capacitance to neutral in farads per 1000 ft

$V_{(L-N)}$  = line-to-neutral voltage in kilovolts

$\cos \Phi_d$  = power factor of dielectric (insulation) at given temperature

#### Example 4:

A single-conductor belted cable has a conductor diameter of 0.814 in., inside diameter of sheath of 2.442 in., and a length of 3.5 mi. The cable is to be operated at 60 Hz and 7.2 kV. The dielectric constant is 3.5, the power factor of the dielectric on open circuit at a rated frequency and temperature is 0.03, and the dielectric resistivity of the insulation is  $1.3 \times 10^7 \text{ M}\Omega\text{-cm}$ . Calculate the following:

- (a) Maximum electric stress occurring in cable dielectric.
- (b) Capacitance of cable.
- (c) Charging current of cable.
- (d) Insulation resistance.
- (e) Power loss due to leakage current flowing through insulation resistance.
- (f) Total dielectric loss.
- (g) Dielectric hysteresis loss.

#### Solution:

- (a) By using equation (4.10),

$$E_{\max} = \frac{V}{r \ln(R/r)} \quad \text{V/m}$$

$$\begin{aligned} E_{\max} &= \frac{7.2}{0.407 \times 2.54 \ln 3} \\ &= 6.34 \text{ kV/cm} \end{aligned}$$

- (b) From equation (4.29),

$$\begin{aligned} C &= \frac{0.0388K}{\log_{10}(R/r)} \quad \mu\text{F/mi} \\ &= \frac{0.0388 \times 3.5}{\log_{10} 3} \\ &= 0.2846 \mu\text{F/mi} \end{aligned}$$

or the capacitance of the cable is

$$0.2846 \mu\text{F}/\text{mi} \times 3.5 \text{ mi} = 0.9961 \mu\text{F}$$

(c) By using equation (4.36),

$$\begin{aligned} I_c &= 2\pi f C V_{(L-N)} \text{ A} \\ &= \frac{2\pi \times 60 \times 0.9961 \times 7.2}{10^3} \\ &= 2.704 \text{ A} \end{aligned}$$

(d) From equation (4.41),

$$\begin{aligned} R_i &= \frac{\rho}{2\pi l} \ln \frac{R}{r} \\ &= \frac{1.3 \times 10^7}{2\pi \times 3.5 \times 5280 \times 12 \times 2.54} \ln 3 \\ &= 4 \text{ M}\Omega \end{aligned}$$

(e) The power loss due to leakage current flowing through the insulation is

$$P_{lc} = \frac{V^2}{R_i} = \frac{7200^2}{4 \times 10^6} = 12.85 \text{ W}$$

(f) The total dielectric loss is

$$P_{dl} = V_{(L-N)} I \cos \Phi_d$$

or

$$P_{dl} = V_{(L-N)} I \sin \delta$$

or

$$P_{dl} = \omega C V_{(L-N)}^2 \sin \delta$$

or

$$\begin{aligned} P_{dl} &= \omega C V_{(L-N)}^2 \delta \\ &= 2\pi \times 60 \times 0.9961 \times 7200^2 \times 0.03 \\ &= 584.01 \text{ W} \end{aligned}$$

(g) The dielectric hysteresis loss is

$$\begin{aligned} P_{dh} &= P_{dl} - P_{lc} \\ &= 584.01 - 12.85 \\ &= 571.16 \text{ W} \end{aligned}$$

## **1.5 LOCATION OF FAULTS IN UNDERGROUND CABLES**

There are various methods for locating faults in underground cables. The method used for locating any particular fault depends on the nature of the fault and the extent of the experience of the testing engineer. Cable faults can be categorized as

- 1. Conductor failures or**
- 2. Insulation failures.**

In general, conductor failures are located by comparing the capacity of the insulated conductors. On the other hand, insulation failures are located by fault tests that compare the resistance of the conductors.

In short cables, the fault is usually located by inspection, that is, looking for smoking manholes or listening for cracking sound when the kenetron<sup>†</sup> is applied to the faulty cable.

The location of ground faults on cables of known length can be determined by means of the balanced-bridge principle.