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**Thème:**

# Study and simulation of the electric power cables degradation

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# Thanks

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# 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 Université

HICHAM

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# Summary

## Chapter I : General information on electrical cables.

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# List of symbols

| | | |
|---|---|---|
| $\vec{D}$ | $[Cm^{-2}]$ | the electric induction or electric displacement vector |
| $\rho$ | $[Cm^{-3}]$ | the electric charge density |
| $\vec{E}$ | $[Vm^{-1}]$ | the electric field vector |
| $\vec{B}$ | $[T]$ | the magnetic induction vector |
| $\vec{H}$ | $[Am^{-1}]$ | the Magnetic field vector |
| $\vec{J}'$ | $[Am^{-2}]$ | the electric current density |
| $\vec{J}$ | $[Am^{-2}]$ | the conduction current density |
| $\overrightarrow{J_D}$ | $[Am^{-2}]$ | the displacement current density |
| $\varepsilon$ | $[Fm^{-1}]$ | permittivity of the medium |
| $\varepsilon_0$ | $[\ Fm^{-1}]$ | vacuum permittivity |
| $\varepsilon_r$ | [Per unit] | relative permittivity of the medium |
| $\mu$ | $[Hm^{-1}]$ | permeability of the medium |
| $\mu_0$ | $[Hm^{-1}]$ | vacuum permeability |
| $\mu_r$ | [Per unit] | relative permeability of the medium |
| $\sigma$ | $[Sm^{-1}\ ]$ | Electrical conductivity |
| **XLPE** | | cross linked polyethylene |

# General Introduction

# General introduction

Nowadays the electrical power cables have a substantial role in the power transmission and delivery distribution network. Consequently, it is essential a complete knowledge of the cable performance and behavior in order to evaluate life time and to prevent ageing, degradation and fails.

Moreover, installation of Very High Voltage (VHV) cables often are hidden in underground tunnels in urban area is non-trivial.

Hence, it is necessary to evaluate the impact of electrical defect, environment, overload and heating on the power cables and electrical network quality.

Nevertheless, public urban installations tend to have complex Smart Grids characterized by variable loading systems.

The study of cables behavior under different critical conditions affects directly the thermal, mechanical and electromagnetic proprieties and performances.

The numerical simulation of power cables with Finite Elements Method (FEM) is an effective tool, characterized by good accuracy and reliability that permits good representation of all phenomena.

In this work, the Finite element method (FEM) is used for electromagnetic study of three core submarine HV cable by numerical simulation. The memory contain three chapters:

**The first Chapter**: includes basic definitions, forms and constitution of different parts of power cable and network, including the various submarines and underground power transmission systems are described.

**The second chapter**: contains basic concepts about electromagnetic fields, methods of calculating them, and how to model and simulate the submarine electric cables.

**The third chapter:** includes highlighting the simulation results obtained, analyzing them, commenting on them, and comparing them in the normal and in the case of defect. The goal is to count the values of electric field, in different position x and y with several magnitude.

# Chapter I

# General information on electrical cables

## I.1.Introduction:

Nowadays the underground and submarine power cables have a big role in the power electrical network and, consequently, it is essential a complete knowledge of the cable state and behavior in order to evaluate performance and to prevent ageing, degradation and fails. Hence, it is necessary to evaluate the impact of electromagnetic fields produced inside and near the power cables. Nevertheless, the electrical installations have complex implementation (Smart Grids): characterized by continuously increasing loading of systems, and multiple distributed generators injecting power into the networks. This chapter introduces the basic concepts about submarine and underground cables, including their types and applications in transmission systems, defects, advantages and disadvantages [1].

## I.2.General on electrical networks:

The transport and interconnection networks ensure the transmission of energy from these units to places of consumption through power lines (overhead or underground). Power lines are of limited capacity due to thermal limitations cables [2].

## I.2.1.Structures and topologies of an electrical network:

### I.2.1.1.VHV Transport Network:

The transport network allows the transfer of electrical energy from the electrical centers to consumers through a very high voltage VHV Network, it connects the power plants high power (> 300 MW). Most of these networks are overhead and underground. in cities or near them.

They are studied for a given transit corresponding to the thermal limit of the line [3].

### I.2.1.2.HV Distribution Network:

The second voltage level is the distribution network is dedicated to high voltage ,its role is to distribute power to the load centers within a radius of about 100 kilometers from a dispatch station. The distribution network is there form formed of lines and stations supplying the distribution network from the transmission network. The network of Dispatch is overhead and even underground dispatch facilities.

### I.2.1.3.Distribution Network:

The function of the distribution network is to supply all customers mainly connected to this network. Distribution networks mainly have a radial structure. Operation is managed by a Distribution Network Manager (GRD).Distribution network voltage levels The New standard in force in France UTE C18-510 defines the levels alternating voltage,(figure I.1.) as follows:

- HVB → for a line voltage greater than 50 kV
- HVA → for a line voltage between 1 kV and 50 kV
- LVB → for a line voltage between 500 V and 1 kV
- LVA → for a line voltage between 50 V and 500 V
- VLV → for a line voltage less than or equal to 50 V

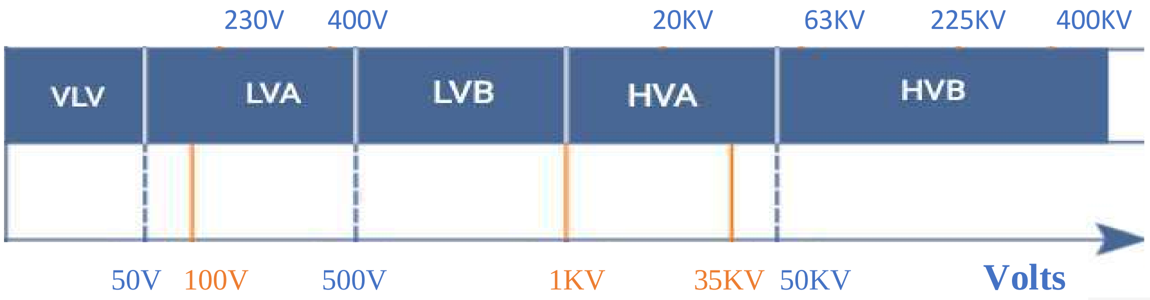
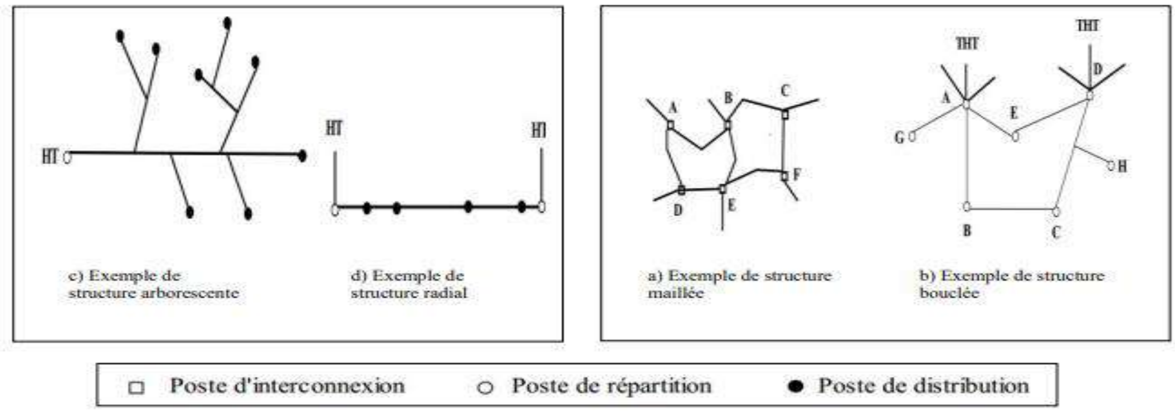


**Figure I.1.**Normalized voltage levels [4].

## I.3.Architecture of electrical networks:

The electrical energy produced is directly injected into the meshed transmission network at very high voltage to be transported over long distances with a minimum of losses.

It then "goes down" on the distribution networks, then those of distribution from where it is distributed to large consumers and low voltage distribution networks. Networks of energy transport and interconnection are linked together in the form of loops, here is their different connection structure, (see figure I.2).



c) Exemple de structure arborescente

d) Exemple de structure radial

a) Exemple de structure maillée

b) Exemple de structure bouclée

**Figure I.2.**Architecture of electrical networks [3]

## I.4.Constitution of the electrical network:

The transmission of electrical energy is currently provided by:

- Airline.
- Underground, overhead submarine cable.
- Electric post and substation.

## I.5.Transmission lines:

Most electricity companies have taken the decision not to establish new overhead connections below 150 kV. Ultimately, therefore, the entire distribution network and progressively that of distribution will be done in underground cables. The use of cables in higher voltage - although there are a few cases at 220 kV, 400 kV and 500 kV - is faced to significant technological problems (especially junctions) as well as to a very high cost(if the low voltage cost is similar or even lower for an underground connection, it becomes up to about 20 times higher at 400 kV compared to an overhead link). In 2006,the order of magnitude of the cost of a 400 kV aerial link of 1 million €/km. Overhead lines are made of bare aluminum conductors (often an alloy to reinforce the mechanical properties), sometimes with a steel core [5].

### I.5.1.Overhead lines:

It is composed of bare conductors, generally made of aluminum alloy, insulators, pylons and a ground wire for the high voltage lines. His role main objective is to transport electrical energy from the source of production to the area consumption (Figure I.3.). It has the following characteristics:

- The voltage remains constant over the entire length of the line and for all loads between zero is the rated load.
- Good performance.
- Joule losses must not overheat the conductors.

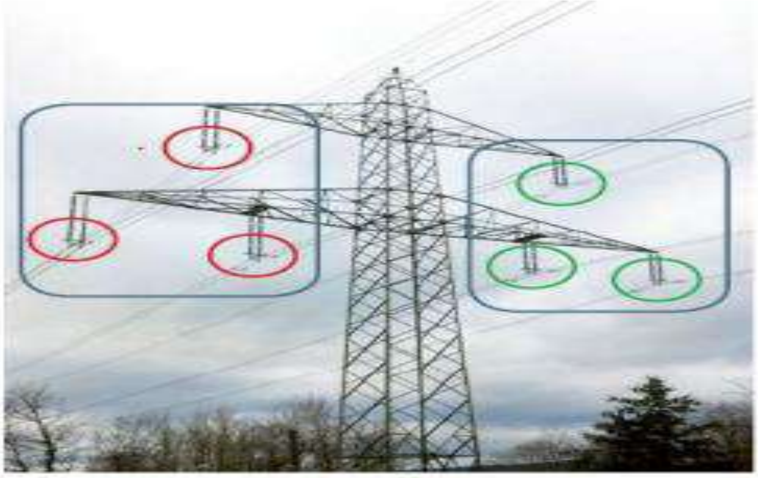


**Figure I.3**.Overhead transmission lines [6]

### I.5.1.1.The advantages of overhead lines:

- Are less expensive than underground lines from a fee perspective installation and repair.
- They allow easy monitoring of their condition and easy identification of accidents and flaws.
- They can be repaired very quickly in the event of an accident or defect.
- They can be overloaded in current intensity without too much danger.

### I.5.1.2.The inconvenient:

- Exposure to overvoltage of atmospheric origin.
- They raise problems of aesthetics and respect for the sites.
- They are likely to induce disturbing electromotive forces or hazardous in telecommunications circuits.
- They are liable to produce radio electric disturbances hampering radio and television receptions.
- According to some, electric and magnetic fields can exert an influence harmful to health [3].

### I.5.2.Underground lines:

It is made up of different parts assembled concentrically, themain components are: in the center a conductor is used to transport electricity,then comes electrical insulation to prevent current from flowing to ground, the everything is surrounded by a metal sheath in order to confine the electric field inside thecable and an external protection which ensures good mechanical properties and protects itexternal attacks (figure I.4.) [3].

**Figure I.4.**Underground transmission lines.

#### I.5.2.1.Advantages:

- Constitute the only possible solution in dense agglomerations.
- Are shielded from atmospheric over voltages (lightning).
- Do not cause interference with telecommunications circuits.
- Produce no interference with radio and television reception.
- The only possible solution for crossing large rivers or inlets when the distance to be covered exceeds 3km [3].

### I.5.2.2.The inconvenient:

- Are much more expensive than airlines. The difference is greater as the voltage is higher.
- Identifying faults is tricky and slow.
- Repairs are expensive and sometimes difficult.
- Their armor and sheaths must be protected against the effects of corrosion due to stray currents.
- Risk of being damaged in the event of ground movements.
- Their insulation is liable to be damaged by a rise in temperature of the conductors in case of overload [3].

## I.6.types of electric cables:

### I.6.1.Classification of electrical cables according to the type of conductor:

There are two types of conductors, copper and aluminum, both of which are good electrical conductors, although copper is better, as its conductivity coefficient reaches 1.724 micro ohms. CM compared to the conductivity coefficient of amnion, which reaches less than half of this figure. However, aluminum is characterized by being cheaper and lighter in weight, as the specific density of aluminum reaches less than a third of the density of specific copper.

But one of the disadvantages of using aluminum is the formation of a thin, hard layer of aluminum oxide on the surface of the conductor, and although this layer on the one hand protects the conductor from corrosion, on the other hand it causes many problems in welding and cable installation operations.

It should be noted that the presence of other elements buried underground next to the aluminum cables, may help in the process of corrosion of the aluminum cables, and this problem appears clearly when installing aluminum cables on them. Copper rods inside the distribution board, as it starts after a period of corrosion in aluminum, so we use the so-called BI-METAL GLAND to prevent this problem from happening inside the distribution boards, and BI-METAL GLAND is a special metal connector designed for use between two different metals [7].

### I.6.2.Classification of electrical cables by type of insulator:

In electrical cables used in electrical installations, the insulating material is often one of the Polymeric materials, such as [7]:

### I.6.2.1.Polyvinyl chloride PVC:

It is characterized by excellent electrical properties at low voltage and low temperatures in addition to its cheap price, and therefore it is always the first choice all over the world up to a voltage of 3.3 KV, where the value of insulation losses rises from higher voltages, but this type is defective that its insulation is affected by temperature Hence, it is not suitable for high-temperature uses.

When the temperature rises, PVC is softer, and this is of course undesirable. Its resistance is weak at very low temperatures and cracks may occur in it.

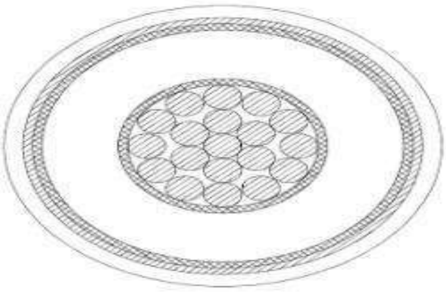
PVC is characterized by the self-extinguishing property of flame, as it ignites when A flame is brought close to it, but it is extinguished as soon as the flame is removed from it, but it produces toxic gases when ignited. Finally, it must be taken into account that PVC is not exposed to sharp bends, as it is not like rubber in this property.

### I.6.2.2.XLPE cross linked polyethylene:

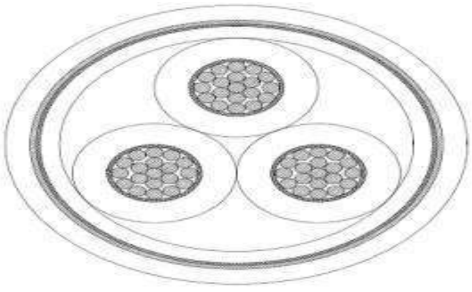
It is characterized by high resistance to moisture, bearing high temperatures, shortening and overloading, and it is the hardest known insulator and therefore does not often need reinforcement except when it is expected to be exposed to violent mechanical stresses, especially when buried in the ground, noting that this hardness requires avoiding exposure to severe bends during laying.

### I.6.2.3.Rubber insulators:

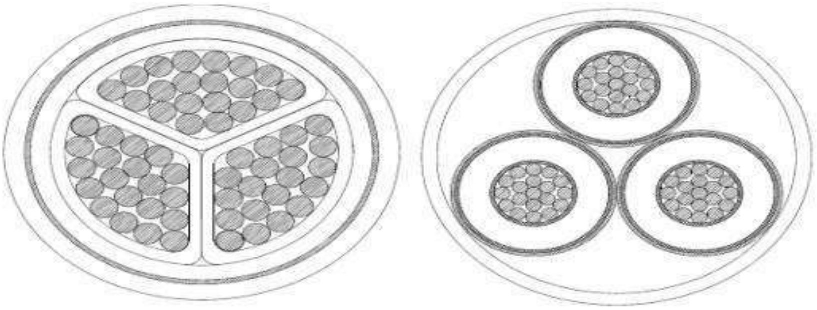
The main one is ethylene propylene (EPR).
The rubber is water-resistant, but it is not resistant to oil and gasoline.



Monopole cables



3-pole conductors with insulating belt



Tripolar sectoral shape. Circular sectoral shape

**Figure I.5.**Conductors of different shapes [11].

**Table.I.1.**Cable insulation bearing capacity for each type [8].

| **Insulating materials** | **Maximum 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, Silicone IE-5 | 150°C |

### I.6.3 Classification of electrical cables according to operating voltage:

- **Low Tension Cables:** These have a maximum voltage handling capacity of 1 kV.
- **High Tension cables:** These have a maximum voltage handling capacity of 11 kV.
- **Super Tension Cables:** These have a maximum voltage handling capacity of 33 kV.
- **Additional High Tension Cables:** These have a maximum voltage handling capacity of 66 kV.
- **Extra super voltage cables**: These are used for applications with voltage requirements above 132 kV [7].

## I.7.Underground HVA networks:

Urban or mixed areas with high load density are supplied by MV cables buried in double bypass (figure I.6) or in artery cut (figure I.7). Two fold derivation, the HVA/LV substations are normally supplied by the working cable, the emergency cable guarantees good continuity of service in the event of a fault. The artery cut technique is less expensive than the previous one and allows isolation faults quickly, but requires a longer intervention time.

The dimensioning of underground works is mainly related to the admissible currents in the cables due to the density of the loads to be served. New distribution structures or renovations in rural areas are also carried out with cable, due to the notorious reduction in the additional cost linked to this technique. Moreover, a growing political will for environmental quality tends to reduction of the visual impact of structures.

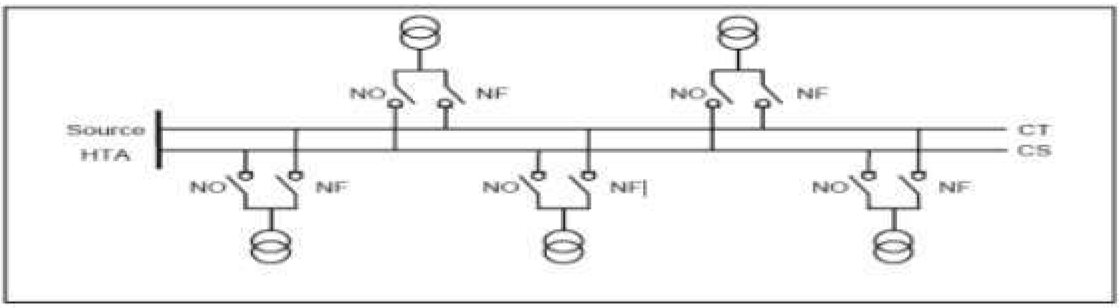


**Figure I.6.**Double branch underground HVA networks.

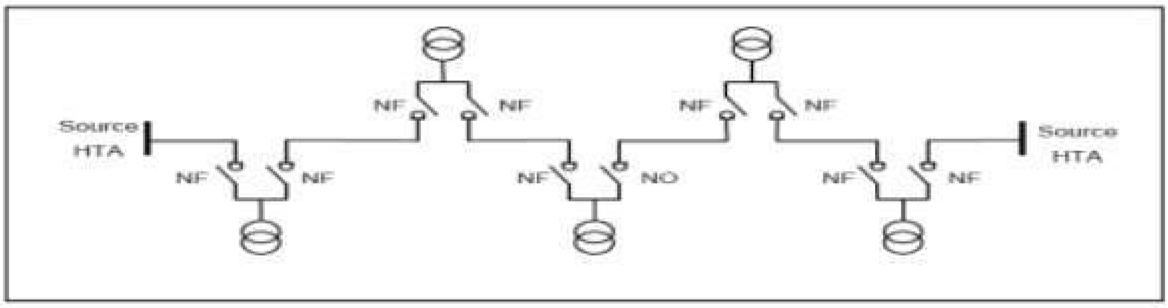


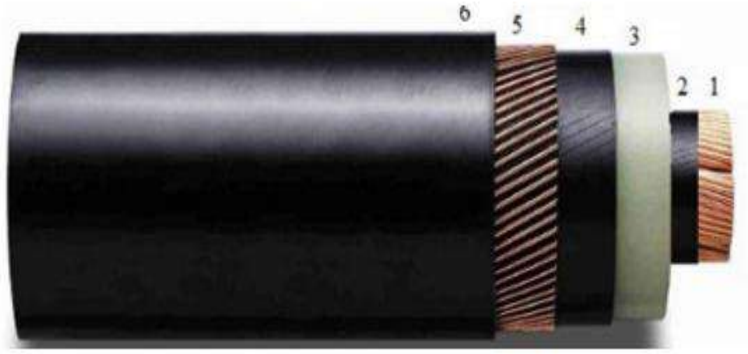
**Figure I.7.**Underground HTA networks with feeder cut [3].

### I.7.1.underground electric cables:

Certainly, the investments related to the installation of new cables are sometimes prohibitive. But in return, their environmental and aesthetic impact is well less than that of airlines. With this in mind, underground cables have taken and will continue to take on a certain scale.

### I.7.2.Underground VHV cables:

Very high voltage VHV underground cables are mainly used for the transmission and distribution of electrical energy in highly urbanized areas (large cities (Figure I.8.).), sometimes to solve particular local problems, technical or environmental, for which the implementation of overhead lines is difficult or impossible [9].



(1):conductive core.
(2):inner semiconductor layer.
(3): cross-linked polyethylene insulation.
(4): outer semiconductor layer.
(5): driver screen.
(6): PVC protection.

**Figure I.8.**Composition of an underground cable insulated with cross-linked polyethylene.

### I.7.3.HV underground cables:

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

**I.7.3.1.Compact round conductor:** composed of several layers of concentric wound wires spiral.

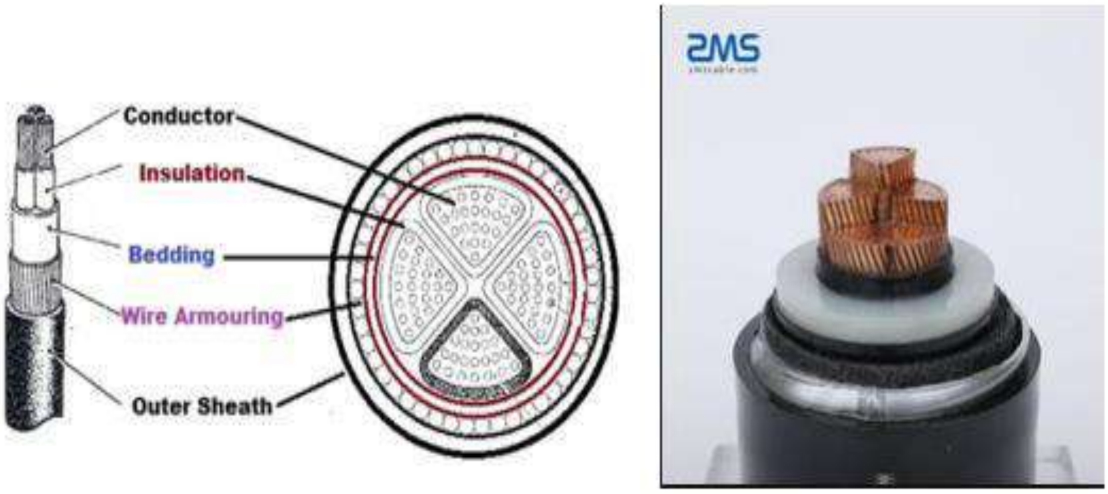
In compact conductors with round conductors, due to the low resistance of electrical contacts between wires, skin and proximity effects are practically identical to those of a solid conductor (figure I.9)

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

**Figure I.9.**2D section of VHV cables for underground networks [6].

**I.7.3.2.Segmental conductors:** also called "Milliken" conductors (figure I.10), are composed of several segment-shaped conductors assembled to form a cylindrical core.

**I.7.3.3.The large section conductor:** Is divided into several segment-shaped conductors. There are 4 to 7 of these conductors, called segments or sectors. They are isolated from each other others by means of semiconductor or insulating tapes. The Milliken-type structure reduces extremely adverse skin and proximity effects [10].



a- Compact round conductors b- Segmental conductors

**Figure I.10.**Compact and segmental conductor cables.

### I.7.4.MV Medium Voltage underground cables:

Medium voltage underground power cables have the same shape and the same constitution than the VHV and HV cables but with a smaller diameter because of the level of the power transmitted (figureI.11) [11].

### 1.Constitution:

### A. Single-core cable:

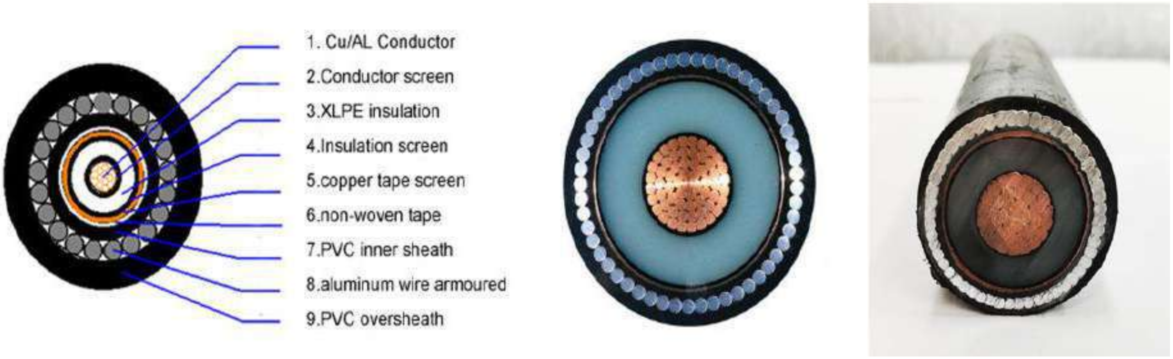


**Figure I.11.**Single-core cable [11].

### B. Three-pole cable:

**Figure I.12**.Composition of a three-pole cable [11].

### I.7.5.LT underground cables:

Low voltage underground power cables are constructed with conductors rigid, solid or stranded copper and aluminum and flexible copper conductors (bare or tinned). XLPE, PVC, LSF/LSOH and elastomeric compounds are the main insulating and protective compounds for these types of cables (Figure I.13). The wires or steel tapes (or aluminum tapes for single core cables) can be applied under the outer sheath, which provides additional mechanical protection [12].

**I.7.5.1.Phase conductors:** is the metal part of the cables that carries the current electrical these materials are: Aluminum core.

**I.7.5.2.Neutral conductor:** Wired circular aluminum core. Lead sheath Extruded PR insulation. Assembly (stuffing and ropes). Steel tape screen. PVC sheath [11].

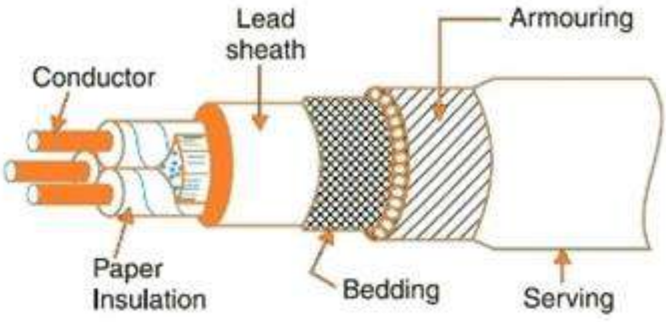


**Figure I.13.**Underground cable basic construction [13].

## I.8.Electric fields and magnetic fields:

### I.8.1.Effects of magnetic fields:

The 50 Hz magnetic field induces electric currents in the human body. Alone exposure to strong magnetic fields can lead to immediate perception. Immediate perception thresholds adopted by the World Health Organization (WHO) are the following:

- for magnetic fields at 50 Hz between 500 µT and 5,000 µT effects Minor biological have been reported.

- for magnetic fields at 50 Hz between 5,000 µT and 50,000 µT, there are effects on the nervous system and vision.

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

- for magnetic fields at 50 Hz greater than 500,000 µT ventricular fibrillation has been reported [14].

### I.8.2.Effects of electric fields:

The human body is a conductor of electricity, when the body is subjected to a field electrical power, electrical charges will accumulate on the surface of the body. The accumulation of these electrical charges can result in:
vibrations of hairiness, superficial tickling of the skin. Micro-sparks between the skin and objects in contact (clothes, glasses, watches, etc.)The threshold of perception of 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 [14].

## I.9.Submarine power cable types:

Submarine cable types can be categorized in many ways: type of insulation, models of current carrying conductor…etc. The type of cable selected for subsea application is highly dependent upon the transmission method, the voltage level and power capacity and the surrendering environment conditions. Thus it is of great important to understand the structure and characteristics of these cable types for further design of transmission system..The following sections shows the submarine cable categorization based on the cable insulation procedure [15].

### I.9.1.Self-contained fluid filled:

This type of cables relies on fluids as the insulation material; the fluid can be oil pumping with high or law pressure, or gas compression. The fluid used to fill in this cable is usually oil hence. For a single-conductor cable, the center of the conductor is the fluid channel but for a three-core cable, the slots between the conductors act as fluid oil ducts where the insulations for the cables are paper impregnated with synthetic oil. the application of this type of cable is limited to the transmission with extra high voltage and greater carrying capacity of current [15].

The following picture show the oil duct in the single core and three core cable applications:

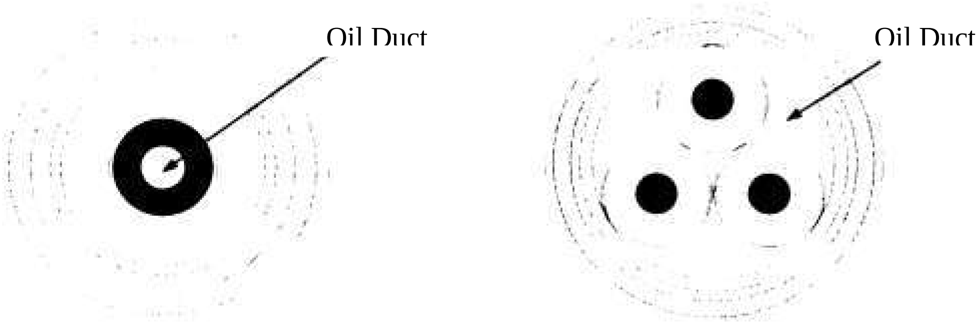


**Figure I.14.**Oil ducts in single core and three core SCOF cables [15].

The most extended cable type is cellulose paper impregnated in synthetic or mineral oil. here the core is covered by a hollow shaft where oil is circulated by pumps at both ends of the line, he can be built with transmission line up to 50 Km . Their diameter spans between 110 and 160 mm and their weight is 40-80 kg/m while the conductor sizes up to 3000 $mm^2$.

The figure I.15 show the single core SCFF structure

**Figure I.15.**The structure of a single core SCFF cable [16].

### I.9.2.Mass impregnated cables:

Mass impregnated cables are of similar construction of SCOF, but the paper insulation is impregnated in resin and high viscosity oil and no oil circulation system is needed .

Mass-impregnated cables are used up to 500 kV and operate up to a maximum temperature of 55 °C. The conductor sizes up to 2500 $mm^2$ while the external diameter spans between 110 and 140 mm with a weight of 30-60 kg/m.

The structure of a mass impregnated cable is shown in figure I.16.

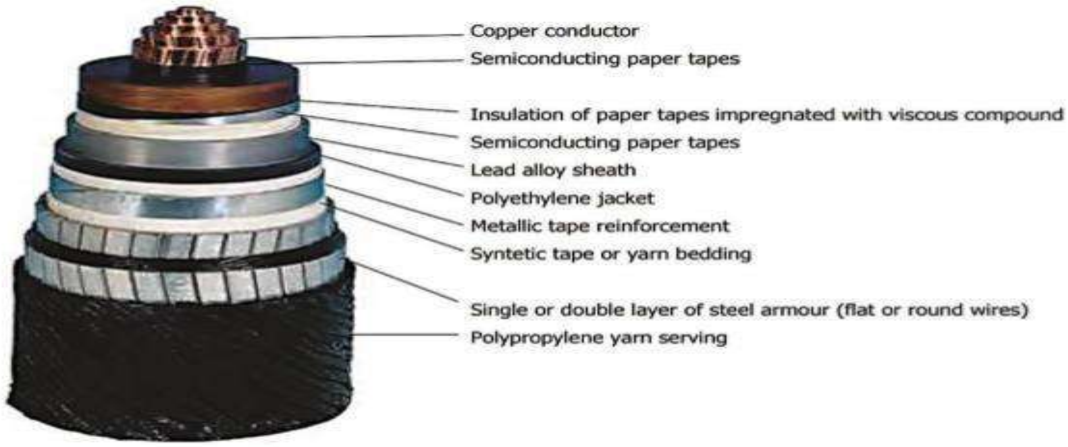


**Figure I.16.**The structure of a mass-impregnated cable [16].

### I.9.3.Extruded cables:

Extruded cables are used for voltages up to 300kV.Extrusion makes the cable surface extremely smooth against the insulation

The structure of a DC extruded cable is shown in figure I.17.

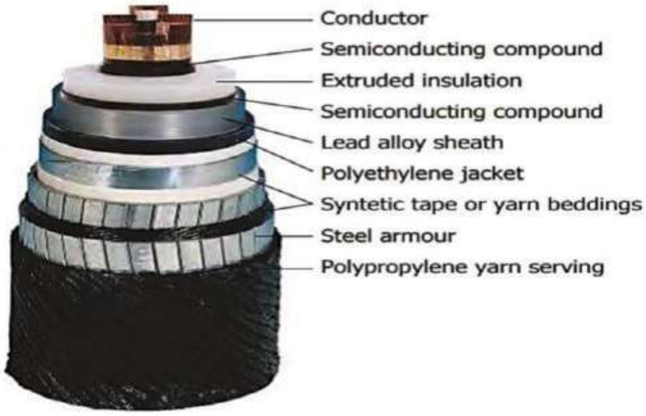


**Figure I.17.**The structure of extruded cable [16].

The insulation material in this cable may be:

- Ethylene propylene rubber (EPR).
- Polyethylene (PE).
- Cross-linked polyethylene (XLPE).

But it is mostly used XLPE insulation due to its superiority in advantages over other materials
The following picture figure I.18show example about the extruded AC XLPE insulation cables.

**Figure I.18.**Three-core and single core XLPE cable [15].

## I.10.Types of faults in electrical cables:

The primary function of an electrical cable is to carry current. When a cable no longer performs this fundamental function, it is said to be in serious fault (short circuit, open circuit). But it can also be affected by a defect which does not interrupt the routing of the currents passing through it.
The acting constraints on subsea power cable system can be regrouped as:

1-Functional (manufacture and decommissioning)
2-Environmental
3-Accidental.

**1.Functional loads include, for instance:**
— Weight of cable and attachments
— External hydrostatic pressure
— Electrical stress

— Heat (internal, external)

— Short circuit induced forces

— Reaction from components and installation vessel (cable engine, rollers), static and quasi-static hydrodynamic forces during installation or recovery, reactions from burial tools

— Reactions from seabed (friction, crushing, settlement)

— Loads from cover (e.g. soil, rock, mattress) and infrastructure crossings [17].

**2. Environmental loads acting directly or indirectly on the cable include, for instance:**

— waves (e.g. slamming, slapping, buoyancy variations)

— currents (e.g. drag, vortex induced vibrations)

— ice (e.g. drifting)

— motions of offshore unit where cable connects[17].

**3. Accidental loads caused by unplanned activities. Accidental loads include, for instance:**

— Extreme wind, wave or current loads

— Seabed subsidence, mudslide

— Earthquake loads (direct, indirect)

— Dropped objects

— Dragged anchor or trawling gear

— Installation vessel positioning failure during installation or recovery [17].

### I.10.1.Electrical fault in power system:

Electrical power systems suffer from faults and malfunctions resulting in them, which cause imbalances and disturbances in the quality of service and the proper functioning of the devices and the equipment that compose them.

Electrical faults represent a major obstacle in electrical submarine cables, as they leave traces and changes in electromagnetic fields an electric fault is defined as an abnormal increase or decrease in nominal values in an electrical circuit constitutes a fault or a disturbance.

Towards defining the most common electrical faults in electrical power systems, from it to marine electrical cables

### I.10.1.1.Overvoltage:

An overvoltage is any voltage between a phase conductor and earth, or between phase conductors, whose peak value exceeds the peak value corresponding to the highest voltage for the material, defined by the standard IEC 71-1

Over voltage stressing a power system can be classified into two main type:

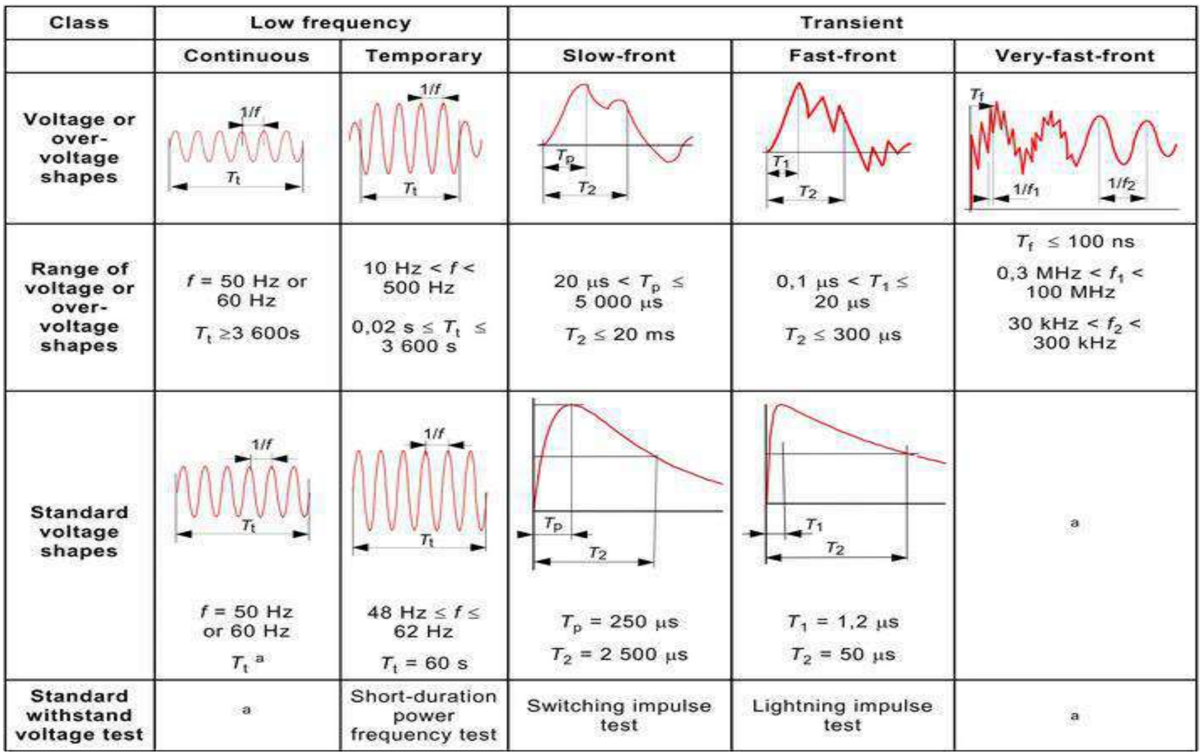
**a- External overvoltage:** generated by atmospheric disturbances of these disturbances, lightning is the most common and the most severe.

**b-Internal overvoltage:** generated by changes in the operating conditions of the network. Internal over voltages can be divided into switching overvoltage and temporary overvoltage.

IEC 60071-1 classify of voltage and overvoltage according to their shape and duration , voltage and overvoltage are divided in the following classes

The table I.2 show the various overvoltage classification and standard overvoltage shapes

**Table I.2.**classes and shapes of over voltages, standard voltage shapes [18].



| Class | Low frequency | | Transient | | |
|---|---|---|---|---|---|
| | Continuous | Temporary | Slow-front | Fast-front | Very-fast-front |
| Voltage or over-voltage shapes | | | | | |
| Range of voltage or over-voltage shapes | $f$ = 50 Hz or 60 Hz<br>$T_t \geq 3\,600$s | 10 Hz < $f$ < 500 Hz<br>0,02 s ≤ $T_t$ ≤ 3 600 s | 20 µs < $T_p$ ≤ 5 000 µs<br>$T_2 \leq 20$ ms | 0,1 µs < $T_1$ ≤ 20 µs<br>$T_2 \leq 300$ µs | $T_f \leq 100$ ns<br>0,3 MHz < $f_1$ < 100 MHz<br>30 kHz < $f_2$ < 300 kHz |
| Standard voltage shapes | $f$ = 50 Hz or 60 Hz<br>$T_t$ [a] | 48 Hz ≤ $f$ ≤ 62 Hz<br>$T_t$ = 60 s | $T_p$ = 250 µs<br>$T_2$ = 2 500 µs | $T_1$ = 1,2 µs<br>$T_2$ = 50 µs | a |
| Standard withstand voltage test | a | Short-duration power frequency test | Switching impulse test | Lightning impulse test | a |

### I.10.1.2.Overloads:

Increase in current from 1 to 10 In (In: Nominal current) of a circuit, for example due to an exaggeration of the receivers (device used beyond its nominal power)

The causes of overloads faults are:

- Short circuit
- Closing long interconnection loops
- Peaks in energy consumption or transit.

### I.10.1.3.Oscillations:

An oscillatory disturbance is an abrupt change in the steady state condition of the voltage or current or both signals at the same time at both the limits of the positive and negative components which oscillate at the frequency of the natural system.

### I.10.1.4.Short circuit:

Sudden increase in current intensity from 10 to 1000 In in a circuit due to an accidental connection of two different potential points.

The causes of short circuit fault in a electric power system are:

- Breakage of an insulator
- Breakdown of the insulating oil of a transformer

We collect some consequences of electrical faults in the following table:

**Table I.3.**Consequences of electrical faults [15].

| **Fault** | **Consequence** |
|---|---|
| Overvoltage | breakdown of the dielectric insulating equipment in the event that the overvoltage exceeds their specified withstand<br>loss of power supply following long cuts caused by the destruction of network elements. |
| Overloads | Slow and progressive heating of active parts, metal masses, insulators |
| Oscillations | Oscillatory disturbance causes a strong power signal which disappears very quickly. Oscillatory disturbance occurs when switching inductive or capacitive loads on or off because they resist change |
| Short circuit | Short circuits, especially poly-phase and close to production plants, cause a disruption of the balance between the engine torque and the resistive torque of the machine |

### I.10.2.Construction defects:

The initial state, and therefore the original physical characteristics of the cable are corrupted. These alterations can affect the geometry or electrical properties and/or mechanics of components and materials.

Soft defaults generally do not pose an immediate threat, but they do may indicate advanced aging or an area of intense stress and therefore be harbingers of a more serious defect (true defect) [5].

### I.10.3.Aging defects:

Several types of defects can occur in a cable insulation with the aging. Water trees are physic-chemical changes that undergo insulation in the presence of water and electrical field. Underground cables are regularly immersed in water due to leaks from the city's aqueduct or any, simply because of the rainwater that accumulates in the pipes. Water in the form diffuses inside the insulation of the cable. PE and XLPE insulations have zones, crystalline zones and also cavities. The latter may have diameters in the nanometer range and host a lot of water molecules. It s actually about free volume between the various polyethylene chains. Water in the form of steam which diffuses inside these cavities can condense if it is in sufficient quantity [19].

There are several factors that lead to damage (aging) electrical cables, including:

- Exposure to hot spots, for example due to a cable passing near a hot pipe.
- High humidity and even immersion.
- Radiation resulting from exposure to ionizing radiation.
- Mechanical limitations such as bending radius and very small disc cable or vibration.

**Figure I.19.**Locally damaged cables (EDF image) [20].

### I.10.4.overheating faults:

Cables consist of 3 layers: outer metallic layer, a dielectric layer, and conductor. When electrical current flows through the cables, it generates heat. As a result, the cable layers generate a different type of loss which could lower the power transmission through the cables.

Therefore, the current ratings of the cables are dependent on how heat circulates through the cables and how it dissipates to the next medium. Mainly, Moore (1997) described, there are: [21].

- Conductor losses
- Dielectric losses
- Sheath eddy current losses
- Sheath circuit losses

This is probably one of the most common electrical faults. It occurs when too many appliances or appliances that consume too much electricity are plugged into a circuit or socket that is not properly sized to deliver as much electricity at a time. Overload over current is characterized by a continuous increase in the intensity of the current circulating in the circuit over time.

This excessive stress on the circuit and its capacities, even if slight, can cause a slow heating of the conductors and insulators if it is prolonged over time [22].

**Figure I.20.**Cable overheating faults.

## I.11.Factors Affecting Cable Insulation Over Time underground:

The insulation of an underground cable is never perfect. Not only do we find defects that derive directly from the production of the cable but in addition the insulation ages inevitably.

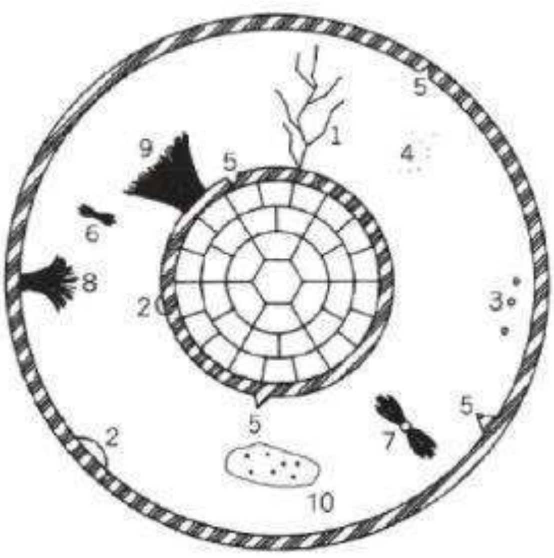
When a cable is in service, its insulation is subject to thermal stresses, electrical, mechanical and finally environmental constraints. Over time, these various loads (Table. I.4) generate irreversible modifications to the insulation.

We generally speaks of an intrinsic aging of the cable concerned, during which the insulation degrades evenly [23].

**Table I.4.**Factors affecting the insulation of a cable over time.

| Thermal | Electrical | Environmental | Mechanical |
|---|---|---|---|
| Maximum temperature<br>Ambient temperature<br>thermal gradient<br>Thermal cycle | Voltage (AC, DC)<br>Running<br>Frequency<br>Impulse | Gas (air, O2)<br>Humidity<br>Water<br>Corrosion | Bending<br>Traction<br>Compression<br>Torsion<br>Vibration |

In addition, the premature aging of the cables can come from contaminants(foreign particles), defects, protuberances or voids which appear in insulation during production, transport or installation of the cable. Initially, these imperfections are point or localized defects in the insulation. On the other hand during over time, they can get worse and gradually spread through the insulation when the cable is in service. They may even involve the complete destruction of insulation [23].



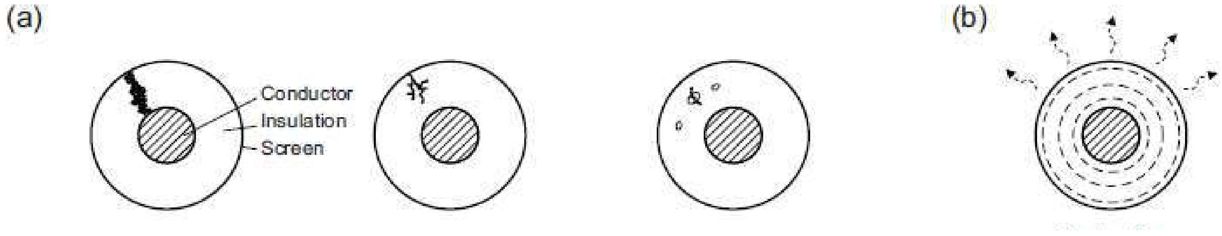
1. Electrical tree
2. Void at the interface
3. Void in insulation
4. Contaminant
5. Protrusion in the semiconductor
6. Discharge from a contaminant
7. Discharge from a vacuum
8. Discharge from insulation
9. Discharge from conductor
10. Humidity

**Figure I.21.**Imperfections in a single-phase cable [23].

## I.12.Subsea power cable failure origin:

Subsea power cables can fail during their service life due to electrical and thermal causes (predominantly, in the operational phase). Examples are given in FigureI.22

and Table I.5.



Insulation breakdown Treeing Partial discharge Overheating

(a) Electrical, (b)thermal

**Figure I.22.**Examples of subsea power cable failure mechanisms [17].

**Table I.5.**Examples of electrical and thermal failure modes of subsea power cables [17].

| **Failure mechanism** | **Demand characteristics** | **Capacity characteristics** | **Response characteristics** |
|---|---|---|---|
| Insulation breakdown (ULS) | Voltage - average, peak | Dielectric strength of insulation | Full discharge between conductor and insulation screen |
| Treeing (SLS) | Voltage, contaminant | Insulation sensitivity to contaminant, contaminant barrier effectiveness | Electrochemical oxidation with contaminant propagation |
| Partial discharge (SLS) | Voltage | Absence of micro-voids, insulation sensitivity to partial discharges | Partial discharge in small insulation voids or imperfections |
| Overheating (SLS) | Electrical current - magnitude, harmonics<br>External heat, solar irradiation | Cable losses, thermal properties of cable components and surroundings, temperatures, insulation sensitivity to overheating | Increase of conductor temperature, soil drying (on land), ageing of insulation |

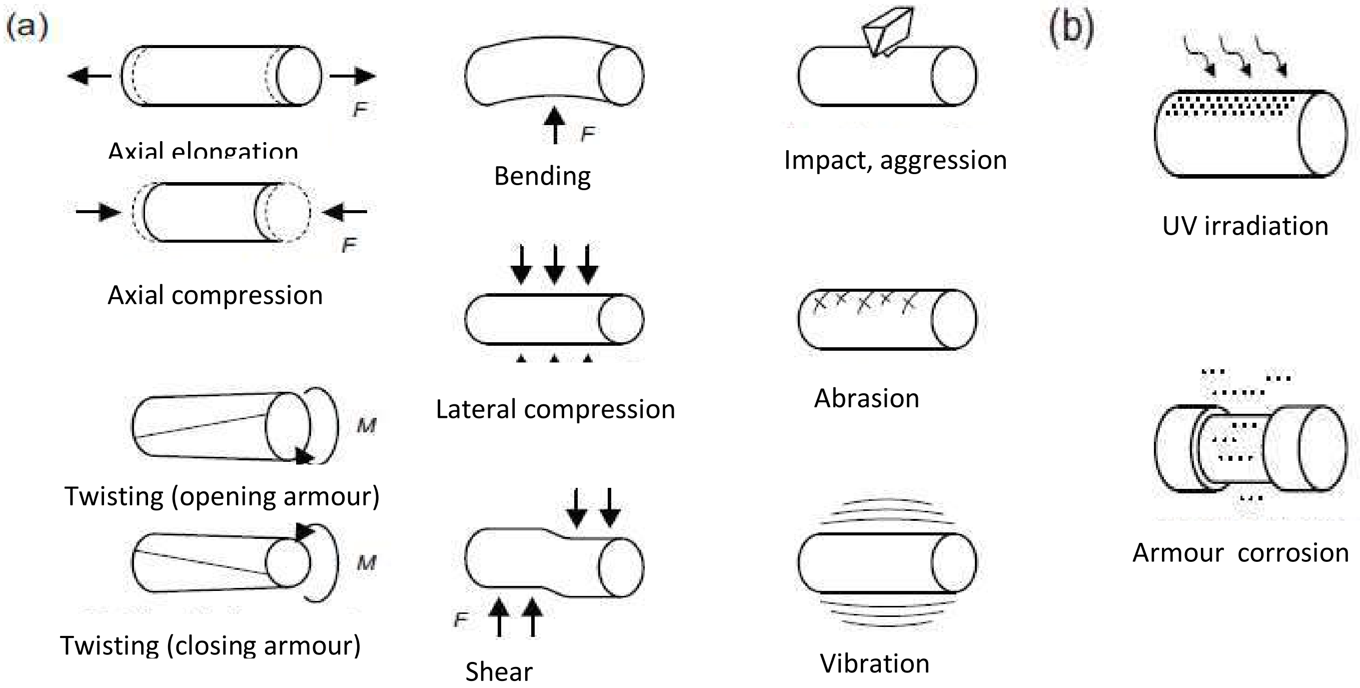
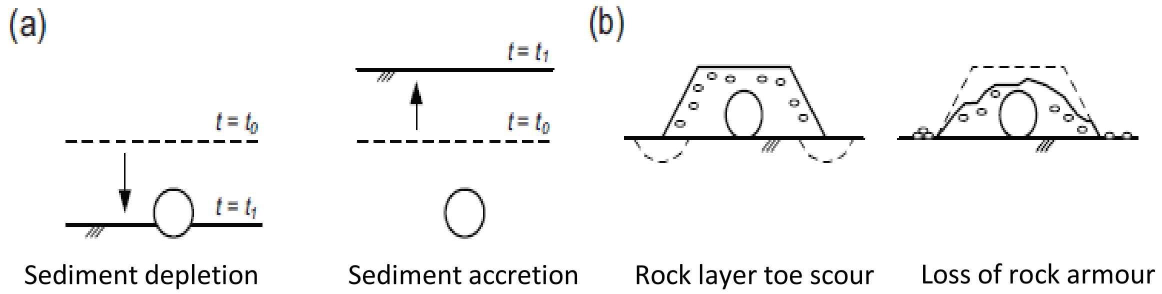
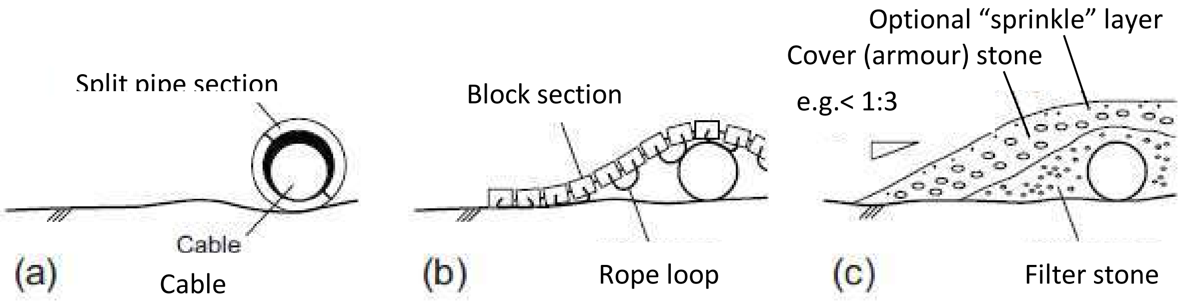


**Figure I.23.**Examples of subsea power cable failure mechanisms.(a) Mechanical, (b**)** chemical.[17]

**Table I.6.**Examples of mechanical and chemical failure modes of subsea power cables [17].

| Failure mechanism | Demand characteristics | Capacity characteristics | Response characteristics |
|---|---|---|---|
| Axial tension (ULS) | Tensile force | Strength, stiffness | Elongation or compression, strain, bonding failure between conductor and insulation |
| Bending (ULS) | Bending moment | Strength, stiffness | Elongation (outside) and compression (inside), strain, bonding failure |
| Torsion (ULS) | Twisting moment | Strength, stiffness | Strain, opening or closing of armour, bird caging, bonding failure |
| Lateral compression (ULS) | Clamping force and area | Strength, acceptable crush / squeeze load | Compression, strain, bonding failure |
| Impact (ALS, ULS) | Impact force and area | Impact resistance | Shear stress and strain |
| Abrasion (SLS) | Lateral and longitudinal forces, surface friction | Abrasion resistance, cable surface friction coefficient | Abrasion of cable sheath |
| Vibration (FLS) | Current - velocity, direction | Length of free span, cable stiffness | Fatigue of cable components |
| Sheath degradation (SLS) | Irradiation - wavelength (e.g. UV), strength | Adsorption | Ageing of outer cable sheath, cracking |





(a) Tubular product, (b) mattress, (c) rock placement

**Figure I.24.**Examples of failure mechanisms of subsea power cable protection. (a) Burial,(b) rock placement [17].

### I.13.Conclusion:

Through what we touched upon in this chapter, we can say that submarine and underground power cables have proven their place in electric power transmission systems as one of the greatest solution in high-voltage devices that receive care and development, which guarantees a promising future.

This is due to its advantages such as the multiplicity of types and structures and the expansion of applications in both direct and alternating currents, but this does not prevent the existence of some defects that vary from one type to another and the occurrence of some defects of an electrical, thermal, environmental or mechanical nature that are caused by both human or natural activities [15].

# Chapter II

# Electromagnetic model of submarine power cables

## II.1.Introduction:

The important of energy flow transport growing using of high voltage underground and submarine power cables instead of overhead lines for safety and aesthetic reasons. However, cable insulation of an underground cable may contain imperfections and defects (include gaseous cavities occurring during manufacturing, water bubbles and contaminants within the insulating layer, ), which, when subject to electrical and physical stresses during operation, cause degradation and accelerated aging, impairing the cable's proper functioning and causing partial discharge (PD) [25,15].

Understanding partial discharge behavior require interesting simulation study to insulation and electric field distribution inside the different parts of cable. The electric field computations need a numerical model and resolution of physical equations by finite element method. In this chapter we simulate the electric cables using COMSOL Multiphysics5.3 software, to study the capacitive effects and the electric field magnitude and distribution [25,26].

## II.2.Calculation of the electromagnetic field:

The aim of electromagnetic devices study is to show the field distribution and magnitude, the spread of its waves at several positions. In theory, the value of the electromagnetic field is computed using differential or integrative equations, depending on the situation and the problem to be solved, as Maxwell's equations [27.28].

Then choose a mathematical method to solve these equations and give the results with approximate values, there are several methods for solving differential equations, as the method of finite elements which our software works.

### II.2.1.Maxwell's equation in variable regime:

Maxwell's equations are four partial differential equations that explain the behavior of electromagnetic fields in the form of a mathematical model that employs proportional relationships related to the properties of materials and media known as constitutive relations.

A variable regime mean that the variation of the fields D and H created by the sources $\rho$ and $J'$ respectively [15]

The following equations represent the Maxwell's law:

Maxwell Gauss equation $div\vec{D} = \rho$ (II.1)

Maxwell-Faraday equation $\overrightarrow{rot}\vec{E} = -\frac{\partial\vec{B}}{\partial t}$ (II.2)

Maxwell flux equation $div\vec{B} = 0$ (II.3)

Maxwell-Ampere equation $\overrightarrow{rot}\vec{H} = \vec{J'} = \vec{J} + \overrightarrow{J_D}$ (II.4)

Where:

$\vec{D}$ : the electric induction or electric displacement vector ($Cm^{-2}$)

$\rho$ : the electric charge density ($Cm^{-3}$)

$\vec{E}$ : the electric field vector ($Vm^{-1}$)

$\vec{B}$ : the magnetic induction vector ($T$)

$\vec{H}$ : theMagnetic field vector ($Am^{-1}$)

$\vec{J'}$ : the electric current density ($Am^{-2}$)

$\vec{J}$ : the conduction current density($Am^{-2}$)

$\overrightarrow{J_D} = \frac{\partial\vec{D}}{\partial t}$ : thedisplacement current density($Am^{-2}$) [15.28].

### II.2.2.The constitutive relation:

It's three law's given the relations between the fields by physical property in the media

Dielectric relation $D = \varepsilon E = \varepsilon_0\varepsilon_r E$ (II.5)

Magnetic relation $B = \mu H = \mu_0\mu_r H$ (II.6)

Ohm's law $J = \sigma E$ (II.7)

Where the following table shows the description, value and units in SI for each property

**Table II.1.**Table giving the descriptions and units of the physical properties[15,30,31].

| Property | Description | Units |
|---|---|---|
| $\varepsilon$ | permittivity of the medium | $Fm^{-1}$ |
| $\varepsilon_0$ | vacuum permittivity | $Fm^{-1}$ |
| $\varepsilon_r$ | relative permittivity of the medium | Per unit |
| $\mu$ | permeability of the medium | $Hm^{-1}$ |
| $\mu_0$ | vacuum permeability | $Hm^{-1}$ |
| $\mu_r$ | relative permeability of the medium | Per unit |
| $\sigma$ | Electrical conductivity | $Sm^{-1}$ |

### II.2.3.The inductive effects model:

The model solves Maxwell-Ampere's law in 2D, using the out-of-plane magnetic vector potential A as a dependent variable [15].

All Maxwell’s equations are either directly or indirectly involved, together with three constitutive relations and applied the mathematical operation for establish the final equation problem.
Let start by combination between Gauss’s and current conservation law:

$$\begin{cases} \nabla.D = \rho \\ \nabla.J = -j\omega\rho \end{cases} \tag{II.8}$$

In the frequency domain this give:

$$\nabla.(J + j\omega D) = 0 \tag{II.9}$$

When we replace the constitutive relations:

$$\begin{cases} D = \varepsilon E \\ J = \sigma E \end{cases} \tag{II.10}$$

We get the following equation:

$$\nabla.(\sigma E + j\omega\varepsilon E) = 0 \tag{II.11}$$

The current density is defined by; $J^{'} = J + j\omega D$ is the sum of both conduction current and displacement current.

The second step of the model is start with Maxwell-Ampere's law ;$\nabla \times H = J^{'}$ then take the divergence of that to get:

$$\nabla.(\nabla \times H) = \nabla.J^{'} = \nabla.(J + j\omega D) = 0 \qquad \text{(II.12)}$$

We add the magnetic constitutive relation;$B = \mu H$

$$(\nabla \times H) = (\nabla \times (\mu^{-1}B)) = J^{'} = (\sigma + j\omega\varepsilon)E \qquad \text{(II.13)}$$

Next, let consider the concept of a vector field A, the magnetic vector potential that is:

$$\nabla \times A = B \qquad \text{(II.14)}$$

And take the divergence

$$\nabla.(\nabla \times A) = \nabla.\mathrm{B} = 0 \qquad \text{(II.15)}$$

The Maxwell's faraday equation is used for expressed E in terms of A

$$\nabla \times E = -j\omega B \qquad \text{(II.16)}$$

$$\nabla \times E = -j\omega(\nabla \times A) = \nabla \times (-j\omega A) \qquad \text{(II.17)}$$

$$E = -j\omega A \qquad \text{(II.18)}$$

Now, both B and E can be expressed in terms of A ,If we substitute this result in (II.11),we will find :

$$\nabla \times (\mu^{-1}\nabla \times A) = (\sigma + j\omega\varepsilon)(-j\omega A) \qquad \text{(II.19)}$$

Finally, if we swap about some terms and put everything on the left side, we get the following 2D partial differential equation for the dependent variable A:

$$-\omega^2\varepsilon A + j\omega\sigma A + \nabla \times (\mu^{-1}\nabla \times A) = 0 \qquad \text{(II.20)}$$

The magnetic fields interface uses this equation in the domains to determine the value of A and consequently, the value of all fields derived from it.

The electric current of the three phases in time variation is as follows:[28,31]

$$I_a = I_0\, , I_b = I_0 e^{\frac{-j2\pi}{3}}\, , I_c = I_0 e^{\frac{j2\pi}{3}} \qquad \text{(II.21)}$$

### II.2.4.The capacitive effects model:

The model solves a 2D in-plane current conservation problem in the frequency domain. Using the electric scalar potential V as a dependent variable, this includes the following equations [28]**:**

$$\begin{cases} E = -\nabla V \\ \nabla . D = \rho \\ \nabla . J = -j\omega\rho \end{cases} \qquad \text{(II.22)}$$

Where the relation between electric field and electric potential, Gauss law and current conservation law is used here when faraday’s law evaluated to be zero

$$\nabla \times E = -j\omega B = 0 \qquad \text{(II.23)}$$

As $\neq 0$, this mean the magnetic flux density is assumed to be zero. more specifically, since this model considers in plane electric fields only

The displacement current is included in the current definition this give$\nabla . J^{'} = 0$ and

$J^{'} = J + j\omega D$for the current conservation law and the current definition, respectively.

$$\nabla . (J + j\omega D) = 0 \qquad \text{(II.21)}$$

The constitutive relations $D = \varepsilon E$ and $J = \sigma E$is add to get :

$$\nabla . (\sigma E + j\omega\varepsilon E) = 0 \qquad \text{(II.22)}$$

When we piece $E = -\nabla V$, in (II.22) we end up with the following 2D partial differential equation forthe dependent variable V :

$$-\nabla . \big((\sigma + j\omega\varepsilon)\nabla V\big) = 0 \qquad \text{(II.23)}$$

The electric currents interface uses this equation in the domains to determine the value of V and consequently, the value of E, J and $J_D$

The electric voltage of the three phases in time variation is as follows: [15,31,32].

$$V_a = V_0 \, , V_b = V_0 e^{\frac{-j2\pi}{3}} \, , V_c = V e^{\frac{j2\pi}{3}} \qquad \text{(II.24)}$$

## II.3.The finite element method:

It is a numerical method used to solve mathematical linear differential equation. The principle of the FEM lies in the division of the elementary domain of finite dimensions on each domain called finite element, the unknown function is approached by a tooth polynomial the degree can vary from one application to another.

The main stages of construction of a finite element method are the following:

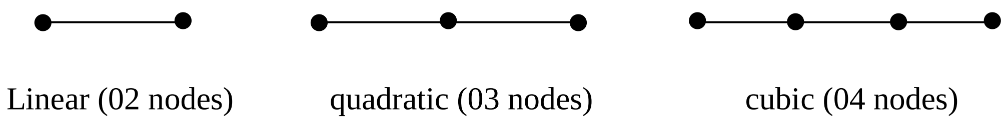
- Discretization of the continuous environment, representing the field of study in sub-field (element).
- Construction of the nodal approximation by sub domain.
- Calculates elementary matrices (for each element) corresponding to the integral from of the problem.
- Assembly of elementary matrices taking into account the boundary conditions
- Solving the equation system.

There are different types of elements:

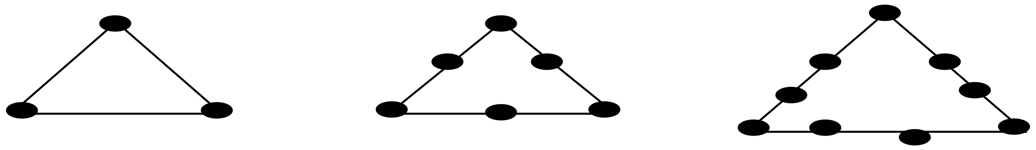
- linear element (1D).
- Surface element (2D).
- Volume in alelement (3D) [15].

In our case, the field of study, which is two-dimensional, we often meet with linear, quadratic or cubic elements. To lead to a better accuracy of the solution, one proceeds to refine the mesh see figure II.1.

The figure II.1 show the discretization of the study domain.

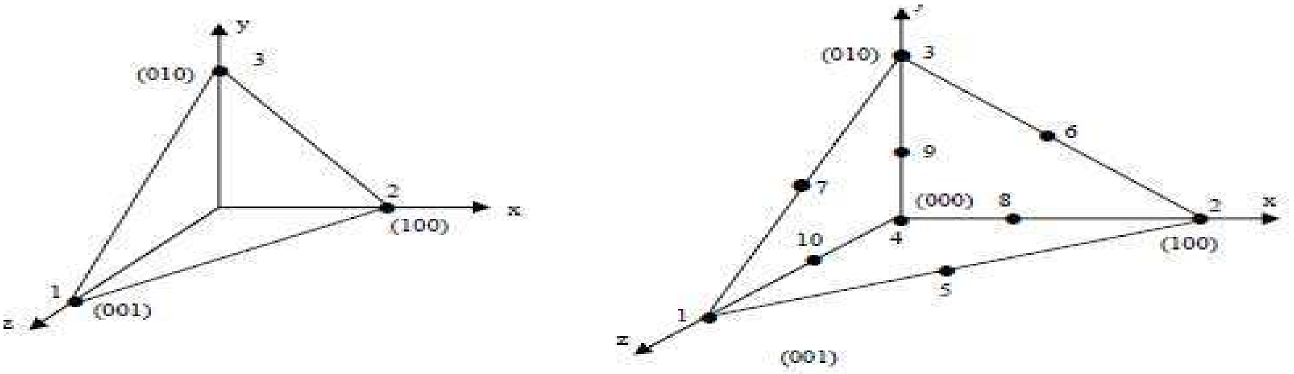


Two-dimensional problem (triangle or quadrilateral)



a) Linear element (03 nodes) b) quadratic (06 nodes) c) cubic (09 nodes)

d) Three-dimensional problem



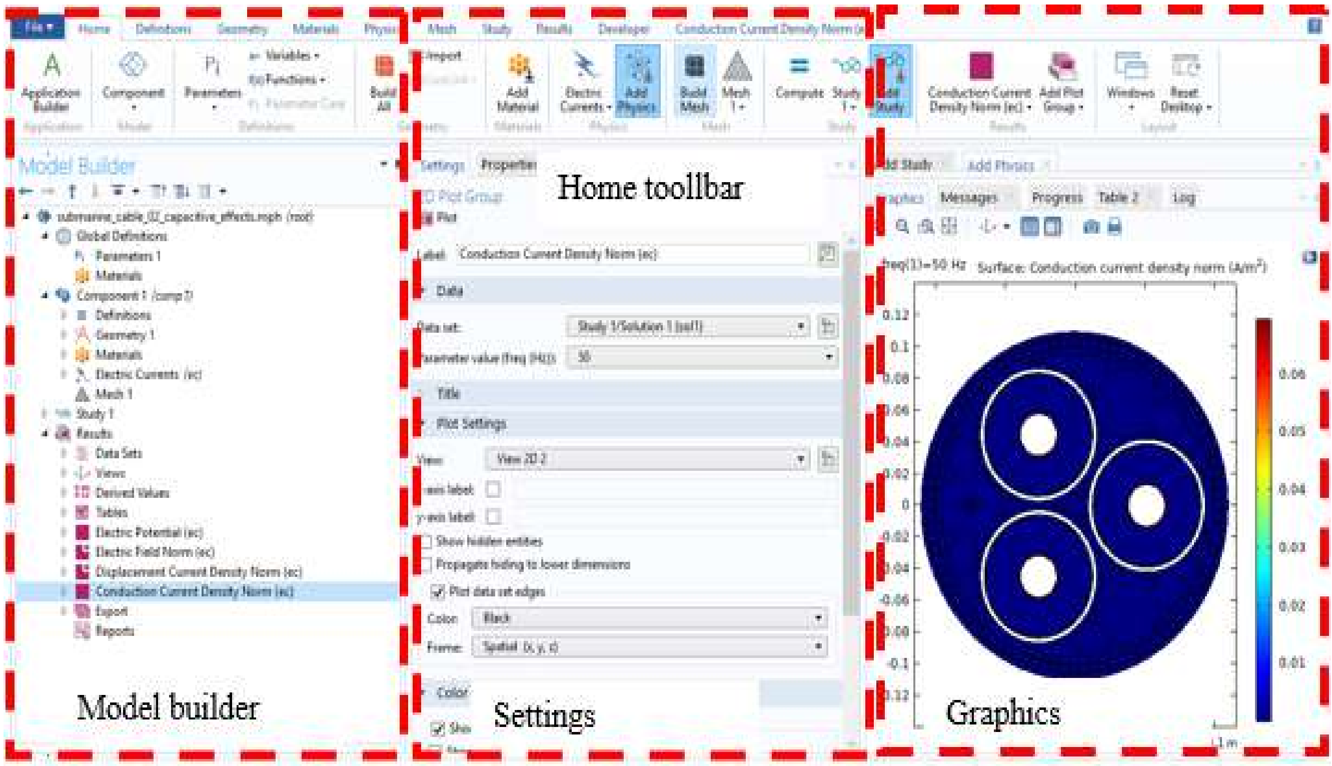
Linear element (04 nodes) Quadratic element (10 Nodes)

**Figure II.1.**Discretization of the study domain (mesh) [15].

## II.4.Presentation of COMSOL Multiphysics 5.3 software:

COMSOL multiphysics 5.3 software calculates and highlights the results and values of several components such as :magnetic flux, electrical potential or temperature … etc. which are a solution to differential equation by means of the finite element method, and these results can be in a frequency domain, stationary domain ,temporary domain,…. etc.

The main screen of COMSOL Multiphysics5.3 software is in figure II.2 it consist a home toolbar which represent a comprehensive bar for all building, addition and study tools that appears the top of the screen and model builder window which the simulate model is structured by adding multiple interfaces from the home toll bar and setting window which all parameters of each interface is declared and a graphic interface to observe the results contains some vision operations as view, zoom ,selection and show (see figure II.2) [32].



Label: Conduction Current Density Norm (ec)

Data set: Study 1/Solution 1 (sol1)

Parameter value (freq (Hz)): 50

View: View 2D 2

☑ Plot data set edges

Color: Black

Frame: Spatial (x, y, z)

Figure II.2.COMSOL Multiphysics5.3 software présentation.

GARDER LA MEME TAILLE DES SOUS TITRES

## II.5.Methodology of simulation:

In order to simulate the electromagnetic phenomena in the cables, we must be aware of the engineering cables' composition and the properties of the constituent materials thereof, the amounts that have a direct relationship to those phenomena such as tension, current, power….etc. Towards explaining simulation steps using COMSOL Multiphysics5.3 software based to finite element method. These model is build by sequence steps using nodes and interfaces, and the necessary settings for each step [32].

### II.5.1.Geometry:

This step is to design a 2D model on an engineering interface by creating the geometry sequence using for the model component, also contains some general settings such as length unit and angular unit and setting for each geometric sequence as type, size and shape, position, rotation angle…etc.(figure II.3), for example this is the geometry of three core XLPE cross linked polyethylene cable in figure II.3:

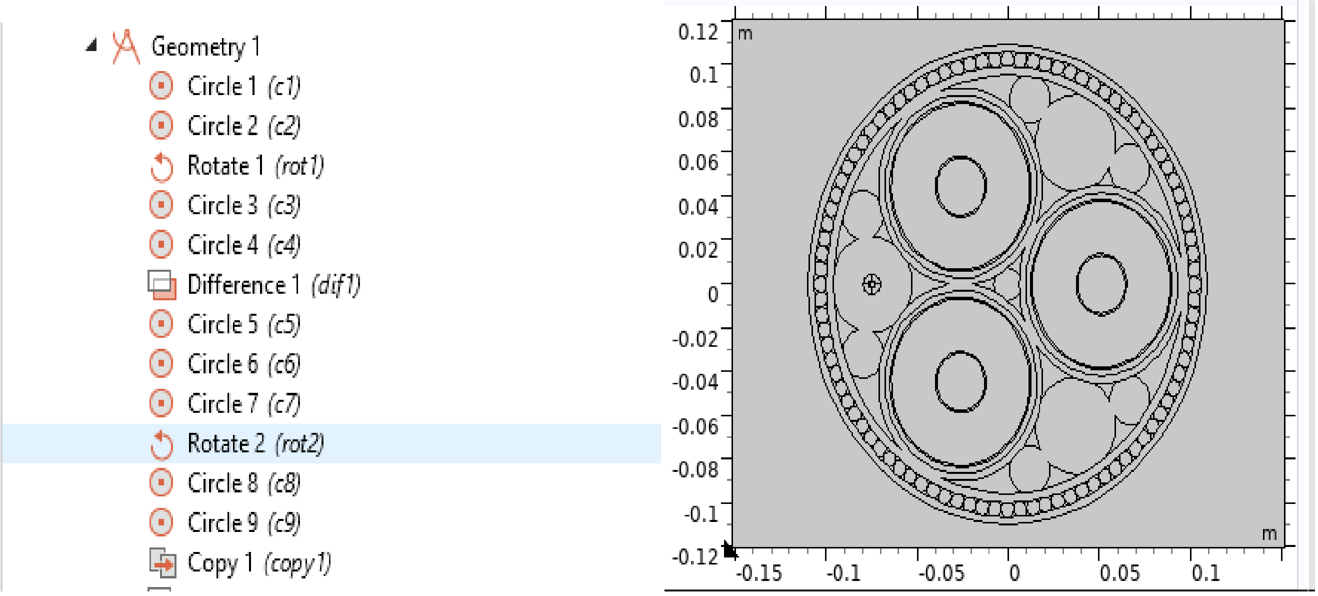
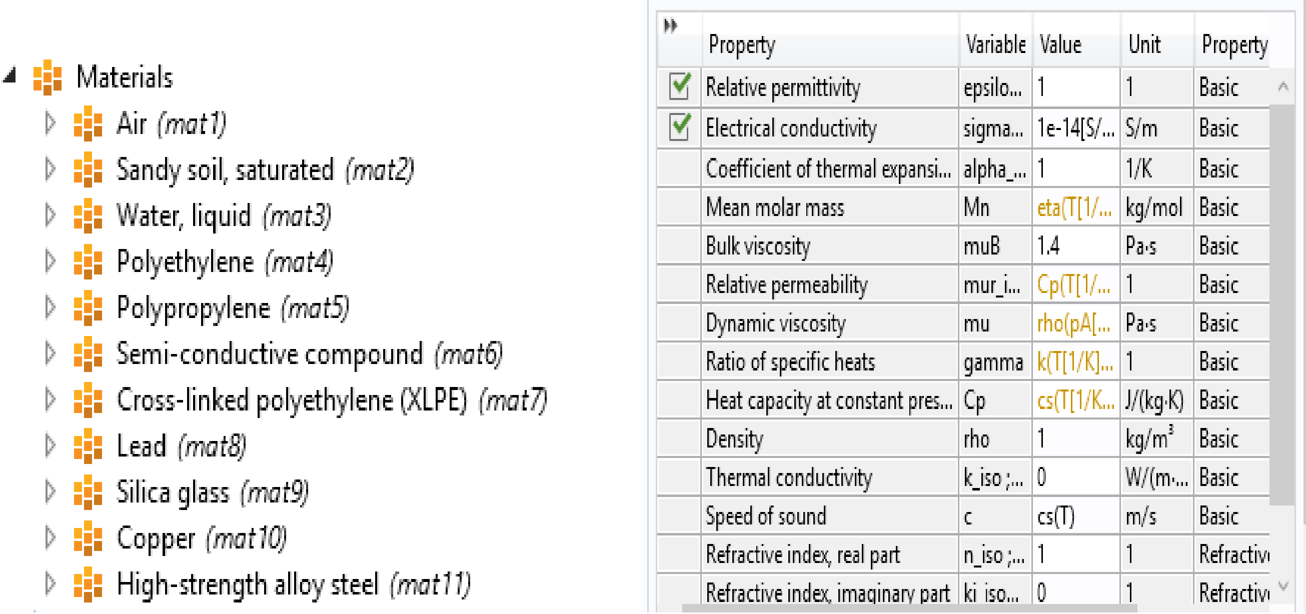


**Figure II.3.**Designerof cable in 2D.

## II.5.2.Materials:

Here we choose and select the materials that match every area of the design (cross section), by add materials to the graphic interface with the conjugate settings including material contents that list the property, variable, value and unit for the material property(figure II.4).



|  | Property | Variable | Value | Unit | Property |
|---|---|---|---|---|---|
| ☑ | Relative permittivity | epsilo... | 1 | 1 | Basic |
| ☑ | Electrical conductivity | sigma... | 1e-14[S/... | S/m | Basic |
|  | Coefficient of thermal expansi... | alpha_... | 1 | 1/K | Basic |
|  | Mean molar mass | Mn | eta(T[1/... | kg/mol | Basic |
|  | Bulk viscosity | muB | 1.4 | Pa·s | Basic |
|  | Relative permeability | mur_i... | Cp(T[1/... | 1 | Basic |
|  | Dynamic viscosity | mu | rho(pA[... | Pa·s | Basic |
|  | Ratio of specific heats | gamma | k(T[1/K]... | 1 | Basic |
|  | Heat capacity at constant pres... | Cp | cs(T[1/K... | J/(kg·K) | Basic |
|  | Density | rho | 1 | kg/m³ | Basic |
|  | Thermal conductivity | k_iso ;... | 0 | W/(m·... | Basic |
|  | Speed of sound | c | cs(T) | m/s | Basic |
|  | Refractive index, real part | n_iso ;... | 1 | 1 | Refractiv |
|  | Refractive index, imaginary part | ki_iso... | 0 | 1 | Refractiv |

**Figure II.4.**Materials declaration.

### II.5.3.Physics interface:

The physics interfaces is used for compute, modeling, calculate…etc. several amount and field as voltage, current, electromagnetic fields, power losses …etc. where each interface contains some nodes connection(figure II.5).

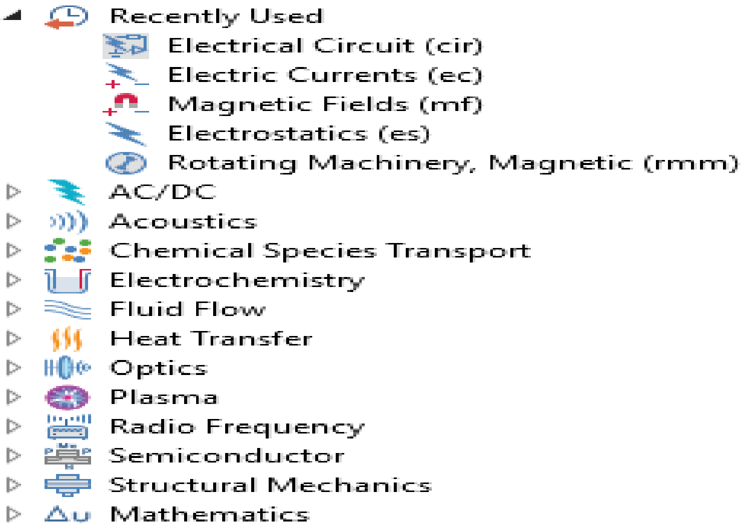


**Figure II.5.**Add physics window.

In our work we applied three physics interface explaining as follows:

### II.5.3.1.The magnetic field interface:

the magnetic field interface is used to compute magnetic field and induced current distribution in and around conductors, depending on the licensed products modeling are supported this interface contains four nodes, we explain it as follows :

●The Ampere's law node adds Maxwell-Ampere's law for the magnetic field and provides an interface for defining the constitutive relation and its associated properties.

● The magnetic insulation node is the default boundary condition for the magnetic fields interface and adds a boundary condition that sets the tangential components of the magnetic potential to zero at the boundary.

● The initial values node adds an initial value for the magnetic vector potential A that can serves as an initial value for a transient simulation.

● The coil node used to model conductors subject to a lumped excitation, such as an externally applied current or voltage.

### II.5.3.2.The electric current interface:

It is used for simulate the capacitive effects, the main nodes of this interface are :

- The current conservation node adds the continuity equation for the electrical potential and provides an interface for defining the electric conductivity as well as the constitutive relation and the relative permittivity for the displacement current.

- The electric insulation node which is the default boundary condition, means that no electric current flows into the boundary.

- The initial values node adds an initial value for the electric potential that can serve as an initial condition for a transient simulation, in our case we put the default initial value is 0 V.

- The ground node implements ground (zero potential) as the boundary condition V=0.

- The terminal node provides a boundary or domain condition for connection to external circuits, to transmission lines, or with a specified voltage[15].

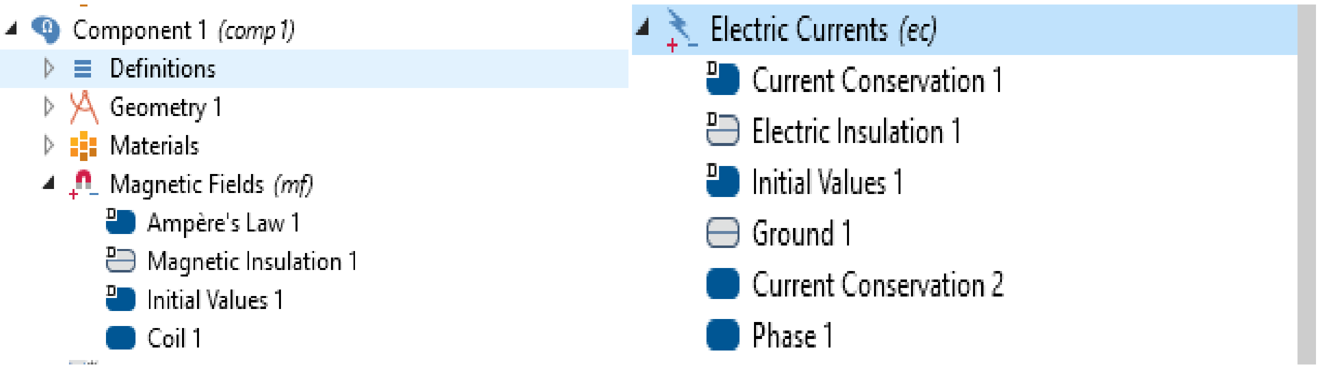
### II.5.3.3.The electrical circuit interface:

It is used for simulate the electrical fault effects causing transit phenomena in the cables (figure II.6), the main nodes connection between them in this are :

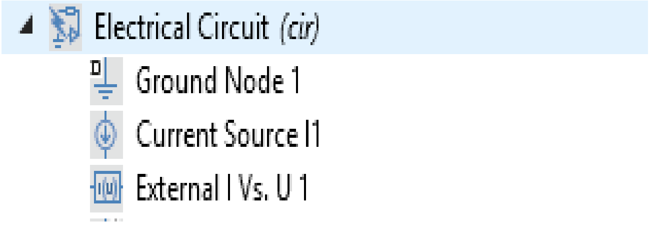
- Ground node

- Source node

- External



a) Magnetic field interface b) Electric current interface



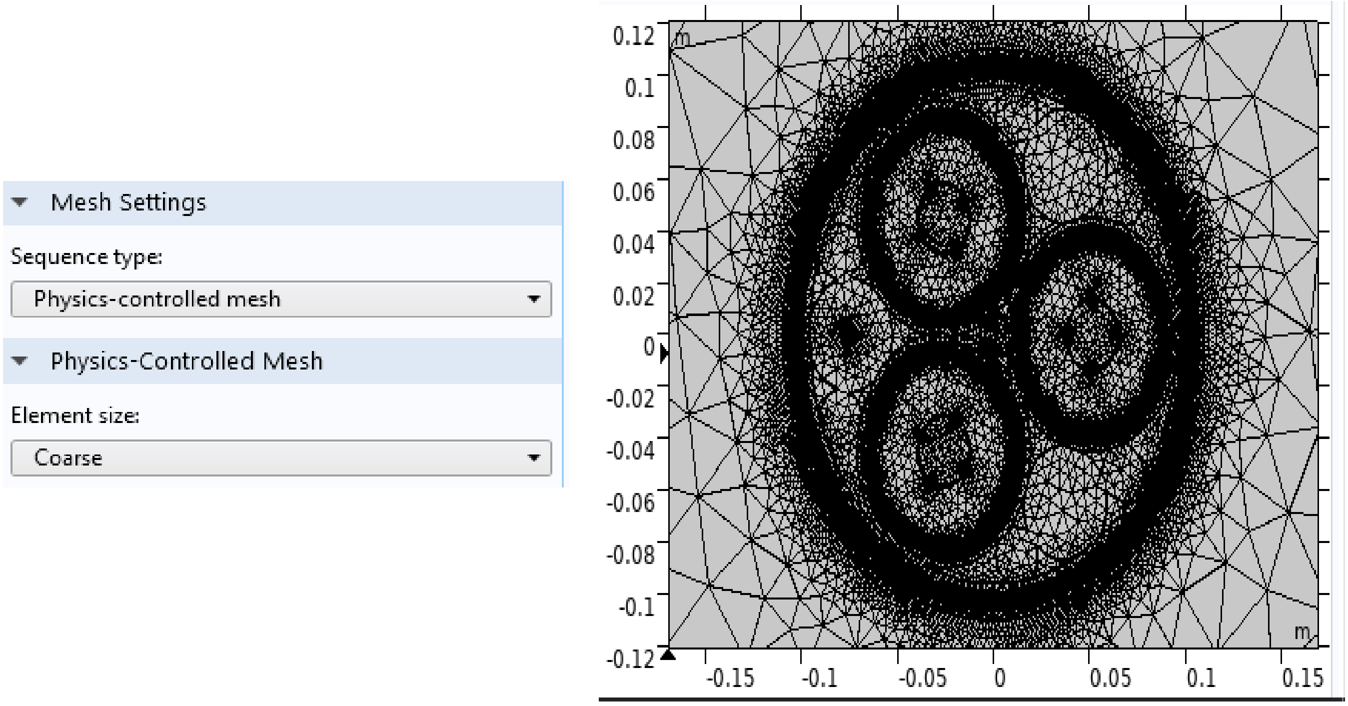
Electrical Circuit (cir)
Ground Node 1
Current Source I1
External I Vs. U 1

c) Electrical circuit interface

**FigureII.6.**Physical interfaces.

### II.5.4.Mesh:

This engineering operation called discretization , nodes and elements are woven onto the design for the finite element method as the figure II.7 show, for mesh settings we choose Physics-controlled mesh sequence type (the default) to let the physics interfaces determine meshing sequence according to the physics-controlled mesh section and coarse element size(figure II.7) [15,32].



Mesh Settings
Sequence type:
Physics-controlled mesh
Physics-Controlled Mesh
Element size:
Coarse

**Figure II.7.**Mesh in 2D.

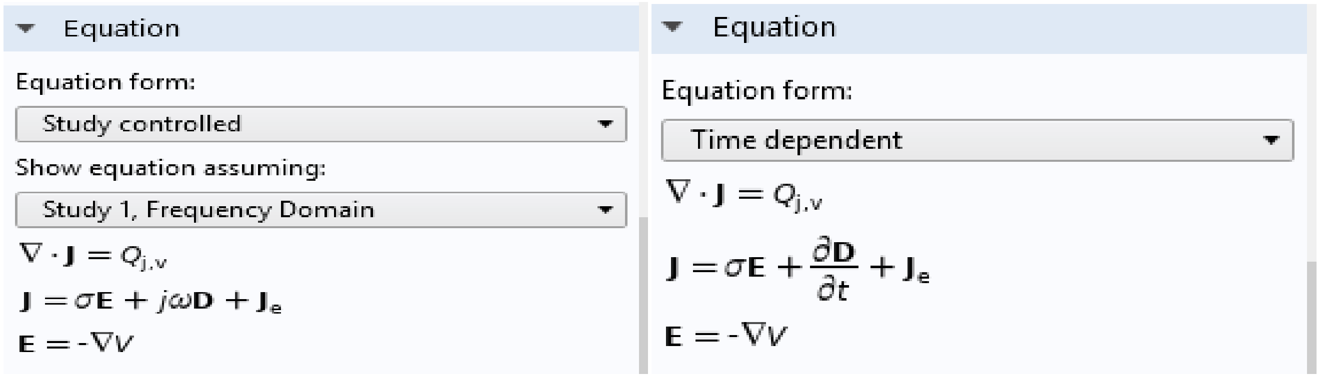
### II.5.5.Study:

Here we add the study step and regulate its parameters for compute A study node holds all the nodes that define how to solve a model, these nodes are divided into two broad categories :

### II.5.5.1.Study steps:

which determine overall settings suitable for a certain study type. The study steps added are based on the chosen study types.

In our work we choose a two deferent study steps for evaluate the results (frequency domain study step, and time dependent study step).where the figure II.8 shows the equations that solving for each study step .



Equation

Equation form:

Study controlled

Show equation assuming:

Study 1, Frequency Domain

$\nabla \cdot \mathbf{J} = Q_{j,v}$

$\mathbf{J} = \sigma\mathbf{E} + j\omega\mathbf{D} + \mathbf{J}_e$

$\mathbf{E} = -\nabla V$

Equation

Equation form:

Time dependent

$\nabla \cdot \mathbf{J} = Q_{j,v}$

$\mathbf{J} = \sigma\mathbf{E} + \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}_e$

$\mathbf{E} = -\nabla V$

a) frequency domain b) Time dependent

**Figure II.8.**Equations corresponding to the two studies.

### II.5.5.2.Solver configurations:

Which contain the solvers and related configurations for dependent variables to solve for, intermediate storage of solutions, and specific solver settings. Those nodes are normally created by the study step [15,32].

### II.6.Program structure:

The following picture shows the structure of the program adopted in our work represented in three successive operational blocks based on Maxwell's equations and the various model data (figure II.9).

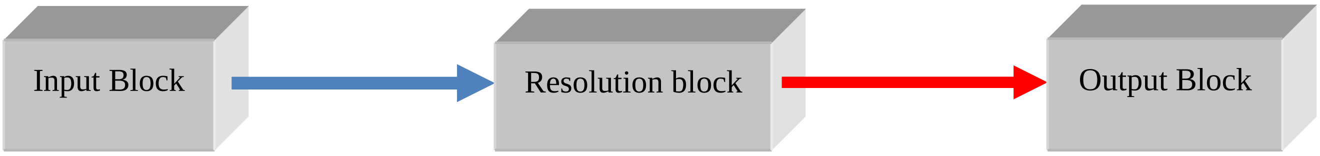


**Figure II.9.**different program blocks [32].

The program is composed of the following:

### II.6.1.Input Block:

This block includes the cable model database for each stage of the construction:

- Geometric dimension parameters
- Material properties (permeability, permittivity and electrical conductivity)
- Equations accompanying the field of study
- Number and size of mesh element

### II.6.2.Resolution block (computation):

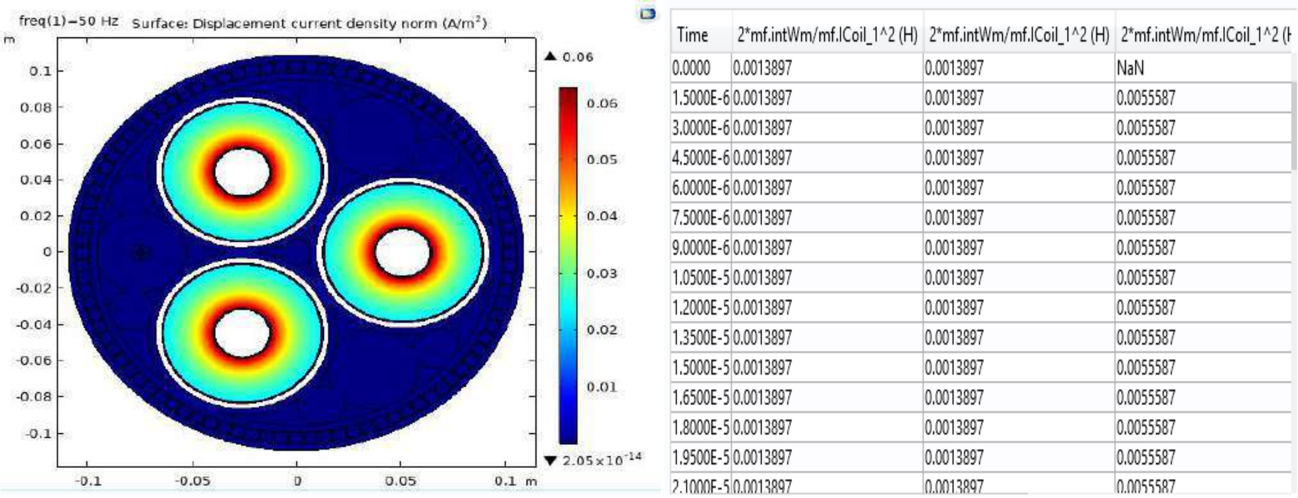
This block receives the input data for the purpose of inserting and processing it into a system that includes:

- Generate a partial differential equation based on Maxwell’s equation using one dependent variable as a out-of-plan.
- Apply the finite element method algorithm for solving the differential equation then calculate the approximate value of the physical unknown in each element.

### II.6.3.Output block:

Here, simulation results that represent solutions to the system of equations and resulting Statistics are displayed and shown, whether in graphic or digital form.

After simulation the results can be exported even to the MATLAB editor.



| Time | 2*mf.intWm/mf.ICoil_1^2 (H) | 2*mf.intWm/mf.ICoil_1^2 (H) | 2*mf.intWm/mf.ICoil_1^2 ( |
|---|---|---|---|
| 0.0000 | 0.0013897 | 0.0013897 | NaN |
| 1.5000E-6 | 0.0013897 | 0.0013897 | 0.0055587 |
| 3.0000E-6 | 0.0013897 | 0.0013897 | 0.0055587 |
| 4.5000E-6 | 0.0013897 | 0.0013897 | 0.0055587 |
| 6.0000E-6 | 0.0013897 | 0.0013897 | 0.0055587 |
| 7.5000E-6 | 0.0013897 | 0.0013897 | 0.0055587 |
| 9.0000E-6 | 0.0013897 | 0.0013897 | 0.0055587 |
| 1.0500E-5 | 0.0013897 | 0.0013897 | 0.0055587 |
| 1.2000E-5 | 0.0013897 | 0.0013897 | 0.0055587 |
| 1.3500E-5 | 0.0013897 | 0.0013897 | 0.0055587 |
| 1.5000E-5 | 0.0013897 | 0.0013897 | 0.0055587 |
| 1.6500E-5 | 0.0013897 | 0.0013897 | 0.0055587 |
| 1.8000E-5 | 0.0013897 | 0.0013897 | 0.0055587 |
| 1.9500E-5 | 0.0013897 | 0.0013897 | 0.0055587 |
| 2.1000E-5 | 0.0013897 | 0.0013897 | 0.0055587 |

Graphic form Numeric form

**Figure II.10.**Simulation results form.

The numerical modeling and simulation of the electromagnetic field lines around the cables requires the numeric calculation method and tools such as software (COMSOL Multiphysics5.3) which will give the magnitude of the magnetic field in each point of the area of study model (figure II.10), [15,32].

## II.7 Conclusion:

In this chapter, we have given the electromagnetic model by partial differential equations (PDE), for our case we will use the finite element method in 2D by the exploitation of the COMSOL software for the resolution of the model of a submarine cable.

# Chapter III

# Simulation results and discussions

## III.1 Introduction

Several studies and research are conducted on electrical power cables in case of damage by electromagnetic characterization because of their consequence on materials ageing, heating and proprieties. In this chapter, we will present the simulation results of submarine power cable by displaying electric field and see the effect of different kind of geometrical defects.

## III.2 Three core submarine cable

HVAC submarine cables are developed to carry a great amount of power across the water. The cable conductors consist of copper or aluminum, depending on size and price. Cross-linked polyethylene (XLPE), with a maximum operational temperature of 90◦C,
is a commonly used insulation material. A common construction of a three-core XLPE separate lead sheath-type submarine cable is shown in figure III.2 , where contains

1:Conductor
2:Conductor screen,
3:Insulation,
4:Insulation screening-semi conductive,
5:Screen,
6:Laminated sheath,
7:Optical fibers-optically used for telecommunications
8:Fillers,
9: Binder tapes
10:Armor Bedding-polypropylene strings,
11: Armor-galvanized round steel wires,
12:Serving.

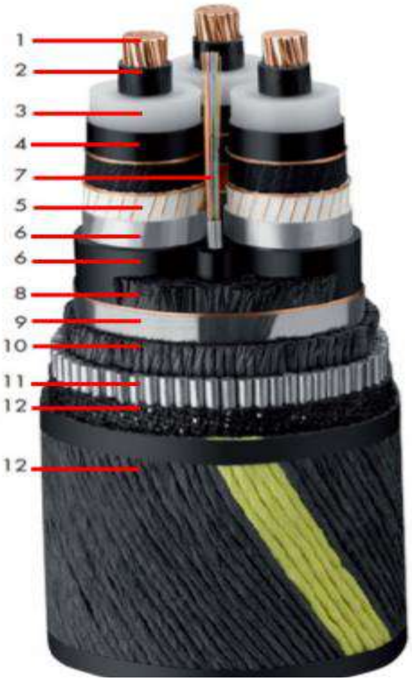


**Figure III.1** Three core cable shape [15].

The structure size of this cable, and the electrical characteristics is shown in the tables III.1 and III.2 respectively.

**Table III 1**Structure size of three core XLPE cable

| **Description** | **Value [mm]** |
|---|---|
| Diameter of conductor (Phase) | 26,2 |
| Insulation thickness (Phase) | 24 |
| Semi-conductive compound thickness (Phase) | 0,85 |
| Lead sheath thickness (Phase) | 2,9 |
| Diameter of fiber optic cable core | 2,5 |
| Armor thickness | 6,5 |
| Outer diameter of cable | 219 |
| Diameter over insulation (Phase) | 77,6 |
| Diameter over phase (Phase) | 89,2 |
| Diameter over fiber optic core | 2,5 |

**Table III.2** .The electrical characteristics of submarine cables

| **Description of character** | **Value** |
|---|---|
| Operating frequency | 50 Hz |
| Rated current (Amplitude) | 926 A |
| Phase to ground voltage (Amplitude) | $\frac{220}{\sqrt{3}}$ KV |

## III.3.Materials data:

The characteristic of different materials used in the model simulation for three core submarine electrical cable is presented in the following table.

**Table III.3**Materials characteristics of submarine power cables

| **Materials** | **Electrical conductivity [S/m]** | **Relative permeability (per unit)** | **Relative permittivity (per unit)** |
|---|---|---|---|
| Air | $1\text{x}10^{-14}$ | 1 | 1 |
| Polyethylene | $1\text{x}10^{-18}$ | 1 | 2,25 |
| Polypropylene | $1\text{x}10^{-18}$ | 1 | 2,36 |
| XLPE | $1\text{x}10^{-18}$ | 1 | 2,5 |
| Lead | $4{,}55\text{x}10^{6}$ | 1 | 1 |
| Copper | $5{,}998\text{x}10^{7}$ | 1 | 1 |
| High-strength alloy steel | $4.032.10^{6}$ | 1 | 1 |
| Semi-conductive compound | 2 | 1 | 1 |
| Silica glass | $1.10^{-14}$ | 1 | 2,09 |
| Sandy | 1 | 1 | 28 |
| Water | $5{,}5.10^{-6}$ | / | / |

## III.4 The geometries of the submarine power cables:

This step consist in drawing the geometric shape and representing the model in a graphic interface of the COMSOL multiphysics5.3 software by choosing the appropriate geometrical shapes such as circles, adjusting their dimensions and coordinates, and performing engineering movements on them such as rotation and with draw all [32]

The construction sequence of the overall model can be summarized in three steps. The first is to build the internal structure of the cables, as shown in the following figureIII.2:

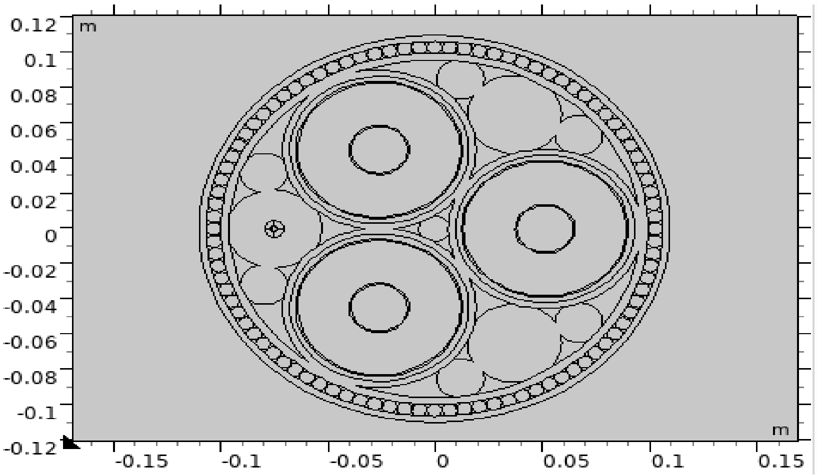


**Figure III.2**Three core of submarine cable

The second step is to add a circuit that forms the electromagnetic domain, as in the following figure:

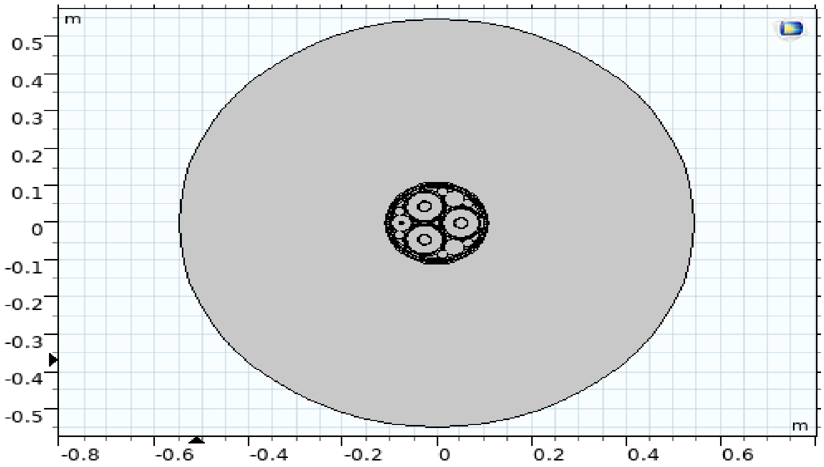


**Figure III.3** Electromagnetic domain section

And finally the external environment in which the cables are placed is modeled with two sub domains (sand: the lower layer water: the upper layer as in the figure III.4.

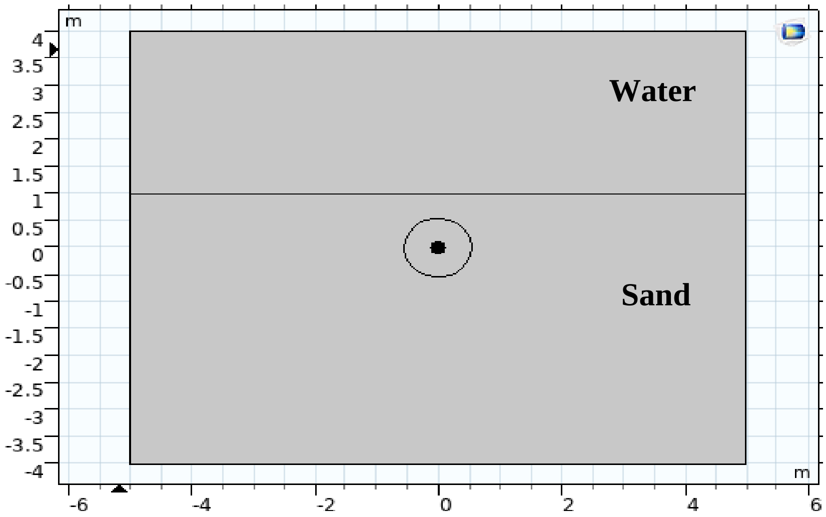


**Figure III.4** Total geometry of submarine cables model by COMSOL 5.3

The parameters of electromagnetic domain circles and external environmental layers are shown in the table III.4.

**Table III.4** Parameters of the model Complementary Layers

| **Parameter/ layer** | **Sandy layer** | **Water layer** | **Electromagnetic domain** |
|---|---|---|---|
| Width | 10 m | 10 m | / |
| Height | 5 m | 3 m | / |
| Radius (Three core cable) | / | / | 547,5 mm |
| Radius ( single core cable) | / | / | 500 mm |

## III.5 The mesh of submarine power cables:

The mesh of submarine power cable is made by the finite element method. The mesh is a discretization which contains a number of nodes, triangles and elements which depend on the system to be studied; the mesh is represented in the figure III.5.

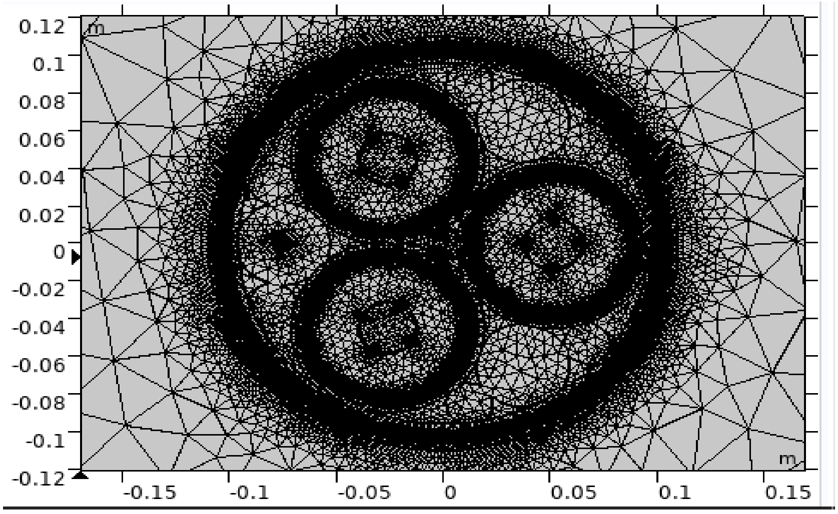


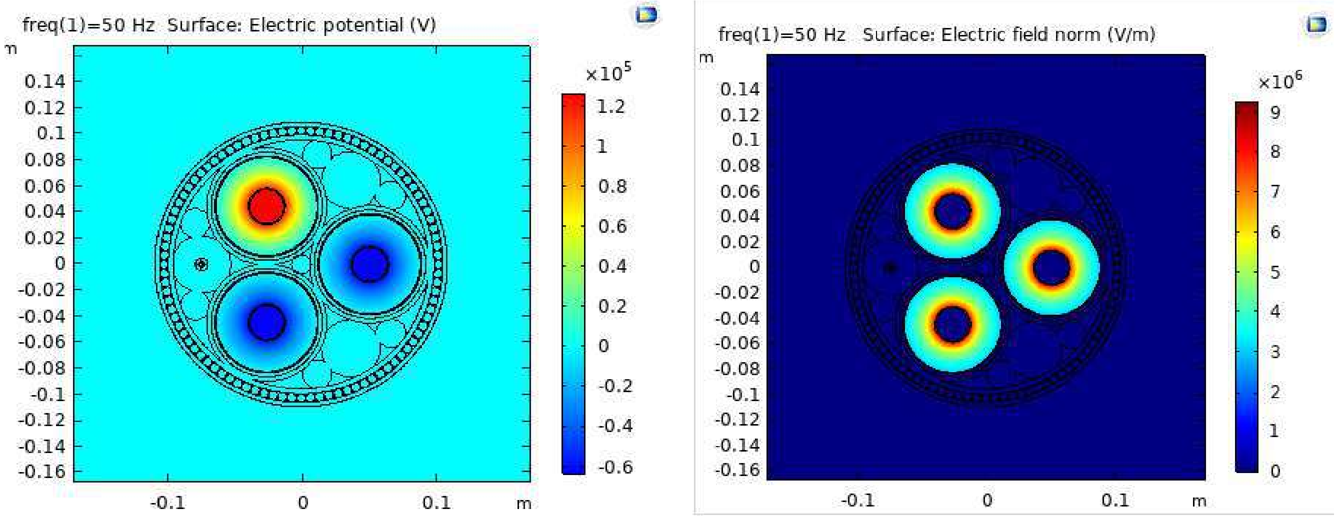
**Figure III.5** Mesh of submarine electrical cable

## III.6.Simulation results and discussions:

Capacitive effects, Inductive effects

### III.6. 1. Capacitive effects:

The following figure show the distribution of the electric potential, electric field in the cables cross sections for three-core in frequency domain.



A- Electric potential in frequency domain b- Electric field in frequency domain

**Figure III.6.**electrostatics characteristics of three core sub marine cable

Regarding figure III.6 of the three-core cable, we note that the signal of the electrical potential value is positive in one phase and negative in the other two phases, due to the phase angle difference between them. The value of the electrical potential in a single core cable is greatest in the conductor and is inversely proportional to the applied voltage. For the three-phase cable is proportional to the distance. In contrast to the distribution of electrical field, we find that the electric field distribution is much neglected or non-existent outside of the conductors, because the insulator layer in a submarine cable.

### III.6.2.Imperfections in a three core submarine cable:

In the second part we study the presence of imperfections (impurities, voids, cavities) in a single-phase of three core submarine cable with different geometries and form.

### III.6.2.1. Cable in normal condition:

The cable simulation model made for normal condition (without grooves) to show distribution of electric voltage and field across different cable parts, the components are in the normal state as shown in Figure 3.

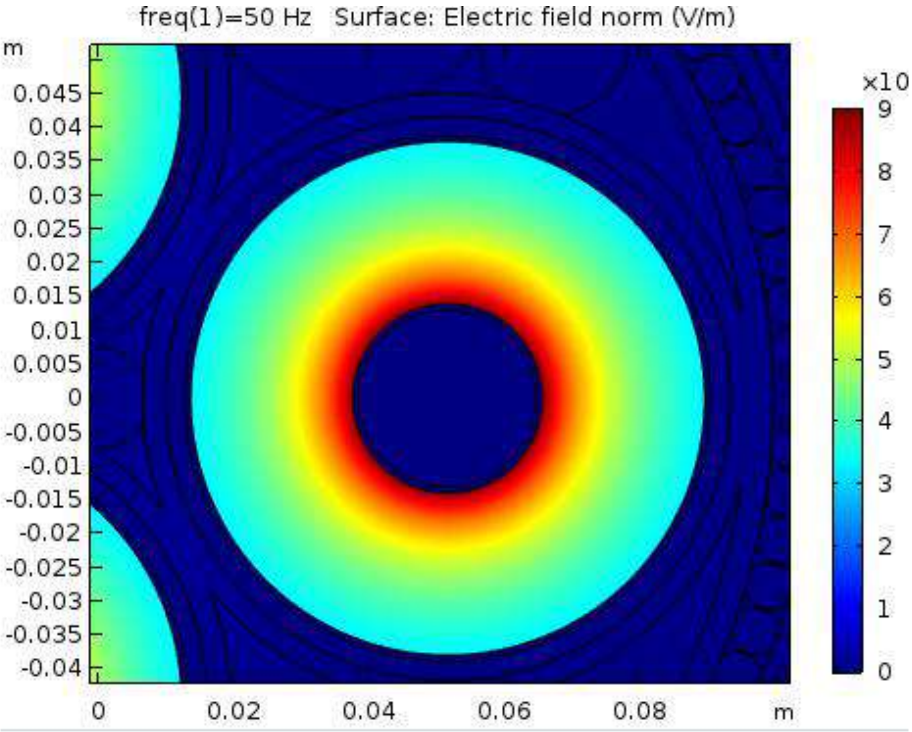


**Figure.III.7** electric field in single phase of three core subsea cable

The electric field is normally distributed and shielded by semi conductor metal

### III.6.2.2. Measuring method:

We measure at the level of the insulator, from the conductor to the semiconductor insulation sifting.

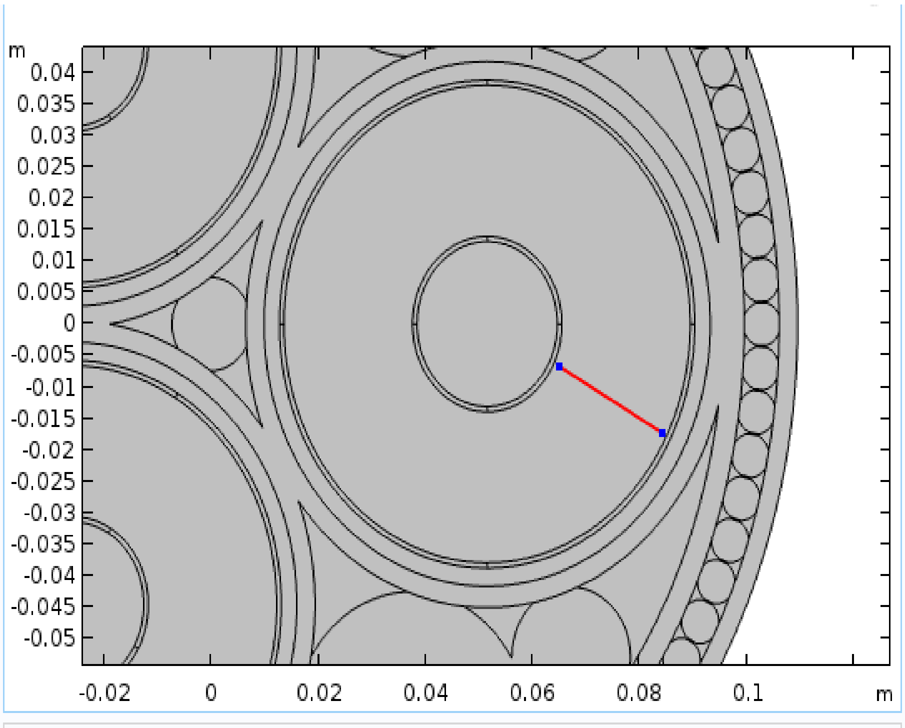


**Figure.III.8**Measuring method

In the normal case we obtain the FigureIII.9

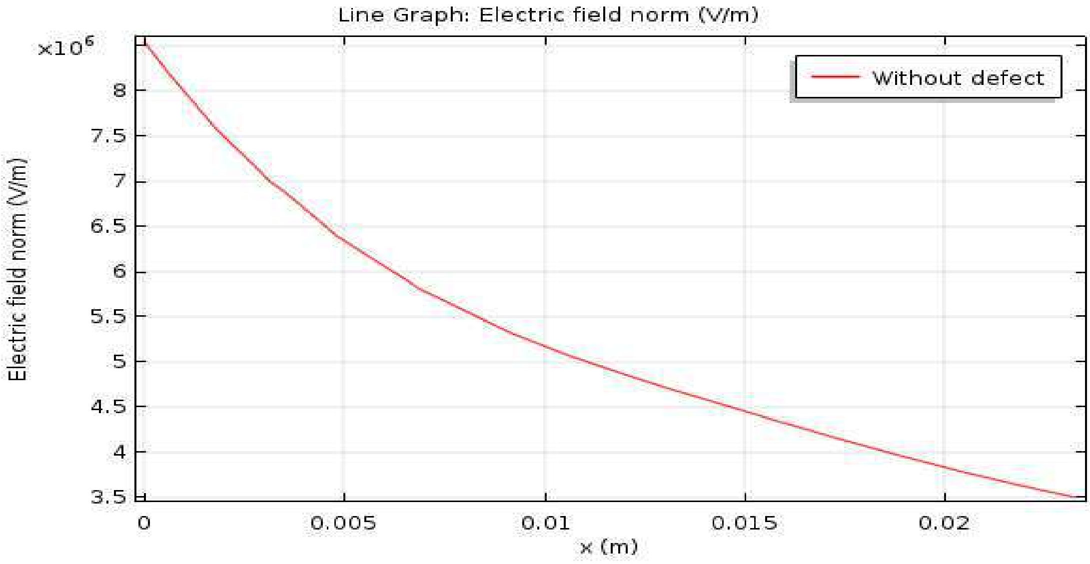


**Figure.III.9.**The distribution of the electric field over the dielectric level in the normal state.

The curve represents the variations of the electric field as a function of the distance from the conductor.

We notice that the further we move away from the conductor, the more the intensity of the electric field decreases until it is absent at the end of the insulation XLPE

### III.6..23. Most of the possible imperfection in the cables are:

We compare the normal state with the presence of impurities or cavity

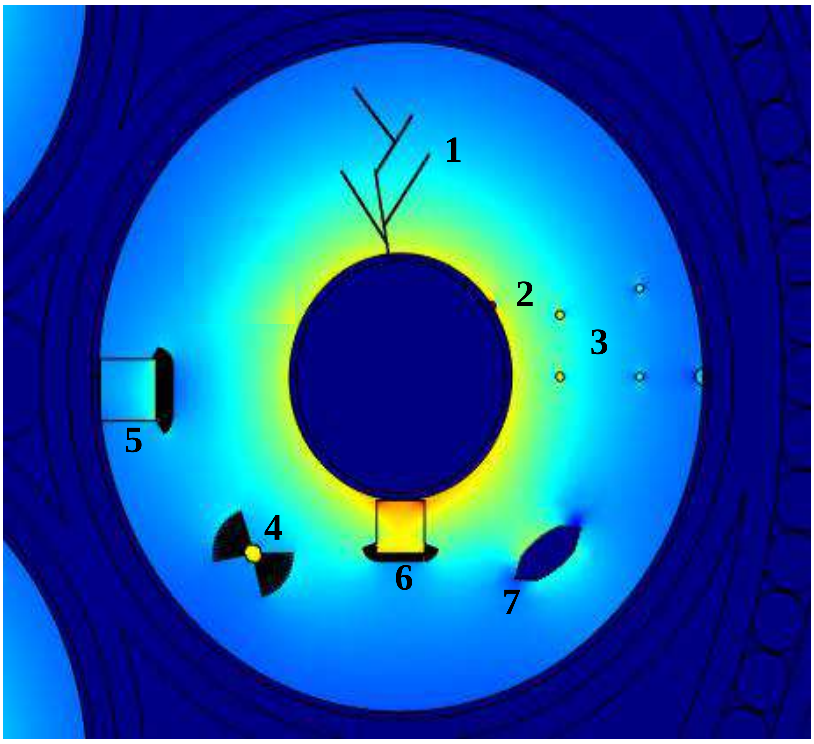


**Figure.III.10** Imperfections in a cable on COMSOL multiphysics 5.3

1 Electric tree
2. Empty at the interface
3. Vacuum in insulation
4. Discharge from vacuum
5. Discharge from insulation
6. Discharge from conductor
7. Moisture

### III.6.2.3.1.Electric tree:

Electrical tree is the prime cause of insulation failure in polymeric cable insulation, a number of fine conductive channels propagating in the similar direction as the electric field collectively form electrical tree. Presence of micro cavities, voids or other contaminating particles present inside the insulation may cause the initiation of electrical tree inside the polymer if the applied electric field is large enough. Growth phases of electrical tree are divided in to three phases i.e. initiation phase, propagation phase and breakdown. Poly ethylene emits visible light when it is subjected to an AC voltage stress above a certain threshold voltage, due to the changes of positive and negative polarities injected inside the polymer. The UV light causes photo chemical reaction to occur which creates free radicals and break chemical bonds forming the first channel of electrical tree. During the propagation phase the main channel branched in to several other branches forming a tree like structure. Discharges of 5 pC are sufficient to cause thermal runaway and widespread local thermal degradation of the polymer.

Propagation rate of electrical tree depends upon frequency and magnitude of applied electric field, environmental and mechanical stresses and temperature. Though the insulations are manufactured with great care still there are impurities remain inside it in the form of small cavities or bubbles, partial discharge process occurs inside the cavity when the electric field exceeds a threshold value. Partial discharge process may give rise to a number of positive ion and free electrons, these free electrons collide with other molecules to form electron avalanche and degradation of that insulation material start. The degradation process will be in the form of conducting channels known as electrical tree.Figure III.11[33].

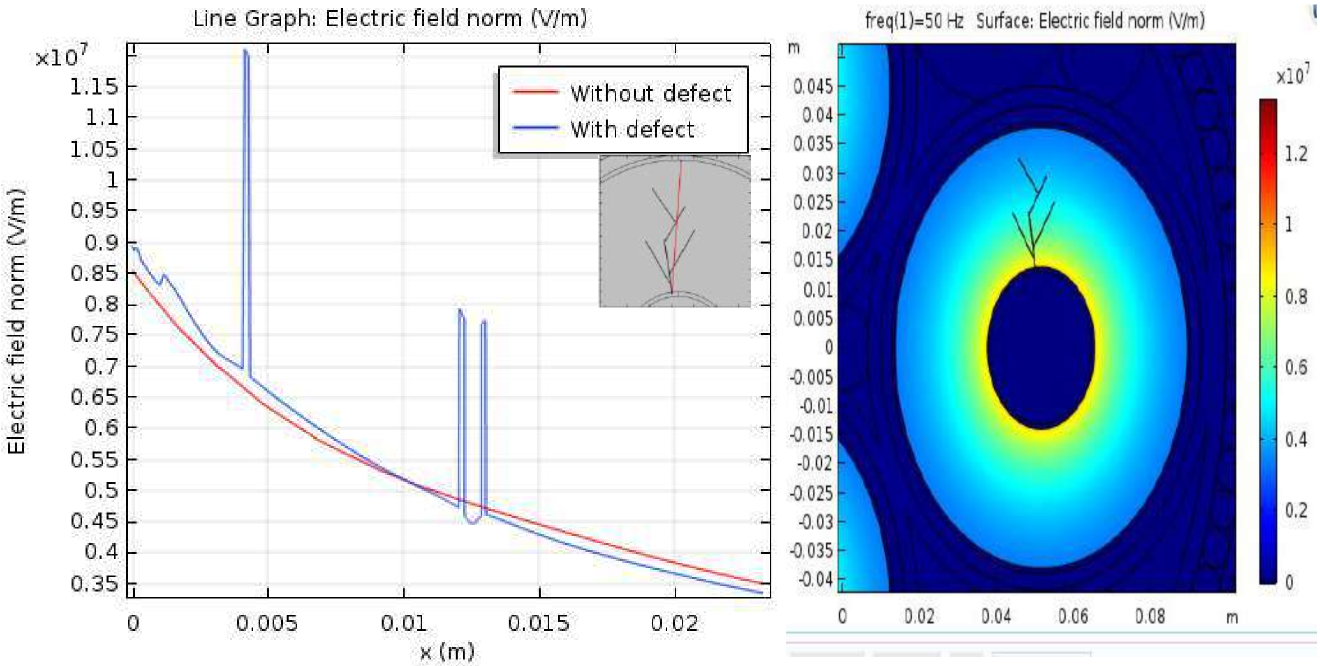


**Figure.III.11** electric tree in the insulator

From figure III.11 we note that the magnitude of electric field (1.25 $10^7$ V/m ) in the tree is much greater than the normal case (0.85 $10^7$ V/m ), the waveform is affected by the shape of tree defect

### III.6.2.3.2. Empty at the interface

It is a small cavity of 0.5 mm at the surface level of the insulator and may be the result of manufacture or during the laying process of the conductor occurs on its plane a partial discharge back, the partial discharge is active in a cavity only when the electric field in the cavity exceeds the strength of gas breakdown in the cavity. There must also be free electrons available to start the electron avalanche. Since the dielectric strength of air is much lower than that of solid insulation, the airspace electrically collapses. An electric spark occurs in the middle of the air that releases a large amount of energy. The electric field in which the gas breakdown force is exceeded is defined as the cavity starting field and the voltage is called the starting voltage.

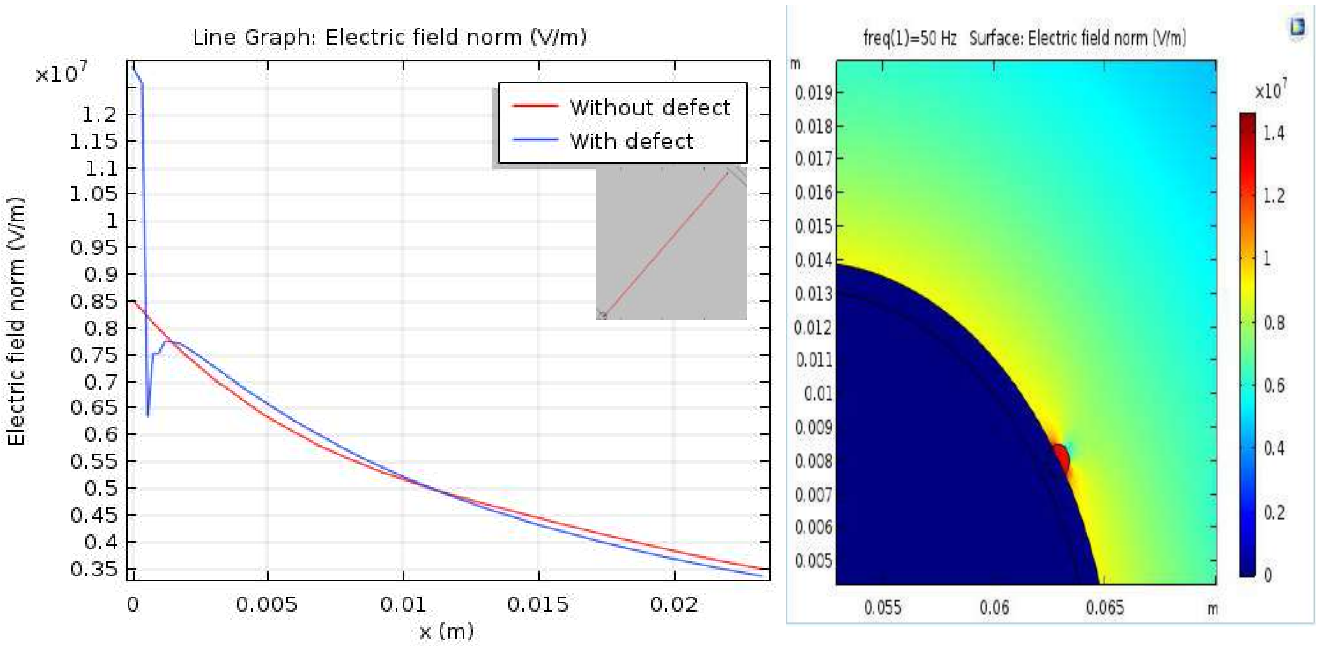


**Figure III.12Empty at the insulator interface**

The electric field will be at the maximum in the empty with big concentration of electric field and the further away they are, they will be less, see the graph.

### III.6.2.3.3.Vacuum in insulation:

They are voids at the insulation level, the size of0.5mm(of four points)inside insulator surface, produced in manufacturing or placing the conductor process Figure III.13

Fine voids often occur in homogeneous, extruded or molded polymeric materials if there is a break in an insulating body during the process and it has the same empty specifications at the interface because the difference is in the location of the cavity. A bracket, the closer the spaces are, the shorter the life of the cables

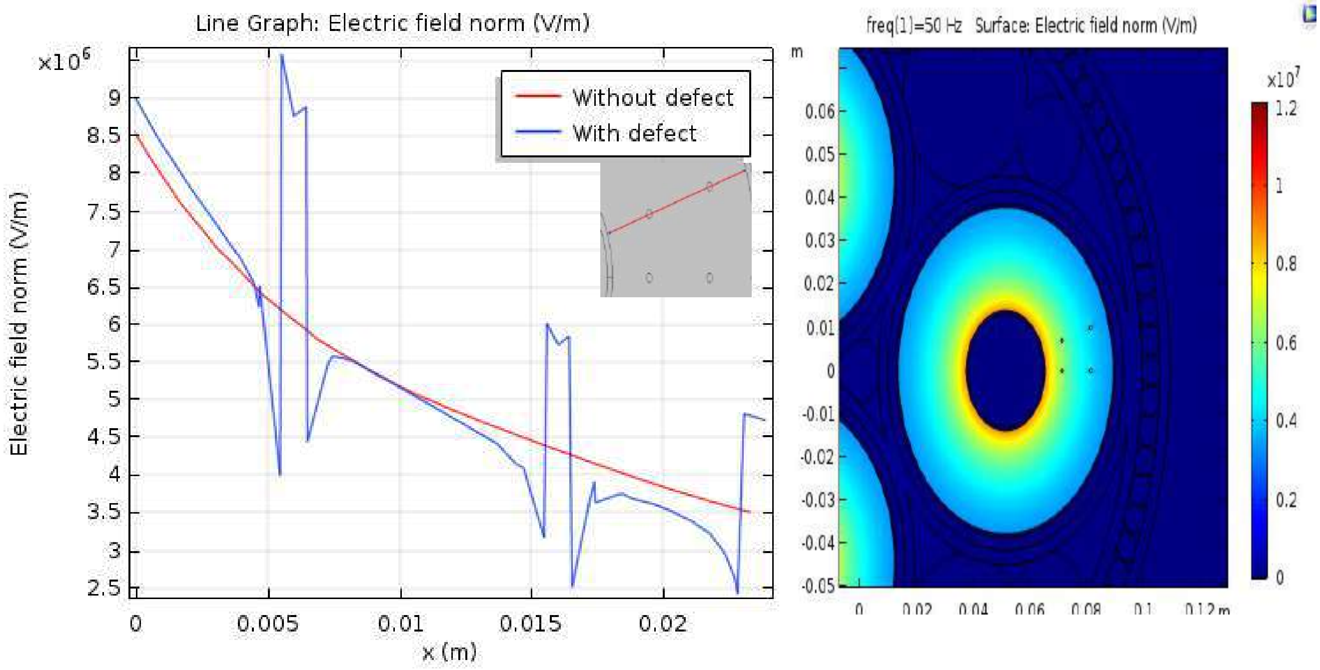


**Figure III.13** Vacuum in insulation

shows the results of inserting a four void-defect (The multiple point of vacuum) in the XLPE layer of phase 1; the void defect causes a distortion and an increase of the electric field. Moreover, this effect becomes stronger as the distance d from the conductor decreases. The plot the electric field stress through the defect as might be seen, in the latter case the waveform of the electric field and exceeds the maximum values expected in the normal case.

### III.6.2.3.4. Discharge from vacuum:

It is a vacuum in the insulator centered in the middle and Figure III.14 shape over time.
When the electric field is higher than the break down strength of the gas and there is an electron available, then the electron will be accelerated by the applied electric field in the cavity and will interact with neutral gas molecules. If the energy of the accelerated electron is high enough it will ionize any gas molecule it will collide with, resulting in an increase in the release of new electrons, positive ions and heat and other by products in the cavity. This process is called ionization. [33].

The recently generated free electrons collide with other gas molecules in the cavity and this process repeats. More free electrons are generated resulting in an increase in the number of free electrons. This repetition of gas ionization process is called “electron avalanche”. This electron avalanche will grow significantly in size until it forms channels in the cavity. The pattern of channels formed determines the type of discharges. During the avalanche process the temperature in the cavity increases due to heat energy released from ionization and this causes pressure in the cavity to increase.

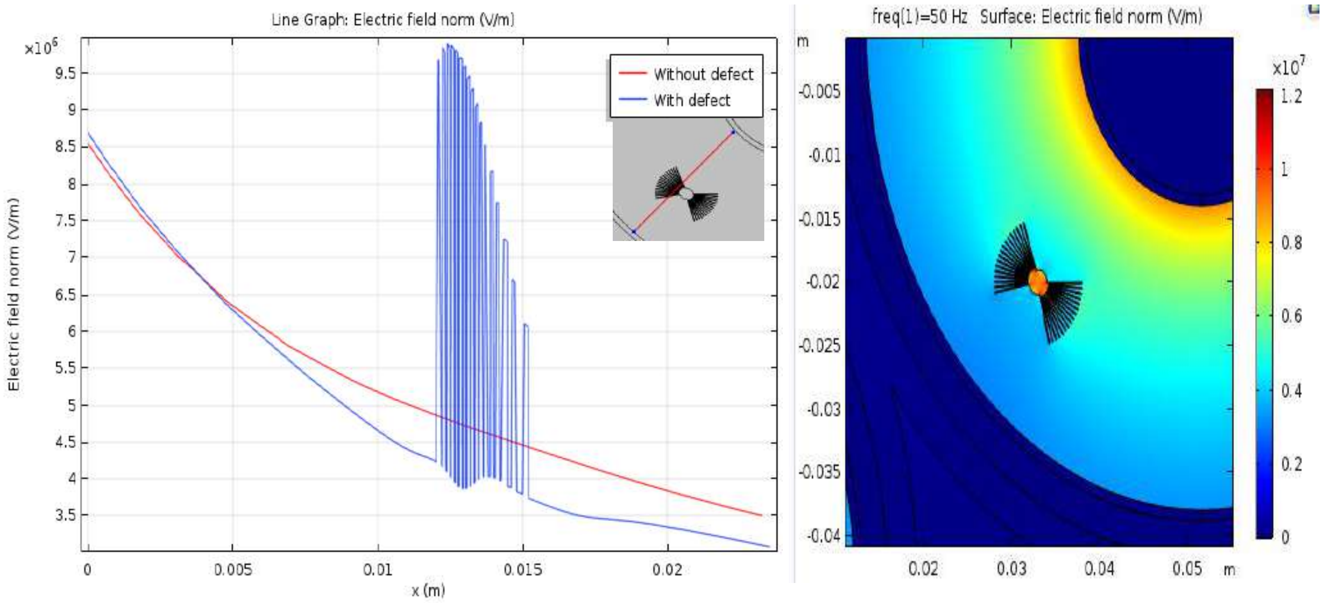


**Figure III.14** Discharge from vacuum

Figure illustrate the electric discharge characterized by special shape produced around the vacuum (electrical tree development to generate the partial discharge), the numerical measuring show the important of electric lines discharge with repetitive modulation and values.

### III.6.2.3.5. Discharge from insulation:

It is a vacuum or cavity formed from impurities or deposits or a vacuum at the level of the superficial part of the insulator, which is several electrical bushes that grow continuously due to thermal, electrical and mechanical factors and may reach this size after years and decrease from the life span of a few years and its effect is weak due to its distance from the conductor It has the same characteristics as the others Figure III.15.

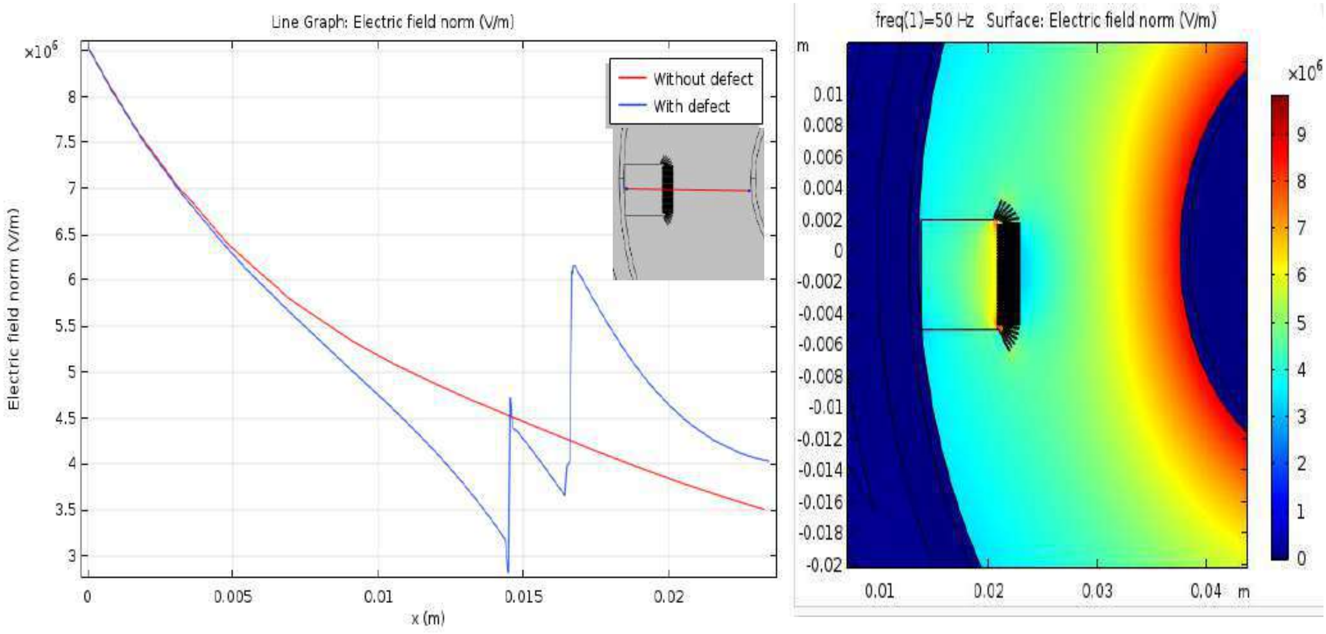


**Figure III.15** Discharge from insulation

The results show the multiple lines of spurs produce the discharge from insulator layer with semi conductor material. The measurement shows the variation of electric field affected by the discharge form.

### III.6.2.3.6. Discharge from conductor:

It consists of the same foundations and takes the same shape because it differs in its position and is quiescent next to the conductor. Too large a discharge causes rapid hollowing of the cables Figure III.16.

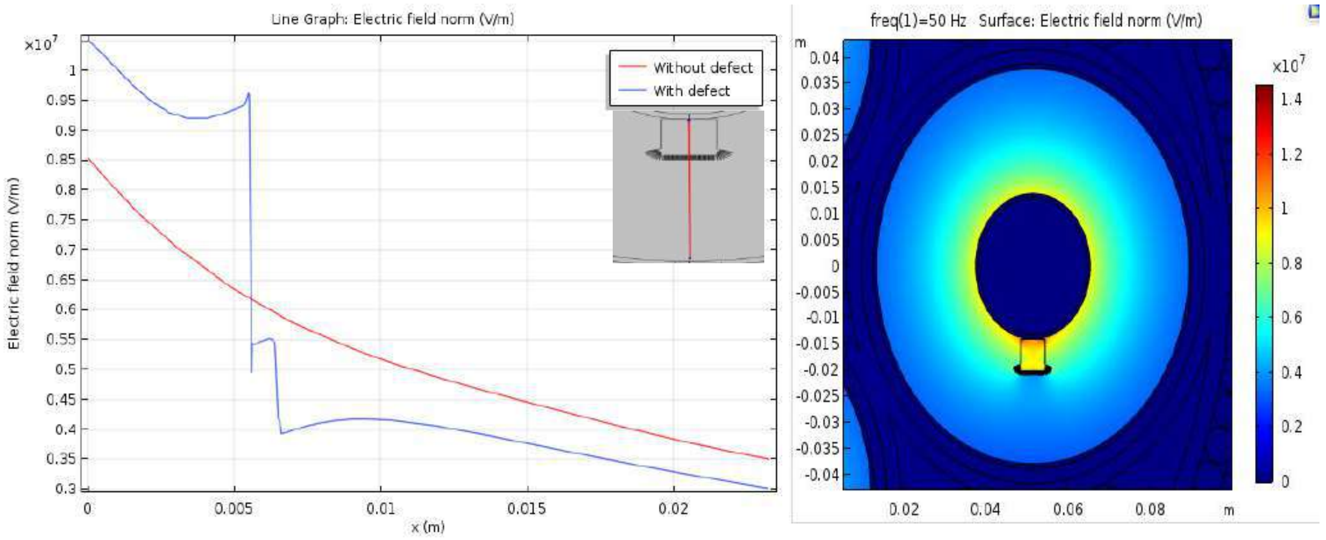


**Figure III.16** Discharge from conductor

The position of discharge from conductor changes the electric field orientation and distribution compared by the last case. The calculation and waveform of electric field varied by compared them with to previous forms.

### III.6.2.3.7. Moisture:

It is formed from drops of water and is considered a complete conductor of electric current and takes the role of a conductor, thus showing from its horror the electric field as shown in the following figure.

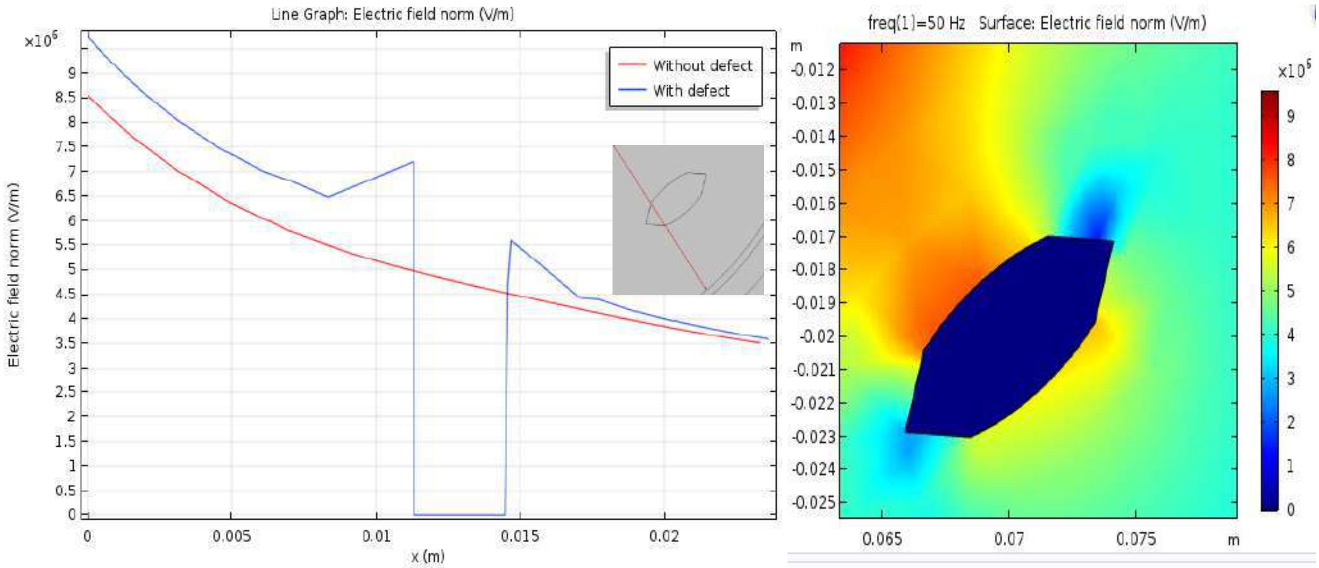
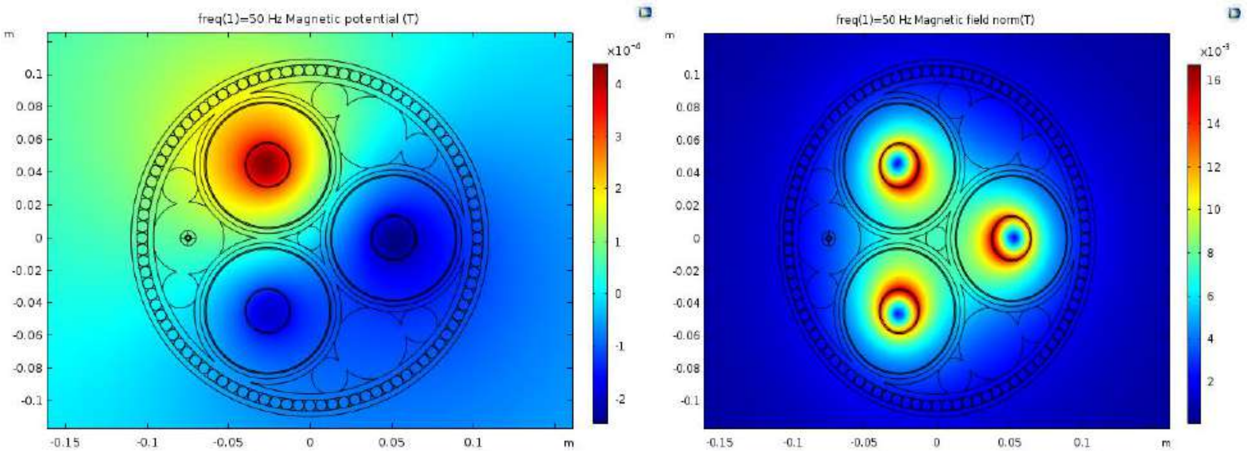


**Figure III.17** Moisture

The last case is characterized by the presence of water as conductor, the electric field is neglected inside them (numerical wave form measurement), but the electric field concentrates around the moisture form and extremities.

### III6.3.Inductive effects:

The following figure show the distribution of the magnetic potential, magnetic field in the cables cross sections for three-core in frequency domain



A- Magnetic potential in frequency domain b- Magnetic field in frequency domain

**Figure III.18** Magnetic characteristics of three core sub marine cable

Regarding figure III.18 of the three-core cable, we note that the signal of the Magnetic potential value is positive in one phase and negative in the other two phases, due to the phase angle difference between them. The value of the Magnetic potential in a single core cable is greatest in the conductor and is inversely proportional to the applied voltage. For the three-phase cable is proportional to the distance. In contrast to the distribution of Magnetic field.

### III6.3.1.Cable in normal condition:

The cable simulation model made for normal condition (without grooves) to show distribution of magnetic field across different cable parts, the components are in the normal state as shown in Figure III.19.

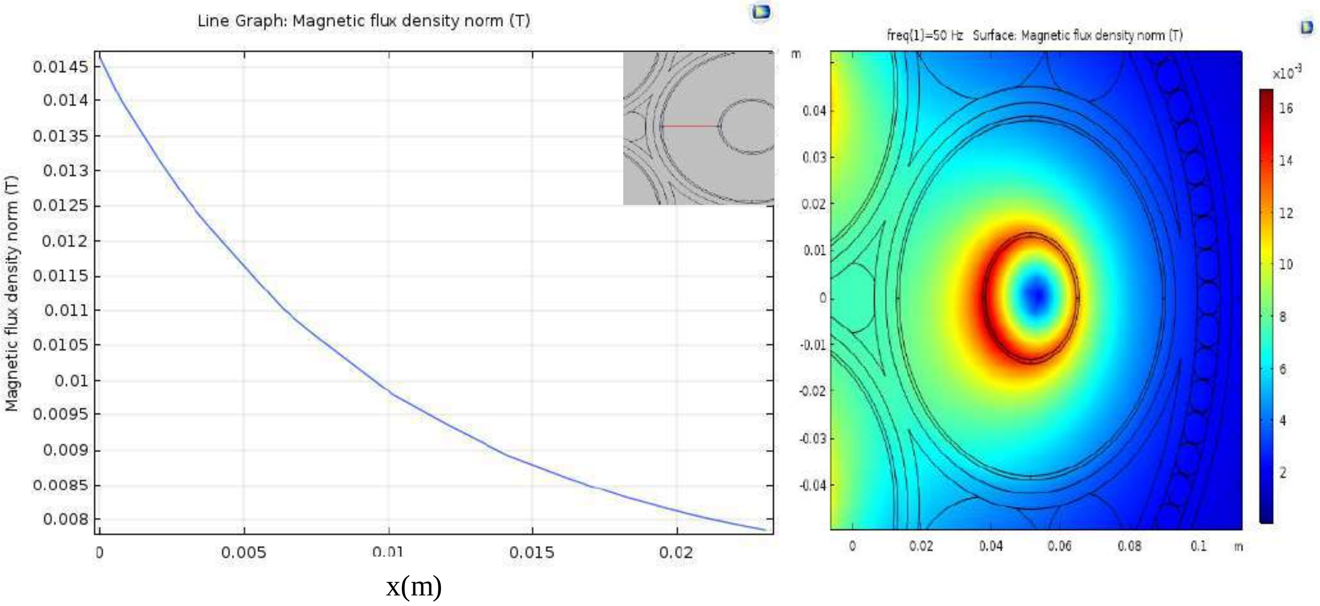


**Figure III.19** The distribution of the Magnetic field over the dielectric level in the normal state

The curve represents the changes of the magnetic field as a function of the distance from the conductor.

We notice that the more we move away from the conductor, the more the intensity of the magnetic field gradually decreases and does not disappear at the level of the insulators, but extends to the outer circumference around the cable.

### III6.3.2.Vacuum in insulation:

They are voids at the insulation level, the size of 1 mm inside insulator , produced in manufacturing or placing the conductor process Figure III.20.

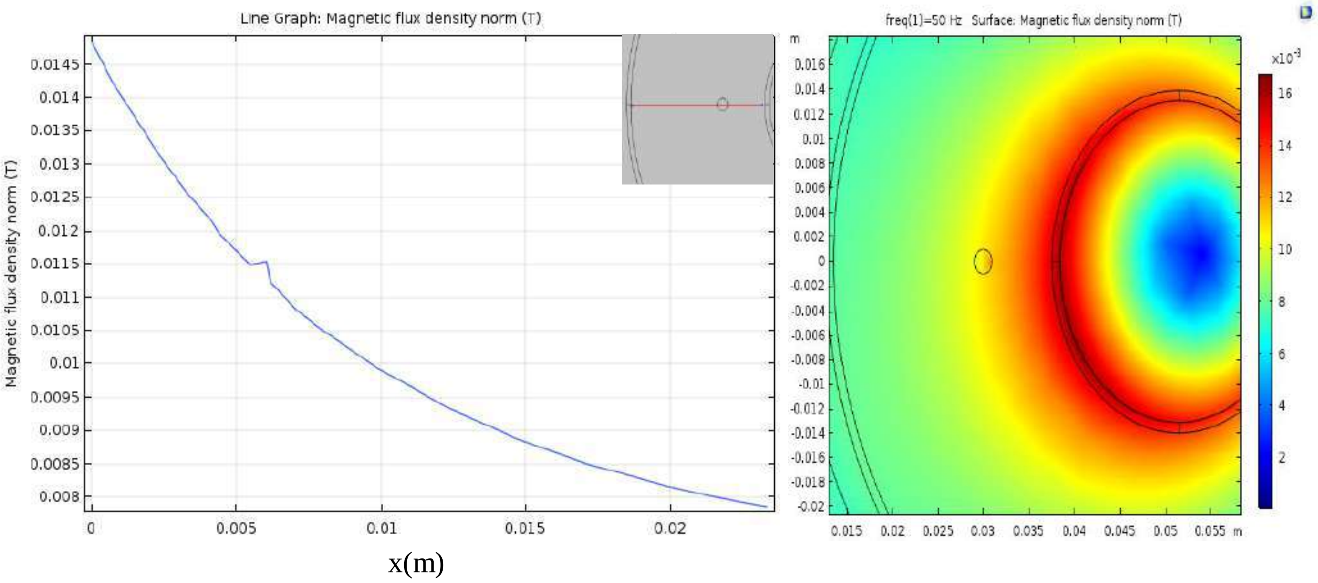


**Figure III.20** The distribution of the magnetic field on the level of the insulation at the vacuum in the insulation

Shows the results of vacuum defect introduction in the XLPE layer of phase 1; the void defect causes a distortion and an increase very small of the magnetic field.

We conclude that the insulator XLPE works to isolate the electric field in a special or by the magnetic field, as the worker controlling its decrease is after the distance.

This focused in two studies on the electric field.

## III.7.Conclusion:

In this chapter we show the effect of the impurities presence inside one phase of three core submarine XLPE 220 kV cables was studied and simulated in the COMSOL 5.3 multiphysics software. The simulation with finite element method helps to produce the seven kind of defect and show the measurement of electric field distribution, values and variation, across the different layers of the cable components in the normal and abnormal states. The simulation results complete to understand the relationship between electrical tree development and partial discharge of very high voltage XLPE 220 KV .The defect nature position, size and shape on partial discharge affect the discharge behavior lines and variation, these results can provide criteria for determining defects in cable insulation and their impact on electrical loss.

# General Conclusion

# General conclusion

A very considerable studies and research concerning the study of very high voltage cable behavior in presence of gaseous cavity were carried out to know the electric fled values and discharge causes. A three Core submarine VHV XLPE 220 kV cable used for transmission power network was modeled and simulated by solving mathematical modeled with Finite Element Method by COMSOL 5.3multiphysics software. The established model and simulation give a very exact and interesting solution since it reduces the calculation time, simplified non linear model and complex geometry, those influence the threshold electric field.

Electrical study and analysis showed the effect of several parameters (impurities size, nature of defect, position, materials, shape...) on the electric field distribution and magnitude it was demonstrated. . The presence of defects in a very high voltage cable is usually the main cause of its deterioration and ageing. The electric field strength and waveform are affected by the presence of defect in insulation or near the conductor layer could cause relevant peaks higher than the maximum values in normal case, rises considerably

The simulation results complete to understand the relationship between electrical tree development and partial discharge of very high voltage XLPE 220 KV.

The defect nature affect the discharge behavior lines and variation, these results can provide criteria for determining defects in cable insulation and their impact on electrical loss.

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خلاصة : يمكن أن يؤدي وجود أعطال في كابل الجهد العالي إلى الشيخوخة والتسخين أو التفريغ الجزئي للكهرباء داخل الكبل وإيقاف التشغيل عن طريق التفريغ الكهربائي الكلي. في هذا البحث تم دراسة كابل بحري ثلاثي النواة عالي الجهد يستخدم في الشبكات الكهربائية بطريقة العناصر المحدودة في وجود تجويف أو فراغ. أظهرت نتائج المحاكاة أن وجود العديد من العيوب بالقرب من العزل والموصل يعدل توزيع المجال الكهربائي وشكل الموجة.

**الكلمات المفتاحية -الجهد العالي جداً، الكابلات البحرية، طريقة العناصر المحدودة، المجال الكهربائي.**

**Abstract:** The presence of faults in the high voltage cable can cause the ageing and heating or electrical partial discharge inside the cable and decommissioning by total electric discharge. In this paper a three core very high voltage submarine cable used in electric networks is studied by Finite Element Method in the presence of cavity or vacuum. The simulation results show that the presence of several defects nears the insulation and conductor modifies the electric field distribution and waveform.

**Keywords— Very High Voltage, submarine Cable, Finite Element Method, Electric Field.**

**Résumé :**La présence de défauts dans le câble haute tension peut entraîner le vieillissement et l'échauffement ou la décharge électrique partielle à l'intérieur du câble et la mise hors service par décharge électrique totale. Dans cet article, un câble sous-marin à très haute tension à trois conducteurs utilisé dans les réseaux électriques est étudié par la méthode des éléments finis en présence de cavité ou de vide. Les résultats de la simulation montrent que la présence de plusieurs défauts à proximité de l'isolant et du conducteur modifie la distribution et la forme d'onde du champ électrique.

**Mots-clés— Très Haute Tension, Câble sous-marin, Méthode des Eléments Finis,**