Power Cable Basics

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1.0 Introduction

Understanding power cables is fundamental for anyone involved in electrical design, installation, or maintenance. Being familiar with the different components of a wire or cable allows you to grasp why cables are constructed in specific ways, helping you appreciate the engineering decisions behind their design. This knowledge also enables you to select the most appropriate materials for your cables, ensuring durability, safety, and optimal performance under varying environmental and operational conditions. Most importantly, understanding the components and characteristics of cables empowers you to choose the right cable for each application, whether it's for residential wiring, industrial power distribution, or outdoor and harsh-environment installations.

Throughout this course, we will explore the essential elements of power cables, their functions, and their importance in real-world applications.

2.0 Basics of Electricity

2.1 What is Electricity?

The discovery of electricity happened over many centuries, starting with the observation of electric fish in Ancient Egypt.

Benjamin Franklin, one of the Founding Fathers, studied electricity and is famous for his 1752 kite experiment, where sparks traveled down a wet string to a metal key during a storm.

Later, scientists like Michael Faraday, Alexander Graham Bell, and Nikola Tesla expanded this knowledge, turning electricity into the energy source we use today.

Electricity is a form of energy. It can occur naturally and can also be produced and maintained.

It is type of energy produced by the movement of charged particles, such as electrons, which generates an electric current.

It can also exist as a buildup of electric charge, known as static electricity. This natural force is harnessed to power devices ranging from simple lights and heaters to advanced computers.

Electricity is generated by transforming primary energy sources—such as coal, natural gas, wind, and solar into electrical power.

2.2 Some Useful Terms

Voltage (Volts, V)

- Force (or push) that moves electrons in a common direction through a material
- The greater the voltage, the greater the pressure

Current (amps, A)

- Rate of flow of electrons through a conductor
- Current flows when electrons are pushed by the force of an applied voltage
- The greater the current, the greater the rate of flow of electrons

A helpful analogy to understand voltage and current as it relates to cables is the *classic gargen hose example.*

Water (electrons) is pushed through the hose (conductor) by the pressure (voltage) from the pump (generator)

The higher the pressure (voltage) from the pump (generator), the thicker the hose (insulation) needs to be to withstand the pressure (voltage), The higher the volume of water (electrical current), the larger the diameter of the hose (conductor cross sectional area).

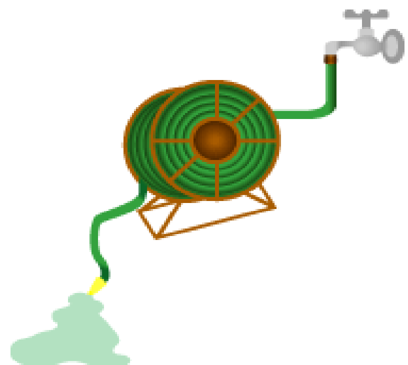


Figure 1 – Garden hose example

Power (Watts, W)

- Rate at which electrical energy is transferred by an electric circuit
- **Real power (P)** = Portion of power flow that results in net transfer of energy in one direction
- **Reactive power (Q)** = Portion of power flow due to stored energy that returns to the source in each cycle

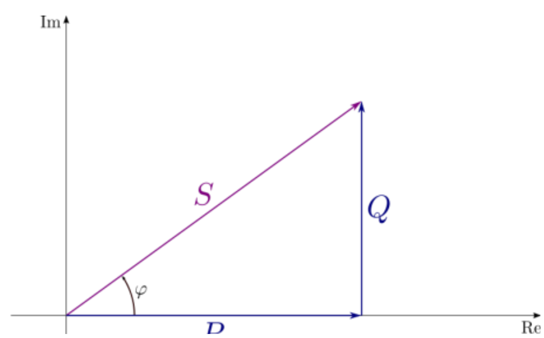


Figure 2 – Apparent Power

- **Apparent power (S)** = Vector sums of these powers
- Electrical engineers use the apparent power when designing and operating power systems
- Conductors, transformers and generators must be sized to carry the total current, not just the current that does useful work

A helpful analogy to understanding real and reactive power is the *classic pint of beer example.*

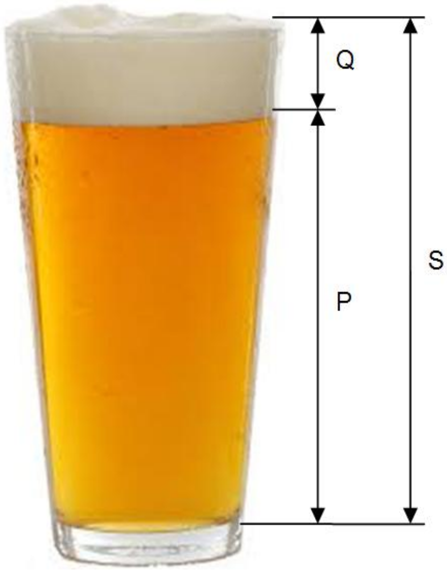


Figure 3 – Pint of beer

Real Power (kW) is like the beer in the glass. It is the useful part that quenches your thirst. In electricity, this is the power that does real work (i.e. running a motor, lighting a bulb, or heating a stove).

Reactive Power (kVAR) is like the foam on top of the beer. It does not do any useful work, but it comes along with the beer because of how it is poured. In electricity, this represents the energy that flows back and forth due to magnetic and electric fields (in inductors and capacitors). It does not do real work **but** is necessary to keep the system running.

Apparent Power (kVA) is the entire glass of beer plus foam. It is the total power delivered by the source, both the useful part (beer) and the non-useful part (foam).

2.3 Electrical Systems

Familiaring with the electrical system and understanding how electricity is generated, transmitted, distributed, and eventually used, is important if we want to know why power cables are designed the way they are.

There are many different types of cables out there and choosing the right one to use depends on many factors, including which parts of the the electrical system the cable will be connecting. **Figure 4** shows an illustration of a basis electrical system which involves 4 stages:

1. Power Generation
2. Power Transmission
3. Power Distribution
4. Power Usage

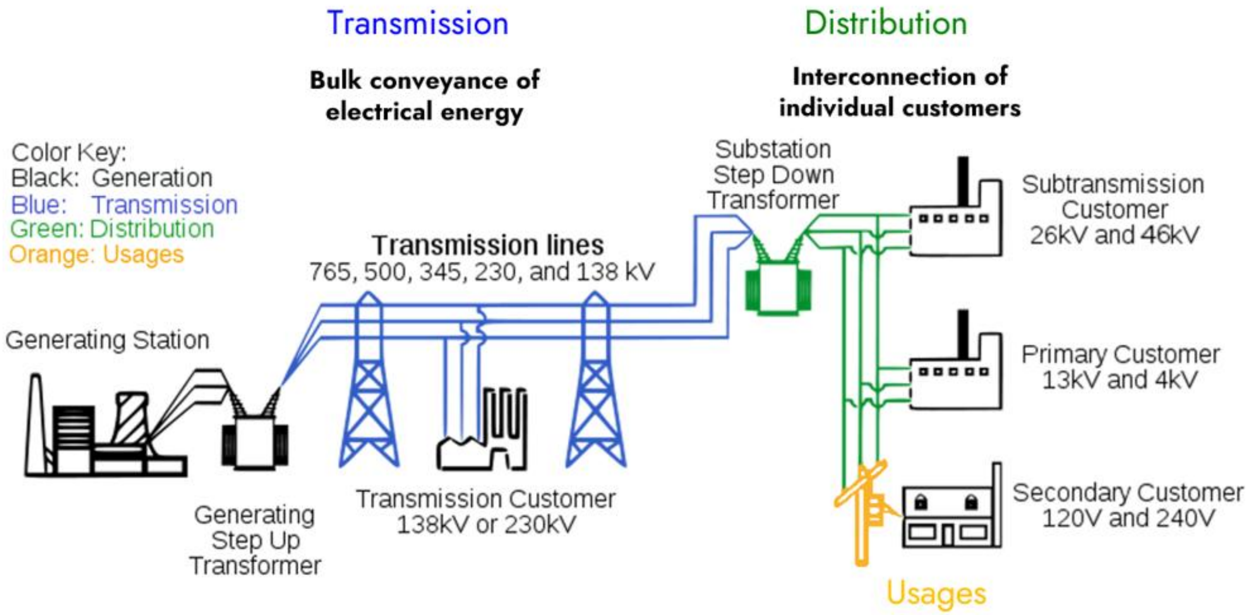
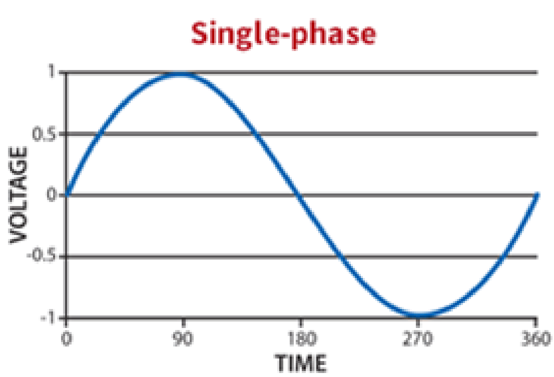


Figure 4 – Basic Electrical System

Power is generated at some sort of generating station (i.e. nuclear power plant, natural gas plant, hydroelectric plant, solar power plant, wind turbine, geothermal power plant, etc.). This power is transformed up to an extra-high voltage (138 kV +) and transmitted over long distances. At various locations (i.e. regions/blocks in a city), substations are installed to transform this power down to lower voltage (15 – 69 kV) for distribution to various sub-transmission and primary utility customers. Power is then delivered to buildings including factories, hospitals, small businesses and homes to be used to power day to day operations and living.

2.3.1 Single-Phase AC Systems

Single phase AC systems are most often used in homes or small businesses, where the power requirements are low – typically up to 72 kW (300 A service, with a 120V / 240V system). These systems require 2 conductors – a live conductor and a neutral conductor.



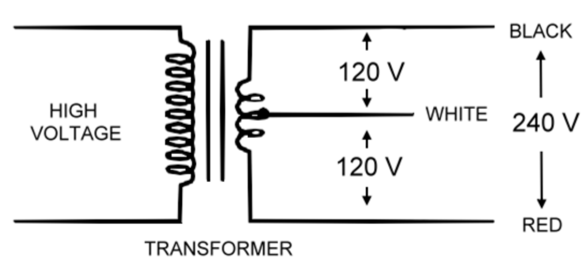


Figure 5 – Single Phase AC Power

2.3.2 Three-Phase AC Systems

By using three conductors, a three-phase AC system can provide 173% more power than the two conductors of a single-phase system.

Three-phase systems allow heavy-duty industrial equipment to operate more smoothly and efficiently. These systems can transmit power over long distances with a smaller conductor size, making it more economical than single-phase systems.

There is a case to be made for DC systems, however for the purposes of this course, DC systems will not be discussed.

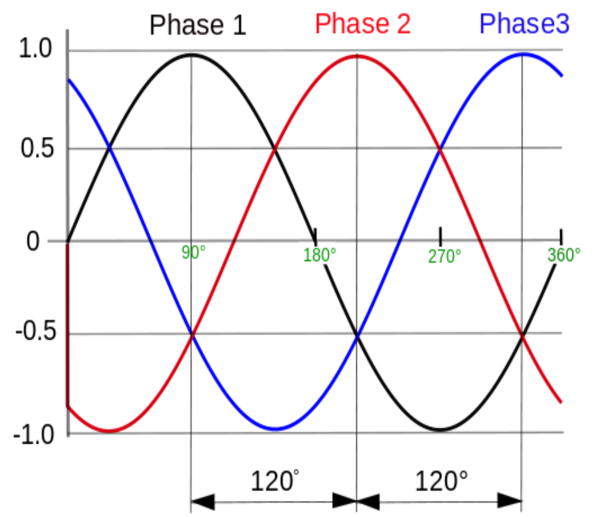


Figure 6 – Three Phase AC Power

2.3.2.1 Three-Phase, 4 Wire Systems

A 3-phase 4-wire system (Wye or "Y" connection) consists of three alternating current (AC) phase wires, each 120° out of phase with the others, plus a neutral wire. See **Figure 7**.

The neutral is connected to the center (star) point of the transformer or generator winding, allowing both three-phase and single-phase loads to be supplied from the same system.

Loads can be connected line-to-line, which provides a higher voltage for heavy machinery, or line-to-neutral, which provides a lower voltage suitable for homes, lights, and small appliances.

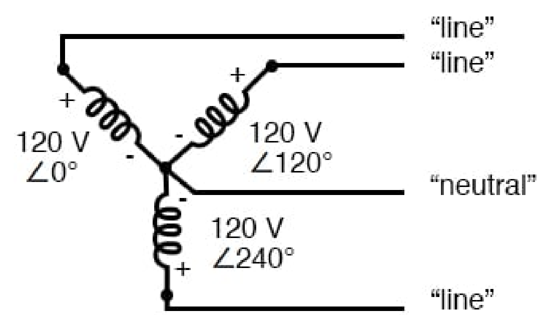


Figure 7 – 3 Phase, 4 Wire Systems

For example, in the US and some parts of Canada, the line-to-line voltage is 480 V, while the line-to-neutral voltage is 277 V. This setup is widely used in industries for running motors and large equipment, as well as in commercial and residential buildings, where single-phase loads can be drawn safely from one phase and neutral.
The neutral helps balance the system and provides a return path for current in single-phase loads, making the system both versatile and efficient.

2.3.2.1 Three-Phase, 3 Wire Systems

A 3-phase 3-wire system (Delta or "Δ" connection) consists of three alternating current (AC) phase wires, each separated by 120° in phase, but it does not have a neutral wire. See **Figure 8**.

In this system, loads are typically connected line-to-line, providing a higher voltage suitable for industrial equipment and heavy machinery. Because there are no neutral, single-phase loads cannot be directly supplied
from this system without
additional arrangements.

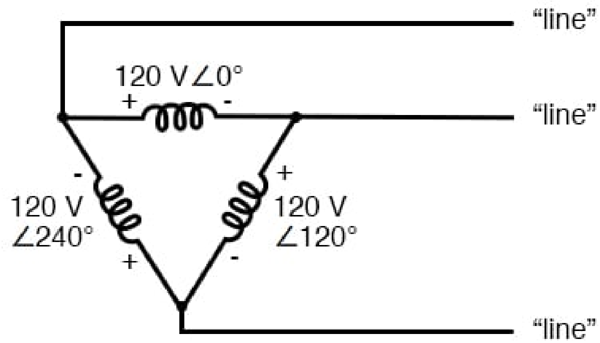


Figure 8 – 3 Phase, 3 Wire Systems

The 3-phase 3-wire system is simpler and often used in industries where only three-phase motors and large loads are required, as it efficiently delivers power while reducing the amount of wiring compared to a 4-wire system.

3.0 Power Cable Standards

There are various industry standards that govern the design, manufacture and testing of power cables in Canada and the US including CSA, UL, and ICEA.

In Canada, CSA defines various cable standards covered in the C22.2 series. Some examples include:

CSA C22.2 No. 38 - Thermoset-insulated wires and cables
CSA C22.2 No. 75 - Thermoplastic insulated wires and cables
CSA C22.2 No. 51 - Armoured cables
CSA C22.2 No. 131 – Type TECK90 Cable
CSA C68.5 - Primary shielded and concentric neutral cable for distribution utilities
CSA C68.10 - Shielded power cable for commercial and industrial applications, 5-46 kV

In the US, UL is the governing body. Some example standards include:

UL 44 - Thermoset-insulated wires and cables
UL 83 - Thermoplastic insulated wires and cables
UL 1569 - Metal-Clad Cables
UL 1072 - Medium-Voltage Power Cables

There are also various ANSI- and NEMA-approved ICEA standards and guides that cover insulated cables such as:

ANSI/ICEA S-94-649 - Standard for Concentric Neutral Cables, Rated 5 Through 46 KV
ANSI/ICEA S-97-682 - Utility Shielded Power Cables Rated 5 Through 46 kV
ANSI/ICEA S-113-684 - Performance Based Standard for Electric Utility Extruded Dielectric Shielded Power Cables Rated 5 Through 46 KV
ANSI/NEMA WC 70 / ANSI/ICEA S-95-658 - Non-Shielded Power Cables Rated 2000 V or Less ICEA

4.0 Power Cable Components

4.1 Conductor

Conductors are designed to carry electrical current. The larger the conductor, the more current it can carry at a lower temperature. The limitation in any circuit is the heating caused by the resistance of the conductor. The greater the number of strands, the more flexible the conductor is. However, the increase in number of strands can lead to termination difficulties.

4.1.1 Conductor Material

The 4 best electrical conductors are silver, copper, gold and aluminum, in that order. See **Figure 9** below.

Figure 9 – The four best conductors electricity

Note – there are many more metals which are conductive, for example steel, but are not used for their conducting properties. Rather, they may be used for other properties such as mechanical strength.

However, there are advantages and disadvantages that should be considered, including price, availability, weight, processability, and durability. See **Figure 10** for a comparison of some of these characteristics.

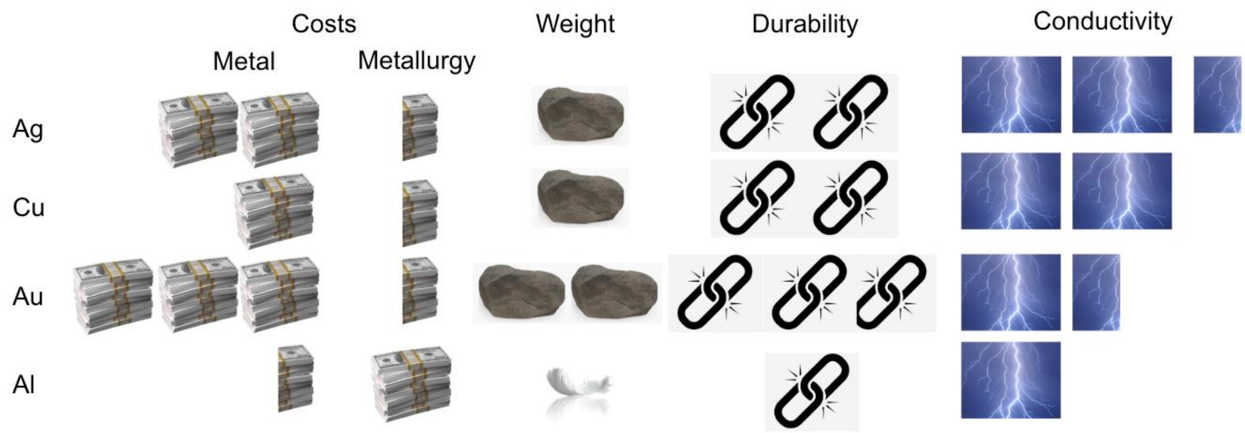


Figure 10 – More comparisons between silver, copper, gold, and aluminum

Silver is easy to work with, has reasonable weight, excellent durability, and great conductivity since silver oxide is also conducting. However, it is very expensive. It is used in surface plating for RF applications and use in specialized electronics.

Copper is also an excellent conductor, easy to work with, has a reasonable weight and durability. It can also be expensive, but as much as silver. It is the workhorse of the cable industry.

Gold is a good conductor and extremely easy to work with, it has excellent durability but is heavy. However, it can be rather expensive. It is used for ultrafine wires and plating for connectors and switches, mostly in aerospace and electronics applications.

Aluminium has acceptable conductivity, a reasonable price, is lightweight, but is somewhat difficult to process. It also generates a layer of insulating oxide (alumina) making connections slightly more challenging.

The two most common conductor materials are **copper and aluminum**.

Copper has a density of 3.3 times that of aluminum and has a lower resistance (and subsequently, higher conductivity). For equivalent conductivity, aluminum is:

1. 50% lighter than copper;
2. 30% larger in diameter; and
3. Less expensive.

The drawbacks include:

1. Requires more insulation material, screening and jacketing due to the larger diameter;
2. Special techniques for connections/terminations due to the oxide film; and
3. Cold flow can cause high resistance joints and leads to overheating.

4.1.2 Conductor Size

Conductor size in North America is determined by the **American Wire Gauge (AWG)** up to 4/0 and **Circular Mils (kcmil)** for sizes larger than 4/0. The size units used in Europe are mm^2 (500 kcmil ≈ 250 mm^2).

AWG is a measure of *diameter* (not area) and has been in use since 1857, predominantly in North America. It is also known as the Browne & Sharpe gauge (B&S). See **Figure 10.**

Rules of Thumb:

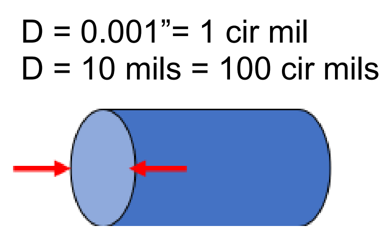
- When the diameter of the wire is doubled, the AWG size will decrease by 6
- When the area of a wire is doubled, the AWG size will decrease by 3.
- More accurate to define conductor size by "Circular Mils" or "mm2)
- This yields a direct measurement of conductor area → ampacity

Conductor characteristics	
Conductor size, AWG or kcmil	Dia, mm
14 AWG	3.36
12 AWG	3.84
10 AWG	4.47
8 AWG	5.99
6 AWG	6.95
4 AWG	8.17
3 AWG	8.88
2 AWG	9.7
1 AWG	11.23
1/0 AWG	12.27
2/0 AWG	13.44
3/0 AWG	14.74
4/0 AWG	16.21
250 kcmil	17.9
300 kcmil	19.3
350 kcmil	20.53
400 kcmil	21.79
450 kcmil	22.91
500 kcmil	23.95
600 kcmil	26.74
700 kcmil	28.55
750 kcmil	29.41
800 kcmil	30.25
900 kcmil	31.85
1000 kcmil	33.32
1250 kcmil	37.56
1500 kcmil	40.68
1750 kcmil	43.58
2000 kcmil	46.27

Figure 11 – Conductor size (AWG / kcmil) to mm

Circular Mil (cmil), by definition, is the area of a circle of diameter 1 mil (0.001 in.)

1 cmil = π / 4 sq mils



Area in circular mils = 1.2732 x 10^6 x area in square inches

Therefore, cmil = 10^6 x D^2

For example, a solid round conductor of 1 inch diameter

= **1,000,000 cmil** OR **1000 kcmil** OR **1000 MCM** (roman numeral "M" = thousand)

Another example:

4/0 AWG = 0.46"

cmil = 10^6 x $(0.46)^2$

4/0 AWG = 211,600 cmil or 211.6 kcmil or 211.6 MCM

4.1.3 Conductor Classes

Most common for power cables:

- **Class AA:** Usually specified for bare conductors on overhead lines.
- **Class A:** Usually specified for weatherproof conductors for overhead lines; or for greater flexibility than provided by Class AA stranding.
- **Class B:** Usually specified for insulated overhead and underground conductors (cables); or where greater flexibility than Class A stranding is required.

More common for specialty cables:

- Class C: Usually specified when greater flexibility than Class B stranding is required
- Class D: As above
- Class G: For portable cables
- Class H: For extremely flexible cords & cables
- Class I: For apparatus cables & motor leads
- Class K: For special flexible portable cords
- Class M: For welding cables

4.1.4 Conductor Stranding

Conductors are typically composed of a group of wires or any combination of groups of wires. Conductors are stranded to increase flexibility during installation and to increase mechanical strength in tension applications (i.e. overhead installations).

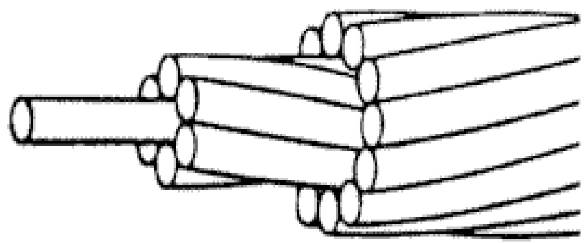


Figure 12 – Stranded conductor

Stranding is the application of subsequent layers of individual strands of wire around a centre point. Each layer has 6 or more wires than the layer below it. This forms an almost natural construction.

1 wire = solid
7 wires = 1 centre wire plus 6 around it
19 wires = 1 + 6 + 12
37 wires = 1 + 6 + 12 + 18
…

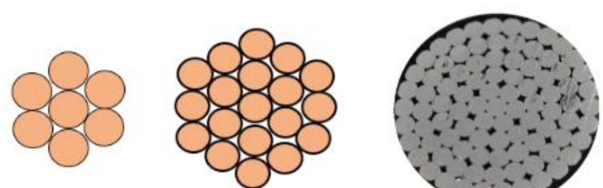


Figure 13 – Conductor strand layers

Some relevant terminology include: regular round, compressed, compact, lay, concentric lay, unilay, rope lay, bunching, and strand block.

4.1.4.1 Regular Round, Compressed, and Compact

Conductors can either be regular round, compressed, or compact stranded. **Figure 14** demonstrates the differences between each type of stranding for a 500 kcmil conductor. Important to note here that the metal volume remains constant, meaning that ampacity/resistance is the same regardless of stranding type.

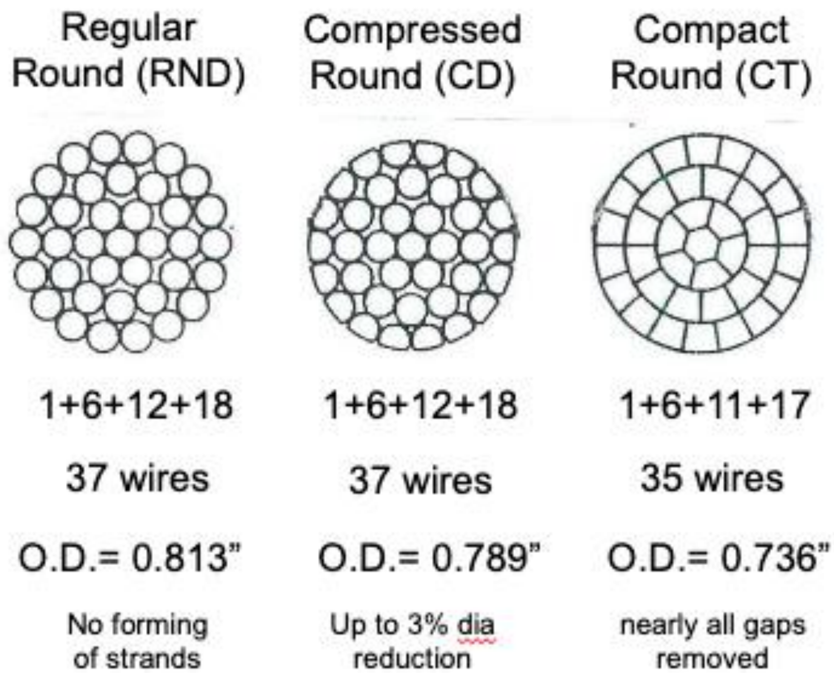


Figure 14 – Regular, Compressed, and Compact Stranding

Conventional strand designs force manufactures to draw a unique strand diameter for each conductor produces.

The discussion on stranding is augmented through the mention of Single Input Wire (SIW) stranding. This type of stranding allows manufactures to use the same strand diameter regardless of conductor size. A table comparing conventional conductors and SIW conductors is shown in **Figure 15**.

Conventional Conductor	Number of Wires	7	18	18	18	18
	Strand Diameter (inches)	0.1057	0.0735	0.0935	0.1050	0.1170
	Overall Diameter (inches)	0.268	0.336	0.376	0.423	0.475
	Conductor Size (AWG)	2	1/0	2/0	3/0	4/0
Single Input Wire (SIW) Conductor	Overall Diameter (inches)	0.268	0.336	0.376	0.423	0.475
	Strand Diameter (inches)	0.1160	0.1160	0.1160	0.1160	0.1160
	Number of Wires	6	10	12	16	19

Figure 15 – Convention conductor stranding vs SIW conductor stranding

<u>4.1.4.2 Conductor Lay</u>

Each layer of strands in a conductor is typically laid in a specific direction. The lay direction defines the direction of twist of each layer. See **Figure 16**.

Right Hand (RH) – strands are twisted clockwise when looking down the axis of the conductor.
Left Hand (LH) – strands are twisted counter-clockwise when looking down the axis of the conductor

Industry convention:

- The outer layer on overhead conductors is always RH lay
- The outer layer on underground conductors is always LH lay

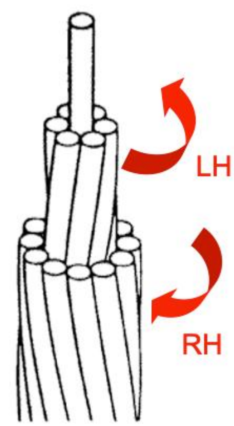


Figure 16 – Conductor Lay direction

Lay length is the measured distance, along the strand, between each of these twists. Cable design standards typically specify a minimum and maximum lay length. Lay length directly affects a conductor's flexibility, durability and overall performance. Shorter lay lengths increase flexibility and longer lay lengths may reduce production time but also make the conductor stiffer. See **Figure 17**.

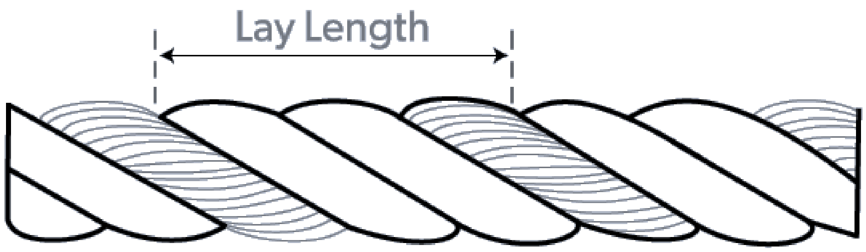


Figure 17 – Lay Length

4.1.4.3 Concentric Lay, Unilay, and Rope Lay

Concentric lay conductors have each layer of strands twisted in opposite directions with longer lay lengths on the subsequent layer. On the other hand, **unilay** conductors have each layer of strands twisted in the same direction with the same lay length. Unilay conductor are slightly more compact and flexible than concentric lay conductors, however they do not offer the same level of mechanical strength or crush resistance.

Rope lay conductors are conductors that are stranded in a more complex manner where each individual strand is a stranded conductor. See **Figure 18**. Rope lay conductors offer extreme flexibility making them suitable for applications like robotics, portable equipment, and welding leads and flexible connectors.

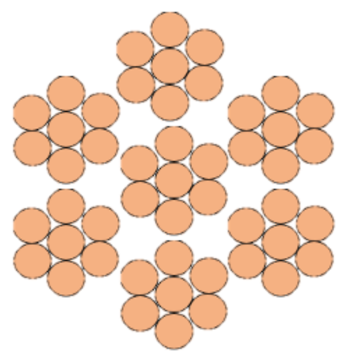


Figure 18 – Rope-lay conductor

4.1.4.4 Bunching

Some conductors may be bunched, meaning the individual strands are twisted together without control over the final strand location. See **Figure 19**. Conductor bunching is the lowest cost and fastest production method for stranding and results in a highly flexible conductor. The drawbacks are that it offers less precise dimensional control and a rougher surface which may impact the application of material in the subsequent layer of the cable.

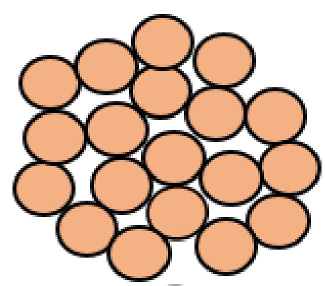


Figure 19 – Bunched conductor

4.1.4.5 Strand Block

Conductor water-blocking can be achieved using strand-blocking materials. The use of these materials is optional and typically only beneficial for medium or high voltage underground cables.

The traditional method of achieving this is by pumping a semi-conducting bitumen onto the surface of each layer to fill in the voids (air gaps) between strands. Other methods can include a combination of strand fill material, water swellable powders/tapes/yarns.

These materials prevent water that enters the conductor from travelling along its length in between the strands. The materials used must be qualified and tested for performance and compatibility for use in approved cables. See **Figure 20** for the methodology.

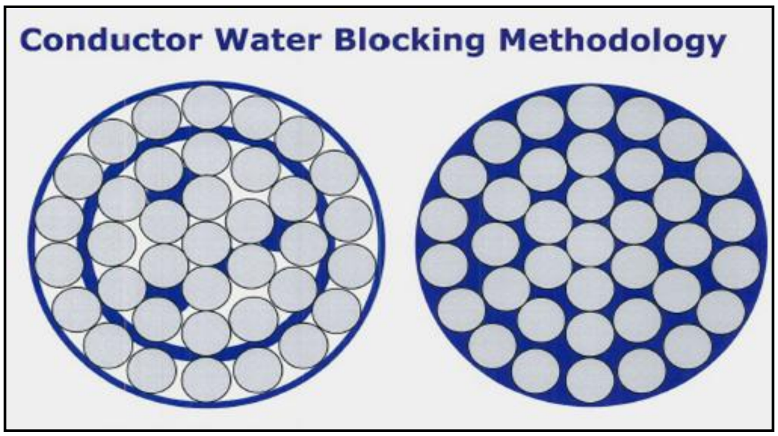


Figure 20 – Conductor water blocking (strand block) methodology

4.2 Insulation

The main purpose of a cable's insulation is to:

1. Withstand voltage stresses
2. Operate a wide temperature range
3. Withstand mechanical abuse (abrasion, crush, impact, and flexing)
4. Withstand chemical attack (oil, gases)

Insulation material is typically a non-conductive (dielectric) material having a specific voltage and temperature rating. The two most common insulation types are **thermoplastic** and **thermosetting**.

A **thermoplastic** material is a type of plastic polymer that softens and becomes mouldable when heated and then hardens when cooled. This process can be repeated multiple times without altering the material's chemical structure. Examples include polyethylene (PE), Polypropylene, and PVC. A **thermoset** material is a polymer that, when heated or chemically treated during a process called curing, undergoes irreversible changes to form a rigid cross-linked network. This gives the material's molecular structure high strength, durability and heat resistance, but also means it cannot be remelted or reshaped once cured. Instead, if overheated, it will char or burn. See **Figure 21** which gives a relatable example/analogy to these two types of materials.

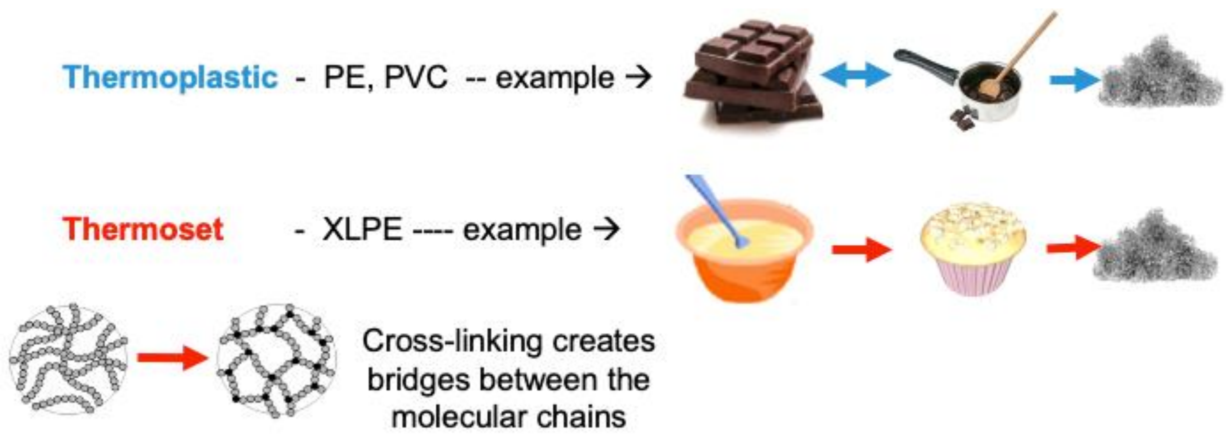


Figure 21 – The two most common insulation types

Thermoplastic Insulation Systems	**Thermoset Insulation Systems**
Have a lower maximum temperature typically 75°C	Have a higher maximum temperature typically 90°C or 105°C
Maximum short circuit temperature of 150°C	Maximum short circuit temperature of 250°C
When overheated, rapidly become liquid, allowing it to flow	When overheated, become somewhat moldable, but will not become liquid

Table 1 – Useful comparisons between thermoplastic and thermoset insulation systems

4.2.1 Insulation and Voltage

Insulation is vital to prevent dangerous electrical shocks and short circuits which cause a breakdown in the circuit and may lead to fires. It also ensures the proper function of the circuit by containing the voltage within the conductor. See **Figure 22**. Insulation provides a protective barrier that prevents users from coming into contact with live conductors. It also helps keep conductor separate, which eliminates undesired paths for current, which could cause short circuits. Insulation also helps maintain the electrical system's integrity by containing the electrical current within the conductor reducing the risk for leakage current.

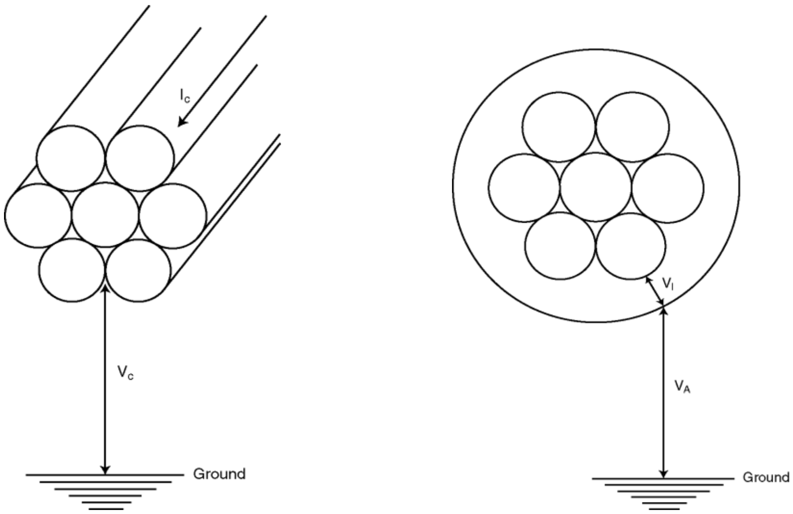


Figure 22 – Location of voltage

Where:

V_c = voltage from conductor to ground
$V_c = V_I + V_A$

Where:

V_I = voltage across the insulation
V_A = voltage from insulation to ground

The thicker the insulation layer is, the higher voltage stresses it can handle.

The common insulation types used for different cables depend on voltage. Typical Voltage Classes in North America are as follows:

1. Low voltage (LV) - 0 – 1000 V
2. Medium Voltage (MV) - 1000 V – 46 kV (or 69 kV)
3. High Voltage (HV) - 46 kV (69 kV) – 230 kV
4. Extra-High Voltage (EHV) - > 230 kV

Table 2 presents common insulation materials used depending on voltage class.

Insulation Material	Voltage Class
Rubber	LV
PVC (Polyvinyl chloride)	LV
PE (polyethylene)	LV
Thermoplastic Elastomer (TPE)	LV
Cross-linked Polyolefin (XLPO)	LV, MV
Ethylene Propylene Rubber (EPR, EPT, EPDM)	LV, MV, HV
Oil Impregnated Paper	MV, HV, EHV
Cross-linked Polyethylene (XLPE)	MV, HV, EHV

Table 2 – Common Insulation Materials

4.2.2 Insulation Systems

Insulation systems differ depending on the voltage class.

LV cables typically employ a single layer insulation system, whereas MV and HV/EHV cables typically employ a three-layer insulation system. The reason for this is due to the higher electrical stresses and risks associated with higher voltages. This three-layer insulation system consists of a non-metallic **conductor shield, insulation, and insulation shield**. In addition, cables in the MV to EHV range require a metallic shield, which will be explored in Section 4.3.

In Section 4.2, we reviewed the purpose of the insulation layer, which is typically always required for underground cables or cables inside a building. The conductor shield and insulation shields, on the other hand, serve an additional purpose.

The conductor shield is tasked with providing a smooth surface at the interface between the conductor and insulation.

The insulation shield is tasked with:

1. Further confining the electric field within the cable;
2. Obtaining symmetrical radial distribution of voltage stress within the cable;
3. Protecting the cable connected to overhead lines or otherwise subject to induced potentials;
4. Limiting radio interference; and
5. Reducing the hazard of shock

Table 3 below outlines when a conductor shield, insulation shield, and metallic shield would be required depending on the voltage rating of the cable.

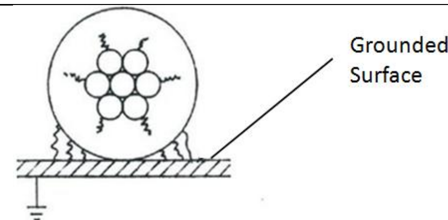
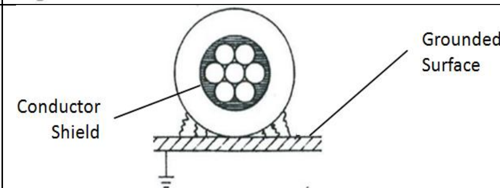
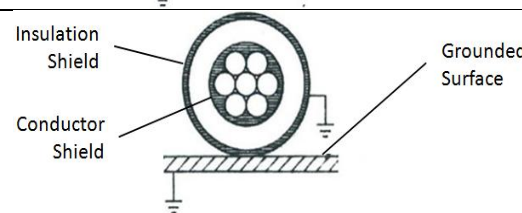
Voltage	Shield Type	Metallic Shield	Visual
< 2 kV	Not required	Not required	
> 2 kV	Conductor only	Not required (optional)	
> 5 kV	Conductor and insulation	Required	

Table 3 – Non-metallic conductor/insulation shields and metallic shield

Cable standards from UL, CSA and ICEA all require a shield material over the conductor at voltages > 2 kV. Modern shield are extruded semi-conducting material that smooth out the ridges over the conductor that effectively provides a smooth interface between the insulation and conductor.

At 5 kV, an insulation shield may or may not be required depending on the cable type.

The insulation shield always has a metallic component over top of it. This metallic component is discussed in Section 4.3.

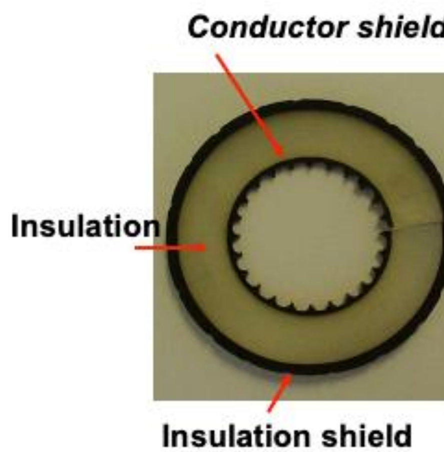


Figure 23 – Non-metallic insulation and CS/IS

4.2.3 MV/HV/EHV Insulation

The most common insulation material for MV/HV/EHV cables is a Tree-Retardant Cross-linked Polyethylene (**TR**-XLPE).

TR-XLPE has a similar list of features and benefits as the low voltage XLPE with the added ability to resist the formation of water trees. Water trees can form in the presence of moisture and electrical

stress. Additives are introducing during the compounding process to slow water tree growth in the insulation. Typical maximum operating temperatures are 90°C or 105°C.
Ethylene Propylene Rubber (EPR) is also commonly used for MV cables due to its high dielectric strength, and particularly, its flexibility.

Both TR-XLPE and EPR are cross-linked.

Cross-linking is the attachment of two chains of polymer molecules by bridges that are chemically bonded tighter. The result is a material with enhanced properties, particularly a higher resistance to heat than polyethylene.

The two main types of cross-linking methods are:

1. **Peroxide Cure Method**

   Crosslinking chemical reaction is initiated by the thermal decomposition of organic peroxide in a vulcanization (CV) tube at high heat and pressure. This process can be used for both XLPE and EPR.

   Mostly used in MV, HV, and EHV insulated cables.

2. **Moisture Cure**

   Silane grafted onto the polymer chain is mixed with a catalyst during the extrusion process. The curing process occurs in the solid phase after extrusion by immersing the material in saturated steam for a predetermined time.

   This process is almost exclusively used for LV power cables.

4.3 Metallic Shields

Metallic shields, as mentioned in the above sections, is required for cables with a voltage rating greater than 5 kV. Some 5 kV cables maybe also required a metallic shield depending on the application.

The metallic shield component of a cable carries leakage current, short circuit current, and in some cases, the neutral current to ground.

The most common metallic shield types are:

1. Helically applied copper tape;
2. Longitudinally applied corrugated copper tape;
3. Concentric neutral wires; and
4. Wire shield

Table 4 presents a comparison between these four metallic shield types.

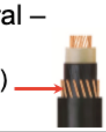
Copper Tape – Helically Applied Copper Tape(s) 	LACT – Longitudinally Applied Corrugated Copper Tape 	Concentric Neutral – Helical Wires (6 AWG to 14 AWG) 	Wire Shield – Helically Applied Small Wires (22 AWG to 18 AWG)
Used on industrial cables	Used on large single conductor sized utility and industrial cables	Used by utilities on underground distribution cables	Same applications as Cu tape (but very uncommon)
Good electrostatic shield	Good electrostatic shield	1/3 or 33% conductance used on 3 phase systems	Similar short circuit & ampacity derating as copper tape
May be applied with gaps or overlapped	Provides a moisture barrier when longitudinal overlap is sealed	Full or 100% conductance used on single phase system	
- Low short circuit capacity. - If grounded both ends, conductor current derating is small	"Medium" short circuit levels (between helical tape and CN)	- Higher short circuit levels - Conductor current derating can be high if grounded both ends	

Table 4 – Comparison between four common metallic shield types

4.3.1 Helically Applied Copper Tape

Helically applied copper tape is widely used on industrial cables where both durability and performance are required. Its primary function is to provide a good electrostatic shield, protecting the cable from external electrical interference and ensuring stable performance. This type of shielding can be applied either with intentional gaps or in overlapping layers, depending on the design and application needs. While it has a relatively low short-circuit capacity compared to other shielding methods, it remains effective in industrial settings where conditions are well controlled.

Another advantage is that, if the shield is grounded at both ends, the conductor current derating effect is minimal, which allows the cable to maintain efficient current-carrying capacity.

4.3.2 Longitudinally Applied Corrugated Copper Tape (LACT)

Longitudinally applied corrugated copper tape (commonly referred to as LACT) is primarily used on large single-conductor sized utility and industrial cables. Like helically applied copper tape, it provides excellent electrostatic shielding, but it also offers an additional benefit: when the longitudinal overlap is sealed, the corrugated design creates an effective moisture barrier. This makes LACT especially valuable in environments where cables may be exposed to damp or wet conditions. In terms of electrical performance, its short-circuit capability is considered "medium," falling between the lower capacity of helically applied tape and the higher tolerance of concentric neutral designs. This balance makes it a suitable choice for heavy-duty applications where both electrical protection and environmental resistance are required.

4.3.3 Concentric Neutral Wires

Concentric neutral shielding, which uses helically applied wires in sizes ranging from 6 AWG to 14 AWG, is most commonly employed by utilities on underground distribution cables. Unlike copper tape or LACT, concentric neutral designs can be tailored to provide different levels of electrical conductance depending on the system configuration. For example, in three-phase systems, they typically provide one-third (or 33%) of the conductor's overall conductance. On single-phase systems, however, they can be configured to provide full or 100% conductance, which ensures strong fault current carrying capability. These designs are known for supporting higher short-circuit levels, making them robust for utility applications. However, one drawback is that conductor current derating can be significant if the concentric neutral is grounded at both ends, as this creates parallel current paths that may reduce the cable's effective performance.

4.3.4 Wire Shield

Helically applied wire shields made of small wires (ranging from 22 AWG to 18 AWG) are another option, although they are far less common in practice. These shields are intended to serve the same role as copper tape, offering electrostatic protection and short-circuit performance. However, because of their smaller wire size and relative rarity in use, they are not often chosen for standard applications. Their short-circuit behavior and ampacity derating are comparable to that of helically applied copper tape, which means they can be used as an alternative under certain design conditions. Still, in most cases, copper tape or concentric neutral shielding is preferred due to greater reliability and wider acceptance in industrial and utility standards.

4.4 Armour

Cable armour is a protective layer incorporated into a cable designed to enhance both mechanical strength and overall durability. Its primary role is to protect the cable's inner conductors and insulation from external physical damage, which may occur through crushing, impact, or abrasion during installation or throughout its service life. In many environments, cables are buried underground, laid in ducts, or installed in industrial facilities where they may be exposed to heavy machinery, sharp objects, or even rodents. The addition of armour ensures that the integrity of the cable is preserved in these demanding conditions.

Armour is typically constructed using aluminum or steel tape or layers of steel wires with the choice of material depending on the required balance between strength, flexibility, and corrosion resistance. Steel wire armour, for example, provides robust mechanical protection and is often used in submarine cables, while aluminum or steel armour is typically used for industrial or commercial cables. In flexible cables, helical wire armour can maintain durability without compromising bending performance.

Although armour is not primarily intended to function as an electrical shield, it can serve a secondary electrical purpose. When properly bonded and earthed, the metallic layer of armour can provide an additional path to ground, improving safety and sometimes contributing to the cable's fault current carrying capacity. This grounding function enhances protection against electrical faults and reduces the risk of damage to equipment or injury to personnel.

Ultimately, the use of cable armour increases the lifespan, safety, and reliability of cable installations, particularly in challenging environments where cables are vulnerable to both environmental and mechanical stresses. It ensures that critical infrastructure, from power distribution to industrial control systems, continues to operate without disruption.

The two most common armours in power cables are aluminum interlocked armour (AIA) and continuously welded and corrugated (CWC) armour.

Figure 24 – Aluminum interlocked armour (AIA) and Continuously Welded and Corrugated (CWC) Aluminum Armor

Table 5 provides a comparison between these two types of armour.

Interlocked Metallic Armour (AIA) 	Continuous Metallic Armour (CWC) 
Wrap a formed tape over the cable	Welded tube (usually corrugated) over the cable
Typically, aluminum, but can be galvanized steel	Typically, aluminum
Cannot be used as a bonding conductor	Can be used as a bonding conductor
More flexible than continuous sheath	Corrugated for flexibility
Can be broken open if bent too sharply	Can be damaged if bent excessively
Will allow moisture to penetrate to core	Will not allow moisture to penetrate to core
Usually supplied with an outer covering	Usually supplied with an outer covering

Table 5 – AIA vs CWC

Interlocked Metallic Armour (AIA) is formed by wrapping a shaped tape around the cable to provide mechanical protection. It is typically made from aluminum, although galvanized steel may also be used in some designs. While this type of armour is effective for physical protection, it cannot serve as a bonding conductor. One of its key advantages is flexibility, as it is easier to handle and install compared to continuous metallic sheaths. However, this flexibility comes with certain limitations. If the armour is bent too sharply, it can break open, compromising the cable's protection. In addition, AIA does not provide a complete moisture barrier, which means that water can penetrate to the core of the cable. For this reason, it is usually supplied with an outer covering to help reduce environmental exposure and extend its service life.

Continuous Metallic Armour (CWC), on the other hand, is constructed using a welded tube, most often corrugated, that is placed over the cable. This design, typically made of aluminum, provides strong and consistent protection while also maintaining some flexibility thanks to the corrugation. Unlike interlocked armour, CWC can serve as a bonding conductor, making it more versatile in certain applications. It also offers a key advantage in terms of environmental resistance, as it prevents moisture from reaching the cable core. However, while durable, CWC can still be damaged if bent excessively, which may reduce its effectiveness. Like AIA, it is usually supplied with an additional outer covering for enhanced protection against mechanical and environmental stress.

It is worthwhile explaining the difference in the armouring process between AIA and CWC. Armouring requires the perfect balance between machine speed, tape positioning, armour tightness, and operator know-how. The armouring machines that produce industrial armoured power cable products are an engineering feat.
The **AIA** process begins with large rolls of aluminum strip, which are carefully fed into the machine. The coil holding the strip is positioned perpendicular to the conductors, allowing the

conductors to pass directly through the center of the coil. The aluminum strip is then helically wrapped around the conductors in a continuous motion, forming a protective layer that interlocks onto itself to ensure structural integrity and resistance to deformation. During this wrapping and forming process, friction between the aluminum strip and the conductors generates heat. To prevent overheating and maintain the quality of the armor, a light application of oil is used to reduce friction and facilitate smooth formation. This process ensures that the conductors are both well-protected and flexible enough for practical handling and installation. See **Figure 25**.

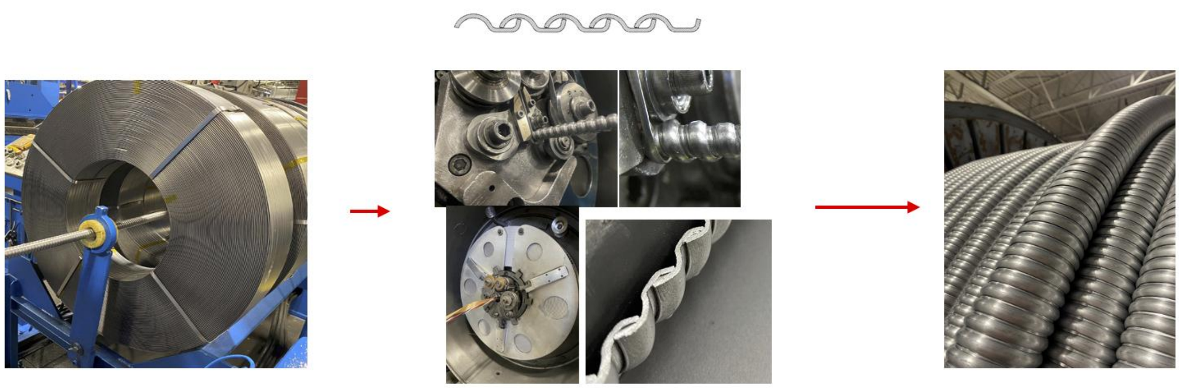


Figure 25 - AIA process

The **CWC** process begins with large rolls of aluminum strip, which are carefully fed into the machine in a controlled manner. Unlike interlocked armouring, the strip is fed parallel to the conductors, and as it is wrapped around them, it forms a smooth, uniform tube. This tube is then continuously TIG welded along its length, creating a seamless and strong armor that provides consistent protection against mechanical stresses and environmental factors. Once the welding is complete, the smooth aluminum tube passes through a corrugator, a machine that imparts a series of ridges or corrugations along its surface. This corrugation significantly improves the flexibility of the armored conductor, allowing it to bend and flex without compromising the integrity of the aluminum armor. Additionally, the corrugation enhances the mechanical strength of the conductor, helping it resist crushing, impact, and other forms of physical stress. The result is a conductor that combines robust protection with practical flexibility, making it suitable for a wide range of electrical installations where both durability and adaptability are critical. See **Figure 26**.

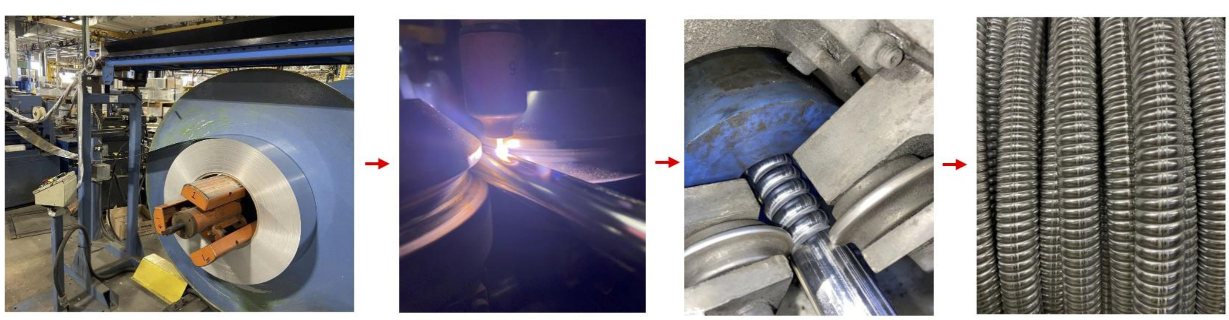


Figure 26 - CWC process

4.5 Jackets

The primary function of a cable jacket is to protect the internal components of the cable from environmental and mechanical stresses, ensuring reliable operation and an extended service life. One of the key protective roles of the jacket is to prevent moisture ingress. Water or condensation can penetrate the cable and compromise the insulation, leading to short circuits, corrosion of conductors, or reduced dielectric strength. Cable jackets also provide protection against sunlight, particularly ultraviolet (UV) radiation, which can degrade polymer materials over time, causing brittleness, cracking, or loss of mechanical integrity. In addition, jackets help to minimize the spread of fire along the cable route. Many jackets are formulated to be flame-retardant or self-extinguishing, thereby reducing the risk of fire propagation in buildings, industrial installations, or outdoor environments. Protection against chemicals is another crucial function; cables are often exposed to oils, acids, alkalis, solvents, and other corrosive substances that can deteriorate the jacket and compromise the safety and reliability of the cable.

In cold climates, low-temperature flexibility is an essential characteristic. A cable jacket must remain pliable and resistant to cracking even at sub-zero temperatures. This flexibility ensures that the cable can be bent, coiled, and installed without damage, maintaining electrical continuity and mechanical strength throughout its lifetime.

Several materials are commonly used for power cable jackets, each offering a combination of environmental resistance, mechanical durability, and flexibility. Polyethylene (PE) is widely used for its excellent moisture resistance, toughness, and resistance to environmental stress cracking. Polyvinyl Chloride (PVC) is also common, providing good flame retardancy, chemical resistance, and flexibility at moderate temperatures. For more demanding applications, specialty materials such as Neoprene, Hypalon, and Nylon are employed. Neoprene offers excellent resistance to oils, chemicals, and weathering, while Hypalon provides superior chemical resistance and long-term UV stability. Nylon is used in applications requiring high abrasion resistance and mechanical strength, such as in industrial or outdoor exposed installations.

Figure 27 – Cable Jacket

Selecting the appropriate jacket material is critical to ensuring the cable performs safely and reliably in its intended environment. Factors such as exposure to extreme temperatures, chemical contact, mechanical abrasion, UV radiation, and fire hazards must all be considered. By choosing the correct material, designers can ensure that the cable maintains its integrity, safety, and functionality throughout its operational life, even under challenging conditions.

Cable jackets can be applied either overlaid or encapsulated as shown in **Figure 28**.

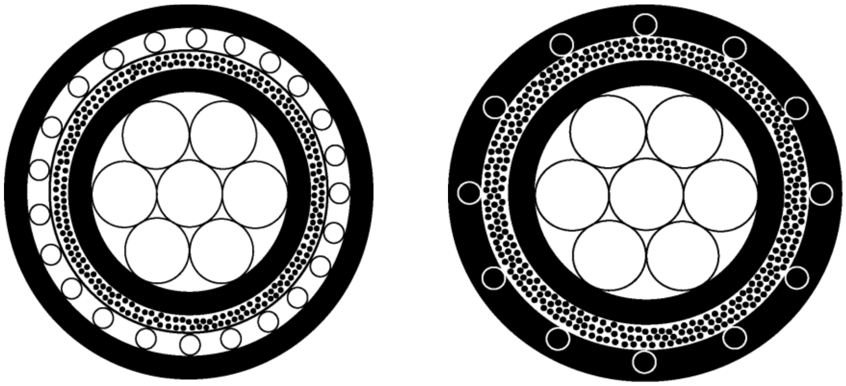


Figure 29 – Overlay jacket (left) and encapsulating jacket (right)

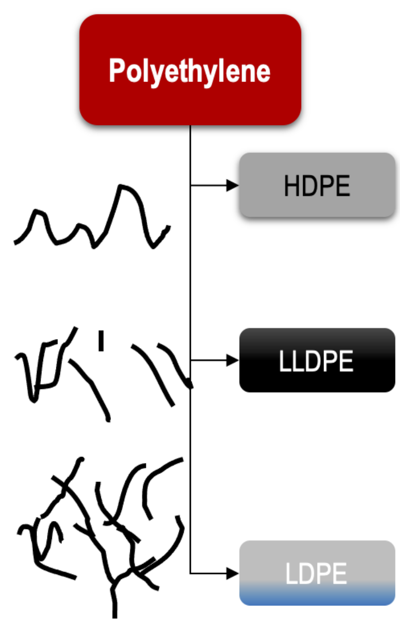
Overlay jackets typically have a separator tape placed over the inner core to prevent fall-in between wires. This set up offers greater flexibility for terminating. On the other hand, encapsulating jackets are extruded to fill void spaces in the inner core. This set up provide less flexibility for terminating.

There are many different cable jacket materials out there, the most common being PE and PVC

4.5.1 Polyethylene (PE) Jackets

This type of cable jacket is specifically designed to provide toughness and water resistance, making it highly suitable for harsh environments. Its durable construction allows it to withstand burial in soil, installation in underground ducts, or exposure to water, ensuring long-term protection of the internal conductors. However, it is important to note that this jacket does not provide adequate flame resistance, which limits its suitability for indoor or building installations where fire safety regulations are critical.

One of the notable strengths of this jacket is its chemical resistance. It is capable of withstanding exposure to a variety of common chemicals, including acids, alkalis, and certain oils, which are frequently encountered in industrial, agricultural, or outdoor applications. This chemical resilience helps to maintain the integrity of the cable even in environments where corrosive substances are present, preventing deterioration of the jacket and potential damage to the conductors inside.



Due to its combination of toughness, water resistance, and chemical protection, this type of jacket is ideal for outdoor, underground, and industrial installations. It provides reliable mechanical and environmental protection under conditions that would compromise less robust materials. However, for indoor installations, particularly within buildings, alternative jackets with higher flame-retardant properties are recommended to meet fire safety requirements and regulatory standards. By selecting the appropriate jacket material for each application, designers and engineers can ensure the cable's performance, longevity, and safety in its intended environment.

4.5.2 PVC Jackets

This type of cable jacket is frequently modified during manufacturing to enhance its physical and environmental characteristics, making it well-suited for a wide range of demanding applications. The modifications improve toughness, allowing the jacket to withstand mechanical stresses such as bending, abrasion, and impact during installation and operation. Additionally, it is designed to resist degradation from prolonged exposure to sunlight, providing excellent ultraviolet (UV) stability and ensuring long-term durability in outdoor environments.

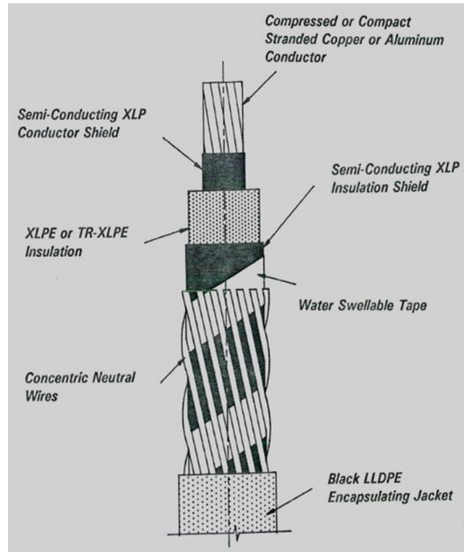
Many variants of this jacket can achieve recognized flame spread ratings, such as FT1 or FT4, which significantly improve safety in installations where fire risk must be minimized. These ratings indicate that the material either limits the spread of flames or self-extinguishes after ignition, depending on the specific rating, making it suitable for both indoor and certain outdoor applications where fire performance is important.

Beyond its mechanical, UV, and flame-resistant properties, this type of jacket is highly resistant to a broad spectrum of chemicals. It can withstand exposure to acids, alkalis, and most oils, which is critical for industrial, agricultural, or other harsh environments where corrosive substances may come into contact with the cable. This chemical resilience helps preserve the integrity of the cable jacket over time, preventing cracking, swelling, or deterioration that could compromise the conductors inside.

Overall, the combination of toughness, sunlight resistance, flame retardancy, and chemical protection makes this jacket highly versatile. It is particularly valuable in outdoor installations, industrial facilities, and environments where cables are exposed to mechanical, chemical, and environmental stresses. By selecting this type of jacket, designers and engineers can ensure that cables remain safe, reliable, and durable, even under challenging operational conditions, thereby extending the service life and reducing maintenance requirements.

4.5.3 Jacket Water Blocking

In many cable designs, special measures are taken to prevent water from propagating along the length of the cable if the outer jacket becomes damaged or compromised. This is particularly important in outdoor, underground, or wet-environment installations, where moisture ingress can lead to serious issues such as insulation failure, short circuits, conductor corrosion, and reduced dielectric performance. To address this risk, cables often incorporate water-blocking components, which are installed beneath the outer jacket along the entire length of the cable.

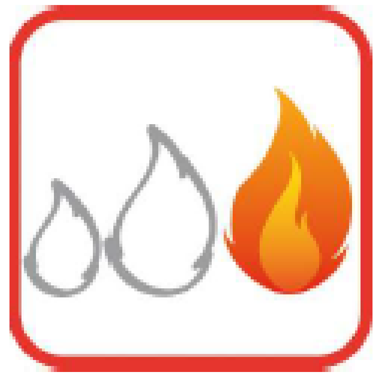


These water-blocking components can take the form of swellable tapes, powders, or gels. When water comes into contact with these materials, they absorb it and expand, filling any voids or gaps within the cable construction. This swelling action effectively creates a barrier that stops further water migration along the cable, protecting the internal insulation and conductors from moisture-related damage. Some designs combine multiple water-blocking elements to provide redundancy, ensuring that even if one component fails, others continue to prevent water propagation.

Water-blocking features are especially critical in applications such as underground power distribution, direct-buried communication cables, and submarine or industrial cables exposed to high humidity, groundwater, or accidental flooding. By incorporating water-swellable materials, these cables achieve enhanced reliability and longevity, maintaining performance and safety even in harsh environmental conditions. The use of such water-blocking technologies is a key consideration for engineers and designers when selecting cables for wet or high-risk installations, ensuring operational integrity and minimizing maintenance requirements over the cable's service life.

5.0 Power Cable Ratings

5.1 Flame Ratings



Cable flame ratings are an essential measure of a cable's ability to resist fire and limit the spread of flames. These ratings are used to ensure safety in installations where fire hazards may be present, such as in buildings, tunnels, or industrial facilities. Flame-rated cables are designed to prevent the rapid propagation of fire along their length, giving occupants more time to evacuate and reducing the risk of fire damage to infrastructure. Flame performance is assessed according to standardized tests, and different ratings indicate the level of protection a cable provides under fire conditions. The three most common flame ratings in North America are **FT1**, **FT4** and **FT6**.

The FT1 rating represents the most basic level of flame resistance. Cables with an FT1 rating are tested for vertical flame propagation in free air and are required to limit the spread of flames along the cable to a minimal extent. FT1 cables are suitable for applications where moderate fire resistance is needed, such as residential or light commercial installations, but they may not provide sufficient protection in higher-risk environments.

FT4-rated cables provide a higher level of flame resistance and are tested for both vertical flame propagation and the ability to limit flame spread when multiple cables are bundled together. This rating ensures that the fire does not easily jump from one cable to another, which is critical in densely wired installations such as commercial buildings, data centers, and industrial facilities. FT4 cables are commonly used where building codes require enhanced fire safety and where minimizing flame propagation along cable trays or conduits is necessary.

FT6-rated cables represent the highest standard in this classification. These cables are subjected to rigorous flame testing that simulates real-world fire scenarios, including exposure to intense heat and high flame intensity. FT6 cables are engineered to provide maximum flame resistance and often combine this property with low smoke emission and low toxicity, making them ideal for critical environments such as hospitals, tunnels, transport systems, and high-occupancy public buildings. The FT6 rating ensures that cables continue to perform under severe fire conditions, protecting both life and property.

Understanding the differences between the different flame ratings is critical for engineers, designers, and safety professionals. Selecting the appropriate flame-rated cable ensures compliance with regulatory standards and provides the necessary level of protection for specific environments, balancing performance, safety, and installation requirements. By choosing cables with the correct flame rating, the risk of fire propagation is significantly reduced, contributing to safer infrastructure and more resilient electrical systems.

5.2 Sunlight Resistance

Sunlight resistance, often referred to as UV resistance, is an important property of cable jackets that ensures long-term durability and safety in outdoor installations. Cables exposed to sunlight are subjected to ultraviolet (UV) radiation, which can break down polymer chains in the jacket material over time. This degradation can lead to cracking, brittleness, loss of flexibility, and ultimately, exposure of the conductors, which compromises both the mechanical integrity and electrical performance of the cable. Sunlight-resistant cables are specifically engineered to withstand these effects and maintain their protective qualities over extended periods.

The level of sunlight resistance required depends on the installation environment and expected exposure duration. Outdoor applications such as aerial cables, rooftop installations, open-air conduits, and exposed power or communication lines demand jackets that can resist UV-induced deterioration. Manufacturers often enhance the polymer formulation of cable jackets with stabilizers, additives, or pigments that absorb or block UV radiation, preventing chemical breakdown and extending the cable's service life. Materials such as polyethylene (PE), cross-linked polyethylene (XLPE), and specially formulated PVC are commonly used for sunlight-resistant jackets due to their inherent UV stability or their ability to be modified for outdoor durability.

In addition to protecting against UV damage, sunlight-resistant jackets also help maintain other critical properties, such as flexibility, tensile strength, and resistance to cracking. This is especially important in regions with high solar intensity or extreme temperature variations, where unprotected cables are more likely to experience accelerated wear. Cables designed for sunlight resistance ensure that mechanical and electrical performance is preserved, reducing maintenance requirements and minimizing the risk of failures due to environmental exposure.

Sunlight resistance is often specified alongside other environmental ratings, such as water resistance, chemical resistance, or flame retardancy, to provide a comprehensive protection profile for cables used in harsh outdoor conditions. For instance, underground, direct-buried, or industrial outdoor cables often combine UV resistance with water-blocking features and chemical protection, ensuring reliability under multiple stress factors simultaneously. Selecting sunlight-resistant cables is a critical consideration for engineers, designers, and safety professionals, as it directly affects the lifespan, safety, and overall performance of the electrical or communication system.

5.3 Cold Temperature Ratings

Cold temperature ratings are a critical specification for cables that ensures reliable performance in low-temperature environments. Cables installed in cold climates, outdoor winter conditions, refrigerated facilities, or high-altitude locations can be exposed to temperatures well below freezing. At these temperatures, many materials can become brittle, crack, or lose flexibility, which may lead to mechanical failure or compromised electrical performance. Common low-temperature ratings for cables include -25°C and -40°C, indicating the minimum temperatures at which the cable can operate safely while maintaining its mechanical and electrical integrity.

The performance of a cable at low temperatures depends largely on the properties of its jacket and insulation materials. Materials such as cross-linked polyethylene (XLPE), low-temperature PVC, and specially formulated thermoplastics are commonly used in cold-rated cables because they maintain flexibility and toughness even at sub-zero temperatures. The insulation and jacket must resist cracking, tearing, or deformation during handling, installation, or operation, which is especially important when cables are bent or coiled in freezing conditions. Maintaining flexibility also ensures that the cable can accommodate thermal contraction and expansion without stress-induced damage.

Cables installed at very low temperatures require careful handling and specific precautions to avoid damage. It is recommended to store the cable at room temperature for at least 24 hours before installation to allow the materials to regain flexibility. During installation, bending and pulling the cable should be performed more slowly and carefully than under normal conditions to prevent cracking or other mechanical damage. These precautions are essential to ensure that the cable maintains its integrity and continues to perform reliably in cold environments.

Cold temperature ratings are particularly important in applications such as outdoor power distribution, underground cabling in cold regions, marine environments, and industrial settings where refrigerated or cryogenic processes are involved. Engineers and designers must carefully consider the minimum operating temperature of the cable to ensure safe and reliable operation throughout its service life. Improperly rated or mishandled cables can experience insulation failure, conductor exposure, or mechanical damage, leading to outages, safety hazards, and costly repairs.

By selecting cables with appropriate cold temperature ratings and following proper handling procedures, designers and installers can ensure reliable operation in freezing conditions, minimizing the risk of mechanical failure, insulation breakdown, and electrical faults. These ratings and installation practices are essential for designing resilient electrical and communication systems in environments where low temperatures are a significant operational factor.

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