KASDI MERBAH OUARGLA UNIVERSITY
Faculty of Applied Sciences
Department of Electrical Engineering

MASTER ACADEMIC Thesis
Field : Science and technology
Sector: Electrical Engineering
Specialty : Electrical networks
Presented by :

Belabbes Mouafak   Moutou Mahfoud

Theme:

Harmonics influence on thermal effects in underground power cable

The composed jury :

Mr Mahdi Benaouadj	MCB	President	UKM Ouargla
Mr MrAyad Ahmed Nour ElIslam	MCA	Supervisor	UKM Ouargla
Mr Boudjella Houari	MCB	Examiner	UKM Ouargla

Academic year 2020/2021

Gifting and Alckrat

With the last touches of this note, we should have thanked and thanked To God, the Blessed and Exalted, who enabled us to do this work and complete it.

We also extend our heartfelt thanks to the parents for their efforts throughout our school life, which did not He is stingy with their directives, despite their intense preoccupations, God made them a treasure above our heads.

We also extend our heartfelt thanks to the honorable Dr. **AYAD AHMED NOUR ELISLAM**, who gave us a helping hand. In this work of ours, may God reward him with all the best, and may God protect his offspring, God willing.

All of the professors, specialists and students who helped us in accomplishing this work.

And in the end, we thank everyone who contributed from near or far, even with a kind word. If we are injured, it is from God alone and if we make a mistake, it is from ourselves and from the accursed Satan.

Nomenclature

Δt: is the temperature rise in the cable.

W_d: is the dielectric losses.

θ_a: is the ambient temperature.

I: is the load current.

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

T1: is the thermal resistance of the insulation.

T2: is the thermal resistance of the shield/sheath.

T3: is the thermal resistance of the jacket.

T4: is the thermal resistance between cable surface and ambient.

λ: is 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 at 20°C

A : cross-sectional area of metal in mm²

$\alpha 20$: the temperature coefficient of the conductor material per K at 20oC.

θ : the conductor operating temperature (°C)

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

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

θsc : the cable screen operating temperature (°C)

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]

Nomenclature

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

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].

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].

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]

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].

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

***L**: Sample* cable length 15.25m

$\theta_{c,(I,t)}$: 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 rises in the cableθ_{Ci} = initial conductor temperature $RTCT$ = cable time constant [minutes]

Table of contents

Table of contents

Chapter I: underground electric power cables

Table of contents

Chapter II: Thermal model of underground electric power cables.

List of Figures

List of Figures

Chapter I: underground electric power cables

Chapter II: Thermal model of underground electric power cables.

Chapter III: Simulation of harmonics current presence in underground power cable.

List of Figures

Tables List

Tables List

Chapter I: underground electric power cables

Chapter II: Thermal model of underground electric power cables.

Chapter III: Simulation of harmonics current presence in underground power cable.

General Introduction

Electrical energy is very important in our daily life ,and our need for it is increasing all over the world ,this requires that the transmission of electricity responds to different geographical conditions ,and aesthetic requirements, there are basically tow ways of transmitting power: overhead lines and underground cables, where the latter is considered more responsive to the aesthetic appearance of cities and does not distort the landscape ,so work is being done to expand their use despite its high cost . **[1]**

Underground cables differ from overhead lines mainly in terms of the presence of insulation materials that withstand a specific temperature. when the insulation breaks, the cable fails to transmit power, and as the cables are hidden underground, it is necessary to estimate the heat that the cable can reach under different loading conditions, this is what will be discussed in this work Specifically, the effect of harmonics on the temperature of the cable**. [1]**

This thesis consists of three chapters:

The first chapter the first chapter presents an overview of underground electrical power cables, cable structure, power cables classifications, some electrical phenomena such as electromagnetic field phenomena, Harmonic pollution, different defects that occur in cables, Finally, we mentioned some cable monitoring techniques.

The second chapter this chapter presents some mathematical models that are used to calculate the temperature of conductor, insulation and jacket.

The third chapter this chapter shows cable simulation results under different load conditions: Normal conditions and in the presence of some disturbances, such as harmonics, where the effect of such disturbances on cable heat can be easily known.

Chapter I: Underground electric power cables.

I.1. Introduction

There are two main ways of transporting electrical energy. One is the overhead transmission, and the other is the underground transmission. The overhead transmission uses wires while underground uses cables. Overhead transmission wires can be noticeable from their high structures, and wire. Unlike underground transmission cable, there are buried under the ground and cannot be seen. Underground cable installations are more expensive than overhead wires. Urbanization does not like the fact of having high tower structures and high voltage wire running beside homes and businesses. Underground cables have a lower forced outage rate than overhead wire, but the outage durations are typically much longer. For these reasons, there is a high demand for underground cable projects. However, underground cable has a high dielectric loss; this loss is present any time the cable is energized, and it reduces the amount of power that can be transferred on the cable. Hence, power transfer levels for underground cable are lower than those for overhead wires. This is because the XLEP insulation has a temperature limit of 90^{o} C under normal load conditions**. [1]**

I.2. Comparison between overhead lines and cables

Overhead lines are x times cheaper than cables. In case of very high voltage, problems arise with long cable runs. On the other hand, cables are better protected against external damage (lightning, storm) than overhead lines. Failures are more quickly detectable on overhead lines. Repairs are easy to carry out for overhead lines; for cables, on the contrary, they require major work. However, overhead lines can be disruptive to the landscape.**[2]**

I.2.1. Overhead line

I.2.1.1. Advantages:

- Detectable faults.

- Problem solved more quickly.

I.2.1.2. Disadvantages:

- More frequent breakdowns (depends on the weather).

- Impact on the landscape.

I.2.2. Cables

I.2.2.1. Advantages:

reduced space requirements.

- Better acceptance by the population.

I.2.2.2. Disadvantages:

-expensive repair work (underground).

- The renewal of cables is more expensive than for overhead lines.

I.3. Power cables structure

Cables are manufactured to transmit electricity using their conductive materials, but they also contain other components that contribute to isolating the electric current from the external environment, protecting the cable from mechanical stress and giving it the usual circular shape. the figure I.1. Show the different layers of the cable.

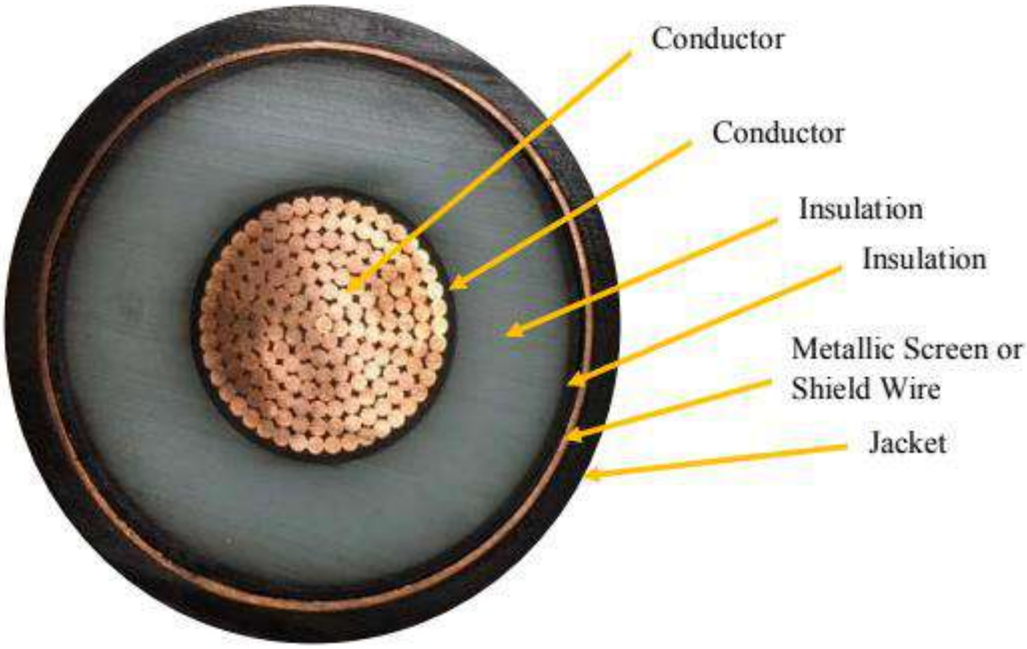


Figure I.1: cable layer.**[2]**

I.3.1. 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 1.2. 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.

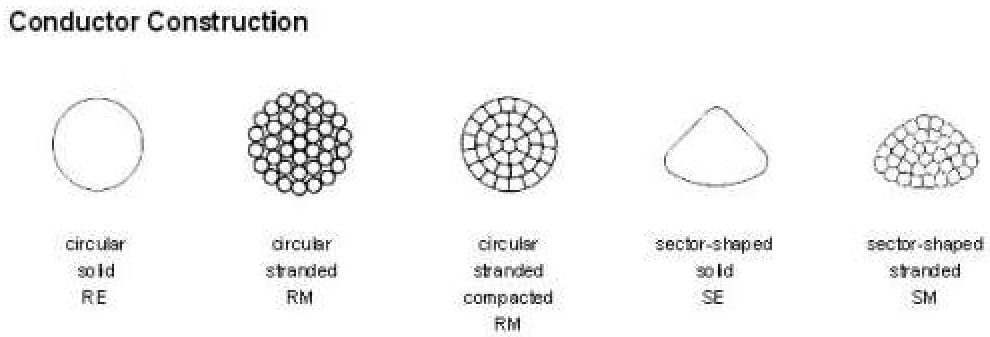


Figure I.2: Conductor construction

I.3.2. Conductor screen

The conductor screen is a semiconducting polyethylene compound extruded around the conductor. This semi-conducting compound minimizes the electrical stresses in the conductor. These are due to the stranded configuration of the conductor. The semi- conducting material used for conductor screen has no deleterious effect on the conductor **[3]**. In some cable designs, an additional layer of a semi-conducting tape is applied as a separator between the conductor and the semiconductor.

I.3.3. Insulation

The insulation is the layer of the cable that electrically insulates and protect the conductor. The thickness of the insulation defines the maximum rated AC or DC voltage and impulse voltage of the cable. Also, the insulation should be able to withstand switching over-voltage during transients. The insulation material is an extruded cross-linked polyethylene (XLPE) produced from a polyethylene under high pressure and temperature with organic peroxides as additives. Using heat and pressure, the extrusion process is carried out under strictly controlled atmospheric conditions. The individual molecular chain to link with one another which in turn cause the material to change from a thermoplastic to a flexible material **[3].** Hence, the XLPE material will still be thermoplastic, but now it will also be polymerized and crosslinked, which gives it flexibility.

I.3.4. Insulation screen

The insulation screen is the semi-conducting layer over the insulation. Just like the conductor, this semi-conducting compound is extruded concentrically and circularly to minimize the possibility of ionization on the outer surface of the dielectric (insulation) **[1,4].** The conductor-screen, the insulation, and the insulation screen are extruded simultaneously in one process to ensure that the screen and XLPE are intimately bonded together and free from all possibilities of voids between these layers. Voids in XLPE cables causes partial discharge and eventually lead to higher voltage stress on the insulation.

I.3.5. Metallic screen

This layer of the cable consists of shield wire, and it is the short circuit current carrying component. The metallic screen can be a copper wire with open helix copper tape as a binder or a lead alloy sheath it can also be a corrugated aluminum sheath **[1,4]**. The cross-sectional area of this metallic screen/shield wires is design to satisfy the phase to earth faultlevel in the network.

I.3.6. The jacket

The jacket is the protective layer of the cable; it protects the metallic sheath and all other underlying layers from physical abuse, sunlight, flame, or chemical corrosion. The jacket is a nonconductive material made of PVC or PE (HDPE, LDPE, MDPE) **[5]**

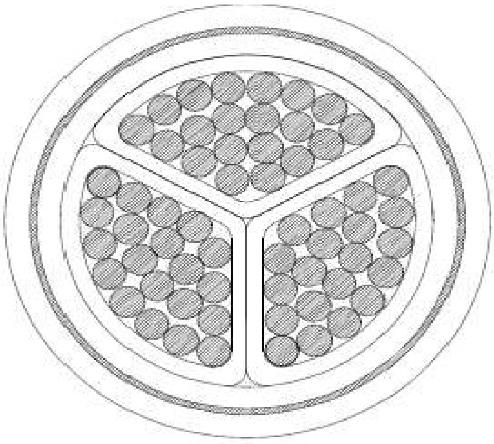
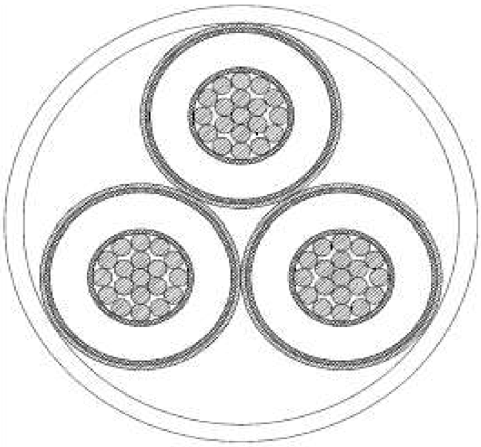
I.4. Underground power cables classifications

We can classify underground electric cables according to several criteria:

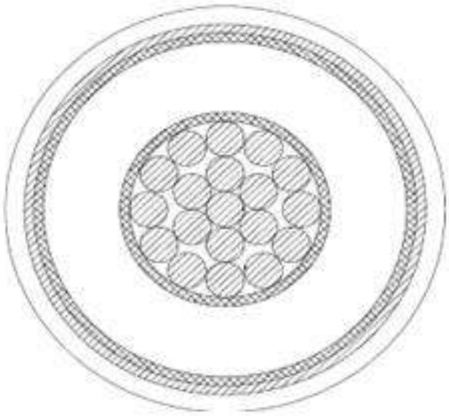
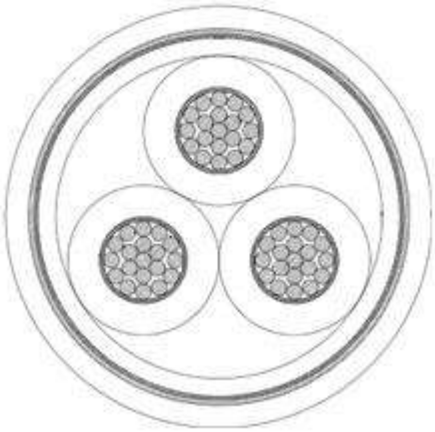
-According to the nature of the Phases (single-pole or three-pole cable).

-According to the type of insulation (Synthetic cable or XLPE insulation, insulation by impregnated paper).

-According to the shape or the structure (Circular or sectoral conductors)

Monopolar cable three-pole conductors with insulating belt

Tripolar sectoral form Sectoral circular form

Figure I.3: different forms of conductors **[6]**

I.5. Underground electric cables

Of course, the investments related to the installation of new cables are sometimes prohibitive. But on the other hand, their environmental and aesthetic impact is much less than that of overhead lines. With this in mind, underground cables have taken and will continue to gain a certain extent.

I.5.1. Extra high voltage underground cables EHV

Extra high voltage underground cables are mainly used for the transport and distribution of electrical energy in highly urbanized areas, sometimes to solve particular local, technical or environment, for which the installation of overhead lines is difficult or impossible **[7]**

I.5.2. High voltage underground cables HV

The structure of the cross-linked synthetic polyethylene high voltage cable always implies the following terms:

I.5.2.1. Compact round conductor

made up of several layers of concentric wires wound in a spiral. In compact conductors with round conductors, due to the low resistance of the electrical contacts between the wires, the skin and proximity effects are almost identical to those of a solid conductor.

225 KV cable with a diameter=11cm 400KV cable with a diameter=13cm

Figure I.4: 2D cutting of high voltage cables for underground networks **[8]**

I.5.2.2. Segmental conductors

also called "Milliken" conductors (figure1.6), Are composed of several segment-shaped conductors assembled to form a cylindrical core

The large section conductor is divided into several conductors in the form of a segment. There are 4-7 of these conductors, called segments or sectors. They are isolated from each other by means of semiconductor or insulating tapes. The Milliken-type structure reduces extremely harmful skin and proximity effects

a-Compact round conductor **b**- Segmental conductors

Figure I.5: compact and segmental conductor cables **[9]**

I.5.3. Medium voltage underground cables MV

Medium voltage underground electrical cables have the same shape and the same construction than the EHV and HV cables but with a smaller diameter because of the level of power transmitted

Figure I.6: Single-core cable **[6]**

I.5.4. Low voltage underground cables LV

Low voltage underground power cables are constructed with rigid, solid or stranded copper and aluminum conductors and conductors of flexible copper (bare or tinned). XLPE, PVC, LSF / LSOH and elastomeric compounds are the main insulating and protective compounds for these types of cables. Steel (or aluminum for single-core cables) wires or tapes can be applied under the outer jacket, providing additional mechanical protection. **[10]**

Phase conductors: is the metallic part of the cables which carries the electric current these materials are: Aluminum core

Neutral conductor: Circular wired aluminum core. Lead protective sheath extruded PR insulation. Assembly (stuffing and ropes). Screen in steel ribbons. PVC sheath **[6]**

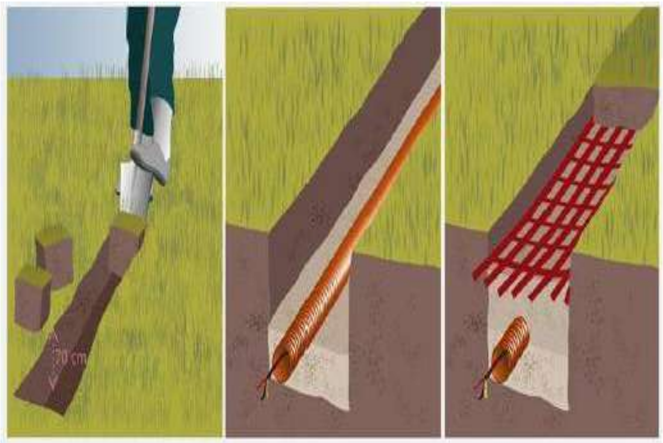


Figure I.7:LV Cable laying technique **[6]**

I.6. Laying methods

In addition to the electrical and thermal aspects of the cable design, it is necessary to take into account the mechanical and thermo mechanical stresses to which the cable system will be subjected during installation and commissioning. The choice of a duct is made according to the external influences of the room, see figure 1.8 and Table I.1.

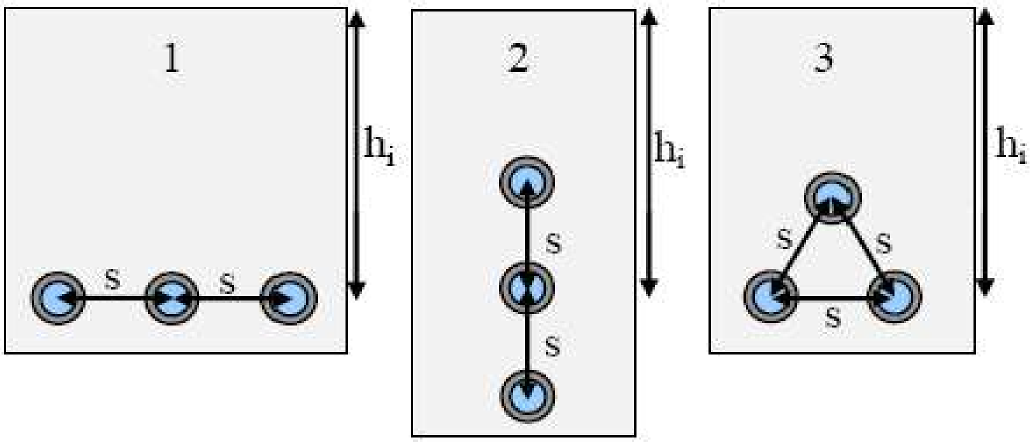


Figure I.8: different geometric configurations for the three-phase underground cables (1) horizontal, (2) vertical, (3) triangular **[11]**

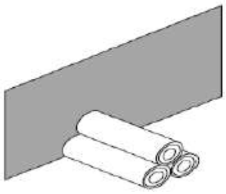
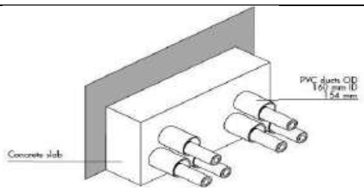
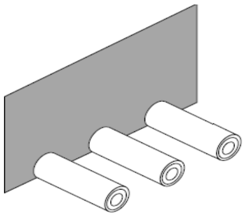
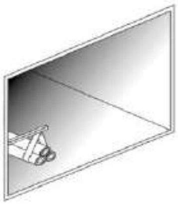
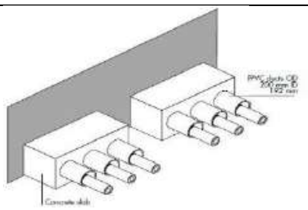
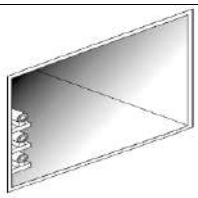
	Cables buried directly in the clover formation
	Cables buried in conduits forming a cloverleaf
	Cables directly buried in flat formation
	Cables in the air inside a three-lobed gallery
	Cables buried flat in conduits
	Cables laid flat in a gallery

Table I.1: laying methods of underground cables **[9]**

A duct must have the following characteristics:

• Mechanical resistance (shocks, crushing).

• Sealing (water, dust).

• Non-flame propagator

I.7. Electric fields and magnetic fields

I.7.1. Effects of magnetic fields

The 50 Hz magnetic field induces electric currents in the human body. Only exposure to strong magnetic fields can bring about an immediate perception.

The thresholds of immediate perception retained by the World Health Organization

(WHO) are the following:

- for 50 Hz magnetic fields between 500 µT and 5 000 µT, minor biological effects have been

reported.

- for 50 Hz magnetic fields between 5000 µT and 50 000 µT, there are effects on the

nervous system and vision.

-for 50 Hz magnetic fields between 50 000µT and 500 000 µT, there is a stimulation of excitable tissues and damage to health is possible.

-for 50 Hz magnetic fields greater than 500,000 µT ventricular fibrillation has been reported **[12]**

I.7.2. Effects of electric fields:

The human body is a conductor of electricity. When the body is subjected to a strong electric field, electric charges will accumulate on the surface of the body. The accumulation of these electric charges can result in:

• Vibrations of the hair, a superficial tickle of the skin.

Micro-sparks between the skin and objects in contact (clothing, glasses, watches, etc.)

The threshold for perceiving electric fields varies from one individual to another.

• below 10 kV / m, a minority of people perceive a sensation of “breath” on the skin.

• From 20 kV / m, the majority of people perceive electric fields, in the form of

tingling. **[12]**

I.8. Electromagnetic induction phenomena in underground cables

I.8.1. Ohmic resistance - Skin and proximity effects

The AC resistance of an underground cable conductor is higher than direct current resistance as a result of skin and proximity effects.

The DC resistance can be considered as equal to the resistance of a circular conductor of the same section and whose length is equal to the length of the cable increased by 2% to take into account the spiral age of the strands that constitute each conductor. In three-core cables, the conductors, with their insulation, are twisted together, this must be taken into account by an additional length increase of 2%.

It is difficult to calculate exactly the increase in resistance due to the film effect in the case of conductors subdivided into a large number of strands, as is the case for underground cables. The proximity effect does not lead to an appreciable variation in effective resistance only for very large sections **[13]**

I.8.2. Induced currents in metallic shield (sheath, lead envelope) - energy losses

The alternating magnetic flux due to the current flow in the conductors produces longitudinal alternating electromotive forces in the screen of the cables, if several cables are located side by side and their screens are in electrical contact, these e.m.f. give rise to currents in the screens, which creates additional losses.

It is convenient to take these losses into account, attributing them in a conventional way to a fictitious increase of the resistance of the conductors.

Locally induced FOUCAULT currents causing losses may nevertheless occur for three-core cables of very large cross-section normally carried by intense currents. As a reminder, a similar problem exists with the shielded busbars between the alternator and the transformer.

I.8.3. Energy losses in underground cables

In solid insulators subjected to an alternating electric field, energy losses due to the following causes:

1. The mass conductance of the insulator which is never perfect,
2. The surface conductance, which depends on the state of the surface,
3. The dielectric hysteresis,
4. The effluence and discharge in the empty spaces **[14]**

I.9. Harmonic pollution in underground cables

I.9.1. Harmonics

Unwanted electrical signals appearing on the basic wave, whose frequency is multiples of the basic wave frequency, that distorts the current or tension wave or both.

I.9.2. Sources of harmonics

Harmonics are produced by nonlinear loads or devices that draw no sinusoidal currents. An example of a nonlinear load is a diode, which permits only one-half of the otherwise sinusoidal current to flow. Another example is a saturated transformer, whose magnetizing current is no sinusoidal. But, by far the most common problem-causing nonlinear loads are large rectifiers and ASDs.

Nonlinear load current waveshapes always vary somewhat with the applied voltage waveshape. Typically, the current distortion of a nonlinear load decreases as the applied voltage distortion increases – thus somewhat of a compensating effect. As a result, most nonlinear loads have the highest current distortion when the voltage is nearly sinusoidal and the connected power system is “stiff” (i.e., low impedance).

In most harmonics' simulation cases, these waveshape variations are ignored and nonlinear loads are treated as fixed harmonic current injectors whose harmonic current magnitudes and phase angles are fixed relative to their fundamental current magnitude and angle. In other words, the harmonic current spectrum of a nonlinear load is usually assumed to be fixed in system simulation studies. The fundamental current angle, which is almost always lagging, is adjusted to yield the desired displacement power factor. Harmonics phase angles are adjusted according to the time shift principle to preserve waveshape appearance.

I.9.3.THD

The most commonly-used measure for harmonics is total harmonic distortion (THD), also known as distortion factor. It is applied to both voltage and current. THD is defined as the rms value of the harmonics above fundamental, divided by the rms value of the fundamental. DC is ignored. Thus, for current,

$$THD_i = \frac{\sqrt{\sum_{k=2}^{\infty}\left(\frac{Ik}{\sqrt{2}}\right)^2}}{\frac{I1}{\sqrt{2}}} \qquad (I,1)$$

The same equation form applies to voltage THD_V. **[15]**

I.9.4. Impact of harmonic pollution on underground power cables

I.9.4.1. Increase in Joule losses

The presence of harmonics will, for the same power, increase the effective value of the current flowing in the electric cables. As a first approximation, the losses in a cable are the Joule effect losses, which are proportional to the square of the RMS value of the current. It is then easy to understand that the current harmonics will create additional losses in electrical cables. The calculation of Joule losses in cables can be defined as follows

$$P_j=\sum_{n=1}^{\infty} RI^2 = R_1 I_1 + \sum_{n=2}^{\infty} RI_n^2 = P_1 + P_h \quad (I,2)$$

The neutral conductor of LV cables will also be affected by the presence of current harmonics on electrical networks because the homopolar components flow in it. This increase of losses, created by the harmonics circulating in the cables, will increase the operating temperature of the cable. **[16]**

I.9.4.2. Increase in temperature

The increase of the Joule effect losses in the cables will increase the temperature of these, and in particular in the ducts containing the 3 phases and the neutral. In an installation with non-linear loads generating a lot of harmonics 3, the current in the neutral can reach 1.73 times that of the phase while the neutral often has the same or a smaller the same cross-section or a smaller cross-section than the phase.

I.9.4.3. Influence on the life cycle

The increase in the operating temperature of the cables will result in premature aging of the insulation surrounding the conductor, and therefore a reduction of the cable life. The aging law mainly used is the Arrhenius law. The increase in temperature will considerably reduce the theoretical lifetime of the cable. (50% reduced lifetime for a THDi of 24%).

I.9.4.4. Special case of the neutral conductor

The increasing presence of non-linear single-phase loads with a high harmonic 3 component on the electrical network will lead to problems at the neutral conductor. In balanced mode, with linear loads connected to the three-phase network, the current in the neutral is zero but currently, because of the numerous non-linear loads (computers, televisions, low consumption lamps...), the harmonic content of the current is rich. The RMS value of the current in the neutral can reach, in the worst case, 1.73 times the RMS value of the current in the phase.

These non-linear loads can then create an excess of current in the neutral which could lead in the worst case to a fire.

I.10. Magnetic fields above an underground cable:

Underground cables laid in a "non-joined cloverleaf" with a concrete coating with a transit of 1000 A, the magnetic fields measured at 1 m above the ground are given by table 1.2:

Voltage	The axis	5 m	10 m
400 kV	13,2 µT	2,7µT	0,7 µT
225 kV	11,5 µT	2 µT	0,6 µT
63/90 kV	8,6 µT	1,4 µT	0,4 µT

Table I.2: magnetic field of an underground line. **[17]**

Magnetic fields vary with the intensity of the current carried and the distance, temperature, the nature of the earth. **[13]**

Underground cables do not produce an electric field. Indeed, this one is inside the metal sheath that surrounds the conductors. Magnetic fields are not attenuated by the underground burial of the conductors. Underground cables generate magnetic fields that can be even greater than those generated by an overhead line, but they decrease faster with distance. **[18]**

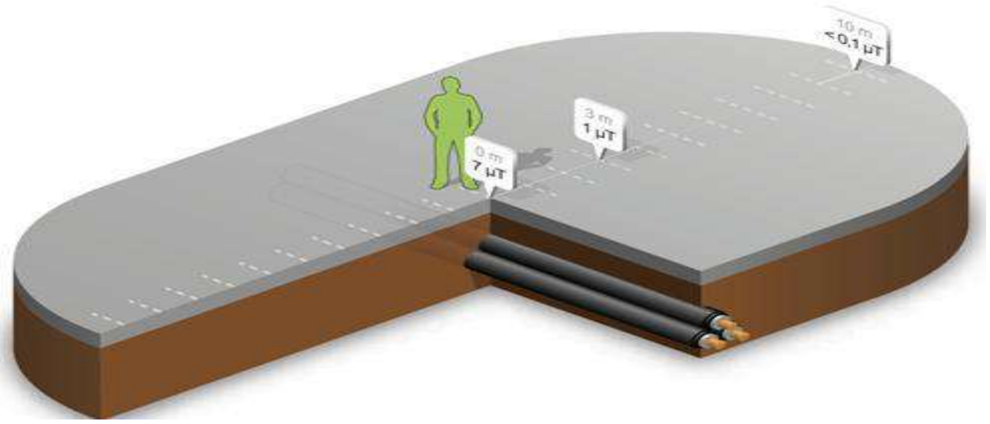


Figure I.9: cross section of an earth contains an underground line. **[18]**

A person standing just above the centerline of an underground cable is exposed to a magnetic field of about 7 µT at the feet level (but five times lower at height, figure 1.9). At a distance of 3 m from the cable axis, the field does not exceed micro-Tesla (regardless of the measurement height) and becomes quite negligible at10 m. **[18]**

I.10.1. Short-term effects

Electromagnetic fields can exert a force on electrically charged particles in the human body, and even particles in the human body, and even induced currents can lead to biological changes in the body. The nervous system is the most sensitive to the effects of the fields. They can see flashes of light in their field of vision because the retina is highly innervated. Uncontrolled contractions of their muscles.

I.10.2. Long-term effects

Epidemiological studies have long shown a weak statistical link, but nevertheless significant, between prolonged exposure to low-frequency magnetic fields generated by the high-voltage network and an increased risk of leukemia in children and even other diseases for technicians and maintenance workers. This refers to residential exposure to magnetic fields averaging greater than 0.3 - 0.4 µT over a prolonged period.

I.10.3. Difference between the field profile of an overhead line and an underground cable

The figure on the right illustrates the difference in magnetic field below a transposed 150 kV overhead line and above a 150 kV underground cable, measured respectively at 1.5 m from the ground and at ground level notice figure I.10 The maximum field is at ground level, just above the axis of the underground cable, can be up to 2 times higher than under an overhead line. However, it decreases very quickly. Thus at 10 meters from the axis of the underground cable, the field is already insignificant.**[18]**

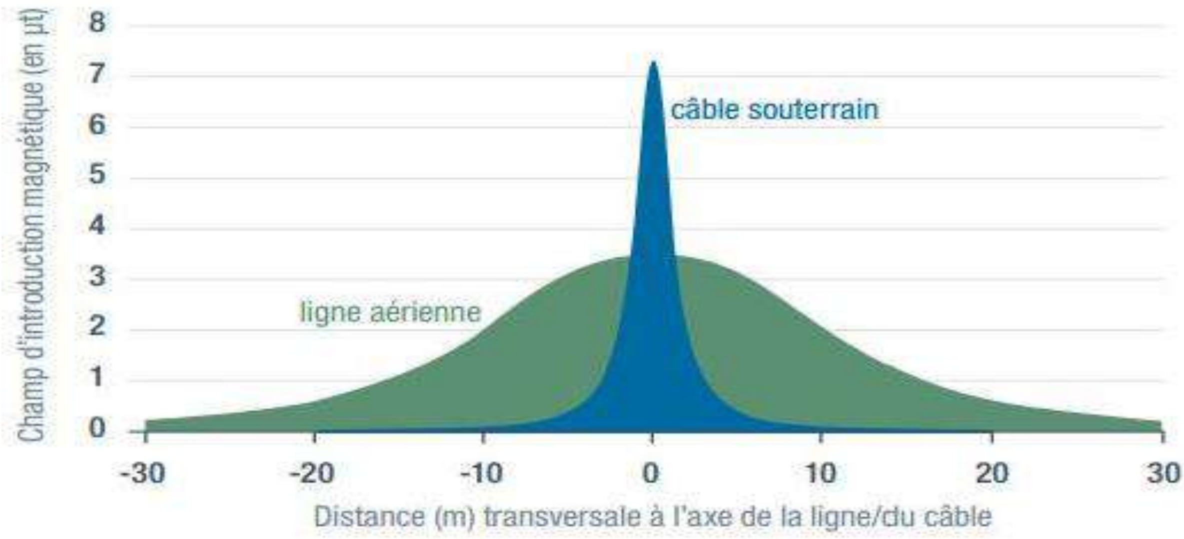


Figure I.10: Difference between the field strength of an overhead line and an underground cable. **[18]**

I.11. Factors affecting, over time, the insulation of an underground cable:

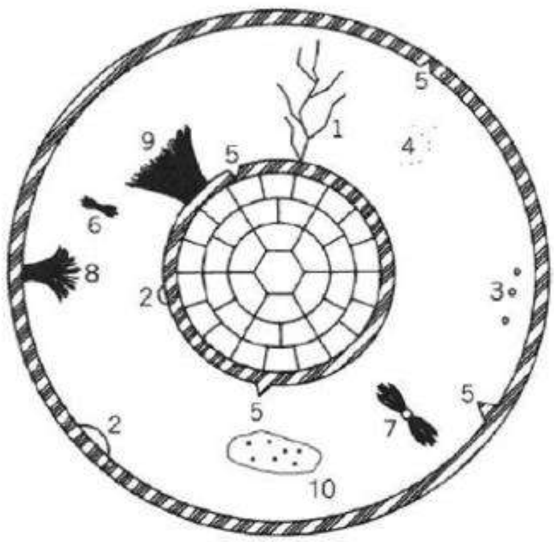
Underground cable insulation is never perfect. Not only are there defects that are a direct result of the production of the cable, but also the insulation inevitably ages.

When a cable is in service, its insulation is subject to thermal, electrical, mechanical and environmental stresses. Over time, these various loads (Table I.3) cause irreversible changes in the insulation. We generally speak of an intrinsic ageing of the cable concerned, during which the insulation degrades in a homogeneous way. **[19]**

Thermal	Electrical	Environment	Mechanics
Maximum temperature Ambient temperature Thermal gradient Thermal cycle	Voltage (AC, DC) Current Frequency Pulse	Gases (air, O2) humidity Water Corrosion	Flexion Traction Compression Torsion Vibration

Table I.3: Factors affecting the insulation of an underground cable over time**.**

In addition, premature aging of cables can be caused by contaminants (foreign particles), defects, protrusions or voids that appear in the insulation during production, transportation or installation of the cable. Initially, these imperfections are localized defects in the insulation. However, over time, they can worsen and progressively propagate within the insulation when the cable is in service. They can even involve the complete destruction of the insulation. **[19]**



1- Electrical tree
2- Empty in the interface
3- Vacuum in the insulation
4- Contaminant
5- Protrusion in semi-conductor
6- Discharge from a contaminant
7- Discharge from a vacuum
8- Discharge from an insulator
9- Discharge from a conductor
10- Humidity

Figure I.11: Imperfections in a single-phase cable. **[11]**

I.12. Defects in the cables

The primary function of an electrical cable is to carry a current. When a cable no longer performs this fundamental function, it is said to be in clear fault (short circuit, open circuit). But it can also be affected by a fault that does not interrupt the routing of the currents that flow through it.

The non-critical defect: the initial state, and therefore the original physical characteristics of the cable are altered. These alterations can affect the geometry or the electrical and/or mechanical properties of the components and materials.

Non-clear defects are not usually an immediate threat, but they may indicate advanced aging or an area of intense stress and thus be a precursor to a more serious defect (clear defect).

This aging can be accelerated by an aggressive environment and the occurrence of degradation due to local stresses. Indeed, several constraints are likely to be applied locally to the cables:

- Exposure to hot spots, e.g. from running the cable close to a hot pipe.
- High levels of humidity, even immersion.
- Irradiation due to exposure to ionizing radiation.
- Mechanical stresses such as very small bending radii, cable pinching, or vibration.
- Chemical attacks resulting from contamination by reagents (borated water, coolants)

These constraints are all causes of defects inherent to the environments in which the cables operate. When they are prolonged, they can cause a modification of the geometry of a cable (spacing between conductors, tearing of the screen, abrasion of the insulation) or material properties (permittivity, conductivity, etc.). Note that assembly or manufacturing defects can be added to the above-mentioned phenomena. . Figure I.12 shows damaged cables above a nozzle in a power plant **[20]**

Figure I.12: Locally damaged cables. **[20]**

I.13. underground cable monitoring

The breakdown of cable insulation leads to its failure to transmit power, so the protection of underground cables depends mainly on protecting their insulators, which are usually made of materials that bear a certain temperature. This means the need to monitor the cable's temperature and limit its rise to dangerous levels. Among the devices used to monitor the temperature of the cables there is the infrared camera, a thermocouple, as well as temperature sensors.

I.13.1. Thermal Imaging

It seems appropriate to start by describing what is meant by thermal imaging. It is a well-known fact of physics that a body at a temperature greater than absolute zero (−273°C) emits electromagnetic (EM) radiation. Absolute zero is the temperature where the lowest quantum energy states for electrons, atoms, and molecules are occupied and no transitions between energy states are possible that would result in the emission of EM radiation. At temperatures above absolute zero EM radiation is emitted, and the amount of radiation and its distribution over the wavelength spectrum will depend primarily on the temperature of the body and a characteristic of its surface known as its emissivity. The latter will normally be a function of wavelength and may, to a lesser extent, also depend on the temperature of the object. The maximum radiation energy that can be emitted by a body at a given wavelength a function of its temperature and its surface emissivity for that particular wavelength. **[21]**

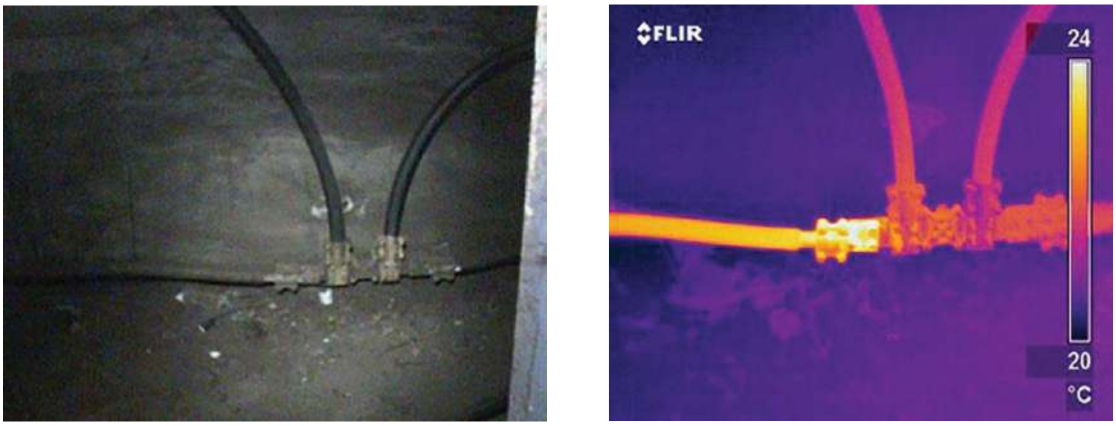


Figure I.13: This thermogram shows an increased temperature (white area) at a cable termination

I.13.2. The thermocouple

The thermocouple must surely be one of the simplest measuring devices ever conceived. What could be simpler than two different wires joined at one end? With this arrangement, a voltage is produced along the wires that increases in magnitude as the temperature difference between the joined end and the open-end increases. All that is needed to determine the temperature at the junction of the wires is to measure the voltage at the open end, make adjustments to compensate for differences between the open-end temperature and the open-end temperature used in calibration, and convert this compensated voltage into temperature using the calibration for the wire types.

This approach is a proven technology for temperature measurement in industry. Thermocouples account for more temperature measurements in U.S. industry than any other sensor type. Thermocouples are rugged, inexpensive, and easy to use. However, they have significant inherent inaccuracies and a tendency to degrade with use. Users should understand these phenomena so they can properly assess the accuracy of their measurements, select the proper thermocouple for a given application, and install and operate the thermocouple in the most advantageous way.

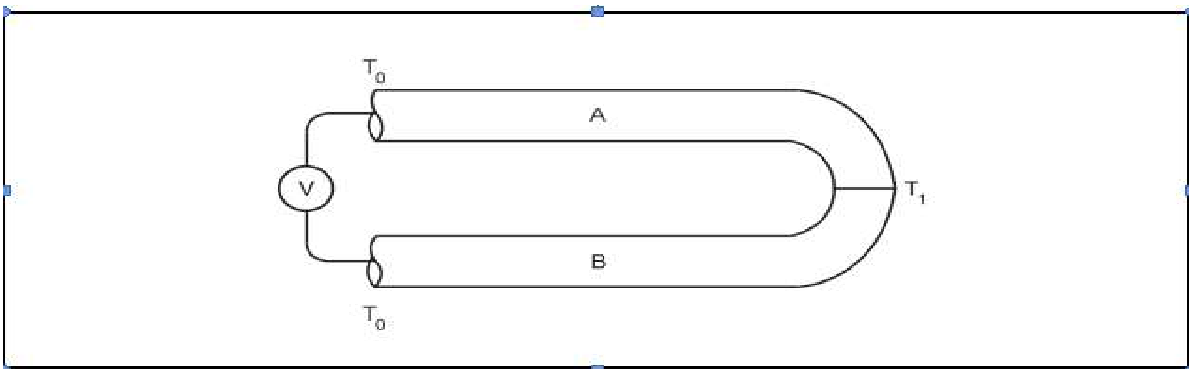


Figure I.14: Schematic View of Thermocouple

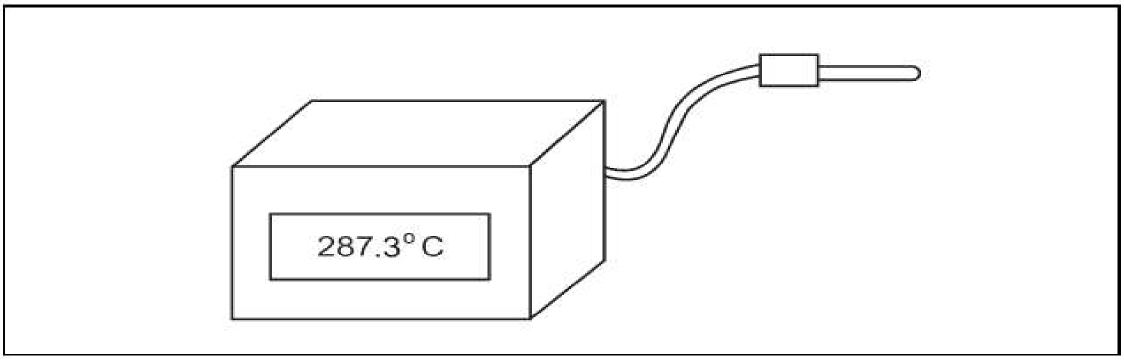


Figure I.15: Thermocouple in Practical Applications **[22]**

I.14. Conclusion

In this chapter, we have presented general information about power cables, We've made: a comparison between overhead power lines and underground power cables, We also saw the general structure of the power cable and its various classifications, the different types of underground cables available, And some phenomena associated with the electric current, such as the electromagnetic field, the electric field, the phenomenon of harmonics and their effect on the cable and the surrounding environment, finally we mentioned some of the defects that can occur in cables, and some techniques of cables monitoring.

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). **[5,23,25]**

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) **[5,26,30].**

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

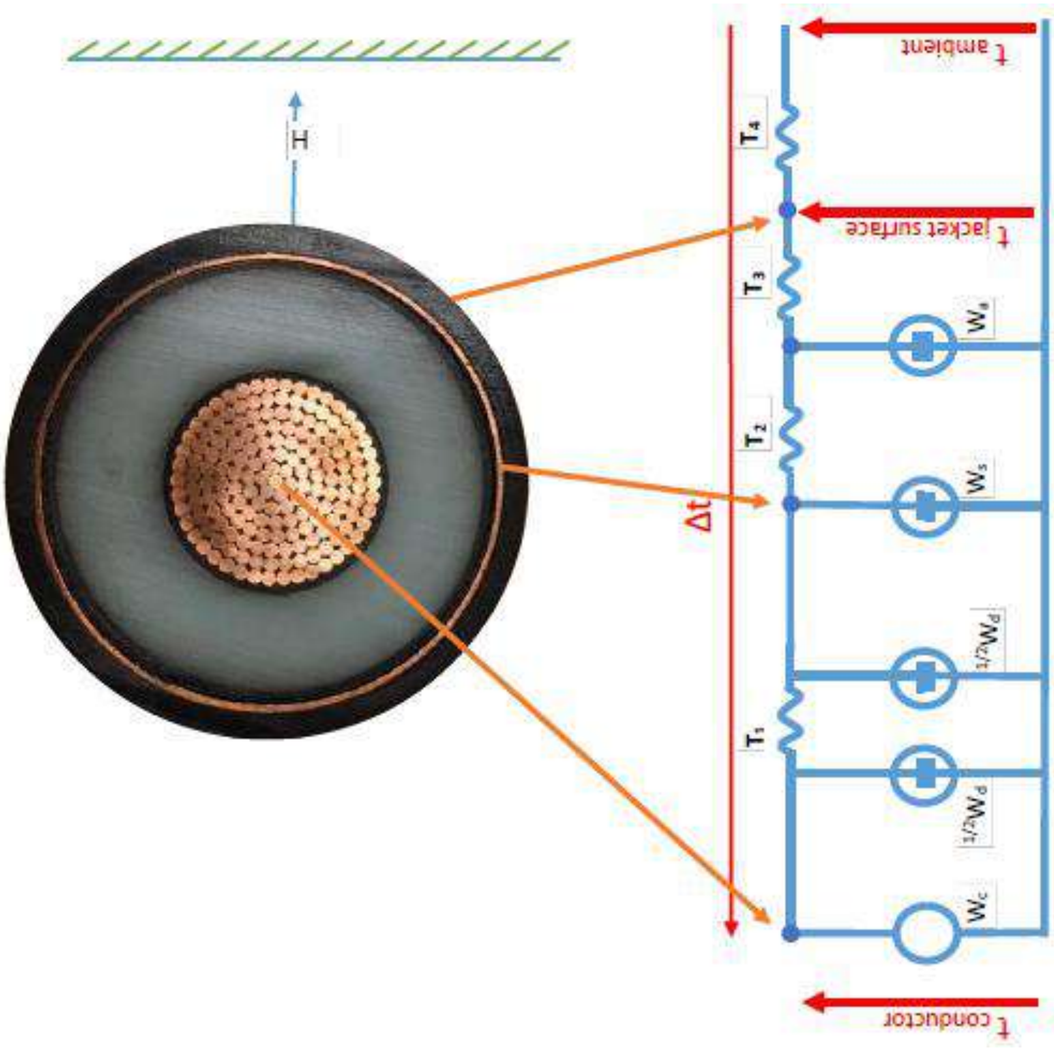


Figure II.1: Thermal equivalent circuit of underground Cable. **[5]**

II.2. Calculation principles:

The ampacity depends 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 depends 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.

3. Calculate dielectric loss in different 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. **[5]**

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

$$W_c = \mathrm{I}^2 R_{ac} \quad (2)$$

$$W_d = \omega C U_o^2 \tan\delta \quad (3)$$

$$W_s = \lambda_1 W_c \quad (4)$$

$$W_a = \lambda_2 W_c \quad (5)$$

We substitute the equation 2 to 5 in 1

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

$$\Delta\theta = \theta_c - \theta_a$$

$$\theta_c = \Delta\theta - \theta_a$$

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

Where:

Δt : is the temperature rise in the cable.

W_d: is the dielectric losses.

θ_a: is the ambient temperature.

I: is the load current.

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

T1: is the thermal resistance of the insulation.

T2: is the thermal resistance of the shield/sheath.

T3: is the thermal resistance of the jacket.

T4: is the thermal resistance between cable surface and ambient.

λ: is the loss factor of screen.

n: is the number of cables. **[5]**

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. **[5]**

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:

$$W_d = \omega C U_o^2 \tan\delta \left[{}^{W}\!/_{m}\right] \tag{8}$$

Where:

$\omega = 2\pi f$

$tan\delta$=the dissipation factor

U_0= the voltage to earth

C = the capacitance of the cable

$$C = \frac{\varepsilon}{18ln^{Di}/_{dc}} 10^{-9} [{}^{F}\!/_{m}] \tag{9}$$

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]. **[5]**

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:

$$R_{dc20} = \frac{1.02\times10\text{^}6\times\rho20}{A}[1+\alpha_{20}(\theta-20)][^{\Omega}/_{m}] \tag{10}$$

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"). **[11]**

$$\lambda_1 = \lambda_1{}' + \lambda_1{}'' \tag{11}$$

Where:

$$\lambda_1' = \frac{R_{sl}}{R_{ac}}\frac{1}{1+(\frac{R_{sl}}{Xsl})^2} \tag{12}$$

$$X_{sl} = 2\omega.10^{-7}ln\frac{2s}{d} \tag{13}$$

Where:

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

$$\omega = 2\pi f \text{ [rad/s]} \tag{14}$$

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 **[11]**

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

$$R_{sl} = R_{so}[1 + \alpha_{20}(\theta_{sc} - 20)] \qquad [\Omega/m]. \qquad (15)$$

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:

$$T_1 = 0.00522\rho_i G \text{ or } T_1 = \frac{\rho_i}{2\pi}\ln\left(\frac{\text{Doi}}{\text{Dc}}\right) \qquad [°C/w] \qquad (16)$$

And,

$$G = \ln(D_c + 3T_i) - 0.86\ln(D_c) + 0.05 \qquad (17)$$

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] **[5]**

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.

$$T_2 = 0 \qquad [°C/W] \qquad (18)$$

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.

$$T_3 = \frac{\rho_j}{2\pi}\ln\left(1+\frac{2t3}{D'ij}\right) \quad \text{or} \quad T3 = \frac{\rho_j}{2\pi}\ln\left(1+\frac{D'oj}{D'ij}\right) \quad [°C/W] \tag{19}$$

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]. **[5]**

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. **[5]**

$$T_4 = T_4{}' + T_4{}'' + T_4{}''' \tag{20}$$

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

$$\boldsymbol{T_4{}'} = \frac{\boldsymbol{U}}{\boldsymbol{1+0.1(V+Y\theta m)De}} \quad [°C.m/W] \tag{21}$$

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 $T''4$:

$$T_4{}'' = \frac{\rho T}{2\pi}\ln\left(1+\frac{D_o}{D_d}\right) \tag{22}$$

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:

$$\boldsymbol{T_4}''' = \frac{\boldsymbol{\rho T}}{\boldsymbol{2\pi}} \ln \left(\frac{\boldsymbol{4H}}{\boldsymbol{D_o}}\right) \tag{23}$$

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:

$$T_{air} = \frac{1}{h \times A_{air}} \quad [°C/W] \tag{24}$$

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

L = Sample cable length 15.25m

$$A_{air} = \frac{L^2}{4\pi} \tag{25}$$

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.

$$\theta_{c,}(I,t) = \Delta\theta_c \left(1 - e^{-t/R_T C_T}\right) + \theta_{ci} \quad [\,°C\,] \tag{26}$$

The rise in temperature from equation six is given as

$$\Delta\theta_c = (I^2R_{ac} + 5W_d)T_1 + [I^2R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4) \quad (27)$$

Equation 6 in 28

$$\theta_{c,(I,t)} = (I^2R_{ac} + 5W_d)T_1 + [I^2R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4)\left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad (28)$$

Hence

$$\theta_{ins,(I,t)} = [\theta_c - (I^2R_{ac} + 5W_d)T_1]\left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [\,^\circ\mathrm{C}\,] \quad (29)$$

$$\theta_{ins,(I,t)} = [I^2R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4)\left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [\,^\circ\mathrm{C}\,] \quad (30)$$

Hence

$$\theta_{jac,(I,t)} = [\theta_c - [I^2R_{ac}(1 + \lambda_1 + \lambda_2) + W_d](T_3 + T_4)]\left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [\,^\circ\mathrm{C}\,] \quad (31)$$

$$\theta_{jac,(I,t)} = (I^2R_{ac} + 5W_d)T_1 \times \left(1 - e^{-t/R_TC_T}\right) + \theta_{ci} \quad [\,^\circ\mathrm{C}\,] \quad (32)$$

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 rises in the cable θ_{Ci} = initial conductor temperature $RTCT$ = 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** shows the specific heat capacity and density of some common cable layers. **[5]**

$$C_{Th} = V \times C_p \times \rho \quad (33)$$

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

Table II.1: Specific heat capacity and density of some common cable layers. [5]

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 performances.

Chapter III: Simulation of harmonics current presence in underground power cable

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. The electric power network is designed to operate at frequencies of 50 or 60Hz. However, certain types of loads produce currents and voltages with several frequencies that are integer multiples of the 50 or 60 Hz fundamental frequency. The superposition of harmonic currents on the first current fundamental causes the waveforms not sinusoidal associated with nonlinear loads. These multiple frequencies affect the power quality and they have a form of electrical pollution known as power system harmonics caused by saturated iron in transformers and machines in load and substation system. **[5,15]**

III.2. Introducing the HV power cable

The shape of a power cable is determined by the level of energy it transmits, the next figure shows the shape and dimensions of HV power cable.

FigureIII.1: XLPE Cable Sample The cable sample shown in Figure 5 is 138 kV XLPE power cable with copper conductor. **[5]**

III.2.1. HV cable shape

Figure III.2: size and shape of HV power cable

III.2.2. HV Cable characteristics

- Nominal voltage 138 kV
- Max. voltage 145 kV
- Relative permittivity 2.3
- XLPE loss factor 0.05%
- Cable length 15.25 m
- Conductor size 1000 mm^2
- Conductor diameter 40.9 mm
- Insulation thickness 15.011 mm
- Diameter over insulation 86.4 mm
- Cross-section of shield 180 kcmil
- Diameter over sheath 96.2 mm
- Overall jacket dia. 104.3 mm
- Capacitance 56.3 pF/ft **[5]**

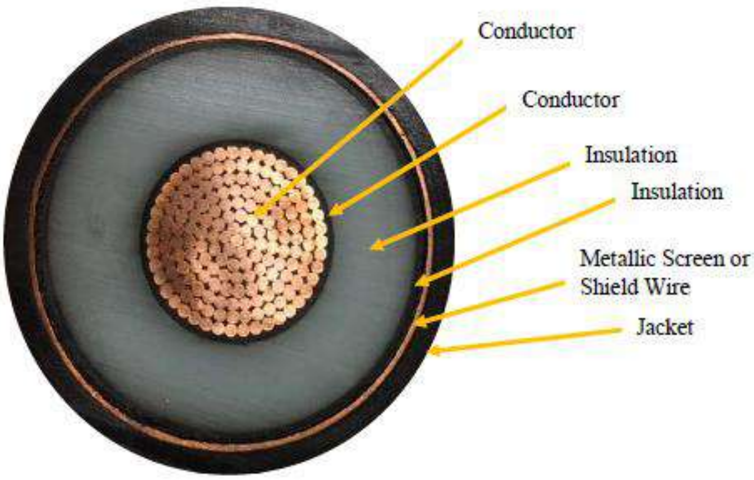


Figure III.3: XLPE Cable layers. **[5,8]**

III.3. Temperature calculation in underground parts:

The temperature calculation in underground parts change from part to another, the temperature variation depends 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.

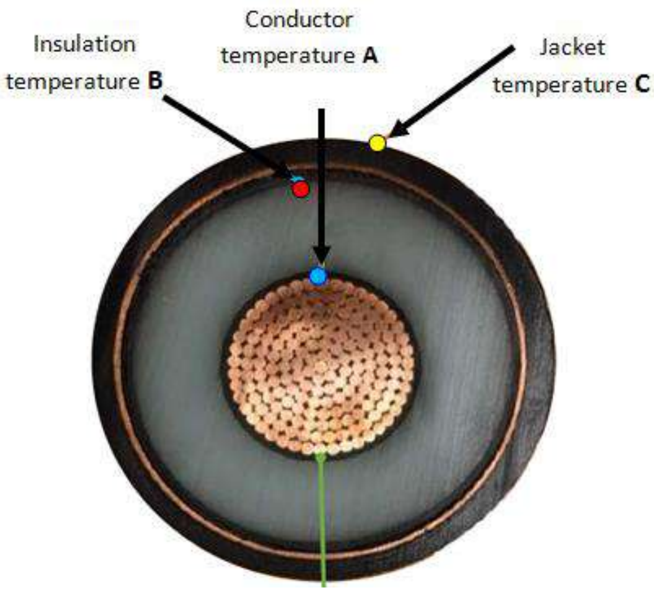


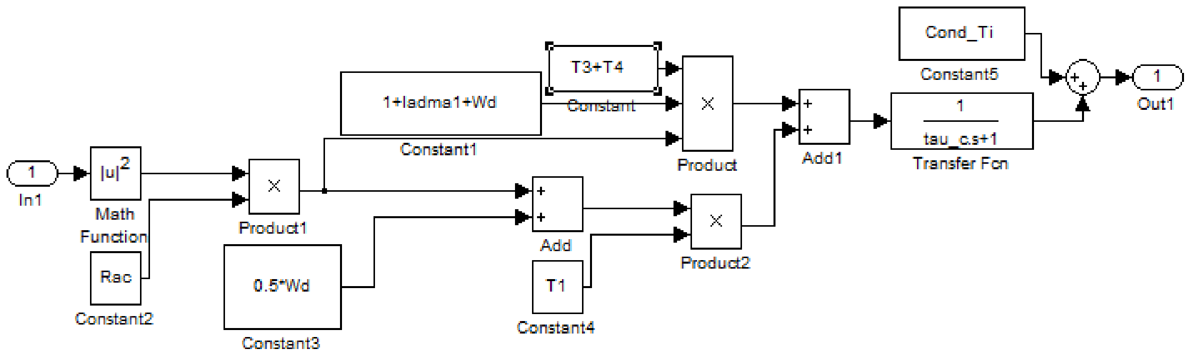
Figure III.4: Cross-section points positions. **[5]**

III.4. Temperature simulation of underground cables:

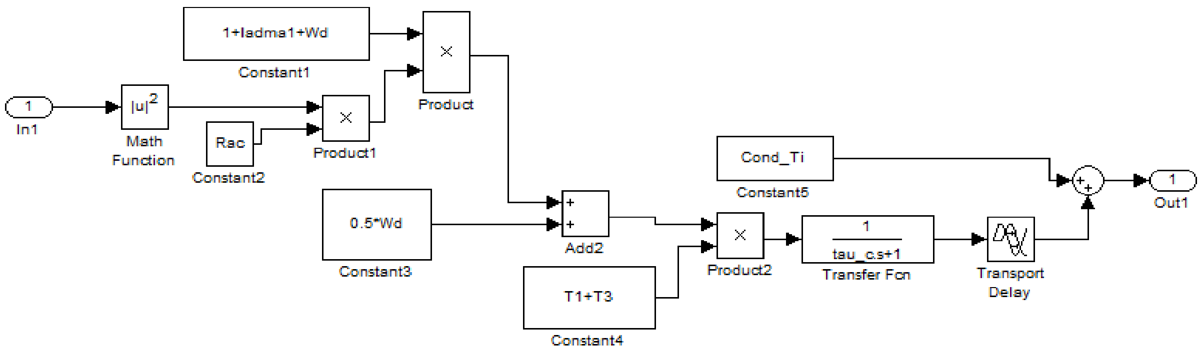
Using physical, electrical, geometrical parameters and the mathematical cable model developed in precedent chapter II, to compute the temperature at differents parts. The computation was done by the modele implementation in MATLAB Simulink.

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

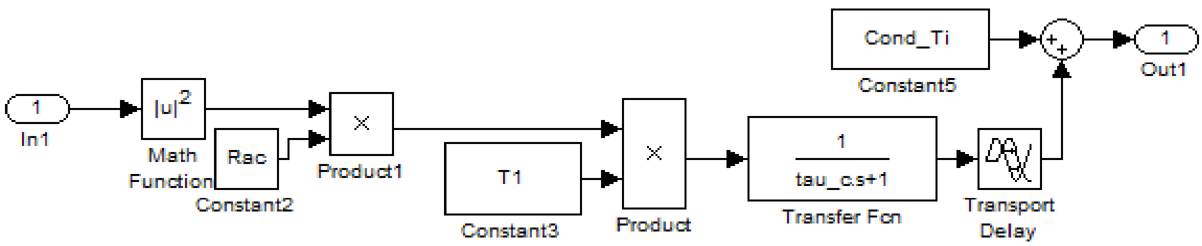
Figure III.5 show the closed loop control system; these subsystems models (MATLAB/Simulink) represent the conductor, jacket and isolation temperature (output conductor temperature in three set points) with load current flow through the underground cable. **[5]**



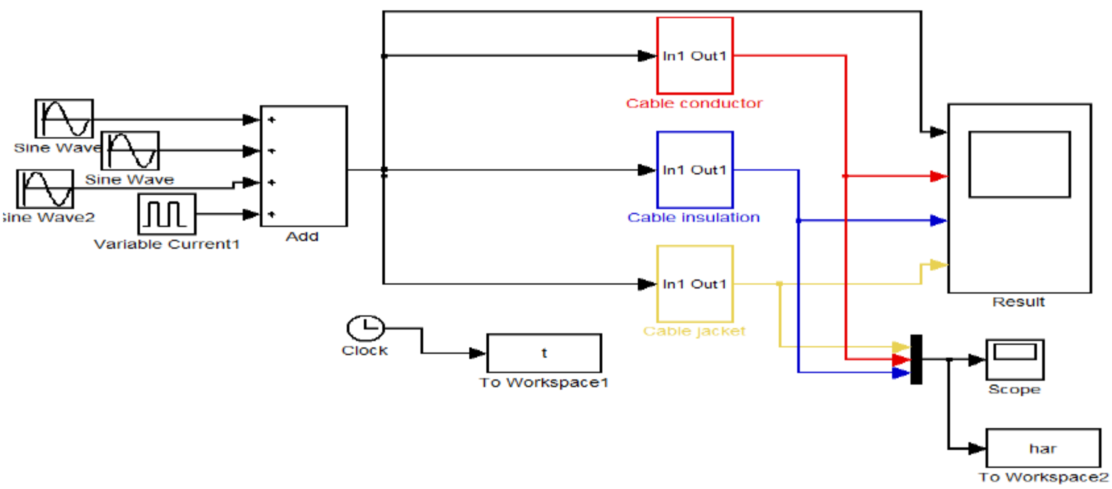
a. Conductor temperature model with current as input.



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

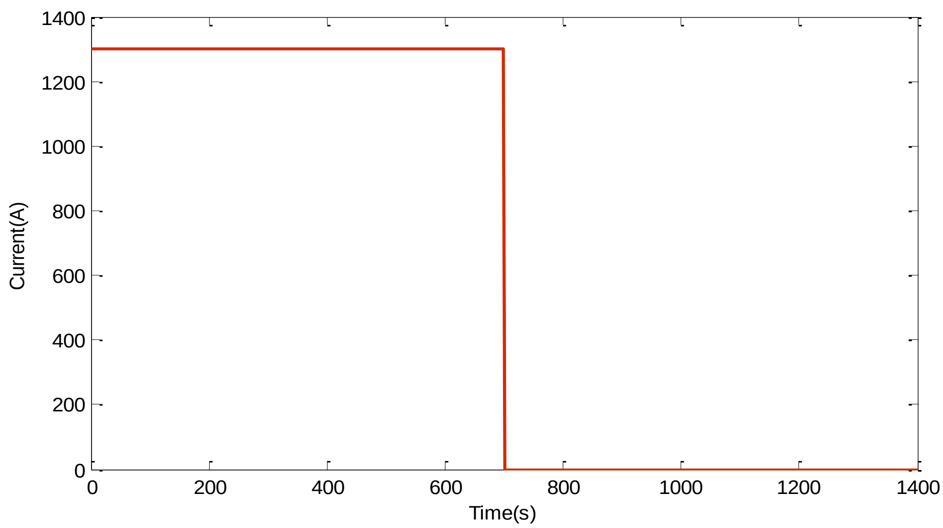
FigureIII.5: XLPE Cable model with current input and temperature output.

III.5. Simulation result

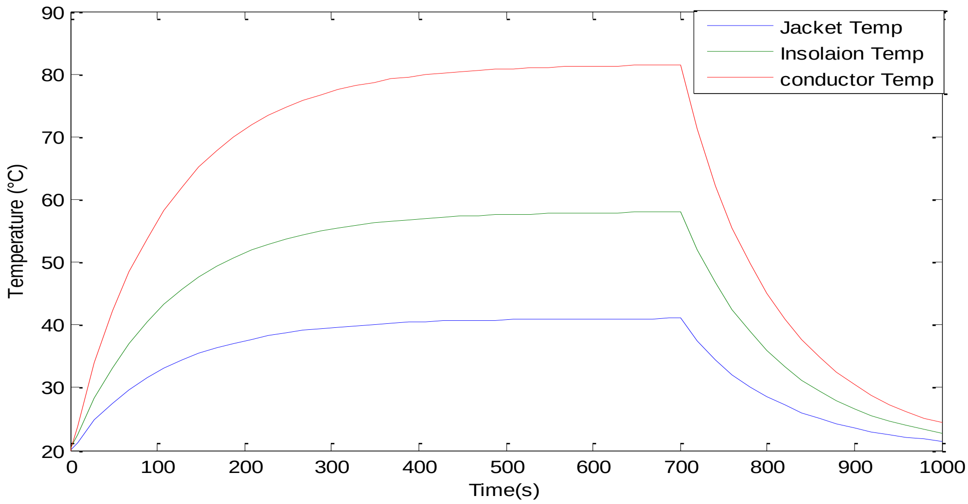
In this section we use the mathematical model of chapter II to implement them in the MATLAB software. The simulation aim is to represent the temperature variation with different THD current load in real time estimation of the conductor, each total harmonics current is characterized by waveforms, shape, magnitude and frequencies. The following curves show the different current waveform influence on the temperature parameters in three layers: jacket, insulation and conductor.

III.5.1. Conductor temperature with step load current

The load current waveform is represented by step signal to show the thermal behaviour of underground cable (figureIII.5. A)



a. Normal current load.



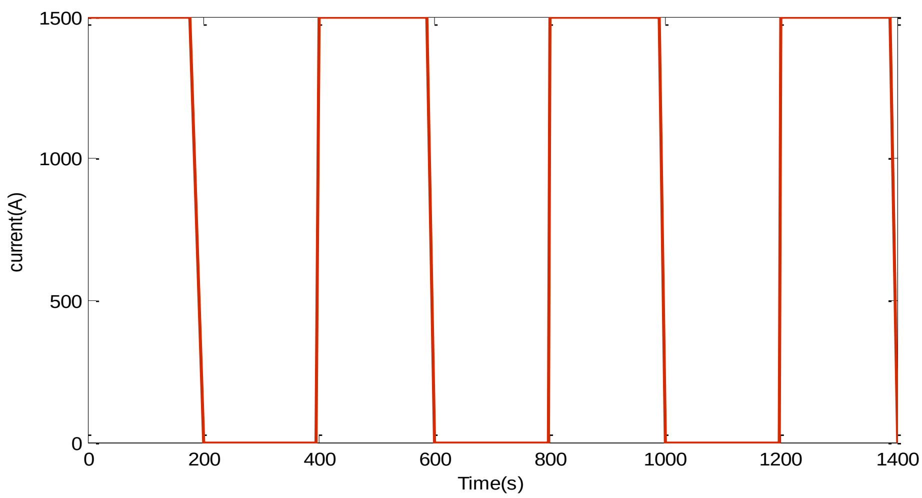
b. Thermal effect with step input

Figure III.6: Cable profile for 1000 seconds with insulated cable

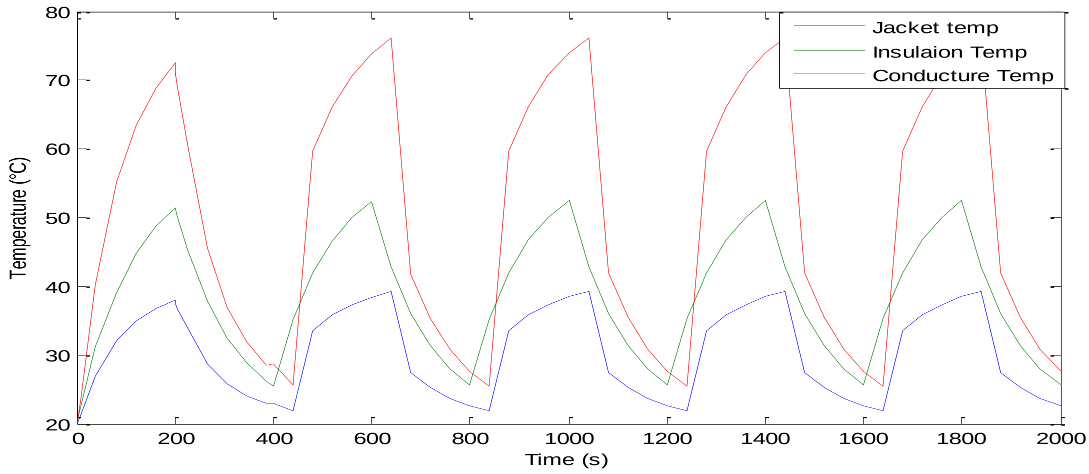
The response of control system model to the rate load current in steady state condition. The conductor temperature increases gradually with time variation in the different parts: conductor, jacket and insulation. The conductor temperature will be maintained after 500s with constant values affected by the load current flow through the cable. Figure III.6 below shows the result of the cable modeling when the load current is cut off after 700 s, the bleu curve represents the jacket temperature, the green curve represents the insulation temperature and the red curve represents the conductor temperature

III.5.2. 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.



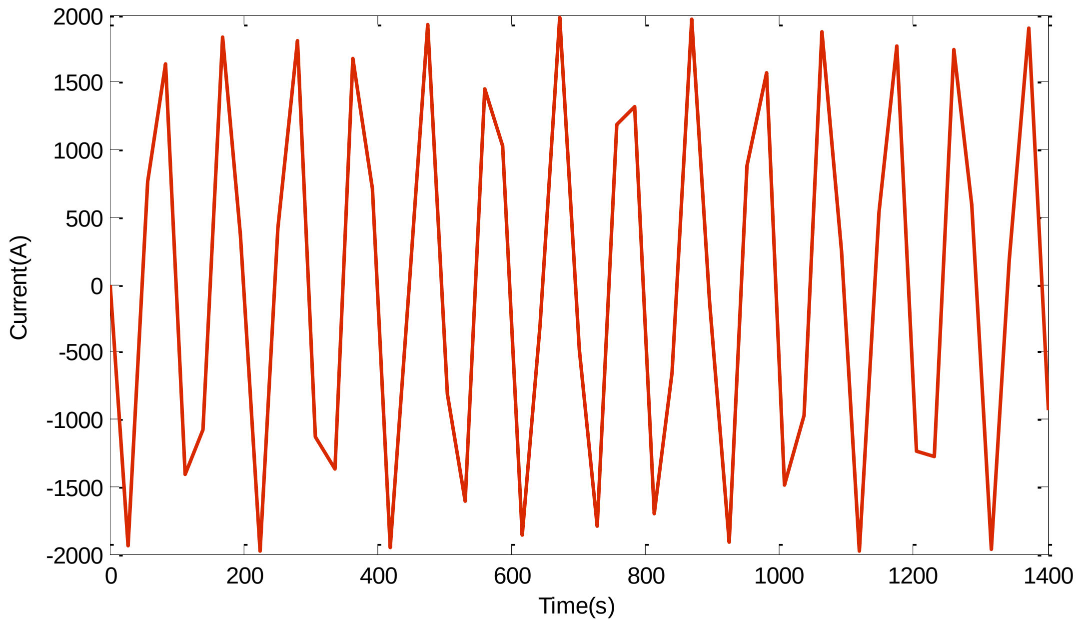
b. Thermal effect with repetitive step input.

Figure III.7: Cable profile for variable load current during 2000 s

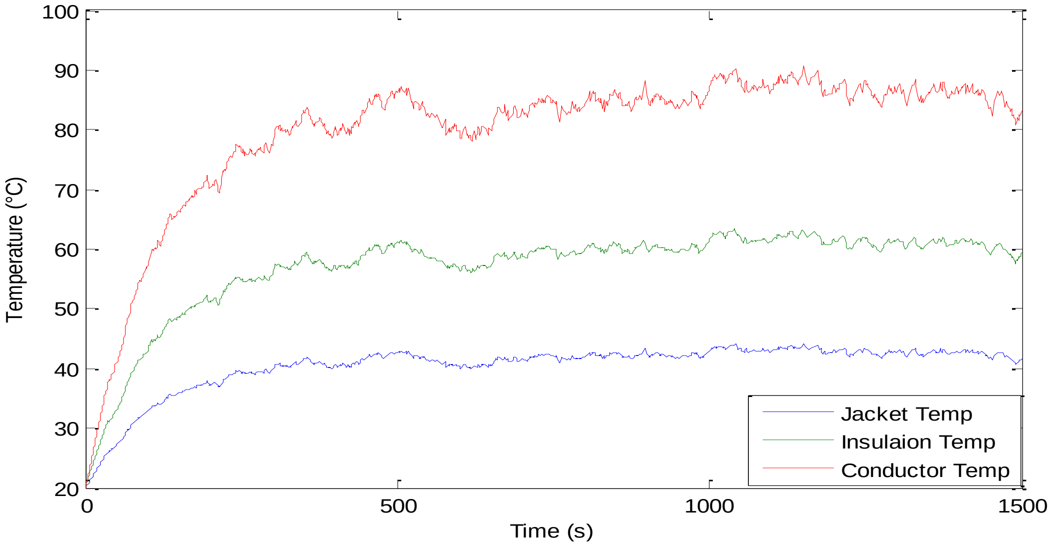
Figure III.7 represents the thermal effect of underground cable feed by repetitive load current, the current nature and form affect the temperature variation (repetitive responses characterized by period with retard time). Similar results between (step load and repetitive step) have been observed for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

III.5.3. 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 profile for sinusoidal signal during 1500 s

Figure III.8 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.5.4. Harmonic mode

In the tableIII.1, we present the supposed four THD cases flow in the underground cable.

	Harmonic (%)			
Range	**Case I**	**Case II**	**Case III**	**Case IV**
5	13.0	9.3	12.7	18.5
7	9.7	5	6.2	15.0
11	5.9	12	11.4	4.9
13	2.0	11	8.4	2.2
THD_I	17.4	19.6	20.1	24.4

Table III.1: Simulated harmonic currents through underground cable.

III.5.4.1. THD=17.4%

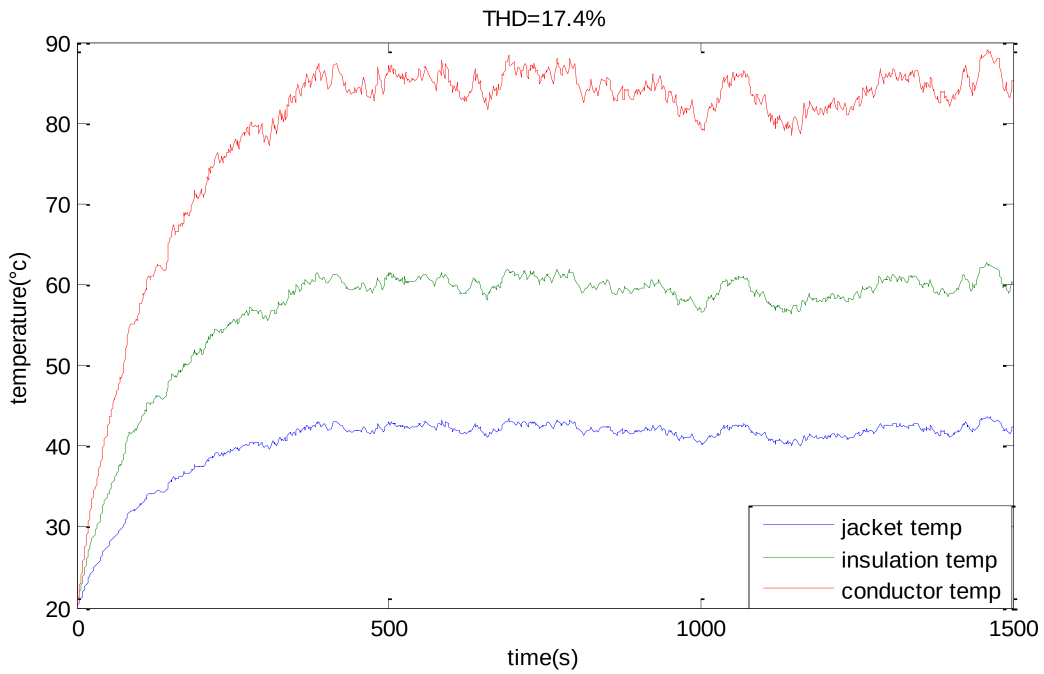


Figure III.9: cable temperature in underground cable with THD=17.4%

Figure III.9 9 shows the result of cable modeling when transmitting a current with a distortion ratio of 17.4% during 1500 seconds, from results we can see the difference between figure III.8 and figure IIII.9 by the variation of magnitude and waveform affected by the presence of harmonics.

III.5.4.2. THD=19.6%

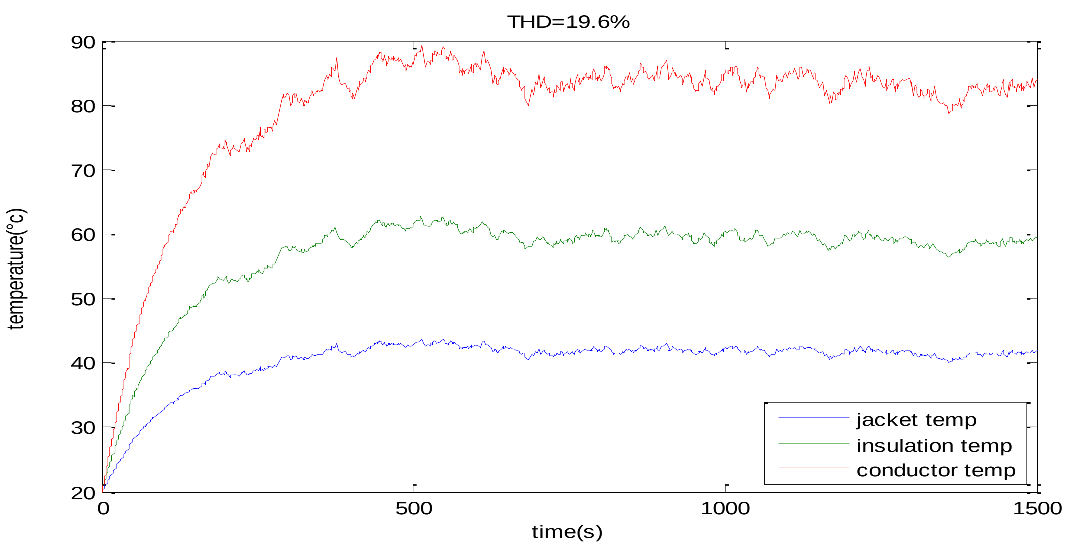


Figure III.10: Cable temperature with THD=19.6%

Figure III.10 shows the result of cable modeling when transmitting a current with a distortion ratio of 19.6% during 1500 seconds, here we can observe a slight different shape of the temperature curve compared to the previous curves, and this is definitely due to the different value of the THD.

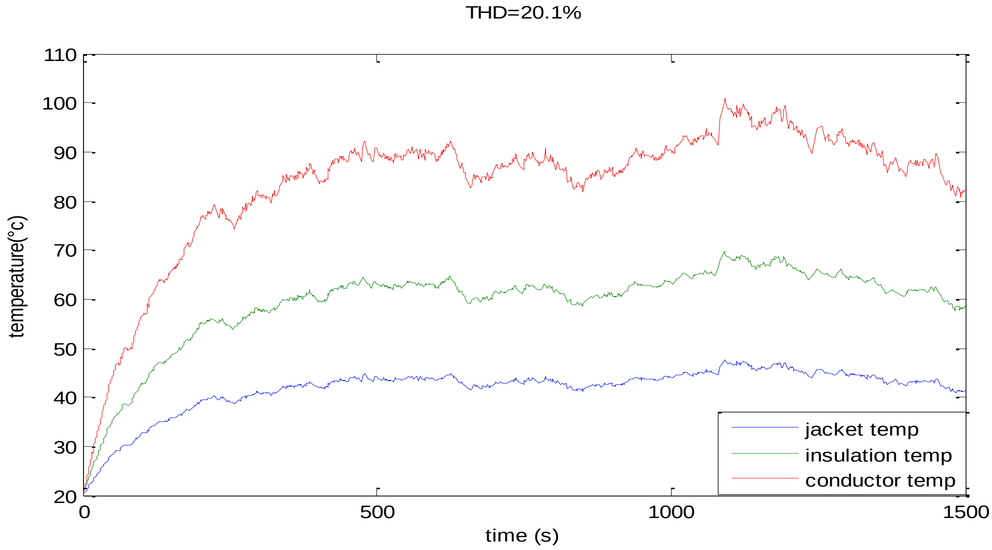


Figure III.10: cable profile with THD=20.1%

Figure III.10 shows the result of cable modeling when transmitting a current with a distortion ratio of 20.1% during 1500 seconds, the bleu curve represents the jacket temperature, the green curve represents the insulation temperature and the red curve represents the conductor temperature, where we can notice a slight increase in the temperature of the cable compared to the previous curve and this is due to the difference of THD.

III.5.4.3. THD=20.1 %

Simulated of harmonic currents in underground cable with THD=20.1% rate.

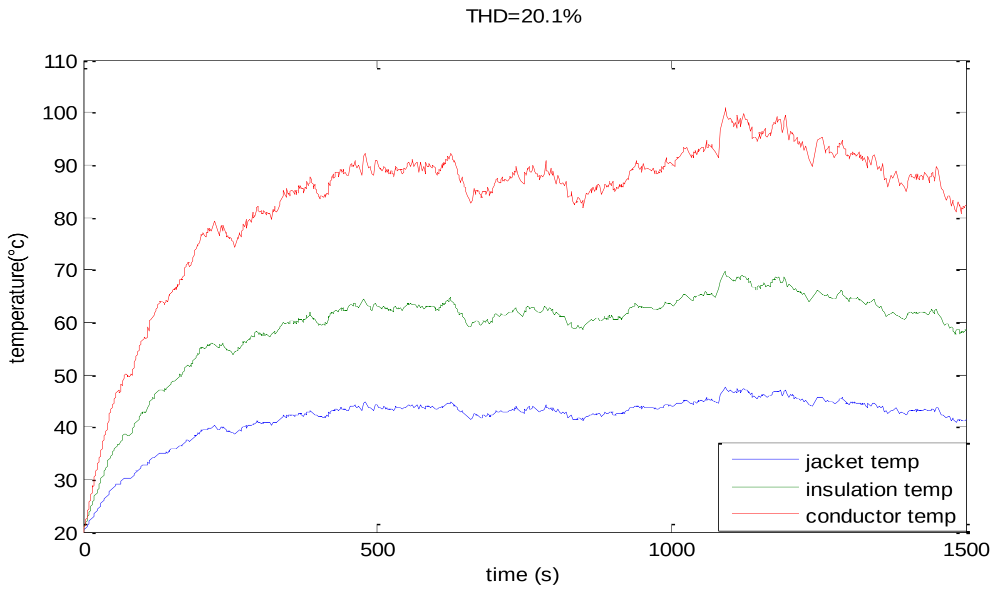


Figure III.11: Underground cable with THD=20.1%

Figure III.11 shows the simulation result of underground cable with current THD of 20.1%, where we can notice an important temperature increase (exceeds 90 in conductor even in the other cable layers temperature) of the cable compared to the previous figures and this is due to the increase of THD.

III.5.4.4. THD=24.4%

Simulated of harmonic currents in underground cable with THD=24.4% rate.

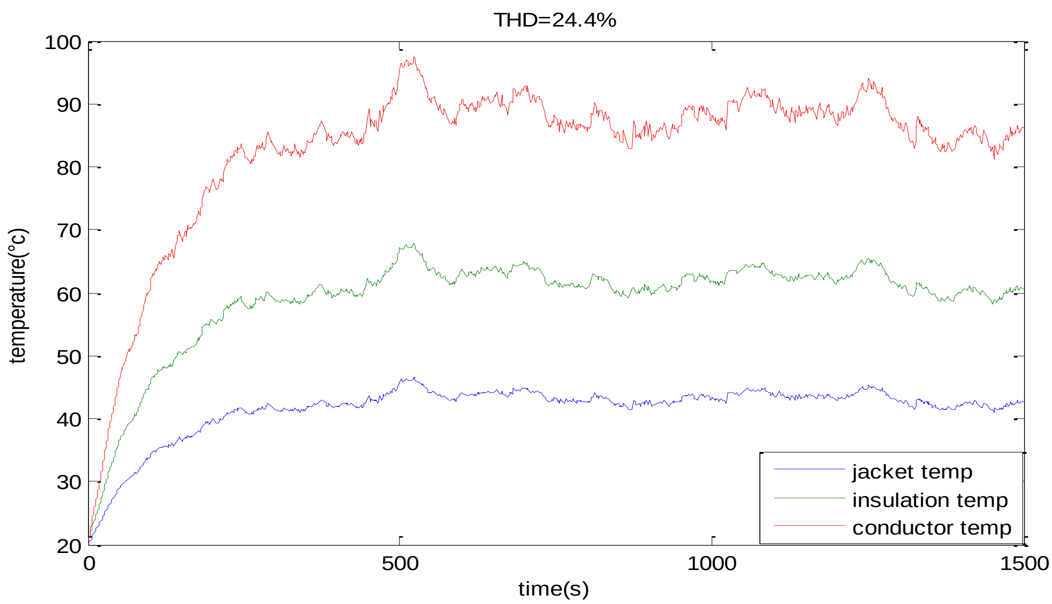
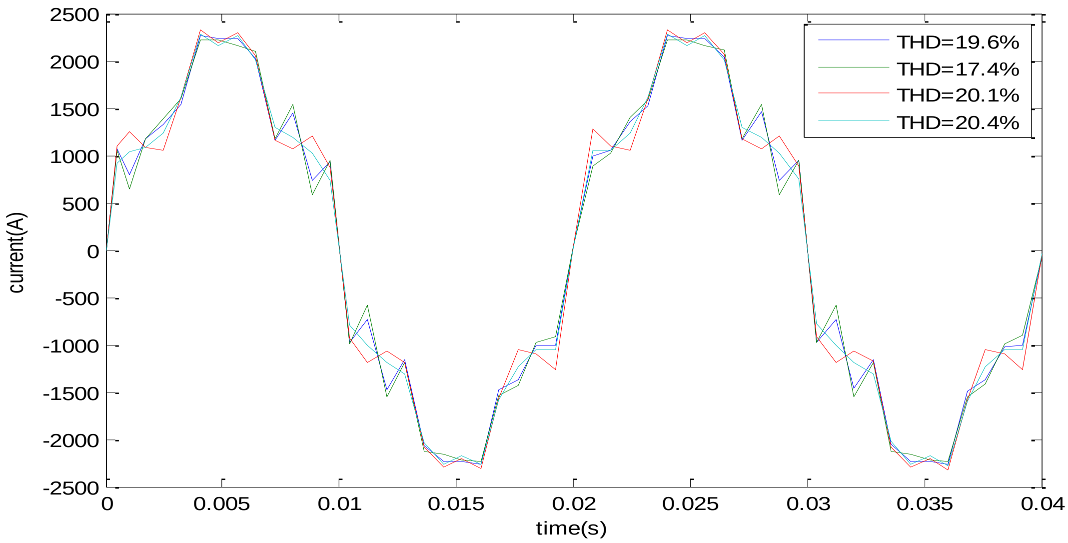


Figure III.12: Cable temperature with THD=24.4%

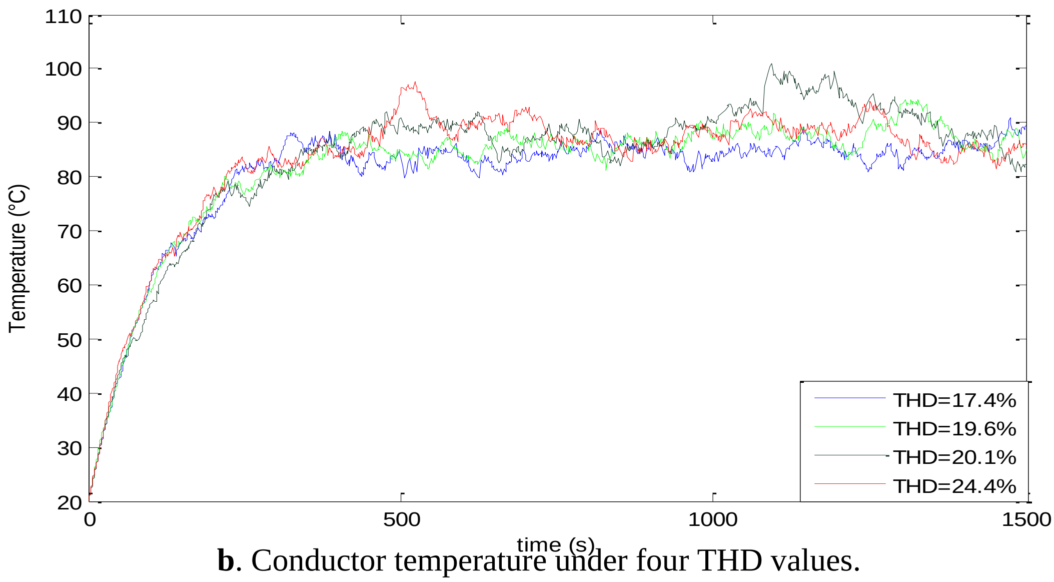
Figure III.12 shows the temperature simulation result of cable with a harmonics distortion ratio of 24.4%, Here, also, we notice a rise in the temperature of the cable (where the jacket, the insulation and the conductor temperature increase with important THD rate), and this is due to the heating effect between cable parts produced by the mutual inductive and capacitive phenomenon of high harmonics range value. Temperature increments are exponential because of their dependence on power loss.

III.5.4.5 Comparison between the effects of different THD values on conductor temperature

The following figure shows the four current cases with time representation.



a. Four total harmonics distortion rate currents



b. Conductor temperature under four THD values.

Figure III.13: conductor profile under different THD values

Figure III.13.B shows the difference in the thermal effect of different deformation values on conductor temperature, where we can see here the effect of four THD values. Cable power loss and heating rises considerably depending on THD% according to harmonic order. Even though low rates of THD% are causing little considerable temperature rising, high rates cause important heating's. For instance, harmonics cause until 100°C temperature conductor increment for 24 THD%. It is obviously seen that the THD 24% is the most cable components heating explained with power and dielectric losses.

III.6. Conclusion

In this chapter, we introduce the characteristics of the 138 kV cable, and present the results of cable modeling in different conditions: normal mode, repetitive signal, sinusoidal signal, Overload mode, short circuit mode, Finally, we saw the effect of the different distortion values in the current on the temperature of the different parts of the cable. The higher the distortion rate, the higher the cable temperature.

General conclusion

Harmonics are considered as one of the worst problems which affect the electric power quality, where it appear widely on the electrical networks all over the world, Because of the wide spread of non-linear loads, which considered as the main cause of harmonics, Therefore, work is being done to find solutions to this phenomenon, Which causes: distorted voltage on the grid, equipment malfunction and damage, a loss of electrical energy …etc**. [15]**

The main objective of this thesis is to show the impact of harmonic pollution on the heat of underground electric power cables, where we included mathematical models that simulate the various components of the cable in MATLAB, we obtained curves that show the heat of different parts of the cable under different conditions and different THD values.

The obtained simulation results showed the existence of a relationship between cable heat and harmonic pollution, Where the heat of the cable rises in the presence of harmonics, which leads to energy losses, that reduce the efficiency of the cable to transmits energy and reducing the life time of the cable.

Bibliographical references

[1] J. H. Neher and M. H. McGrath, "The calculation of the temperature rise and load capability of cable systems," Transactions of the American Institute of Electrical Engineers. Part III : Power Apparatus and Systems, vol. 76, pp. 752-764, 1957.

[2] Pierre BORNARD « Conduite d'un système de production-transport » EDF.

[3] EPRI, Underground Transmission Systems Reference Book, 2006 ed.: EPRI, Palo Alto, CA 2007 1014840.

[4] "SPECIFICATION FOR EXTRUDED INSULATION POWER CABLES AND THEIR ACCESSORIES RATED ABOVE 46 kV THROUGH 345 kVac," AEIC CS9-06, 2006.

[5] Ansovinus Akumawah Nche "Temperature modeling and control algorithm for high voltage underground cables" university thesis North Carolina 2017

[6] Mohamed Zellagui « câbles souterraines MT et BT. » university thesis batna2 2018

[7] Zellagui Mouhemed « Etude des protections des Réseaux électrique MT (30 et 10 KV) ». University mentouri constentine 2010

[8] Meziant Rachida et Sahli Siham « Calcul du champ électromagnétique généré par les Réseaux électriques en vue de la compatibilité électromagnétique. » End of study thesis University Abderrahmane mira – BEJAIA 2017

[9] Nexans France « Les câbles Souterraines HT. » technical notebook 2004

[10] Product Trang Catalog « câble basse tension » companies Helinc Cables S.A

[11] Pierre Lebas « diagnostic des câbles souterrains par détection de décharges partielles » Thesis Faculty of Applied Sciences University of Liège 2008

[12] Ferdinand de Lichtervelde « Les champs électromagnétiques dans les réseaux de distribution» Article: Transmission System Operator belgian.bruxele

[13] Philippe Follenfant « la maitrise de l'urbanisme autour des lignes de transport d'électricité» General Council for the Energy and Technology and Industry August 2010

[14] Scribd « Paramètres Lignes Electriques » technical notebook

[15] Prof. Mack Grady "Understanding Power System Harmonics" Dept. of Electrical & Computer Engineering University of Texas at Austin

[16] Wilfried Frelin « Impact de la pollution harmonique sur les matériels de réseau. » Thesis of Doctorate in Electrical Energy. University of Paris Sud - Paris XI, 2009

[17] Scribd « Paramètres Lignes Electriques » Technical notebook

[18] Elia Group company « Les champs électromagnétiques et le réseau à haute tension» Elia, Communication Department - February 2015

[19] Bouguerioune Noredine « Etude d'une décharge électrique a l'intérieure d'une vacuole dans un cable de haut tension » Master's thesis in electrical engineering University mouloud mammri de tizi-ouzou 2005

[20] Nassif Berrabah « Problèmes inverses pour le diagnostic de câbles électriques à partir de Mesures de réflectométrie » Doctoral thesis Rennes University 1, 2017

[21] Thomas L. Williams" Thermal imaging cameras characteristics and performances"

[22] Dr. Thomas W. Kerlin "Practical thermocouple thermometry"

[23] Abbas Abdelhai, Brahim Salah Abdalla « Étude temporelle des harmoniques dans les câbles électriques souterrains » master thesis Kasdi Merbah University Ouargla Algeria, October 2020.

[24] Smahi Walid, Slimani Ahmed « Simulation d'une agression rayonnée d'un câble électrique » master thesis Kasdi Merbah University Ouargla Algeria, June 2018, DOI:10.13140/RG.2.2.32699.98082 .

[25] Benchebiba Ismail , Makhloufi Omar « Simulation of high voltage submarine power cables » master thesis Kasdi Merbah University Ouargla Algeria, June 2020.

[26] Ayad .ANI, W.Krika, H.Boudjella, F.Benhamida, A.Horch, Simulation of The Electromagnetic Field in The Vicinity of The Overhead Power Transmission Line"European Journal of Electrical Engineering https://doi.org/10.18280/ejee.210108

[27] Krika Wafa , Ayad Ahmed Nour El Islam, Larouci Benyekhlef, Farid Benhamida « Electromagnetic simulation of subsea power cable pollution» International black sea coastline countries scientific research symposium VI Giresun, Turkey april 2021.

[28] Krika Wafa , Ayad Ahmed Nour El Islam, Larouci Benyekhlef, Farid Benhamida « Thermal effect of harmonic and short circuit in underground electric cable» International black sea coastline countries scientific research symposium VI Giresun, Turkey april 2021.

[29] Krika Wafa , Ayad Ahmed Nour El Islam, Larouci Benyekhlef, Farid Benhamida « Electromagnetic simulation of underground power cable perforation by nail» International black sea coastline countries scientific research symposium VI Giresun, Turkey april 2021.

[30] Merabet Haroune, Beriala Bilal « Simulation électromagnétiques des câbles électriques souterrains » master thesis Kasdi Merbah University Ouargla Algeria, July 2019 DOI: 10.13140/RG.2.2.28103.85928.

الخلاصة

تتأثر خطوط نقل وتوزيع الكهرباء تحت الأرض بشدة بجودة الطاقة وتعتمد على وجود التوافقيات وسلوك الأعطال الكهربائية في الشبكة الكهربائية. تولد التيارات التوافقية تسخينًا كبيرًا بين مكونات الكبل ، وتقليل العمر ، وتقليل عمر الخدمة. يقيِّم هذا العمل تباين درجات الحرارة لنظام كبل الطاقة تحت الأرض بمختلف THD باستخدام نموذج رياضي لمستوى الجهد للنظام المستخدم عند 138 كيلو فولت.

الكلمات المفتاحية - النموذج الحراري ، التيار التوافقي ، الكابلات الأرضية ، المؤشر الحراري

Abstract

The underground electric transmission and distribution lines strongly affected by energies quality and depends on the harmonic's presence and electric faults behavior of electrical network. The harmonics current generate an important heating between the components of cable, aging, decrease live time. This work evaluate the underground power cable system temperature variation with different THD using mathematical model for system voltage level were used 138 kV.

Keywords—Heat model, harmonic current, underground cable, thermal rating.

Résumé

Les lignes souterraines de transport et de distribution électriques sont fortement affectées par la qualité des énergies et dépendent de la présence d'harmoniques et du comportement des défauts électriques du réseau électrique. Les courants harmoniques génèrent un échauffement important entre les composants du câble, vieillissent, diminuent la durée de vie. Ce travail évalue la variation de température du système de câbles électriques souterrains avec différents THD à l'aide d'un modèle mathématique pour le niveau de tension du système utilisé à 138 kV.

Mots-clés—Modèle thermique, courant harmonique, câble souterrain, indice thermique.