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Presented by :

KARIMA HEROUINI OMAR BENALIA

Theme:

Thermal effects in underground power cable

Submitted to the jury composed of :

Mr Rouibah Tahar	MCB	President	UKM Ouargla
Mr Ayad Ahmed Nour ElIslam	MCA	Supervisor	UKM Ouargla
Mm Benbouza Naima	MCB	Examiner	UKM Ouargla

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بسم الله الرحمن الرحيم

Thanks

First, we thank Almighty God who has enlightened us on our path and given us the strength to do this work.

First of all, we warmly thank my mothers and fathers who gave us all the tools and conditions for success. Motivation, confidence, education and expense throughout our academic career.

We would like to warmly thank Mr. ***Ayad Ahmed Noor El Islam*** *our rapporteur who has made enormous efforts, with his information, advice, availability and human quality.*

We also thank all my professors at Kasdi Merbah University for all their efforts, information and training

Dedication

I dedicate this humble work to my father, my mother and my brothers

For all my family

To all my dear friends

Especially my friend Nariman

To all electrical engineering teachers and electricians

To all those who supported me during my academic career

karima

Dedication

I dedicate this humble act to all my family

To my dear friends

To all electrical engineering students, to all electrical engineering teachers, and to all electrical workers

For all employees of Kasdi Merbah University

OMAR

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List of symbols

Δt is the temperature rise in the cable

W_d is the dielectric losses

θa is the ambient temperature

I is the load current

R_{ac} is the AC electrical resistance of the conductor

T_1 is the thermal resistance of the insulation

T_2 is the thermal resistance of the shield/sheath

T_3 is the thermal resistance of the jacket

T_4 is the thermal resistance between cable surface and ambient

λ the Loss factor of screen

n is the number of cables

$tan\delta$ the dissipation factor

U_0 the voltage to earth

C the capacitance of the cable

ε the relative permittivity of the insulation

Di the external diameter of the insulation (excluding screen)

ρ electrical resistivity of metal in ohm/m

A cross-sectional area of metal

X_{sl} the reactance per unit length of the sheath or screen per unit length of cable

s the distance between conductor axes

R_{sl} resistance of the screen per unit length of cable at its maximum operating

θsc the cable screen operating temperature (°C)

ρi the thermal resistivity of material

Dc the diameter over conductor

Ti insulation thickness

D_{oi} diameter over insulation

t3 thickness of jacket

D'oj outer diameter of the jacket

D'ij internal diameter of the jacket

$\theta_{c,(I,t)}$ conductor temperature as a function of time and load current

$\theta_{ins,(I,t)}$ insulation temperature as a function of time and load current

$\theta_{jac,(I,t)}$ jacket temperature as a function of time and load current

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General Introduction

General Introduction

The transport modernization of electrical transmission grid and the electrical the design and operation improvement of underground power cable systems has attracted widespread scientific research and attention. The underground electricity transmission lines operate at the maximum possible transmitted electric current.

The electricity transmission losses, in the form of generated heat, depend on the cable core electric resistance, distance, current nature, health of cable and insulation and transmitted electrical current or load variation.

Heat dissipation in the electricity transmission lines depend on several parameters as: the surrounding soil, current waveform magnitude frequencies, life time of conductor, insulation or electric and mechanic defaults.

The current overload and defaults plays a crucial role on life time and insulation of different parts of conductor and the electricity transmission lines for power systems.[1]

The research is divided into three parts:

The first chapter give the initiation and characteristics of the underground electric power cable , structures and components of different layers and parts, the consequences of thermal effect on the underground cable.

The second chapter: shows the mathematical model of thermal effect of underground cable based on the ampacity and the losses of equivalent model.

The last chapter: is dedicated to the model execution on the simulation software, the simulation results show the temperature variation in jacket , insulation and conductor as function of time and current fault and overload variation.

Chapter I

Underground electric power cables

I.1 Interdiction:

The main modes of transporting electrical energy are the overhead transmission, and the others are the underground and submarine transmission. The overhead transmission uses wires while underground uses cables. Underground transmission lines are a common way of energy transportation at middle and high voltage levels, because higher energy demands. Underground cables have been widely applied in power networks due to more secure in bad weather (by storms or lightning), less expensive for shorter distance, environment-friendly and low maintenance.

There are several faults in underground cables, incipient and permanent faults are gradually resulted from the aging process, electrical overstress, mechanical deficiency, unfavorable environmental condition and chemical pollution, can cause the damages in insulation.[2]

Therefore, we find that there are many types that can be classified on different grounds, such as operating voltage, conductor type, insulator type, or the number of cores in a single cable, and they can also be classified according to their field of use.

Figure I.1. Underground Power Cables.

I.2.Advantages of underground cables:

There are several advantages that are associated with the laying of specific types of cables under the ground for purposes of transmitting electricity. The following is a brief outline of these advantages.

•Compared to overhead cables, underground cables are much safer. This is because underground electrical cables are not exposed to the many dangers that head power cables are exposed to.

•It is cheaper to maintain underground cables over the course of time as compared to overhead ones. In practice, the cost of installing underground cables far exceeds what is associated with the installation of overhead ones. But once the underground cables have been installed, it is highly unlikely that will have to be repaired every now and then as it is the case with overhead electrical cable types.

•Underground transmission of electricity is associated with reliability. This is because instances of constant disruption in the supply of power as a result of storms or faults that are associated with overhead transmission lines are not common when power transmission lines are laid underground.[3]

I.3.Disadvantages of Underground Power Cables:

The disadvantages of Underground Cables include:

•Laying of cables requires excavation which might be difficult in congested areas.

•Modifications to existing cable network is laborious as it requires completely new excavation.

•Susceptible to damage due to underground water and moisture in the soil.

•Heat dissipation is less effective.

•As underground cables are thicker than overhead cables, the cost involved is high.[4]

I.4.Maintenance costs:

The following factors determine the overall costs that can be incurred in the process of maintaining underground electric transmission cables.

•It is practically difficult to detect a fault in an underground electric transmission line and address the problem. Therefore, the need for more advanced techniques in detecting and fixing faults in underground cables contributes to the overall costs of maintaining underground power transmission lines.

•It is also difficult to upgrade an underground cable. Regardless of the specific types of cables and system used, upgrading underground lines simply means the installation of new supply lines. Hence, this factor contributes to the overall costs that are incurred in the process of maintaining underground cables.[3]

I.5.Use of Underground Cables:

There are several issues that are usually taken into consideration in relation to the use of underground cables.

1.The first one is the actual manner in which the cables are laid underground. In practice, there are three main methods that are used: placing the cables in concrete-reinforced troughs, directly burying the cables and placing these in underground tunnels. The choice of any of these methods is usually based on the geographical features of the area in which the grounding is supposed to be done.

2.The second issue is related to the actual type of cables that are used in the process. There are different types of cables that can be laid underground and used to transmit electricity. What is important to note is that the choice of the cables is largely determined by the type of installation that has to be done. For example, plastic cables, also known as XLPE and fluid-insulated cables are used when only a small portion of the transmission line has to be put underground. On the other hand, HVDC cables are regarded as heavy-duty underground cable types and they are used for main transmission lines.[3]

I.6.Architecture of Underground Cabling System:

Underground Cabling System consists of various components like temperature condition monitoring systems, Earthing and Bonding systems, Cable Joints, Junction boxes, above the Ground Termination Points etc. Figure I.2 below shows a typical Underground Power Cabling system.

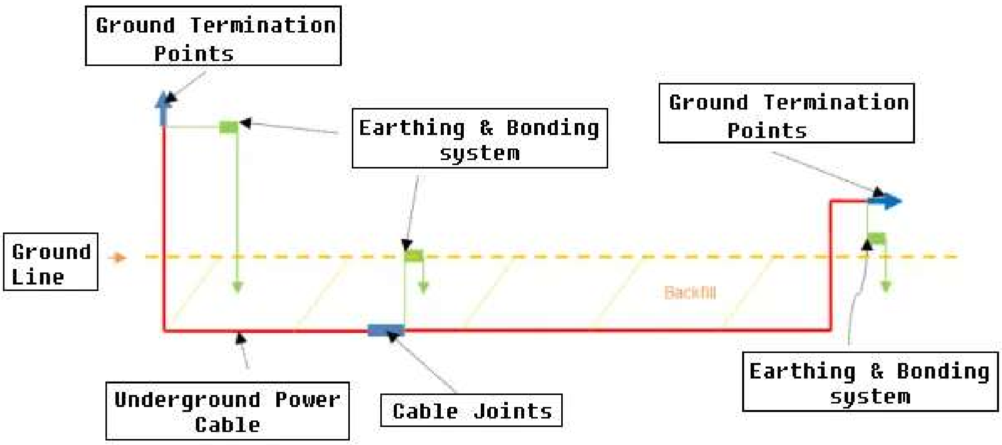


Figure I.2.Underground Power Cable System.[4]

I.7.Structural Components of Underground Power Cables:

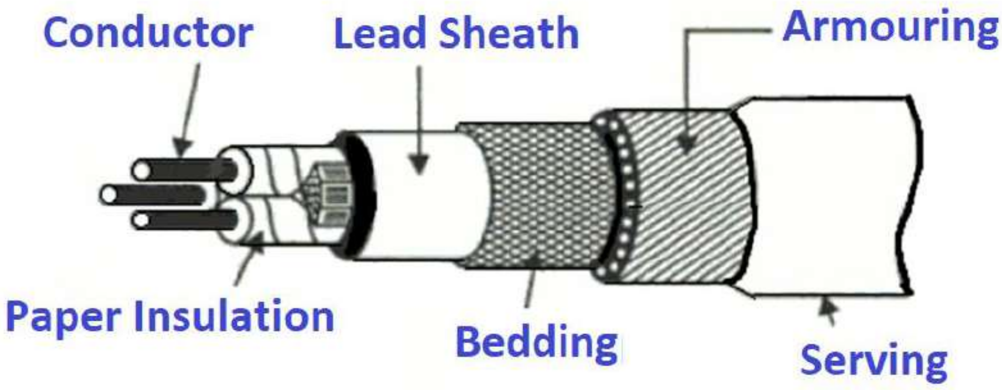


Figure I.3. Structural Components of Underground Power Cables.[5]

1. Conductor: The conductor is the part of the cable that carries the current. It is the most important layer in the cable. This conductor consists of annealed copper or hard aluminum stranded wires; there are classified into three major types: concentric, compacted circular and segmental compacted circular see Figure.I.2. The concentric design is when the wires are wound up concentrically; the compacted circular conductor consists of segments wound up and then compacted. Normally the segmental compacted circular conductor has four segments to prevent the increase of A.C. resistance caused by skin effect when the conductors cross-sectional is less than 630 mm2; the compacted circular is applied.

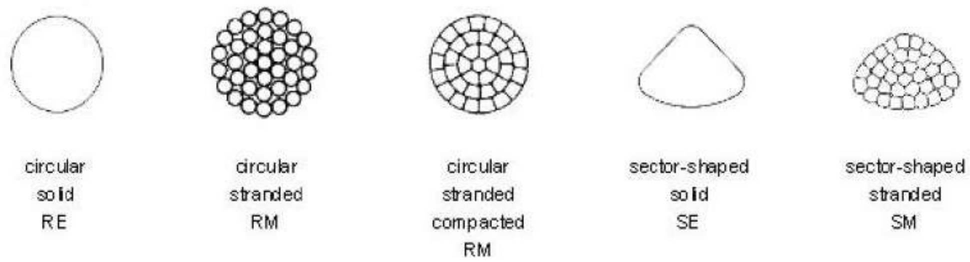


Figure I.4. Conductor construction.[6]

2.Paper Insulation: A layer of separation between the cable conductor at high voltage and bedding at ground potential.

3. Bedding: It acts as a protective barrier between inner and outer layers of the power cable.

4. Armouring: It provides mechanical resistance and protection of the cable-core. It can withstand higher stresses. The armouring is generally used as "earth wire" for the equipment supplied through cable.

5. Outer Sheath: This layer protects the inner metallic sheath and acts as insulator to with-stand induced and transient voltages.[4]

I.8.Classification of Underground Cables:

Cables for underground service may be classified in two ways according to(1) the type of insulating material used in their manufacture (2) the voltage for which they are manufactured.

I.8.1. By Construction:

1.Belted cables: the maximum voltage is 11KVA. Inside has usually three conductors that are clustered together and then joined by an insulating paper belt that is impregnated with a suitable dielectric. The gaps between the conductors and the belt are filled with fibrous dielectric materials. If there's one notable characteristic, that is the shape is not a perfect circle to take advantage of the available space. However, it is not ideal for voltage level above 11KV because the dielectric strength falls after a few years.

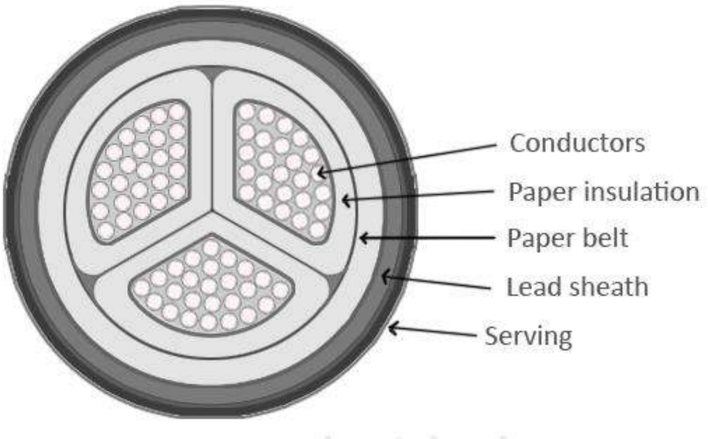


Figure I.5. Belted cables.[7]

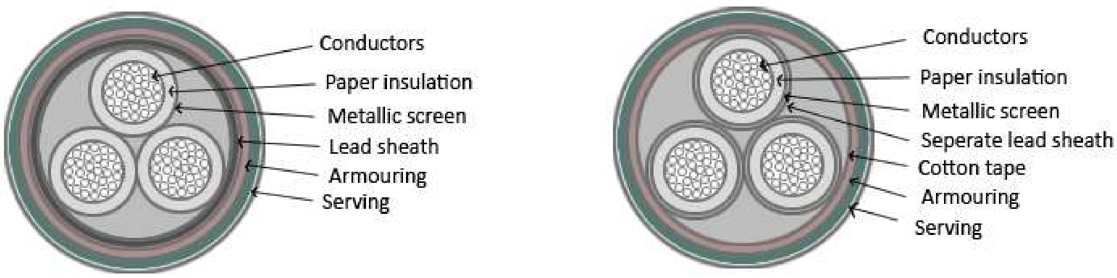
2.Screened cables: the maximum voltage is 66 KVA. This type if divided by two types of cable– H-Type Cables and SL-Type Cables.

•**H-Type Cables**: It was first designed by M. Hochstadter. The three cores are individually insulated with paper and then covered by a metallic screen / cover. These metallic covers are perforated. As a result, such construction allows the three metallic screens to touch each other. These three metallic covers are then grouped together in a metallic tape usually made of copper. A lead sheath surrounds this construction. The metallic covers and the sheath are grounded.

The obvious advantage is the electric stresses are radial, not tangential and hence of lesser magnitudes. Also, the metallic covers improve the heat dissipation.

•**S.L Type Cables**: It is similar to the H type cables, with the difference that each of the three cores has its own lead sheath. With this provision, the need for the overall sheath used previously is eliminated. The advantage of such a construction is that the chances of a core-to-core breakdown are greatly minimized. Also, the flexibility of the cable is improved.

The limitations are severe. Such construction is limited for voltages up to 66kV only. The individual sheaths are thinner, and if there are constructional defects, moisture may enter the cable and reduce its dielectric strength.[7]



H-Type Cable SL-Type Cable

Figure I.6. H and SL –Type Cable.[7]

Advantages of H-type cables:

•Metallic screens improve the heat dissipation of the cable.

•No formation of air pockets and voids in the dielectric, hence a high breakdown strength and less dielectric losses.

Disadvantages H-type cables: the cables are only suitable for low and medium voltages of up to 33KV, but can reach 66KVA at times.

Advantages of S.L type Screened cables:

•The use of separate sheaths reduces chances of core-to-core breakdown.

•Easy to bend the cable.

Disadvantages of S.L type Screened cables:

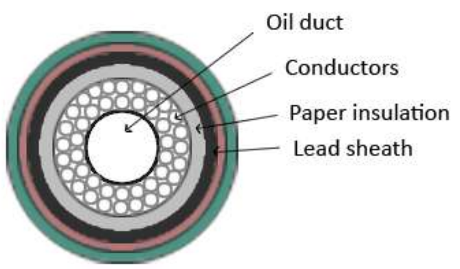
•Thinner lead sheaths are used hence need for greater care in manufacturing and handling.

•Only suitable for low and medium voltages of up to 33KV.[8]

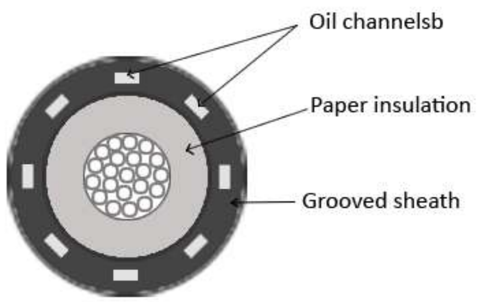
3.Pressure cables: For voltages beyond 66 kV, the electrostatic stresses in the cables exceed the acceptable values and solid cables become unreliable. This occurs mainly because voids are created when voltages exceed 66 kV. Hence, instead of solid cables, we use Pressure cables. Typically, such cables are either oil filled or gas filled.

•**Oil Filled Cables**: Oil is circulated under suitable pressure through ducts provided for such purpose. This oil supply and pressure are maintained through reservoirs kept at proper distances. The oil used is the same that is employed for impregnation of paper insulators.

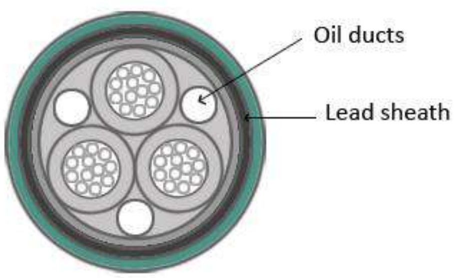
•**Gas Filled Cables**: Pressurized gas (usually dry nitrogen) is circulated around cables in an air-tight steel pipe. Such cables are cable of carrying higher values of load current and can operate at higher values of voltage. But the overall cost is more.



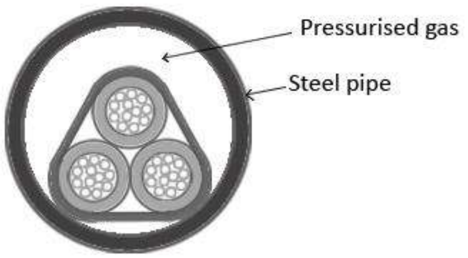
Single core conductor channel oil filled cable



Single core sheath channel oil filled cable



Three core oil filled cable



Three core gas pressure cable

Figure I.7. type of Pressure cables.[7]

I.8.2. By Voltage:

•Low-tension cables – maximum capacity of 1000 V (1KV). It is most widely used among all cables, applied frequently in electric power distribution and control cables that carry signals from electrical devices or switch gears to control room.

•High-tension cables – maximum of 11KV. Commonly used for electric power transmission at high voltage, it may be for underground or underwater. It helps in the reduction of power loss.

•Super-tension cables – rating of between 22 KV and 33 KV. This uses low viscosity oils for impregnation.

•Extra high-tension cables – rating of between 33 KV and 66 KV.

•Extra super voltage cables – maximum voltage ratings beyond 132 KV.[5]

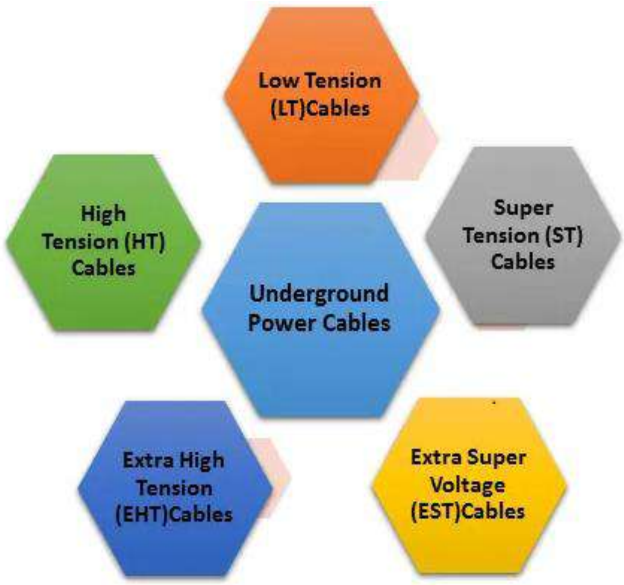


Figure I.8. Types of Underground Power Cables.[4]

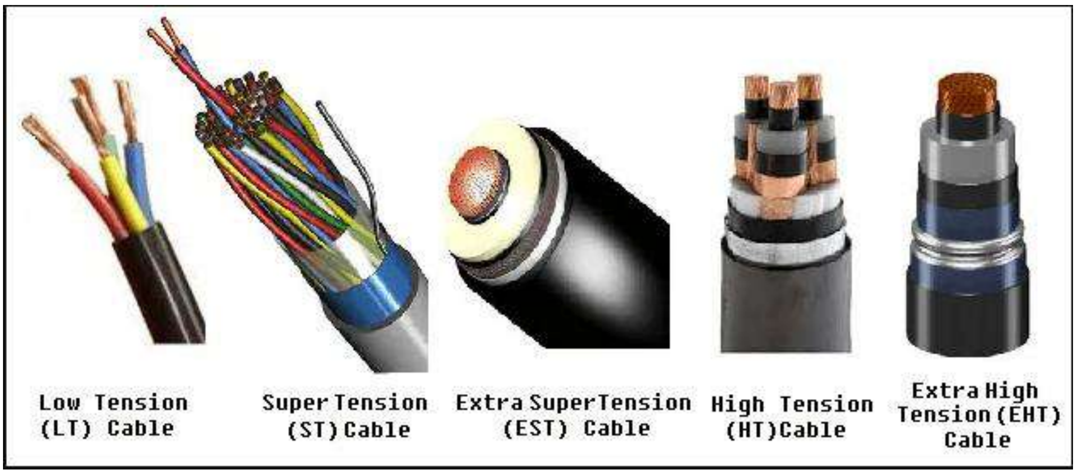


Figure I.9. Underground Power Cables Available in Market.[4]

I.9. Classifications Underground Cable According to Their Core:

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be:

1.Single-core
2.Two-core
3.Three-core
4.Four-core

Underground cable which are used is depending upon the:

1. Operating voltage

2. Load demand.

3. Type of service

I.10.Underground Power Cables On their Service:

Types of Underground Power Cable service may be classified in two ways according to:

1.The type of insulating material used in their manufacture.

2.The voltage for which they are manufactured.

I.11.Classification Based Upon Insulation of The Cable:

Various insulating materials used in cable construction are Rubber, Paper, PVC, XLPE (Cross linked Polyethene) etc. Such classification is based upon operating temperature limitations. Following are some insulating materials used and their maximum operating temperatures.

Insulation material	Max. operating temperature
PVC TYPE A	75°C
PVC TYPE B	85°C
PVC TYPE C	85°C
XLPE	90°C
RUBBER	90°C
RUBBER -EPR IE-2, EPR IE-3, EPR IE-4, SILICON	150°C

Table I.1.some insulating materials used and their maximum operating temperatures.[7]

I.12.Classification Based Upon Installation and Laying of The Cable:

•**Direct Buried**: As the name suggests, the conductors are buried underground in a trench without additional accessories. Sometimes cooling pipes are added if required. Once the cables are installed, there's no visible sign above the ground.

•**Trough**: Concrete troughs are dug and cables are installed in them. They're visible on the surface. Maintenance is easier.

•**Tunnels**: Sometimes, tunnels are dug up for this purpose. Such construction is mainly employed if a river needs to be crossed or if the intended power distribution is to a major city. Maintenance and future expansion is easier, but initial cost is higher.

•**Gas Insulated Lines**: This is a relatively new technology. For cables operating at higher voltages and currents, and handling high power, such gas insulated line construction is safer. It is being employed nowadays for advanced projects.[7]

I.13. Types of Underground cables:

I.13.1.LT Underground cables:

Low tension cables are used for voltage levels up to 1 KV .The electrostatic stresses in LT cable are not dangerous, hence no special construction is used for this cable .The paper is used as an insulation in these LT cables. Sometimes resin is also used which improves the viscosity and helps to prevent drainage.

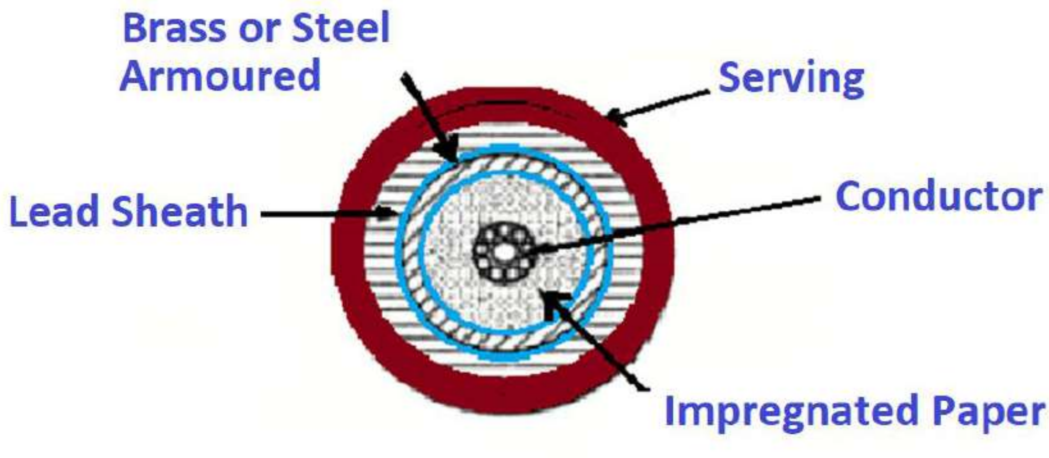


Figure I.10.LT Underground cables. [5]

I.13.2.HT Underground cables:

The primary functions of transmission HV cables are to transfer electrical power between designated locations, within prescribed performance, operating and environmental conditions and to insulate energised components from earthed structures at rated operating voltages and specified switching and lightning impulses.

Secondary functions of transmission HV cables are to:

a) Maintain electrical safety and minimise adverse effects on the environment; and

b) Provide a whole-of-life cost-effective service

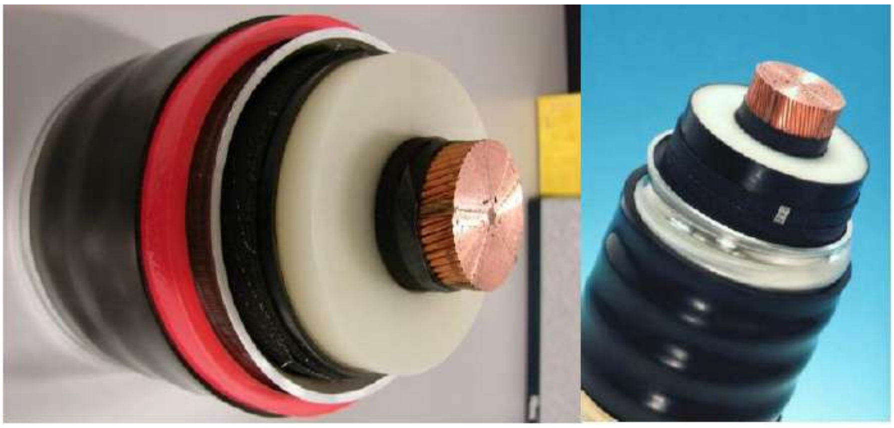


Figure I.11. Typical HV XLPE Insulated Power Cables. [9]

The major components of an underground HV Cable system include:

□ Above ground terminations (either GIS or AIS).

□Buried HV cable and joints.

□Earthing and bonding system to manage safety and minimise losses.

□Monitoring system components (for cable temperature monitoring and joint PD measurements).

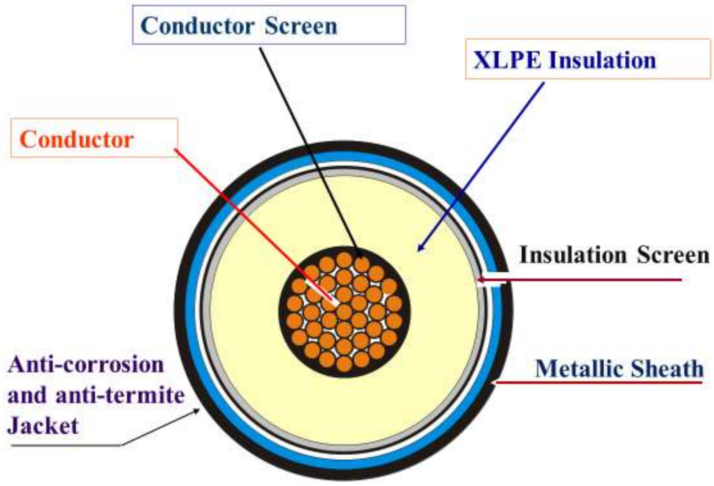


Figure I.12.HV Power Cable Components. [9]

The functions of particular cable components are as follows:

□ Conductor: transport electric current.

□ Conductor screen: provide for uniform electric field in cable insulation.

□XLPE insulation: electrical separation between the cable conductor at high voltage and cable sheath at ground potential.

□ Insulation screen: containment of electric field.

□ Metallic sheath: water barrier and mechanical protection of cable-core. Provide for the flow of fault currents.

□Anti-corrosion and anti-termites jackets: Protect cable metallic sheath and insulate the sheath to withstand induced and transient voltages.[9]

I.13.2.1. XLPE Cable:

Cross-linked Polyethylene, also denoted as XLPE, is an insulating material that is created through both heat and high pressure. The first cross-linking methods emerged in the 1930s . In general, polyethylene has some excellent electrical properties, with its low dielectric losses it is a suitable insulating material for high voltage. The construction of an XLPE cable is explained below.

A typical XLPE Cable is constructed as shown in Figure 1 (a) of a conductor either (copper or aluminum), insulated with the cross-linked polyethylene (XLPE), shield wires, and then shielded with metallic screen (corrugated and seamless aluminum or copper wires with open helix copper tape as a binder). Then it is covered with PVC or polyethylene for anticorrosion (HDPE, LLDPE, MDPE).

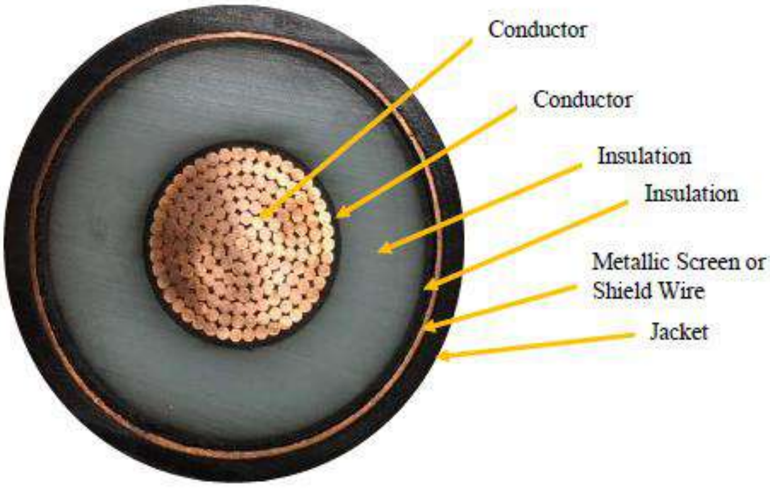


Figure.I.13. XLPE Cable layers.[6]

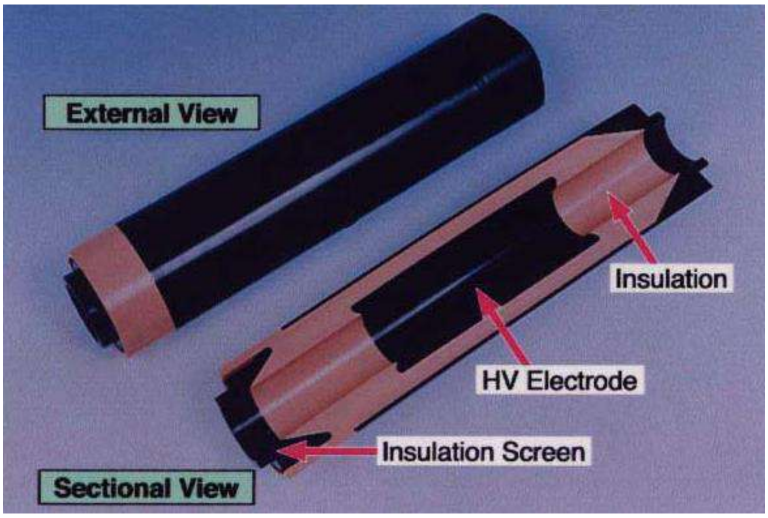


Figure I.14. Joint for XLPE Cable – Joint Insulation Mould Assembly [9]

I.13.3. Extra high-tension cables:

Underground extra-high voltage cables generally have more efficient copper conductors and operate at lower temperatures than overhead lines. These properties combine to transmit energy to end users as efficiently as possible, which is especially important for remote renewable and low carbon generators. Reducing these power transmission losses makes a valuable contribution to lowering greenhouse gas emissions.[9]

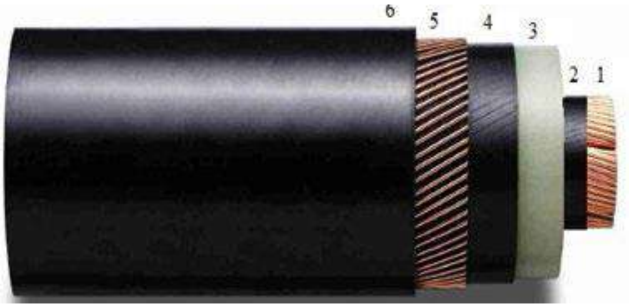


Figure I.15. Constitution of an underground cable insulated with reticulated polyethylene.[10]

(1) conductive core.

(2) internal semiconductor layer.

(3) cross-linked polyethylene insulation.

(4) outer semiconductor layer.

(5) driver's screen.

(6) PVC protection.

I.14. Methods of planting:

In addition to the electrical and thermal aspects of cable design, it is essential to take into account the mechanical and thermo mechanical stresses that the cable system will be subjected to during installation and service.[10] The channel is selected according to the external influences of the room, see Figure. I.16 and Table I.2.

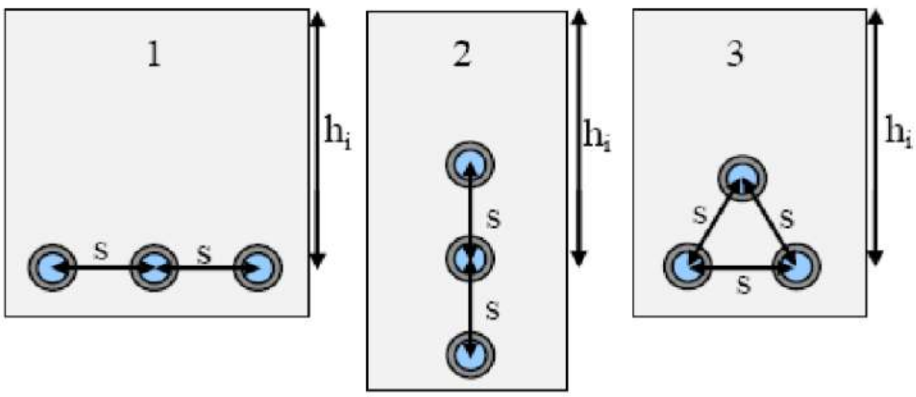


Figure I.16.different geometric configurations for the three-phase underground.

(1) horizontal, (2) vertical, (3) triangular. [10]

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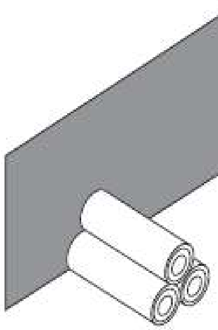
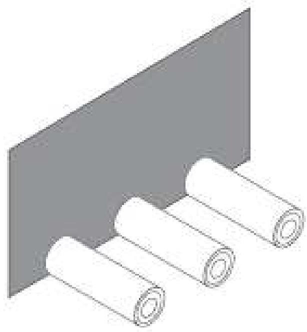
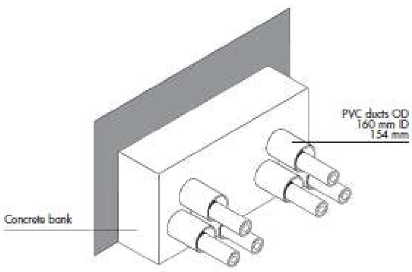
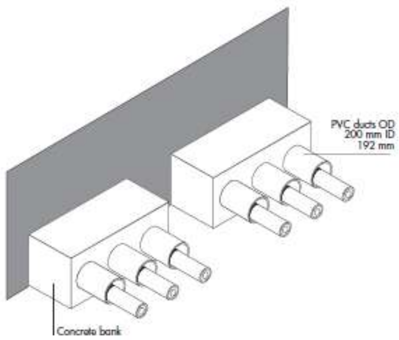
<tr><td></td><td></td><td></td></tr>
<tr><td>Cables buried directly in trefoil formation</td><td>Cables directly buried in flat formation</td><td>Cables in the air inside a gallery in touching trefoil formation</td></tr>
<tr><td>
</td><td>
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<tr><td>Cables buried inside ducts in trefoil formation</td><td>Cables buried flat in ducts</td><td>Cables laid flat in the air inside a gallery</td></tr>
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Table I.2. Methods of planting underground cables.[11]

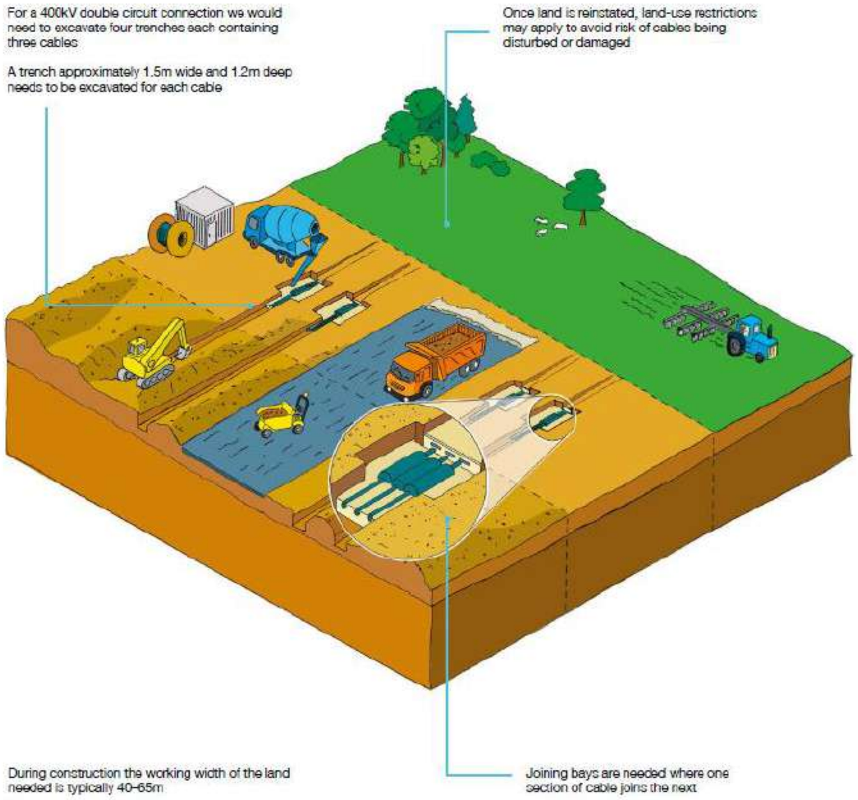


Figure I.17. Direct Buried Cable Installation.[12]

I.15.Faults in Underground Cables:

Most of the faults occur when moisture enters the insulation. The paper insulation provided inside the cable is hygroscopic in nature. Other causes include mechanical injury during transportation, laying process or due to various stresses encountered by the cable during its working life. The lead sheath is also damaged frequently, usually due to the actions of atmospheric agents, soil and water or sometimes due to the mechanical damage and crystallization of lead through vibration. The faults occurring in cables are:[13]

I.15.1. Open Circuit Fault:

As the name suggests, this fault involves an open circuit in the conductors. When one or more cable conductors (cores) break, it leads to discontinuity. This discontinuity also occurs when the cable comes out of its joint due to mechanical stress. This is known as Open circuit fault.

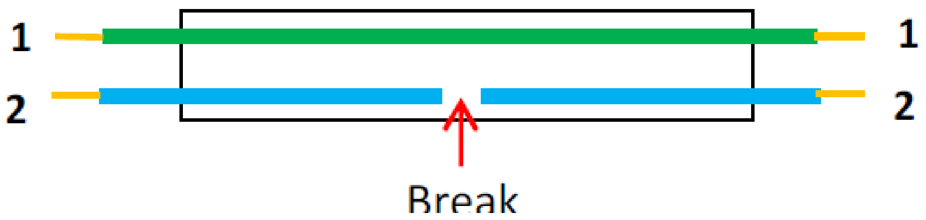


Figure I.18. Open Circuit Fault.[14]

I.15.2. Short Circuit Fault:

When two or more conductors of a multi-core cable come in contact with each other, then this is called a short circuit fault. A short circuit fault occurs when the individual insulation of the conductor core is damaged.

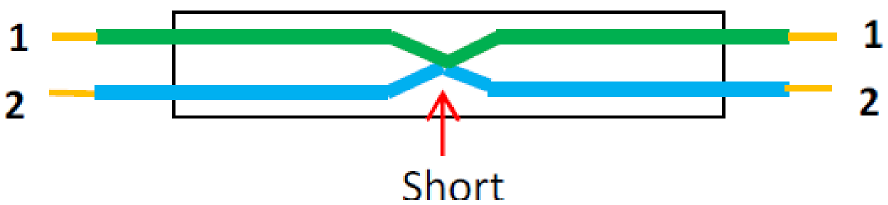


Figure I.19. Short Circuit Fault.[14]

I.15.3. Earth Fault:

When any of the conductors of the cable comes in contact with the earth, it is called an earth fault. This type of fault allows the current, carried by the conductor to leak to the earth directly or indirectly instead of going to the apparatus to which the conductor is connected. This usually occurs when the outer sheath is damaged due to chemical reactions with soil or due to vibrations and mechanical crystallization.

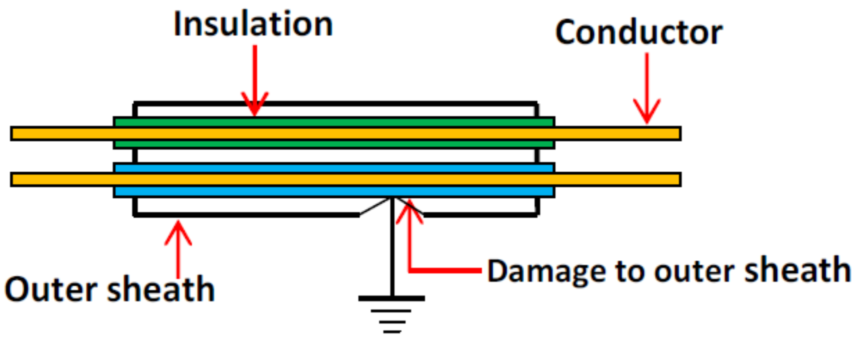


Figure I.20. Short Circuit Fault.[14]

I.16.monitoring devices for thermal cells:

Temperature might be a warning indicator of a cable problem. Therefore, by employing heat sensors of various kinds, we may detect problems before they get out of control.

I.16.1.The temperature sensor:

The temperature sensor is divided into two parts:

I.16.1.1 The Thermocouple Sensor:

Thermocouple is a common temperature measuring element used in industrial temperature testing instruments. It directly measures the temperature and converts the temperature signal into thermoelectric electromotive force signal, which is converted into the temperature of the measured medium by electrical instrument (secondary instrument). Thermocouple is widely used. It has many advantages such as simple structure, convenient manufacture, wide measuring range, high accuracy, small inertia and easy remote transmission of output signal. In addition, because the thermocouple is a passive sensor, the measurement does not need external power supply, which is very convenient to use, and it is often used to measure the temperature of gas or liquid in the furnace, pipeline and the surface temperature of solid.[15]

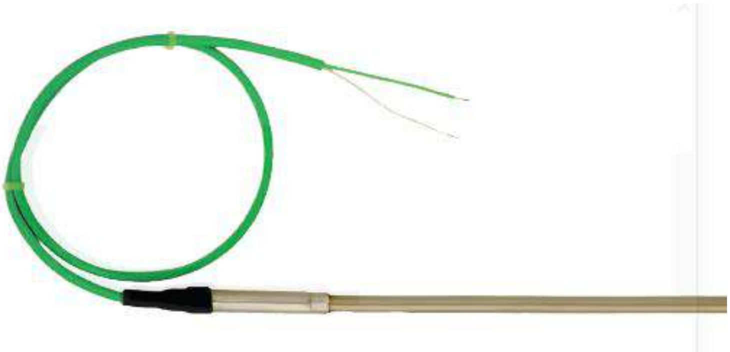


Figure I.21. The Thermocouple Sensor.[16]

I.16.1.2. The RTD Sensor:

RTD (Resistance Temperature Detector) is one of the most commonly used temperature detectors in low - and medium-temperature zones. The temperature measurement of RTD is based on the property that the resistance of a metal conductor increases with the increase of temperature. Its main characteristics are high measurement accuracy and stable performance. Platinum thermal resistance is the most accurate measurement, which is not only widely used in industrial temperature measurement, but also made into a standard reference instrument.[15]

Figure I.22. The RTD Sensor.

I.16.2. Infrared cameras:

An infrared camera (or thermal camera) is a camera which records the various infrared radiations (heat waves) emitted by the body and which vary according to their temperature.[17]

Figure I.23. Infrared cameras.

I.17.Underground cables with Burning faults torn cut:

Almost all utilities and large industrial facilities have extensive systems of power cables. Many of these cable systems are ageing and failures are becoming common. Finding the root cause of cable failures can lead to better maintenance practices and produce more reliable operation in the future. This in turn will lead to lower operating costs.

as an example, Another type of failure is evidenced by signs of burning or arcing on the surface of the semicon. If the burning or arcing becomes extensive, the cable can fail from the outside in, as seen in Figure I.24. The cause was determined to be a damaged jacket, which led to corrosive ground water entering the cable and causing severe corrosion of the metallic shield.[18]

FigureI.24. Cable failing from the outside in [18]

FigureI.25. Damaged 138 kV XLPE cable.[19]

I.18.Thermal effects of underground cable:

The variation in the mother ground thermal conductivity changes the intensity of the heat transfer from power cables. The larger the conductivity, the faster the soil receives the heat, and thus also lowers the temperature of the cable conductor. The soil thermal conductivity changes due to the decrease / increase of the water content (e.g. caused by rains or droughts). The lower the moisture. content, the lower the soil thermal conductivity. Therefore, it may happen that the thermal calculations performed for moist soil that meets the security requirements do not satisfy them when the soil is dry Figure I.18 presents the variation of cable core temperature with the increase in the mother ground thermal conductivity from 0.5 W / (m K) to 1 W / (m K). It is assumed that the cables are placed in thermal backfill (Fluidized Thermal Backfill) with a thermal conductivity of 1.54 W / (m K).

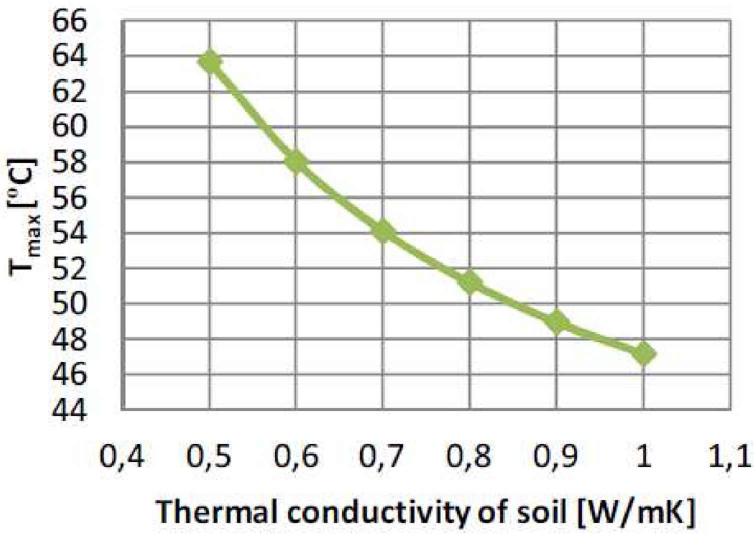


Figure I.26. Soil thermal conductivity effect on temperature distribution in underground power cable system.

Based on Figure I.18, the following can be concluded:

-The thermal conductivity of soil and backfill play an important role in cable line design.

-The higher the thermal conductivity of the soil, the lower the temperature of the cable conductor.[20]

I.19.Conclusion:

The purpose of this chapter is to provide an overview of the classification. The design, composition and engineering of underground electrical cables. The benefits and drawbacks of these cables are discussed. Finally, we discussed some electrical cable issues and malfunctions. Underground, for example, an open circuit fault, A short circuit has occurred Faults in the earth.

Chapter II

Thermal model of underground electric power cables

II.1 Introduction:

The cable ampacity rating is the current-carrying capacity of a cable, it's one of the most important concepts parameters for the underground cable: in steady state, transient (or emergency) and short-circuit cases (standards and norms of IEEE & IEC)[21-29].

In this chapter, we will simulate the steady state ampacity ratings based on the approach to calculating the thermal effect ampacity based upon cable layers and construction.

The modification methods based their ampacity calculations on the following parameters:

• The current and cycle load.

• Conductor size, construction and material type (Copper and Aluminum).

• Dielectric loss and thermal resistances and capacitances of insulation conductor shields sheath, and mutual-heating effects of other cables and other heat sources.

The modification approach based on the thermal calculation of the electrical analogy circuit of a cable; it subdivides the cable into parts: heat sources, the thermal resistances and the thermal capacitances with equivalent electrical parameters following (IEC 60287 norm).

FigureII.1 shows the relationship between the electric cable components and equivalent thermal analogy circuit.

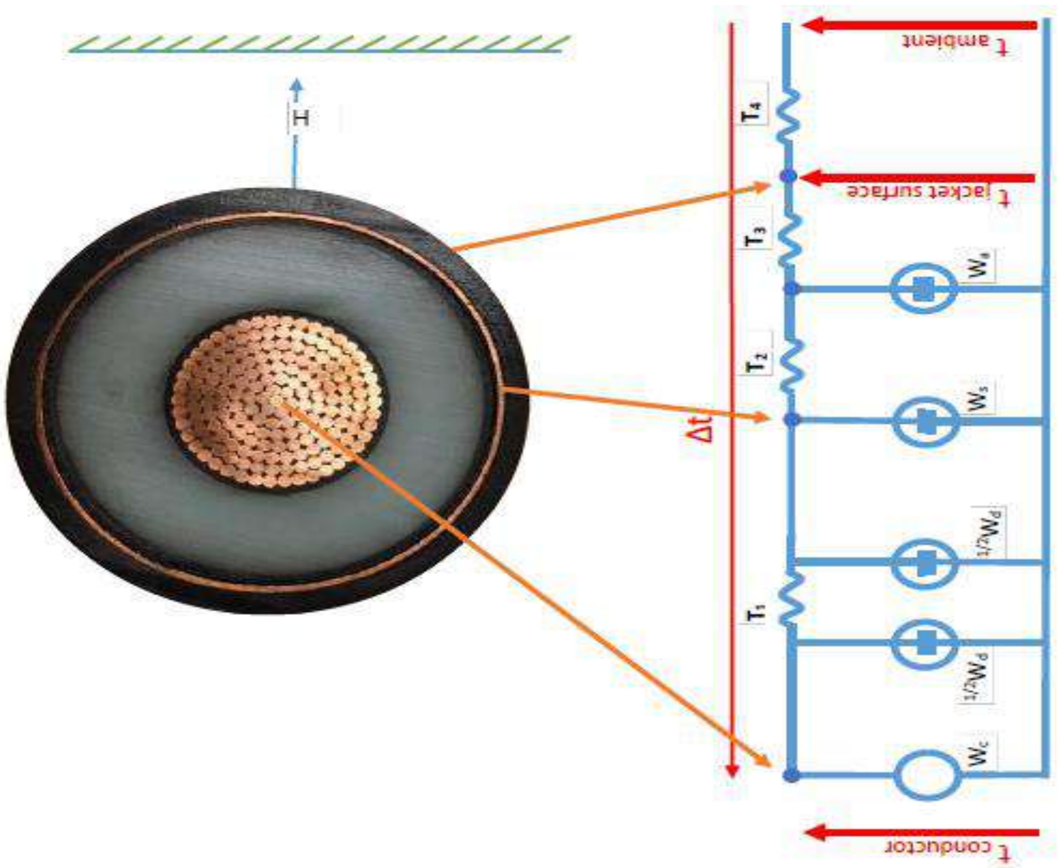


Figure II.1. Thermal equivalent circuit of underground Cable.[6]

II.2. Calculation principles:

The ampacity depend on the heat transfer problem in the conductor temperature dont not exceed the maximum allowable temperature of the insulation. The thermal effect is generated from ohmic losses in the conductor and the other components.

The ampacity depend on the electric circuit parts , every node in the circuit is analog to the temperature the boundary between the layers. The potential difference between the terminals pats of circuits and the innermost current source represents the temperature rise of the core (conductor) of the cable.

The calculation of underground electric cable ampacity depends on:

1. The cable construction and size, the installation ampacity requirements.

2. Manufacturer's limits for the maximum temperature for the insulation material as function of ambient earth temperature[6].

3. Calculate dielectric loss indifferent parts.

4. Calculate the electrical resistances of each current carrying component.

5. Calculate the thermal resistance of each component of the system.

6. Calculate the temperature rise.

7. Determine the ampacity that achieves the allowable temperature rise.

8. Calculated ampacity and make adjustments in conductor size and installation parameters, and repeat these steps as necessary to achieve the optimal ampacity [6].

$$\Delta_t = (W_c + .5W_d)T_1 + (W_c + W_d + W_s)nT_2 + (W_c + W_d + W_s + W_a)n(T_3 + T_4) \tag{1}$$

$$W_c = I^2 R_{ac} \tag{2}$$

$$W_d = \omega C U_o^2 \tan\delta \tag{3}$$

$$W_s = \lambda_1 W_c \tag{4}$$

$$W_a = \lambda_2 W_c \tag{5}$$

We substitute the equation 2 to 5 in 1

$$\Delta_t = \left(I^2 R_{ac} + .5W_d\right)T_1 + \left(I^2 R_{ac}(1+\lambda_1) + W_d\right)nT_2 + \left(I^2 R_{ac}(1+\lambda_1+\lambda_2) + W_d\right)n(T_3+T_4) \quad (6)$$

$$\Delta\theta = \theta_c - \theta_a \qquad \text{becom } \theta_c = \Delta\theta - \theta_a$$

$$I = \sqrt{\frac{\Delta\theta - W_d[0.5T_1 + n(T_2+T_3+T_4)]}{R_{ac}[T_1 + n(1+\lambda_1)T_2 + n(1+\lambda_1+\lambda_2)(T_3+T_4)]}} \quad (7)$$

Where:

Δt is the temperature rise in the cable.

W_d is the dielectric losses.

θa is the ambient temperature.

I is the load current.

R_{ac} is the AC electrical resistance of the conductor.

T_1 is the thermal resistance of the insulation.

T_2 is the thermal resistance of the shield/sheath.

T_3 is the thermal resistance of the jacket.

T_4 is the thermal resistance between cable surface and ambient.

λ is the Loss factor of screen.

n is the number of cables.

II.2.1. Calculation of Losses:

The electric components have heat properties and losses. The heat losses in the cable are due to the Ohmic losses and the dielectric losses due the cable capacitance. This section describes the losses in electrical cable and there affects to the ampacity at steady state.

II.2.1.1. Dielectric Losses:

A high voltage underground power cable is a large capacitor because the important transmission energy through the conductor, charge and discharge the capacitor at 50 Hz. Dielectric losses is relative to the distance and increase the radial heat generated in the cable, ultimately reducing typical ampacity[5]. The dielectric loss is express as:

$$W_d = \omega C U_o^2 \tan\delta \left[W/_m \right]$$

Where:

$$\omega = 2\pi f$$

$tan\delta$=the dissipation factor

U_0= the voltage to earth

C = the capacitance of the cable

$$C = \frac{\varepsilon}{18 ln^{Di}/_{dc}} 10^{-9} [F/_m] \quad (8)$$

Where:

ε= the relative permittivity of the insulation.

Di = the external diameter of the insulation (excluding screen).

[mm]; dc = the diameter of conductor, including screen [mm].

II.2.1.2. Alternative Current resistance of conductor:

The biggest energy losses in a power cable are the conductor and the shield wires losses, by flow of current through an electrical resistance. The AC resistance of cable consists of three components; DC resistance, the skin effect ,and the proximity effect. The DC resistance is expressed as a function of the cross-sectional area, length and the electrical resistivity of the material. It calculated per unit length of the cable as:

$$R_{dc20} = \frac{1.02\times10\text{^}6\times\rho 20}{A} [1 + \alpha_{20}(\theta - 20)][\Omega/_m] \quad (9)$$

Where:

ρ = electrical resistivity of metal in ohm/m at 20°C

For copper conductors, = 1.7241 x 10^{-8}

For aluminum conductors, = 2.8264 x 10^{-8}

A = cross-sectional area of metal in mm²

α20 = the temperature coefficient of the conductor material per K at 20oC.

For copper conductors, = 3.93 x 10^{3}

For aluminum conductors, = 4.03 x 10^{3}

θ =the conductor operating temperature (°C)

II.2.1.3. Loss factor for the screen (λ):

The loss factor for the screen according to IEC 60287-1-1 section 2.2 is defined as (λ1), this loss consists of the circulating current (λ1') and eddy current (λ1").

$$\lambda_1 = \lambda_1{}' + \lambda_1{}'' \qquad (10)$$

Where:

$$\lambda_1' = \frac{R_{sl}}{R_{ac}} \frac{1}{1+(\frac{R_{sl}}{Xsl})^2} \qquad (11)$$

$$X_{sl} = 2\omega.10^{-7} ln\frac{2s}{d} \qquad (12)$$

Where:

X_{sl} = the reactance per unit length of the sheath or screen per unit length of cable [Ω/m]

ω = 2πf [rad/s]

s = the distance between conductor axes in the electrical section being considered [mm]

d = the mean diameter of the sheath [mm]

$\lambda 1''$ = 0. The eddy-current loss is ignored according to IEC 60287-1-1 section 2.3.1

R_{sl} is the resistance of the screen per unit length of cable at its maximum operating Temperature[Ω/m].

$$R_{sl} = R_{so}[1 + \alpha_{20}(\theta_{sc} - 20)][\Omega/m]. \qquad (13)$$

Where:

R_{S0} is the resistance of the cable screen at 20 °C [Ω/m].

θsc = the cable screen operating temperature (°C)

II.2.2. Thermal Resistances:

The thermal resistance for the different cable components is expressed as follow.

II.2.2.1. Thermal resistance of the insulator:

The thermal resistance of the insulator is the thermal resistance between the conductor and the sheath is express as:

$$T_1 = 0.00522\rho_i G \quad \text{or} \quad T_1 = \frac{\rho_i}{2\pi}\ln\left(\frac{\mathrm{Doi}}{\mathrm{Dc}}\right) \quad [°C/w] \tag{14}$$

And,

$$G = \ln(D_c + 3T_i) - 0.86\ln(D_c) + 0.05 \tag{15}$$

Where:

G = the geometric factor according to IEC 60287

ρi = the thermal resistivity of insulation [*K.m/W*]

Dc = the diameter over conductor [mm]

Ti = the insulation thickness [mm]

D_{oi} = the diameter over insulation [mm]

II.2.2.2. Thermal resistance of the sheath T2:

The power cable in this investigation did not contain armour. However, it did have a sheath. Several studies have shown that metallic shields and sheaths, steel casings and pipes, and metallic conduits have negligible thermal resistances. Therefore, the thermal resistance of the metallic shield and sheaths is considered to be zero in the experiment.

$$T_2 = 0 \quad [°C/W] \tag{16}$$

II.2.2.3. Thermal resistance of the jacket T3:

The thermal resistance of the jacket is the resistance between the sheath and the cable surface.

$$T_3 = \frac{\rho_j}{2\pi}\ln\left(1 + \frac{2t3}{D'ij}\right) \quad \text{or} \quad T3 = \frac{\rho_j}{2\pi}\ln\left(1 + \frac{D'oj}{D'ij}\right) \quad [°C/W] \tag{17}$$

Where:

ρj = the thermal resistivity of jacket material [*K.m/W*].

t3 = the thickness of jacket [mm].

D'oj= the outer diameter of the jacket [mm].

D'ij = the internal diameter of the jacket [mm].

II.2.2.4. Thermal resistance of the surrounding T4:

The thermal resistance of a cable surrounding depends on where the cable is installed. If the cable is installed in a duct system, the thermal resistance of the surrounding consists of three parts. T'4, the thermal resistance of the air space between the cable surface and the duct's internal surface; T"4; the thermal resistance of the duct itself; and T"'4; the external thermal resistance of the duct.

$$T_4 = T_4{}' + T_4{}'' + T_4{}''' \tag{18}$$

II.2.2.4.1. Thermal resistance between cable surface and duct inner surface $T'4$:

$$T_4{}' = \frac{U}{1+0.1(V+Y\theta m)De} \quad [°C.m/W] \tag{19}$$

Where:

De = the external diameter of the cable [mm].

Θ_m = the mean temperature of the medium filling the space between cable and duct (air, or nitrogen gas, or dielectric liquid). An assumed value should be used initially and the calculation repeated with a modified value if necessary [°C].

II.2.2.4.2. Thermal resistance of the duct $T''4$:

$$T_4{}'' = \frac{\rho T}{2\pi}\ln(1+\frac{D_o}{D_d}) \tag{20}$$

Where:

D_o = the outside diameter of the duct [mm]

D_d= the inside diameter of the duct [mm]

ρT = the thermal resistivity of duct material [°Cm/W]

II.2.2.4.3. The external thermal resistance of the duct:

$$T_4{}''' = \frac{\rho T}{2\pi}\ln(\frac{4H}{D_o}) \tag{21}$$

Where:

ρ_T= the thermal resistivity of the soil see table 4 [°Cm/W].

D_0 = the outside diameter of the duct [mm].

H = the placement depth [mm].

In this investigation, the cable was in the air with a length of 15.25m. The thermal resistance of air in natural or free convection is:

$$T_{air} = \frac{1}{h \times A_{air}} \quad [°C/W]$$

h = heat transfer coefficient of air [10 w/m2oC]

L = Sample cable length 15.25m

$$A_{air} = \frac{L^2}{4\pi}$$

II.3.Transient Ampacity Analysis:

The transient ampacity analysis of an underground cable involves calculation of the cable response to arbitrary, impulsion dynamic excitations. Transient behavior, in general, is defined as a process' fast variables changes in time before it reaches its steady state, as a function of current and time variation with temperature.

In the transient analysis of a cable, the calculations take both the thermal resistance and capacitance of the different cable layers and its environment into consideration, while steady-state calculations ignore this thermal capacitance and consider only the thermal resistance.

The transient behavior of a cable can be analyzed based on the RC electrical network model consisting of a current source, resistors, and capacitors by an analytic exponential function which describes the temperature response of step-change in load.

$$\theta_{c,}(I,t) = \Delta\theta_c \left(1 - e^{-t/R_T C_T}\right) + \theta_{ci} \quad [\text{℃}]$$

The rise in temperature from equation six is given as

$$\Delta\theta_c = (I^2 R_{ac} + 5W_d)T_1 + [I^2 R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4)$$

Equation6 in 23

$$\theta_{c,(I,t)} = (I^2 R_{ac} + 5W_d)T_1 + [I^2 R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4)\left(1 - e^{-t/R_T C_T}\right) + \theta_{ci} (22)$$

Hence

$$\theta_{ins,(I,t)} = [\theta_c - (I^2R_{ac} + 5W_d)T_1]\left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [\,°C\,]$$

$$\theta_{ins,(I,t)} = [I^2R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4)\left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [°C\,] \qquad (23)$$

Hence

$$\theta_{jac,(I,t)} = [\theta_c - [I^2R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4)]\left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [\,°C\,]$$

$$\theta_{jac,(I,t)} = (I^2R_{ac} + 5W_d)T_1 \times \left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [\,°C\,] \qquad (24)$$

Where:

$\theta_{c,(I,t)}$=the conductor temperature as a function of time and load current

$\theta_{ins,(I,t)}$=the insulation temperature as a function of time and load current

$\theta_{jac,(I,t)}$=the jacket temperature as a function of time and load current

$\Delta\Theta_C$=the temperature rise in the cable

θ_{Ci}= initial conductor temperature

R_TC_T=cable time constant[minutes]

The thermal capacitances for each layer of the cable are the volume of the layer times the specific heat capacity and the density of the layer.Table**II.1**showsthespecificheatcapacityanddensityofsomecommon cable layers.

$C_T = V \times C_p \times \rho$

Layers		**heat capacity[J/kg.°C]**	**Density[kg/m³]**
Conductor	Copper	390	8900
	Aluminum		
XLPE		$2.4e^6$	922
PVC		$2.4e^6$	962

TableII.1. Specific heat capacity and density of some common cable layers.[6]

II.4.Conclusion:

Underground cable transport carrying capacity is limited due to the important heat effect with high temperature. These temperatures affect the insulation and life time of cable. This chapter presents a mathematical model to compute the temperature of the cable conductor, insulation, jacket with load current variation inputs. The model will be used in the next chapter, implement in Matlab software and use to verify these perform.

Chapter III

Simulation of thermal effect in underground cable in abnormal condition

III.1. Introduction:

Underground cables are used into electrical power transmission and distribution systems to transport an important power flow with different corresponding voltage levels. Several research and studies are conducted on thermal phenomena in underground power transmission cables because of their effects on materials and cable isolation and the environment, and how these phenomena behave in case of damage. In this chapter, we will present the simulation results of underground power cable by displaying thermal and heat transfer between different layers of cable with current loading variation condition, the performance evaluation process of the high voltage cable considering the thermal distribution inside the cable has been a major of interest to find the corresponding maximum current carrying capacity (ampacity) [6,26].

III.2. Representation of underground transmission cables:

Electrical cables have different geometric shapes and dimensions depending on the power and voltage transmitted through these electrical cables. The following are the characteristics of the cable used in this study.

The sample cable shown in Figure III.1. of 138 kV XLPE power cable with copper conductor. It has a transitional wall of 850 MIL XLPE copper neutrals with Copper Composite Laminate Sheath. The jacket is Polyethylene with Extruded Semi-Conductive Outer Layer.[6]

Figure III.1.A picture of the 138 kV XLPE insulated cable construction.[19]

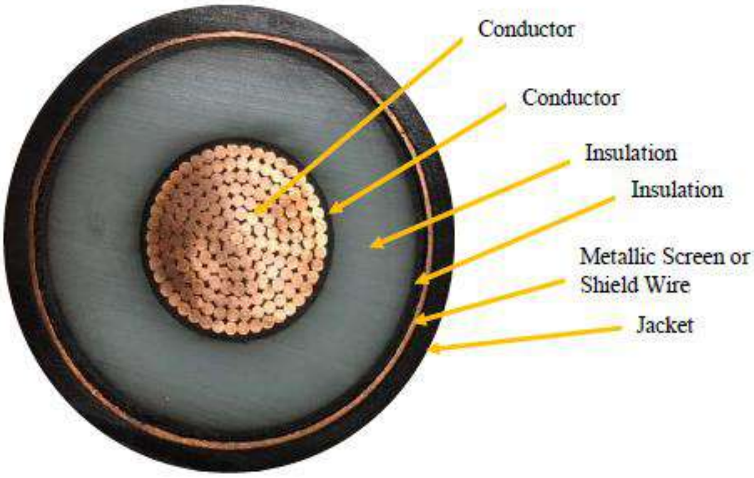


Figure III.2.XLPECable layers.[6]

Cable parameter and size	value
Nominal voltage	138 KV
Max. voltage	145Kv
Relative permittivity	2.3
XLPE loss factor	0.05%
Cable length	15.25m
Conductor size	1000mm²
Conductor diameter	40.9mm
Insulation thickness	15.011mm
Diameter over insulation	86.4mm
Cross-section of shield	180Kcmil
Diameter over sheath	96.2mm
Overall jacket dia	104.3mm
Capacitance	56.3pF/ft

Table III.1. The characteristics of 138 KV XLPE cable.[6]

III.3. Temperature calculation in underground parts:

The temperature calculation in underground parts change from part to another, the temperature variation depend of shape ,nature of materials , section and load current.

The cable temperature measures were computed in three different locations namely A, B, and C in the conductor, insulation, and jacket respectively, to see the magnitude variation.

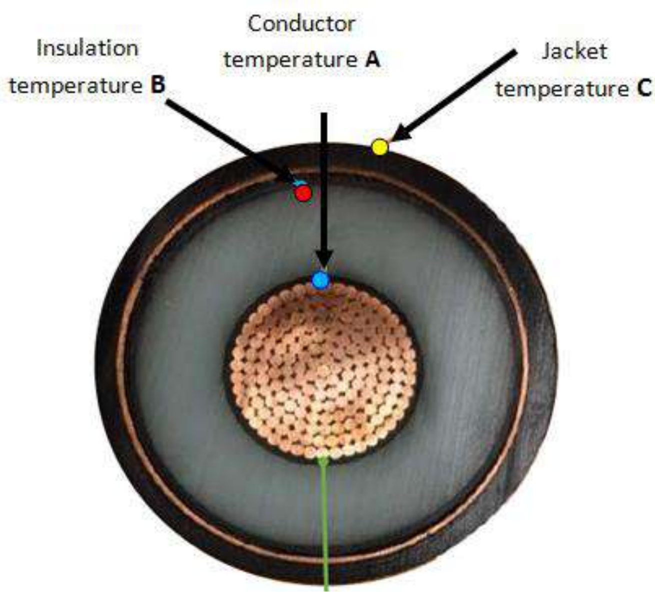


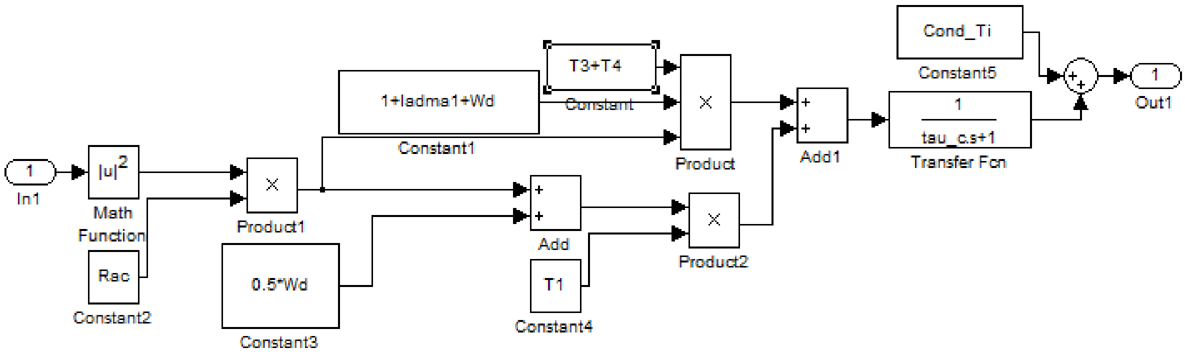
Figure III.3. Cross-section points positions.

III.4.Teperature simulation of underground cables:

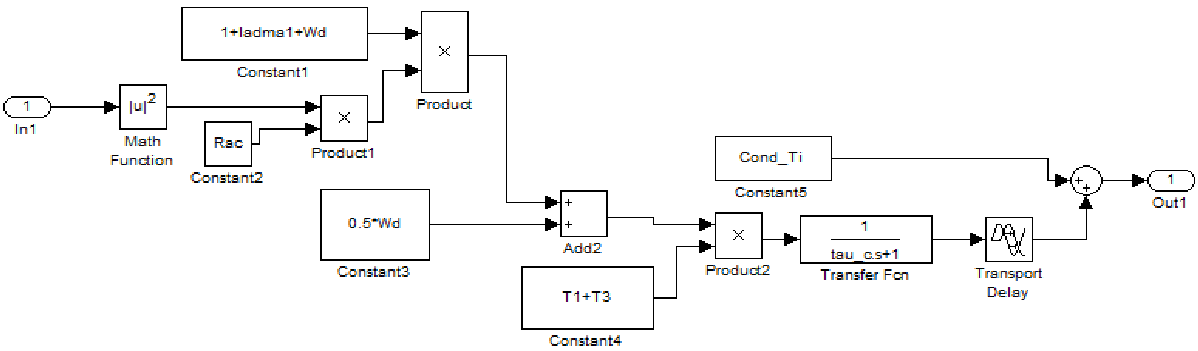
Using physical, electrical, geometrical parameters and the mathematical cable model developed in precedent chapter II, to compute the temperature at differents parts. The computation was done by the modele implementation in MATLAB Simulink.

The temperature developed model of the conductor is presented in frequency domain based on the Laplace transform, with the current input through the conductor.

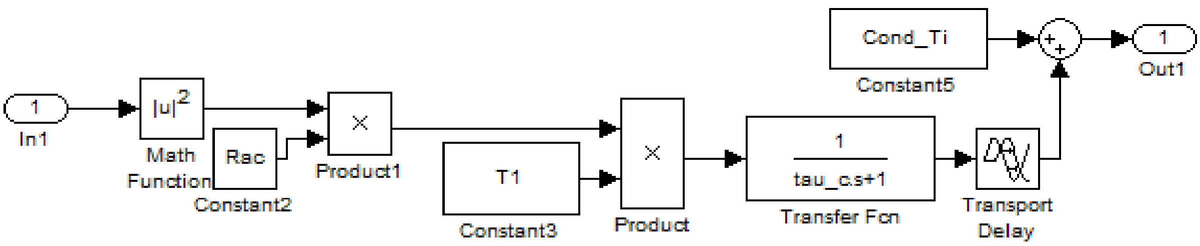
Figure III.4 show the closed loop control system; these subsystems models (Matlab/Simulink) represent the conductor, jacket and isolation temperature (output conductor temperature in three set points) with load current flow through the underground cable.[6]



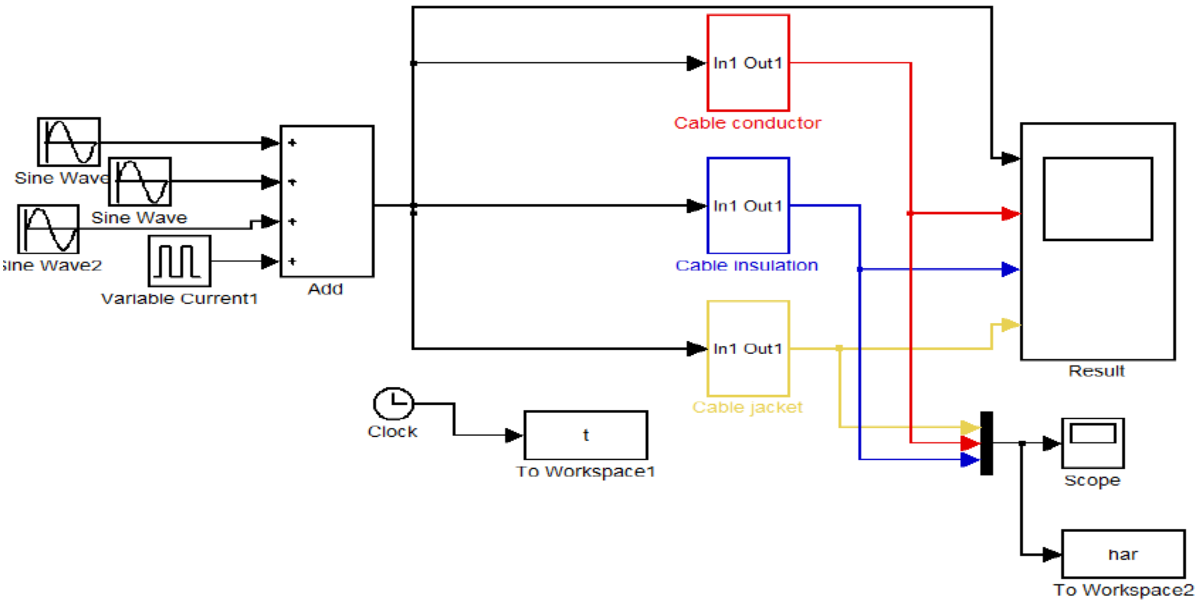
a. Conductor temperature model with current as input.



b. Insulation temperature model with current as input.



c. Jacket temperature model with current as input.



d. The global cable model with different current source

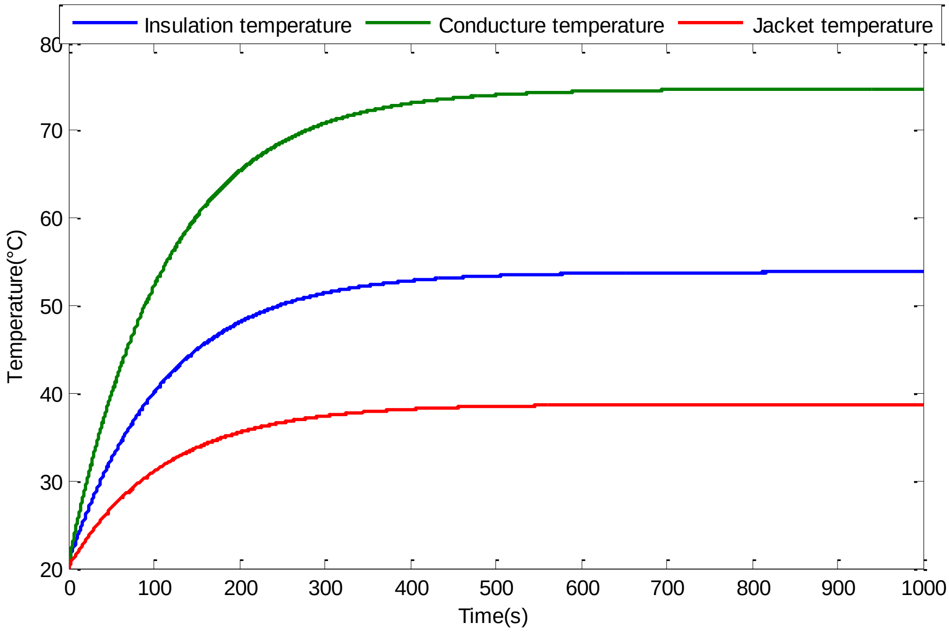
FigureIII.4.XLPE Cable model with current input and temperature output.

III.5. Simulation results of thermal effects in underground cable:

The simulation aim is to predict the static and dynamic variation of current in real time estimation of the conductor temperature with different loading currents waveforms, shape, magnitude and frequencies.

III.5.1.Conductor temperature in steady state:

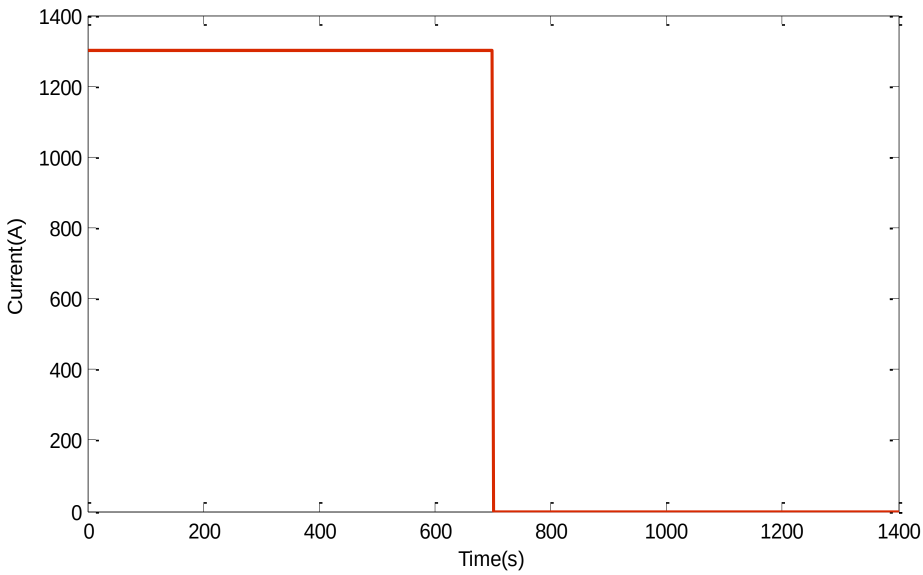
Figure III.5. Illustrate the response of control system model to the rate load current in steady state condition. The conductor temperature increase gradually with time variation in the different parts: conductor, jacket and insulation. The conductor temperature will be maintained after 500s with constant values affected by the load current flow through the cable[24-27].



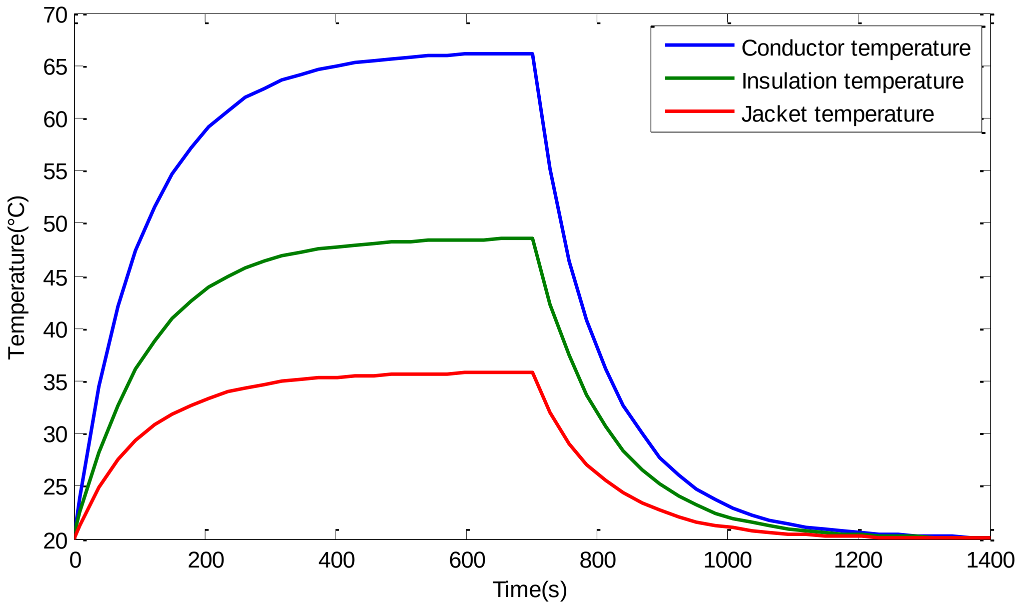
FigureIII.5.conductor temperature response.

III.5.2.Conductor temperature with step load current:

The load current waveform is represented by step signal to show the thermal behaviour of underground cable (figureIII.6.A).



A.normal current load.



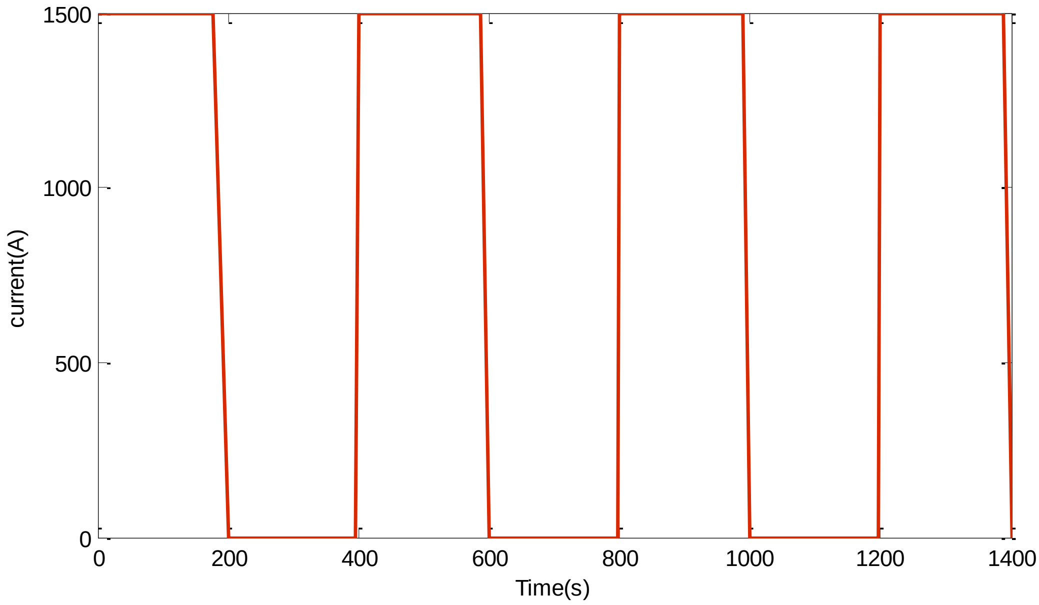
B. thermal effect with step input

Figure III.6. Cable temperature profile1350A with normal current.

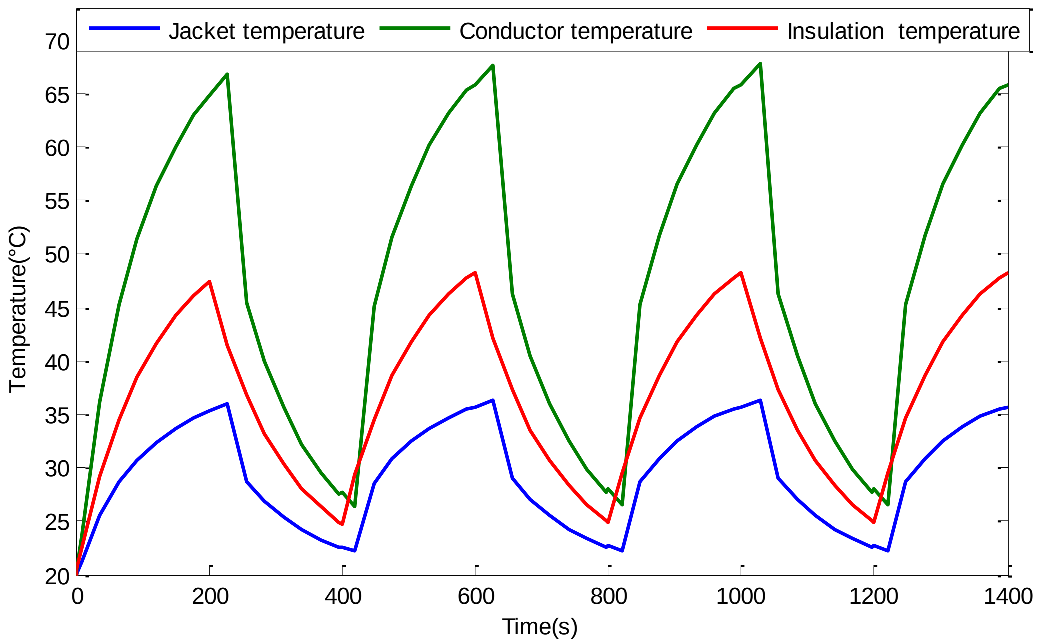
Figure III.6.B show the temperature variation after current step signal, the temperature waveform affected by two steps the first one: fed current and the second one the breaking current. The result shows the thermal effect of cable in normal condition and the cooling of cable (without current) as function of time.

III.5.3. Conductor temperature with repetitive step load current:

The load current waveform is represented by repetitive step signal (variable load) to show the thermal characteristics of underground cable in this condition (figureIII.7.A)



A. repetitive signal current.



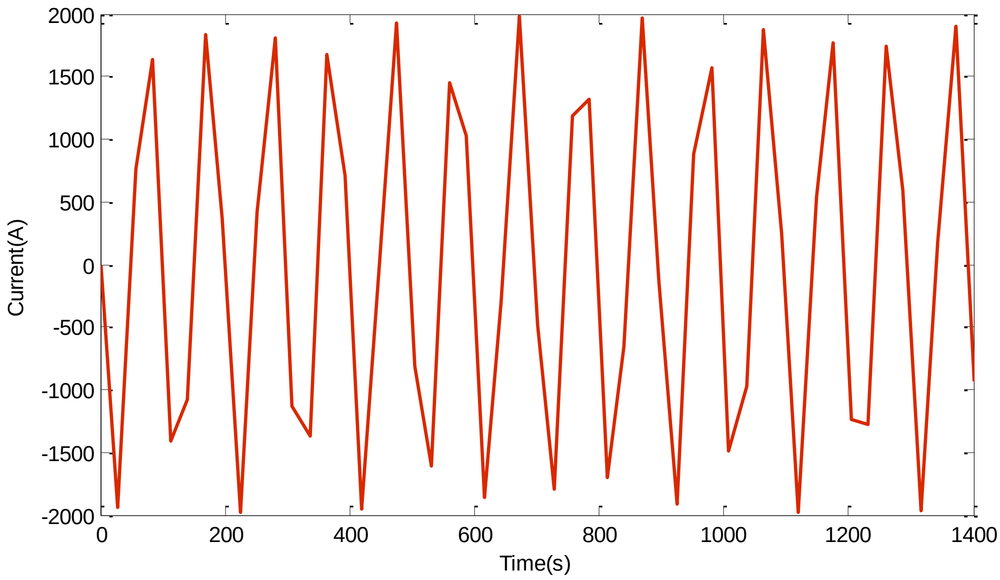
B. thermal effect with repetitive step input.

FigureIII.7. Cable temperature profile 1500A repetitive signal current.

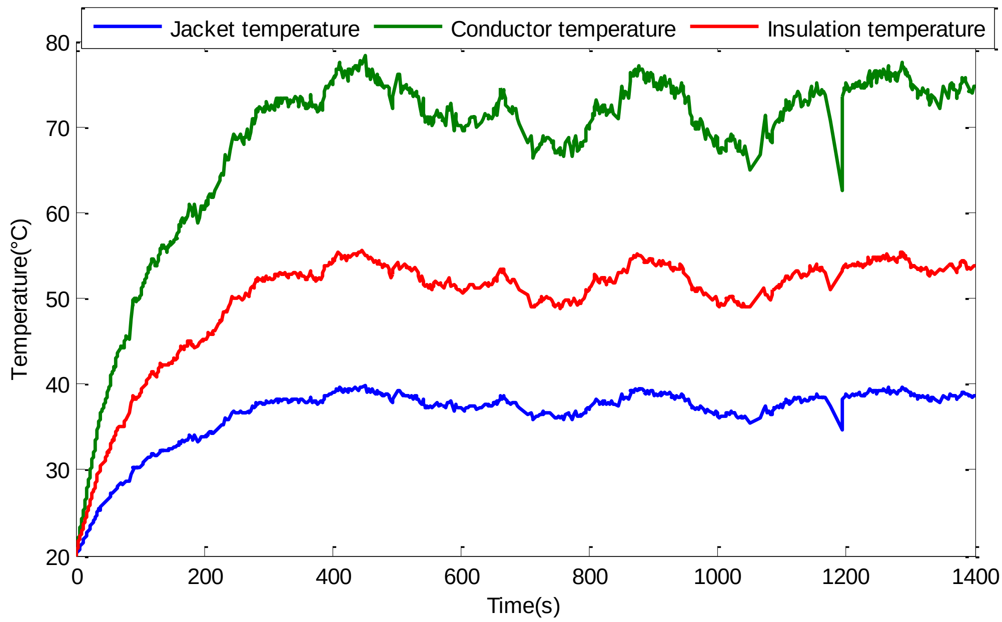
Figure III.7.B represents the thermal effect of underground cable feed by repetitive load current, the current nature and form affect the temperature variation (repetitive responses characterized by period with retard time). Similar results between (step load and repetitive step) has been observed for temperature change with relatively short periods of time.

III.5.4.Conductor temperature with sinusoidal load current:

The sinusoidal current form (load current) applied in the underground cable model (figure.III.8.A).



A. Sinusoidal current.



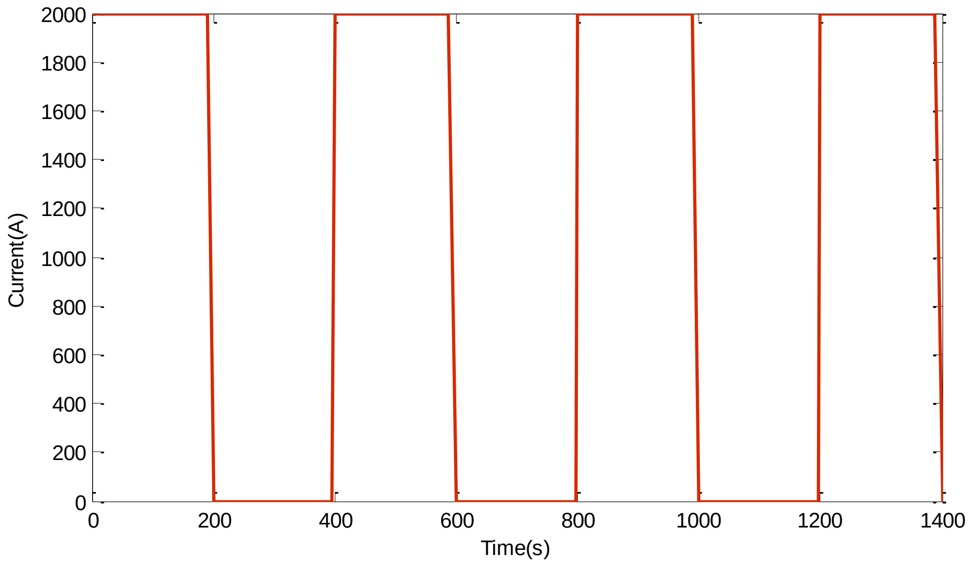
B. thermal effect with sinusoidal input.

Figure III.8. Cable temperature profile 2000A sinusoidal current.

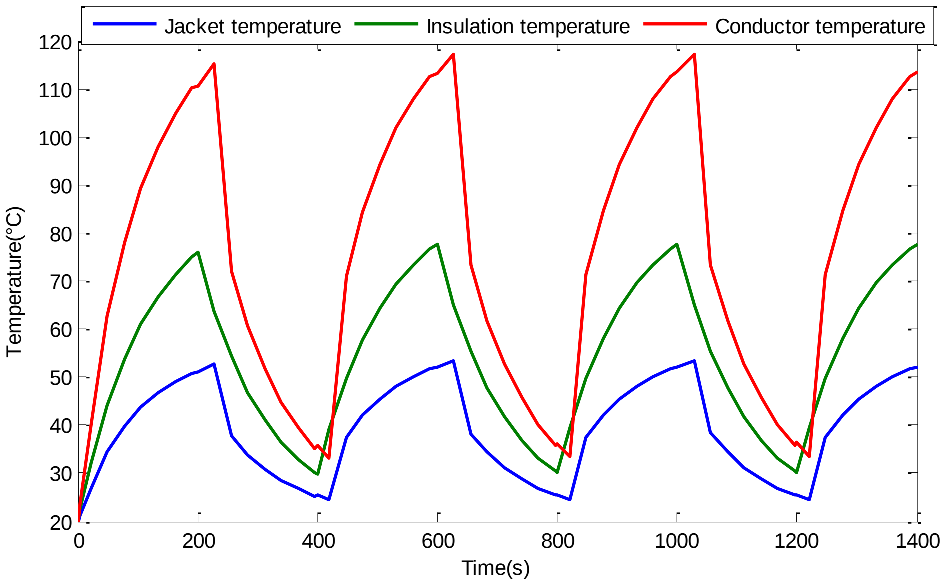
Figure III.8.B shows the temperature simulation with sinusoidal current, the result as compared to the first case (steady state) show the fluctuation in temperature signal caused by positive and negative sequence.

III.5.5. Conductor temperature with overload condition:

The overload current will be applied to the underground cable characterized by 2000Awith repetitive waveform.



A. Overload regime currents.



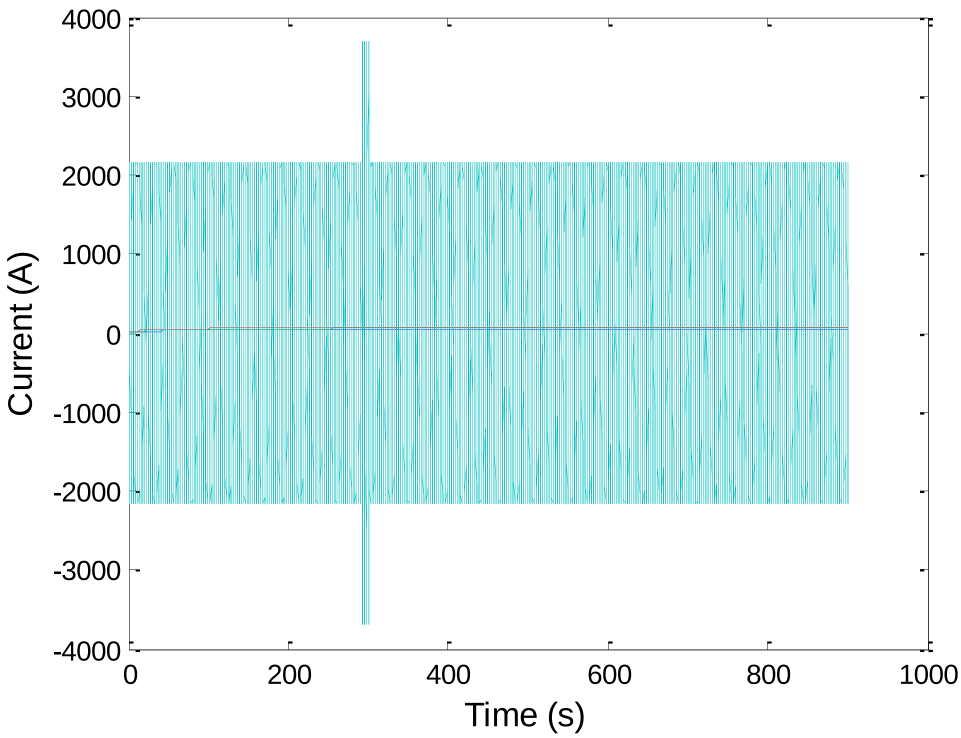
B. thermal effect with overload input.

FigureIII.9. Cable temperature profile to overload current .

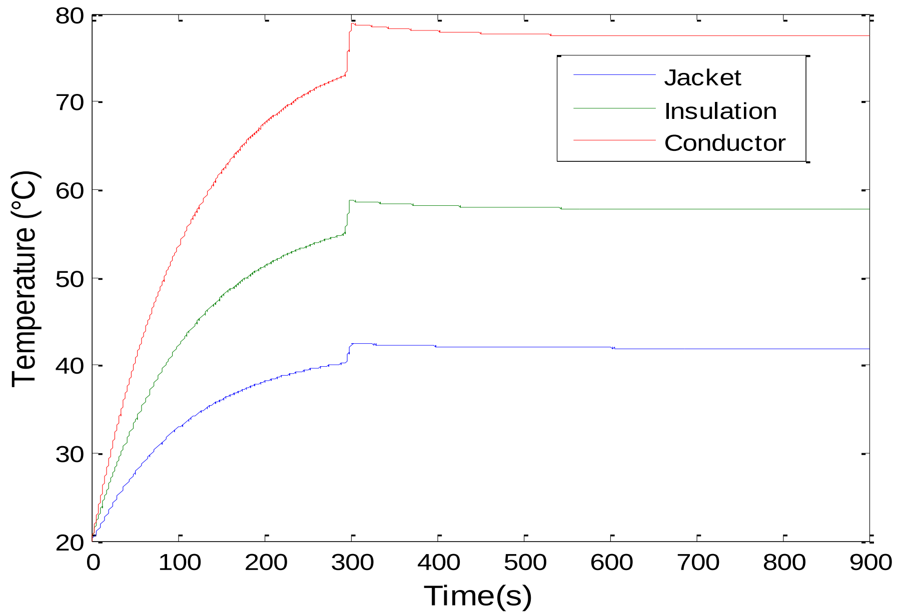
The result represents the overload current influence on the conductor temperature. The excessive heat (increase the temperature) of conductor parts is remarked due the over current (Figure III.9).

III.5.6.Current peak in steady state:

The overload current will be applied to the underground cable characterized by (3700A, f=50Hz) with repetitive waveform.



A. Current peak presence in steady state.



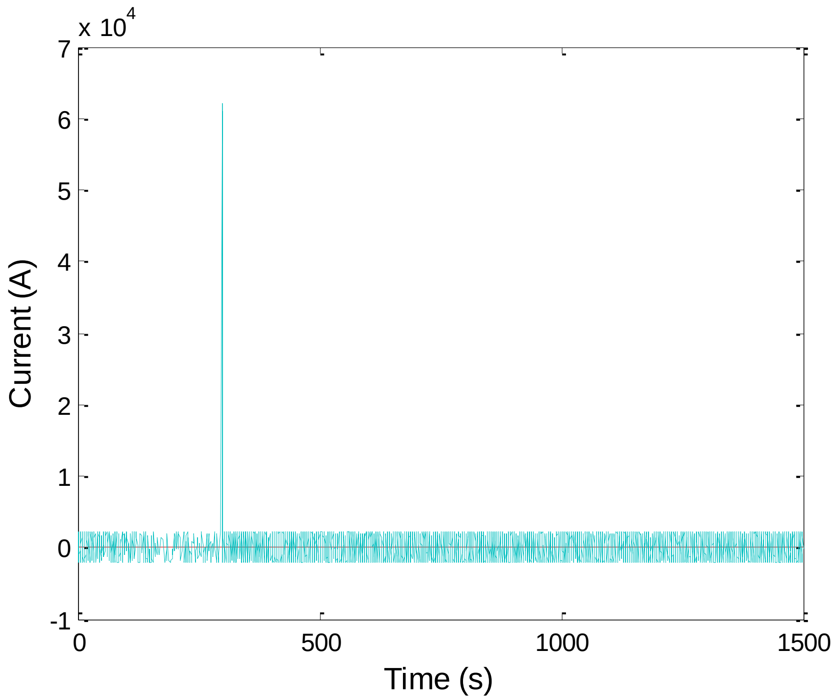
B. Thermal effect caused by current peak.

FigureIII.10. Cable temperature profile with peak current.

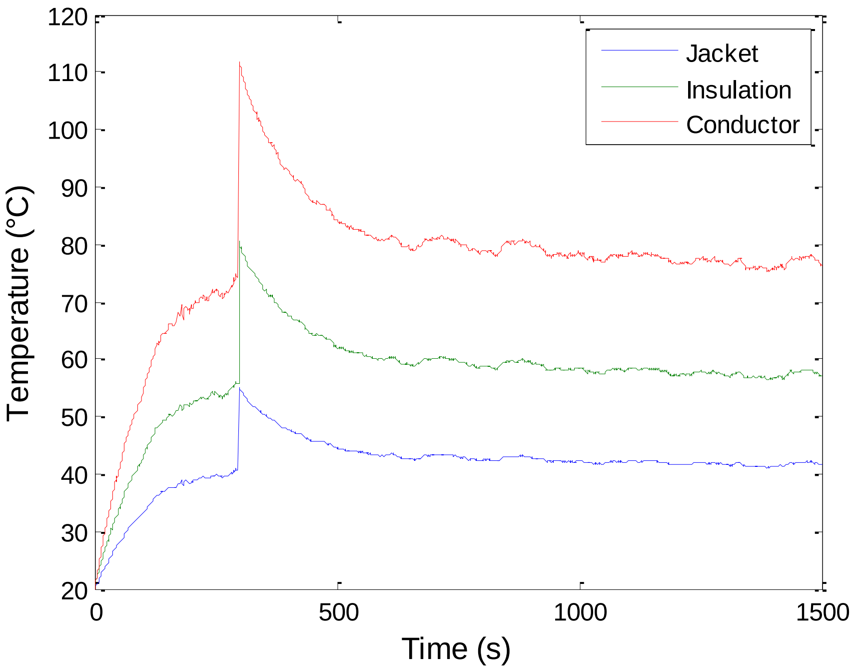
The result presents the current peak current influence on the conductor temperature steady state. The important peak of heat (increase the temperature) of conductor parts is remarked due the current peak fault (Figure III.10).

III.5.7.Conductor temperature with short circuit current:

Short-circuit currents flowing through conductors of various power system equipment create the very important thermal effects due to heating and excess energy input over time (60KA,f=5000HZ).



A. Short-circuit current.



B. thermal change with Short-circuit.

FigureIII.11. Cable temperature profile 60kA Short-circuit current.

The conductor parts temperature during short circuit is also important because the high short-circuit currents. Generally, both ac and dc components of short-circuit current contribute to thermal heating of conductors.

State	Temperature layers (°C)		
	Conductor	Insulation	Jacket
Steady	65	47	35
Step	67	50	36
Repetitive step	67	47	36
Sinusoidal	78	55	40
Overload	111	75	52
Short circuit	114	81	57

TableIII.2. the maximum temperature with different current load (ampacity)

TableIII.2 resume the maximum temperature of different cable layers (conductor, insulation jacket) with several state characterized by current variation.

III.6. Conclusion:

The electrical current flow in underground electrical transmission line is limited due to the ability to withstand high temperature. High operating temperature affects the insulation of the different cable parts. The maximum temperature should not exceed the limits prescribed by the manufacturer. This work presents a mathematical temperature model of the underground cable in conductor, insulation, jacket as function of several loads currents. The simulation results represent the thermal effects and temperature variation in underground cable at various layers, by exploring the numerical model using Matlab/Simulink software. The simulation proves the conductor temperature parts in static and dynamic variation of different loading currents waveforms, shape, magnitude and frequencies (normal and abnormal condition). The ampacity calculation and the results are represented with a thermal model help to designed and predict the conductor temperature as function of given a load current and cable location.

General Conclusion

General Conclusion

Underground power cables are mostly used into electrical power transmission and distribution electrical network in order to ensure a transport power flow with different corresponding voltage levels. The underground transmission line performance relies mainly on the thermal properties of the surroundings and the cable itself (size, power, manufacturing condition). Cable insulation dissipates heat generated by the important current flow to the surrounding soil.

In this work, we present the mathematical model of thermal effect of high-voltage underground cable power cable by Matlab/Simulink software, with time-dependent.

The simulation results show the heat variation in the different parts of cable in steady state, short circuit and overload represented by several current types. The temperature is very important in the copper conductor in the normal condition for the cables to operate and mostly increase event of electrical faults. The maximum temperature exceeds the limits required by the manufacturers in abnormal condition (90°C).

The results confirm the frequency and amplitude of current influence on the temperature variation by heat transfer between of the cable components performance.

This mathematical model can be used to predict and control the temperature of the cable conductor, insulation, jacket and load current in the different conditions (normal and abnormal condition).

Perspectives:

For the perspectives, our objective is to study the electromagnetic interferences and thermal effect by experiment and numerical simulation with finite element method of different electrical submarine and overhead cable. The cable proprieties and design study, materials, current loads harmonics, depth and thermal characteristics of the mother soil.

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الخلاصة: تعتمد مدة الخدمة والحالة الصحية لخطوط النقل والتوزيع تحت الأرض بشكل كبير على جودة الكهرباء وسلوك شبكة الكهرباء وأنظمة العزل. إن وجود أعطال التيار في الكابلات الأرضية عالية الجهد يولد تسخينًا كبيرًا بين مكونات الكبل. يمكن لتيار الشحن العالي جدًا أن يزعج الشبكة أثناء تفكيك خط الكهرباء. يقوم هذا العمل بتقييم تغير درجة الحرارة لنظام كابل الطاقة تحت الأرض في حالة مستقرة ، والجهد الزائد ، وتيار الدائرة القصيرة المسموح به باستخدام نموذج تحليلي لمستوى الجهد لنظام 138 كيلو فولت.

الكلمات الأساسية :نموذج تحليلي ، تيار الحمل ، كابل تحت الأرض ، مؤشر حراري ، حرارة.

Abstract: The life time and health state of underground electric transmission and distribution lines strongly depends on the quality of electricity and behavior of electrical network and insulating systems. The presence of current faults in the high voltage underground cable, generate an important heating between the components of cable. The very important load current can cause network perturbation to the power line decommissioning. This work evaluate the underground power cable system temperature variation in steady-state, overvoltage , and short circuit ampacity using analytical model for system voltage level were used 138 kV.

***Keywords*: analytic model, load current, underground cable, thermal rating , heat.**

Résumé : La durée de vie et l'état de santé des lignes électriques souterraines de transport et de distribution dépendent fortement de la qualité de l'électricité et du comportement du réseau électrique et des systèmes d'isolation. La présence de défauts de courant dans le câble souterrain haute tension, génère un échauffement important entre les composants du câble. Le courant de charge très important peut perturber le réseau lors du démantèlement de la ligne électrique. Ce travail évalue la variation de température du système de câbles électriques souterrains en régime permanent, de surtension et de courant admissible de court-circuit à l'aide d'un modèle analytique pour le niveau de tension du système de 138 kV.

Mots-clés :modèle analytique, courant de charge, câble souterrain, indice thermique, chaleur.