THERMAL EFFECT ON THE UNDERGROUND POWER CABLES

SAKTHIVEL SUBRAMANIAM

A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Electrical)

Faculty of Engineering and Science
University Tunku Abdul Rahman

April 2019

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature	:	
Name	:	Sakthivel Subramaniam
ID No.	:	17UEM05203
Date	:	

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"THERMAL EFFECT ON THE UNDERGROUND POWER CABLES"** was prepared by **SAKTHIVEL SUBRAMANIAM** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Electrical) at University Tunku Abdul Rahman.

Approved by,

Signature : ______________________

Supervisor : Ir. Prof. Dr. Lim Yun Seng

Date : ______________________

Signature : ______________________

Co-Supervisor : ______________________

Date : ______________________

Specially dedicated to

my beloved father, mother and my family members

ACKNOWLEDGEMENTS

This project would not have been completed without the assistance of certain people who were very kind and dedicated. First of all, it is a pleasure to thank my supervisor Ir. Prof. Dr. Lim Yun Seng, for his kindness and endless assistance for this project. Besides that, I am also thankful to everyone who all supported me, for I have completed my project effectively and moreover on time.

Moreover, I would like to acknowledge to my classmates who helped me in certain questions with fascinating ideas and tricks. With the combination of different ideas of classmates, I have been able to tackle the obstacle easily. I would like to thank my family who are my constant source of motivation, inspiration and supportive for me to complete this final year project.

Last but not least, I would like to thank University Tunku Abdul Rahman (UTAR) for providing a fabulous platform to learn in depth.

ABSTRACT

"THERMAL EFFECT ON THE UNDERGROUND POWER CABLES"

In 33KV Single Core 1x630mm² XLPE Cable was investigated with COMSOL software by changing the current carry capacity (ampacity) of the cable and ambient ground temperature in Trefoil position. Result shows that the current makes the operating temperature to rise and also the increased temperature will decrease the current carry capacity of the cable. In matter of fact, the increased temperature causes the current to reduce and consequently leading to increase in the current again. In terms of the operating temperature and current it was achieved in stable values. Based on the designed XLPE insulated cables, with different range of thermal conductivity of soil was practically experienced. Basically, the ampacity of the cables will increase with the higher thermal conductivity and also the ampacity will decrease with the lower thermal conductivity. In fact, increased in the thermal conductivity will reduce the heat production in the cables and also these will lead to reduction of the cables temperature. Besides that, the flat position of the cables was laid next to each other and these causes the temperature of the centre cable to increase due to heat transferred from the side cables. In order to solve this, the current flow of the centre cable conductor was decreased in order to reduce the operating temperature. Furthermore, the impact of temperature distribution on the single core cable in two different burial depth which are 0.5 meter and 1 meter was considered. It proves that the cables laid close to ground surface had higher values of the operating cable conductor temperature and when the single core cable are closer to the surface ground, the cable will receive more heat than the single core cable buried in depth of 1 meter. Besides that, water has been used as surrounding material of the cable by immersed in depth of 1 meter in order to study and analyse the temperature distribution and current carrying capacity of the XLPE insulated cables. In matter of fact, the operating temperature of the cables conductor is higher than that the soil environment. This factor can be experienced because the heat production from cables are slowly dispersed into the water surrounding environment than the soil surrounding environment. In fact, the thermal conductivity of the water can be one of the reason for the heating factor because it changes respectively with the water ambient temperature. In the nutshell, running the power cables in the suitable environment will extend the life expectancy, efficiency of the cables which provides positive commitment to safety and economy of the connected power systems.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE **TOPIC** **PAGE**

LIST OF TABLES

TABLE **TOPIC** **PAGE**

LIST OF SYMBOLS/ ABBREVIATIONS

V	Voltage
A	Current
°C	Temperature
K	Thermal Conductivity
W/K*m	Soil Thermal Conductivity
K*m/W	Soil Thermal Resistivity
Rho	Density
J/kg*k	Heat Capacity
UPC	Underground Power Cables
XLPE	Cross-linked Polyethylene
PVC	Polyvinyl Chloride
Dcon	Diameter of conductor (Phase)
Tins	Insulation thickness (Phase)
Dins	Diameter over insulation (Phase)
Tscc	Semi-conductive compound thickness (Phase)
Tarm	Armor thickness (Cable)
Dcab	Outer diameter of cable (Cable)
Acon	Cross section of conductor (Phase)
Lcab	Total length of cable (Cable)
f0	Operating frequency"
V0	Phase to ground voltage (Amplitude)

I0	Rated current (Amplitude)
Pvc	Thickness of outer sheath
Text	External temperature
Tref	Reference temperature (Metals)
Cu_alpha	Resistivity temperature coefficient (Copper)
Cu_rho0	Reference resistivity,(Copper)
Scon	Copper conductivity, 20 °C (Phase)
Sal	Aluminium conductivity, 20 °C (Phase)
Rcon	Aluminium DC resistance per phase, 20 °C (Analytic)
Rcu	Copper DC resistance per phase, 20 °C (Analytic)
Exlpe	XLPE relative permittivity (Phase)"

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

One of the most important components in the power system is the power cable which are used in the transmission (overhead lines) and distribution (underground lines). Even though for power transmission lines are often chosen with overhead lines, for the distribution site underground power cables are ideal to protect the operation in extreme settlement areas, aesthetic appearance and favoured for ensuring safety of life. When transmitted power range and voltage are increased, the basic structures of power cables become complicated when they are designed to handle extra strength and heat build-up. Furthermore, it is vital of existing systems at the peak capacity it requires specification of maximum current carrying capacity of power cables and definition of current carrying capacities of power cables are available through numerical or analytical approaches. For this case, numerical analysis and among the other numerical approaches, the most preferred methods is the finite element method (FEM) based on the overall structure of the power cables (Kalenderli).

There is a solid connection between current conveying limit and operating temperature of power cables. There will production of heat in the cable, when losses delivered by voltage connected to a cable and current flowing through its conductor. The powerful distribution of production of heat from the cable to the surrounding environment will make the current conveying limits of a cables relies on it. This distribution will be facing some problems because of the presence of high thermal resistances caused by the insulating materials in cables and surrounding environment.
The maximum current value is characterized by the current capacity limit of power cables where the cable conductor can convey constantly deprived of surpassing the breaking point temperature value of the cable components, specifically not surpassing that of protecting material. Along these lines, the temperature estimations of the cable

components during persistent process ought to be decided. Basically, the generated heat inside the cable, numerical methods are applied for calculation of temperature distribution in a cable and its surroundings environment. For this reason, using the given conductor current, the conductor temperature was simulated using the software. The simulation in thermal analysis are conducted by using geometry, material information and boundary temperature conditions (Kalenderli).

1.2 Problem Statements

One of the important parts in the power system which is the high voltage power cable is consistently involved in the increased temperature that will impact on the cable. These will impact the cable properties and cause damages. In order to avoid this, this research will be performed on study and analyse the effectiveness of using different materials as backfill of the cable. After that, the laying of the cable under the soil by choosing the best position of the cable will studied and analysed. Then, the operating temperature of the cable will be measured by using the software with sufficient information. Besides that, the operating cable conductor temperature with and without current rating correction factor will be studied and analysed. Moreover, the operating temperature of single cable conductor with different buried depth under the soil will be studied and analysed. Finally, the operating temperature of the cable conductor immersed in water will be studied and analysed.

1.3 Aims and Objectives

The objectives of conducting this research are listed below:

- To study the cable specifications.
- To study the temperature changes around the cable using Finite Element Software called COMSOL software
- To study, simulate, analyse and determine the effectiveness of using different material as backfill of the cable.
- To study, simulate, analyse and determine the laying position of the cable under the soil in order to select the best position.
- To study, simulate, analyse and determine the operating temperature of the cable will be measured by using the software with sufficient information.
- To study, simulate, analyse and determine the operating cable conductor temperature with and without current rating correction factor.
- To study, simulate, analyse and determine the operating temperature of single power cable conductor with different buried depth under the soil.
- To study, simulate, analyse and determine the operating temperature of the cable conductor which will be immersed in water.

1.4 Structure of the Research Report

This report consists of five main chapters as briefly described below:

Chapter 1: Introduction
In this chapter, the background of this research, the problem statement as the purpose of conducting this project and the aim and objective are specified.

Chapter 2: Literature Review
In this chapter, some research was done on the cable structures and the function of that structures and also on the software used which COMSOL.

Chapter 3: Methodology
In this chapter, the modelling of the underground power cable, the geometry of the cable, the material of the cable, the thermal effect of on the underground power cable was designed.

Chapter 4: Results and Discussions
In this chapter, the effect of the operating temperature of the cable conductor with different conditions using COMSOL was tabulated and discussed.

Chapter 5: Conclusion & Recommendations
In this chapter, concluding for the overall project purpose and recommendation for the improvement that can be made from this project

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Before entering the main purpose of this project which is Thermal Effect on Underground Power Cables, some research was done on understanding about the cable structures. After that, some research was conducted on the FEM software that will be suitable for this project.

2.2 Cable Structures

Power cable structures consist of conductor, conductor insulation, sheath and jackets. The electrical conductor from other cable components through separated by the electrical insulation layer where the current might flow. In order to make available a path for the induced current flowing to the ground, sheath (concentric neutral wires) acts as a layer placed over the insulation surface. The PVC (jackets) is essential as protect to degradation due to sunlight, prevent external corrosion, physical abuse or environmental water. Basically, the power cable chosen for this research is **'33kV Single Core XLPE 630mm^2 Armoured Sheathed PVC Aluminium Cable'**. The next following sections are the list of cable aspects that are important to this research.

2.2.1 Conductors

In cable conductors there are usually two materials are commonly used which are copper and aluminium. In wiring and broad range of applications, both are have their advantages but copper is more popular than aluminium wire. This because it has greater conductivity and able to withstand better load surges. Moreover, it has higher tensile strength, thermal-conductivity, thermal-expansion properties and high stress level prior to breaking because copper is very flexible. Besides that, copper is more expensive than aluminium where mostly used for building wires and also commonly used in power distribution and power generation (BSE Border States-Supply Chain Solutions, 2014).

Even though, the material of choice for conducting electricity copper is famous but aluminium also has some advantages that will be essential for specific applications. Aluminium has 61 percent of the conductivity of copper but at the same time weight of the aluminium is 30 percent lesser than copper but it has the same electrical resistance. Basically, in electrical utilities such overhead transmission lines and underground distribution lines, aluminium are mostly used because of the weight is much less denser and more cost saving than using copper.

In this thesis, the 33kV Single Core XLPE Cable's conductor material is aluminium. There are also two types of conductor cross section can be either solid or stranded. A comprise group of wires which can be either segmented or compacted is called stranded conductors which will provide more flexibility than solid cable (BSE Border States-Supply Chain Solutions, 2014).

CHARACTERISTICS	COPPER	ALUMINUM
Tensile strength (lb/in^2)	50,000	32,000
Tensile strength for same conductivity (lb)	50,000	50,000
Weight for same conductivity (lb)	100	54
Cross section for same conductivity	100	156
Specific resistance (ohms-cir/mil ft)(20°C ref)	10.6	18.52
Coefficient of expansion (per deg. C x 10^{-6})	16.6	23

Figure 2.1: The Comparison of Aluminium and Copper

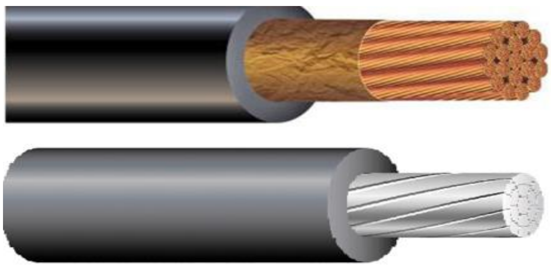


Figure 2.2: The Aluminium and Copper Conductor

2.2.2 Conductor Shield and Insulation Shield (Semi-conductive compound)

The conductor shield is a layer between conductor and insulation (PVC, XLPE) and the insulation shield is a layer between XLPE and Armoured wires which is usually made of a semi-conductor material. The main purpose of conductor and insulation shield is to maintain a homogeneously divergent electric field and to surround the electric field within the cable core. Furthermore, it is basically to achieve a radially symmetric electric field and "smoothest" out the surface irregularities of conductor contour as well. Semi-conducting material of the conductor and insulation doesn't conduct electricity good enough to be conductor but will not hold back voltage. The material are based on carbon black that is dispersed within a polymer matrix where it must be sufficiently great enough to ensure a suitable and consistent conductivity. Basically, to deliver a smooth interface between the conducting and insulating portions of the cable, the integration must be optimized. The amount of regions of high electrical stress also depends on the smooth surface in order to reduce the stress (ANIXER, 2018).

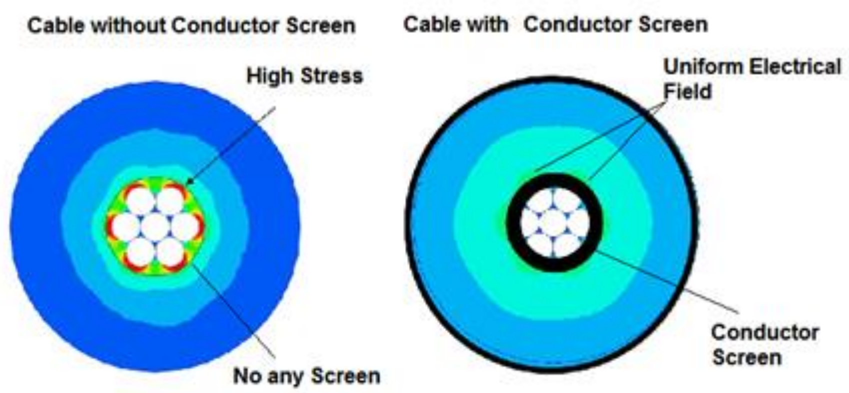


Figure 2.3: Cable with and without Semi-conductive layer

2.2.3 Insulation

In those days, Oil-impregnated paper was used to insulate the cable conductor but now in present mostly extruded solid dielectrics are used. There are several types of solid extruded insulations such as butyl rubber, natural rubber, Cross-linked polyethylene (XLPE), Polyethylene (PE) and high molecular weight polyethylene (HMWPE). Basically, insulation type and cable ratings have strong relationship. For this research cross-linked polyethylene XLPE cable was used because by taking advantage of low dielectric losses (Edvard, EEP-Electrical Engineering Portal, 2014).

As mentioned previously, XLPE stands for "cross-linked polyethylene" and it has linear molecular structure as shown in Figure 2.4. It has bonded in a three dimensional networks as shown in C and D and because of this it has strong resistance to deformation even at high temperature. As shown in Figure 2.4, the molecules of polyethylene are not chemically bonded and easily deformed at high temperature.
In matter of fact, XLPE is produced under high pressure with organic peroxides as additives which is from polyethylene. To effect the cross linking, pressure and heat is used and this causes the material to transform from a thermoplastic to an elastic material when the individual molecular chains to combine with one another (Appendix A).

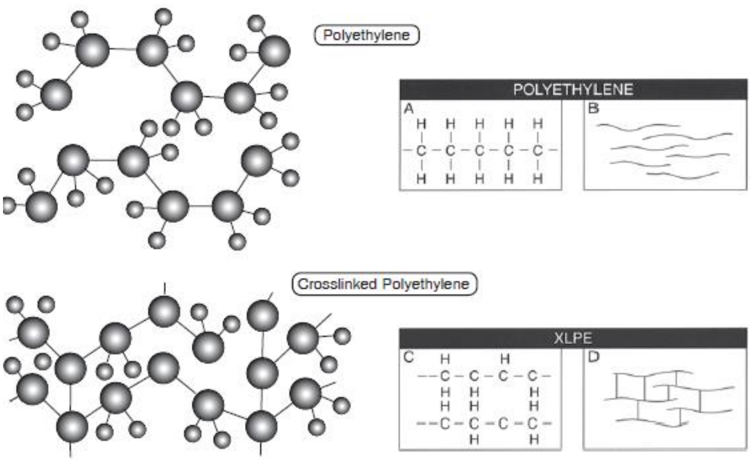


Figure 2.4: The molecules structure of Polyethylene and Cross-linked Polyethylene.

2.2.5 Armoured Wires (Shield)

Medium and high-voltage power cables mostly contain a shield layer (Armoured) of copper or aluminium tapes or wires. The armoured wires is considered as protection layer over the insulation (XLPE). The main function is to improve mechanical strength, chemical corrosion, protect cables against moisture and physical abuse. This also provide the return path for fault currents. Besides that, it must be connected to the ground at least at one point because the induced current will flow on the armoured wires. This will minimize the maximum current rating of the circuit and this current will produce losses and heating. Moreover, it diverts any leakage current to ground by equalizing electrical stress around the conductor. In order to confine the dielectric field to the inside of this armoured wires (shield), the power cable must accomplished by surrounding the assembly on insulation with a grounded as conducting medium. For this research, armoured wires of copper material is used (Edvard, EEP-Electrical Engineering Portal, 2014).

2.2.6 Insulation exterior (Jackets)

The insulation on the exterior layer of the cable is to protect the underlying conductor against cable failures caused by any external electrical or mechanical damages. There are several non-metallic materials can be used as exterior layer of the cable such as Polyvinyl chloride (PVC), Polyethylene (PE) and Ethylene Propylene Rubber (EPR). For this research, Polyvinyl chloride (PVC) insulated cables is used.

PVC is used in wide variety of applications where it is relatively low cost and combines with plasticizers for electric cables.

PVC specification:

- Has high tensile strength
- Higher conductivity
- Better flexibility
- Ease of jointing

Basically, this material type of cable must take precaution not to overheat more than 90 °C, where it is suitable for a conductor up to 90 °C because it is a thermoplastic material (ELAND CABLES, 2019).

2.3 Software Used

2.3.1 COMSOL Multiphysics

COMSOL Multiphysics is a cross-platform finite element analysis, solver and multiphysics simulation software (Littmarck, 2015).

- It provides an Integrated Development Environment (IDE) and unified workflow for electrical, mechanical, fluid and chemical applications.
- It allows conventional physics-based user interfaces and coupled system of partial differential equation (PDEs).
- To control the software externally, an Application Programming Interface (API) for java and LiveLink for Matlab is used with the same API via the Method Editor.
- To develop independent domain-specific apps with custom user-interface, comsol contains an App Builder.
- To create custom physics-interfaces, comsol contains a Physics Builder from the COMSOL Desktop with the same background as the built in physics interfaces.

There are number of modules are available for COMSOL-Multiphysics which was grouped according to the applications such as:

- Electrical
- Mechanical
- Fluid
- Chemical Multipurpose
- Interfacing.

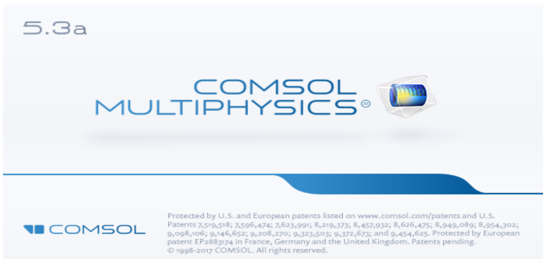


Figure 2.5: The COMSOL Multiphysics Software

2.4 Summary

In brief, the 33kV Single Core XLPE 630mm² Armoured Sheathed PVC Aluminium Cable was chosen for this studies. Basically, the cable structures of these selected cable are conductor, semi-conductive compound, the internal insulation, armoured wires and external insulation. Firstly, the aluminium material are mostly used in the transmission and distribution line because of the weight is much less denser and more cost saving than using copper material. Second, the purpose of semi-conductive layer are to achieve radially symmetric electric field and 'smoothest' out the surface irregularities of XLPE insulation and conductor. Thirdly, XLPE insulation was used to insulate the cable conductor and it has strong resistance to deformation even at high temperature. Furthermore, the main function of armoured wires was to divert any leakage current to ground by equalizing electrical stress around the conductor. Moreover, the PVC insulation on the exterior layer of the cable will protect the underlying conductor against cable failures caused by any external electrical or mechanical damages. This are the cable structures that will be usually in the high voltage power cable constructions. Besides that, the finite element method (FEM) with COMSOL software contains number of modules which was grouped according to the applications such as electrical, mechanical, fluid, chemical multipurpose and interfacing.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the finite element method (FEM) with COMSOL software was used as numerical method to study the thermal effect on the underground power cable. This method is to define the problem with geometry, material and boundary condition. To start off the geometry in this section, it is actually based on parameters. In fact, most of the parameters are based upon on the international standards. Furthermore, the cable type was chosen to model the geometry is **'33kV Single core 630mm² Al XLPE Cable'**. The parameters of this cable based on the 'Central Cable Berhad' specification (Appendix A).

3.2 Modelling the Underground Power Cable

This are the parameters that was used for the modelling the '**33kV Single core 630mm² XLPE Cable'.**

- Dcon 31.1[mm] "Diameter of conductor (Phase)"
- Tins 8.0[mm] "Insulation thickness (Phase)"
- Dins 47.1[mm] "Diameter over insulation (Phase)"
- Tscc 1[mm] "Semi-conductive compound thickness (Phase)"
- Tarm 2.5[mm] "Armor thickness (Cable)"
- Dcab 63.8[mm] "Outer diameter of cable (Cable)"
- Acon 630[mm^2] "Cross section of conductor (Phase)"
- Lcab 500[m] "Total length of cable (Cable)"
- f0 50[Hz] "Operating frequency"
- V0 33[kV]/sqrt(3) "Phase to ground voltage (Amplitude)"
- I0 685[A] "Rated current (Amplitude)"
- Pvc 3.0[mm] "Thickness of outer sheath"

- Text 35[degC] "External temperature
- Tref 90[degC] "Reference temperature (Metals)"
- Cu_alpha 3.9e-3[1/K] "Resistivity temperature coefficient (Copper)"
- Cu_rho0 1/Scon "Reference resistivity,(Copper)"
- Scon 5.96e7[S/m] "Copper conductivity, 20 °C (Phase)"
- Sal 3.77e7[S/m] "Aluminium conductivity, 20 °C (Phase)"
- Rcon 1/Acon/Sal "Aluminium DC resistance per phase, 20 °C (Analytic)"
- Rcu 1/Acu/Scon "Copper DC resistance per phase, 20 °C (Analytic)"
- Exlpe 2.5 "XLPE relative permittivity, from IEC 60287 (Phase)"

3.2.1 Using the COMSOL software

Open the COMSOL software from the file menu to choose the model with this following steps is showed in Figure 3.1.

1. Choose New

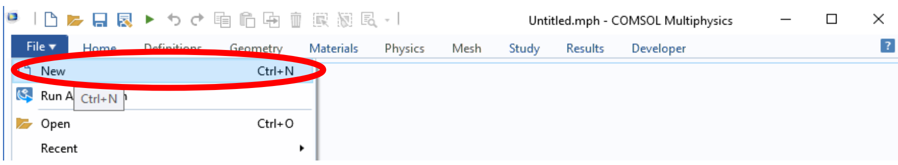


Figure 3.1: New Window

2. In the New window click Blank model.

Figure 3.2: Blank model option

3. Click done and blank model will open as shown in Figure 3.3. This where the modelling work was started.

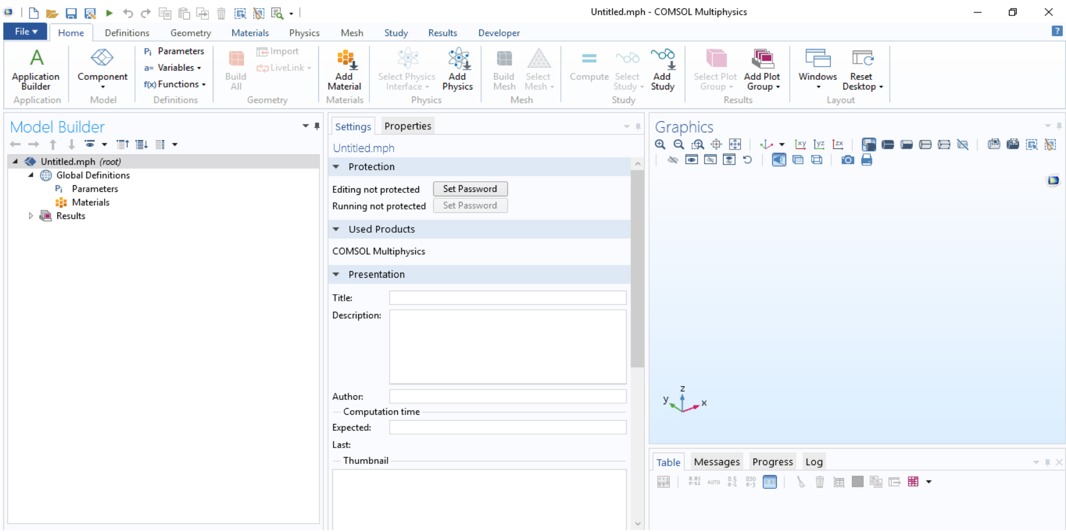


Figure 3.3: Blank model

3.2.2 Designing the Geometry of the Underground Power Cable (UPC)

This section consist of steps for the designed geometry sequence of the cables structures with three cables. This three cables are categorized as Cable 1, Cable 2 and Cable 3. The geometry of these three cables are the same except for the position of the cables will be different since it was set in trefoil position.

3.2.2.1 Designing for Cable 1

3.2.2.1.1 Semi-Conductor layer of aluminium conductor

1. To define the geometry of the semi-conductive layer of aluminium conductor of the cable in the software, choose Circle.

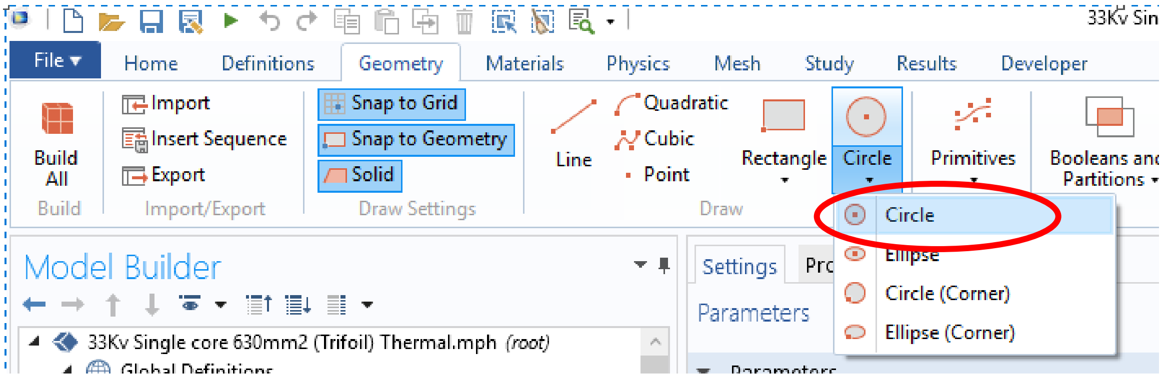


Figure 3.3: Choosing the circle geometry for Semi-conductor.

2. In the Setting window for Circle, locate the object type section and select curve.
3. Locate the Size and Shape section in the radius text field, type Dcon/2.
4. Locate the Position section, in the x, y text field and type 0 and 0.
5. Locate the Layer section, type Tscc for semi-conductor layer.
6. Click the Build Selected and the geometry of the semi-conductive layer was plotted which is shown in Figure 3.4.

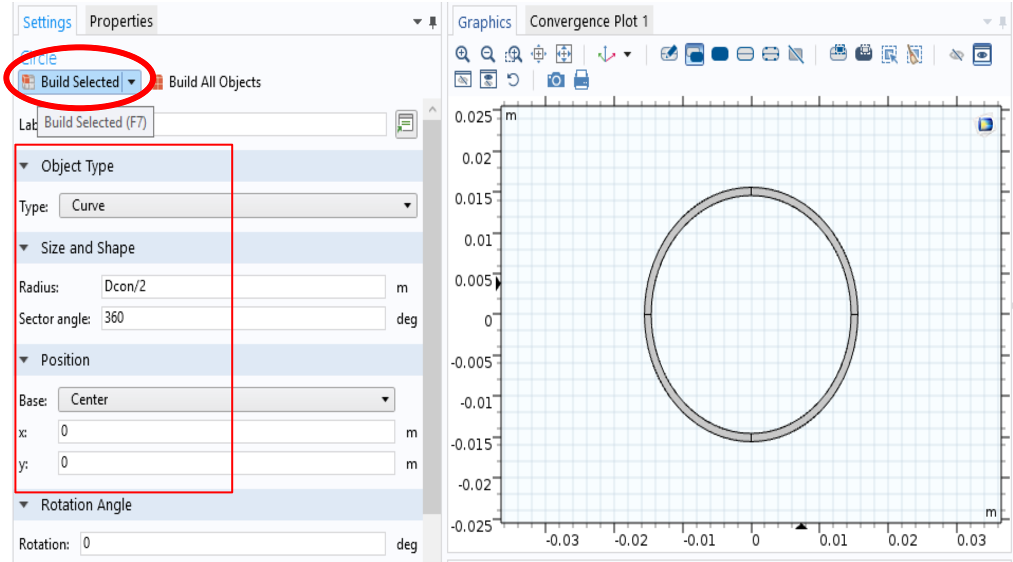


Figure 3.4: Graphic window designed Semi-conductive layer of conductor

3.2.2.1.2 Aluminium conductor

1. To define the geometry of the aluminium conductor of the cable in the software, choose Circle.

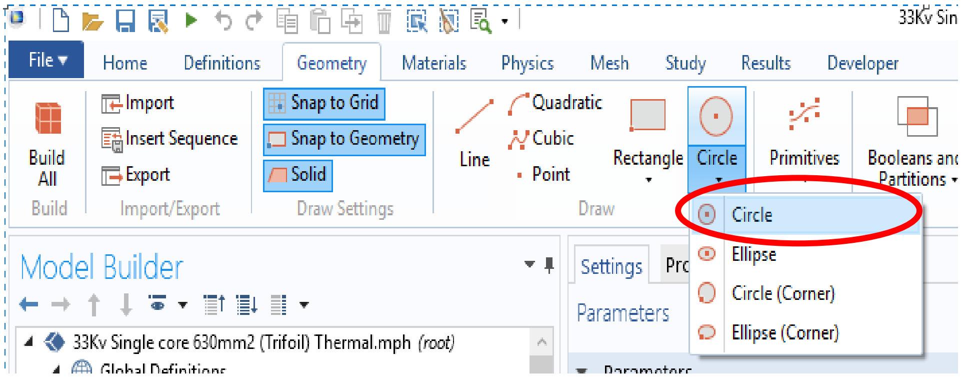


Figure 3.5: Choosing the circle geometry for Aluminium conductor.

2. In the Setting window for Circle, locate the object type section and select solid.
3. Locate the Size and Shape section in the radius text field, type Dcon/2.
4. Locate the Position section, in the x, y text field and type 0 and 0.
5. Click the Build Selected and the geometry of the aluminium conductor was plotted.

All the steps above are shown in Figure 3.6.

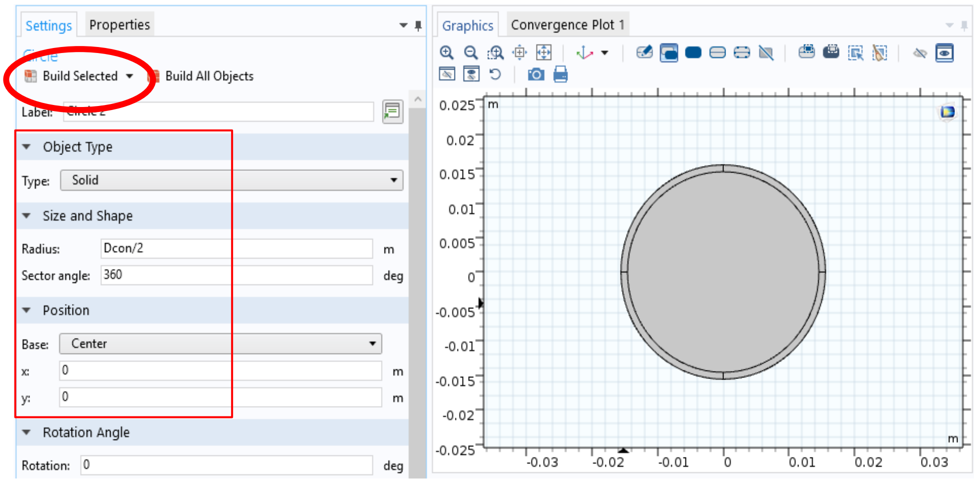


Figure 3.6: Graphic window designed for Aluminium conductor

3.2.2.1.3 Semi-Conductive layer of insulation (XLPE)

1. To define the geometry of the semi-conductive layer of insulation (XLPE) of the cable in the software, choose Circle.

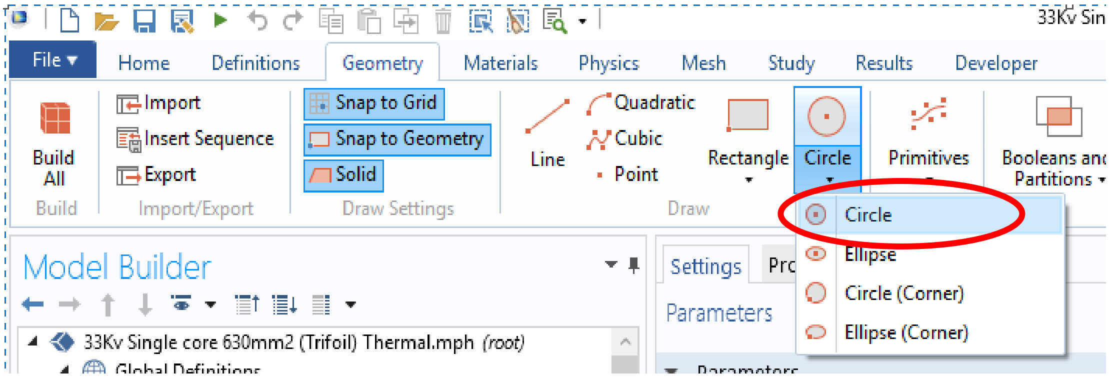


Figure 3.7: Choosing the circle geometry for Semi-conductive layer of insulation (XLPE).

2. In the Setting window for Circle, locate the object type section and select curve.
3. Locate the Size and Shape section in the radius text field, type Dins/2.
4. Locate the Position section, in the x, y text field and type 0 and 0.
5. Locate the Layer section, type Tscc for semi-conductor layer.
6. Click the Build Selected and the geometry of the Semi-conductor layer of insulation (XLPE) was plotted.

All the steps above are shown in Figure 3.8.

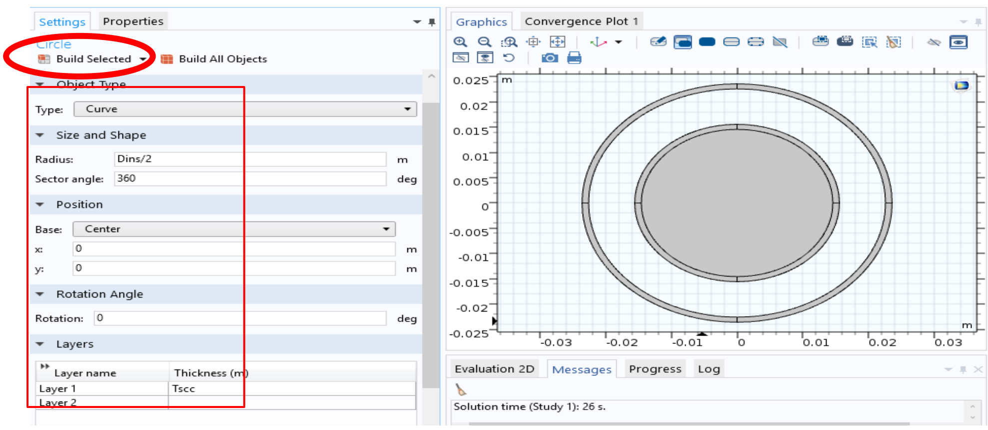


Figure 3.8: Graphic window designed for Semi-conductive layer of insulation (XLPE)

3.2.2.1.4 Polyvinyl Chloride (PVC) Insulation

1. To define the geometry of the PVC insulation of the cable in the software, choose Circle.

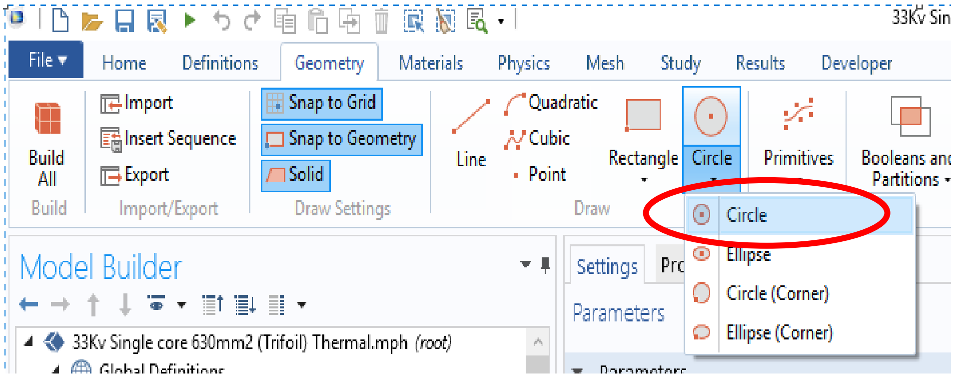


Figure 3.9: Choosing the circle geometry for PVC Insulation

2. In the Setting window for Circle, locate the object type section and select curve.
3. Locate the Size and Shape section in the radius text field, type Dcab/2.
4. Locate the Position section, in the x, y text field and type 0 and 0.
5. Locate the Layer section, type PVC.
6. Click the Build Selected and the geometry of the PVC insulation was plotted.

All the steps plotted above are shown in Figure 3.10.

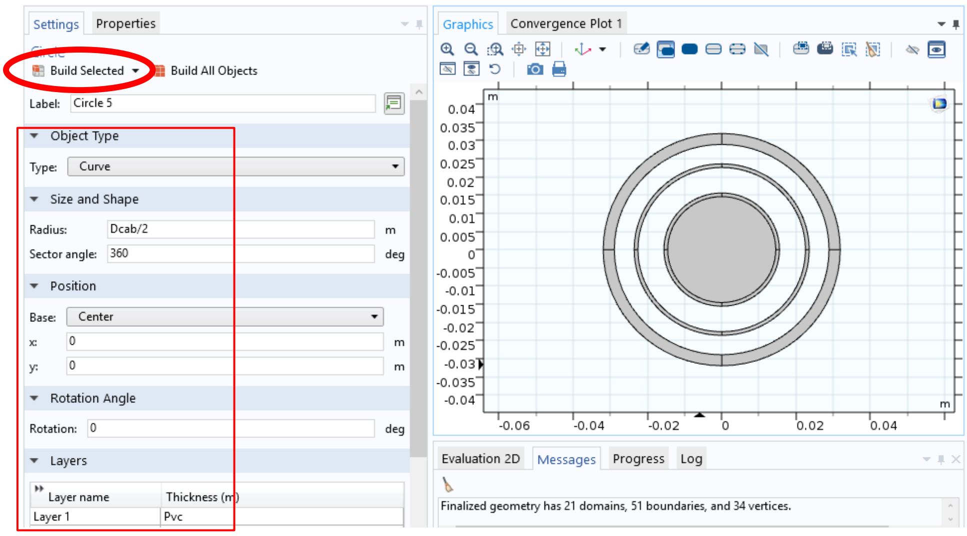


Figure 3.10: Graphic window designed for PVC Insulation.

3.2.2.1.5 Armoured Wires

1. To define the geometry of the armoured wires of the cable, choose Circle.

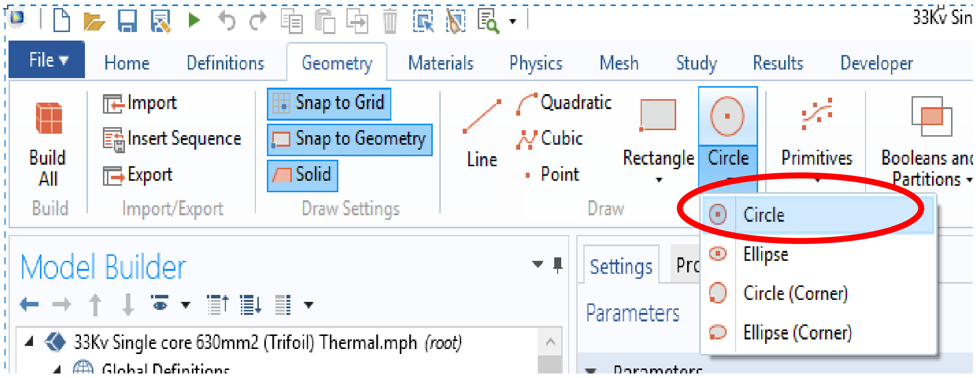


Figure 3.11: Choosing the circle geometry for Armoured wires

2. In the Setting window for Circle, locate the object type section and select solid.
3. Locate the Size and Shape section in the radius text field, type 10*Dcab/2.
4. Locate the Position section, in the x, y text field and type 0 and 0.
5. Locate the Layer section, type Cusheath for Armoured wires layer.
6. Click the Build Selected and the geometry for the armoured wire was plotted.

All the steps above are shown in Figure 3.12.

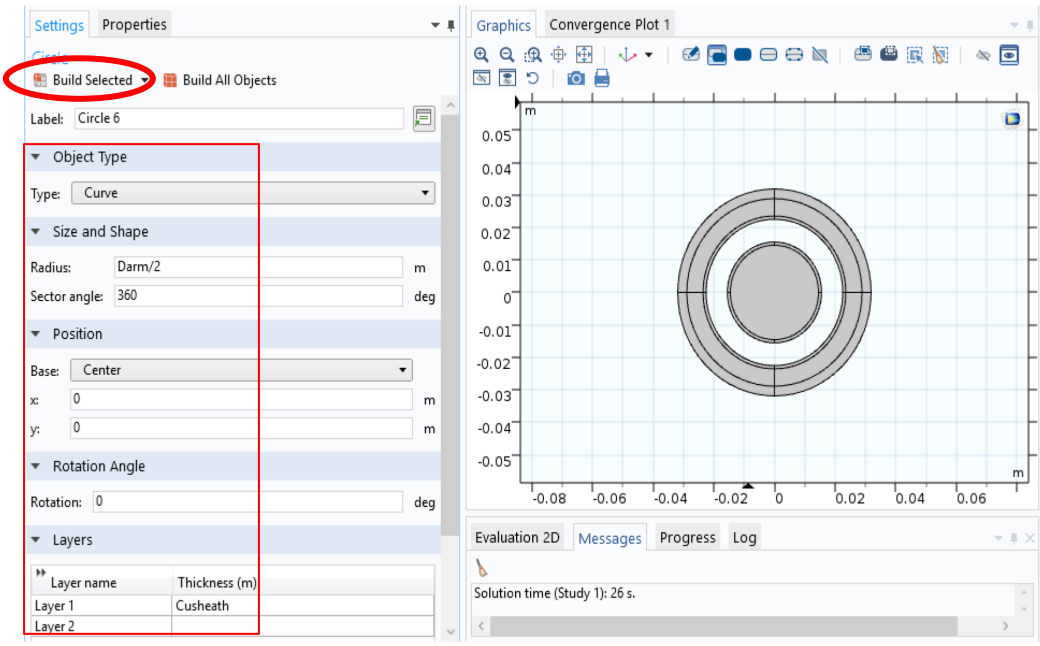


Figure 3.12: Graphic window designed for Armoured Wire

3.2.2.2 Designing for Cable 2

Basically to design the cable 2 doesn't need to follow the same steps as cable 1 where the copy method can used.

1. On the Geometry toolbar, click Transforms choose Copy.

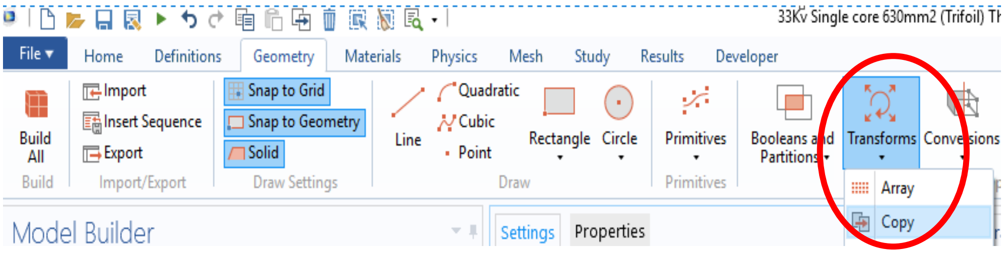


Figure 3.13: Choosing the Transform to copy Cable 1

2. Click and select all the geometry of the Cable 1 as shown in Figure 3.14.

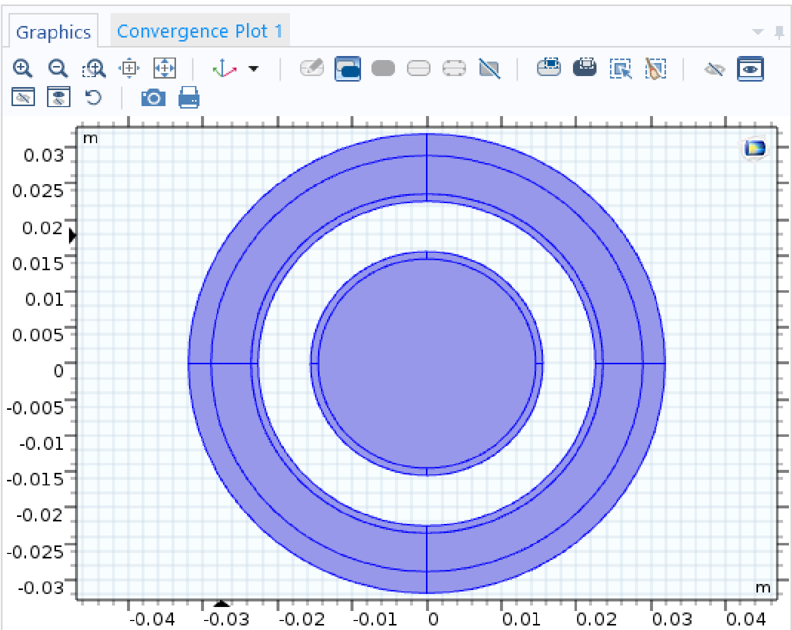


Figure 3.14: Selecting the geometry of Cable 1

3. All the geometry of the Cable 1 will be stored in the input section as and locate Displacement section, in the x, y text field and type 0.032 and 0.057 as shown in Figure 3.15.

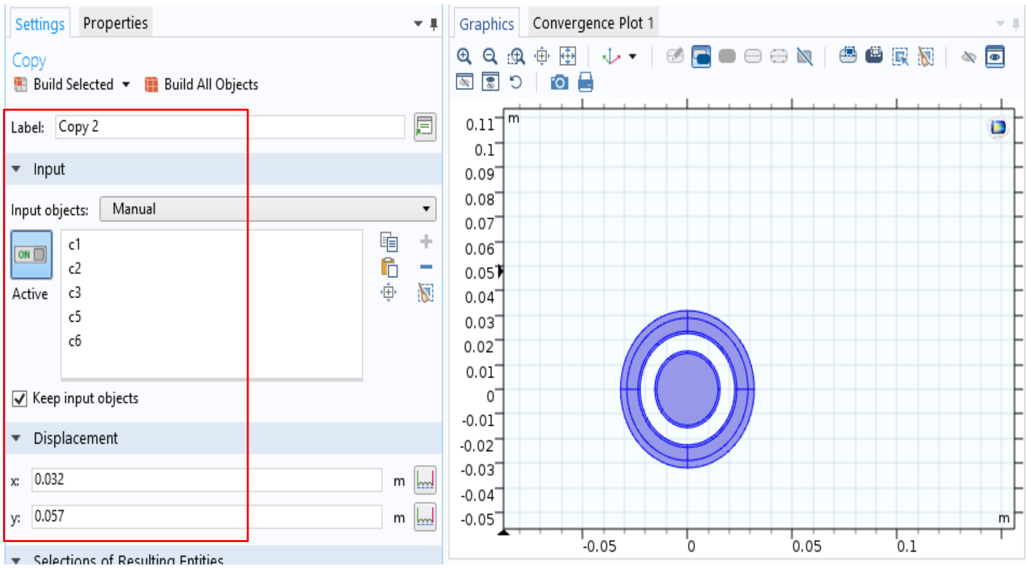


Figure 3.15: Storing the input geometric of Cable 1

4. Click Build Selected on the Settings window the geometry of the Cable 2 was plotted.

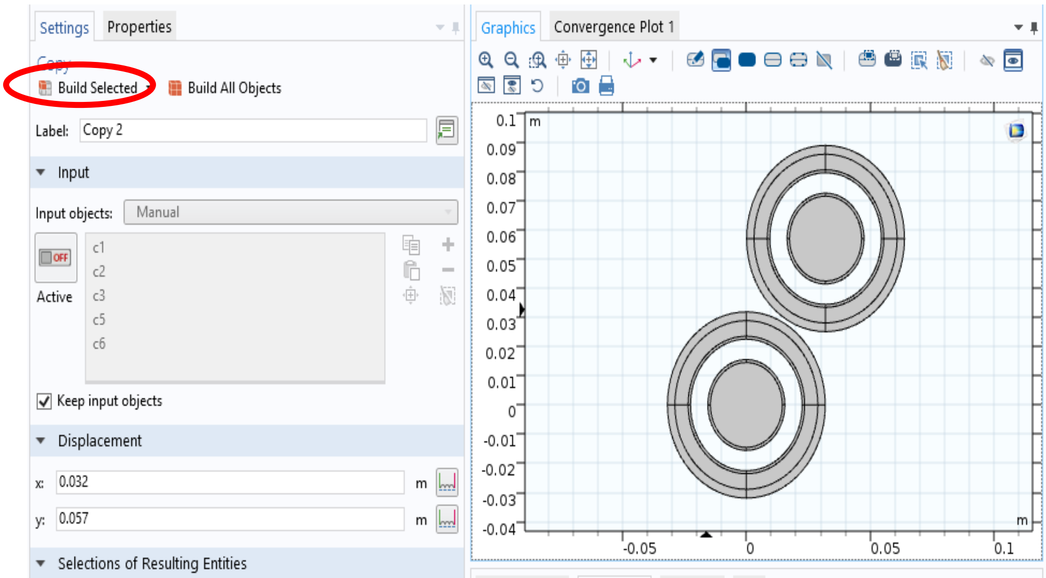


Figure 3.16: Graphic window designed for Cable 2

3.2.2.3 Designing for Cable 3

Same goes to designing Cable 3 which will be the same method as used for Cable 2 which is Copy.

1. On the Geometry toolbar, click Transforms choose Copy.

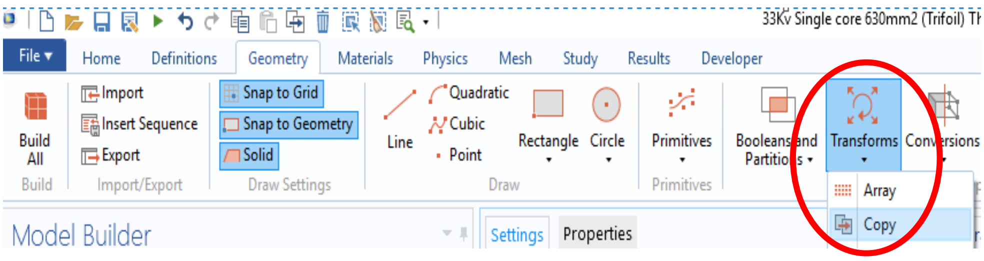


Figure 3.17: Choosing the Transform to copy Cable 1

2. Click and select all the geometry of the Cable 1 as shown in Figure 3.18.

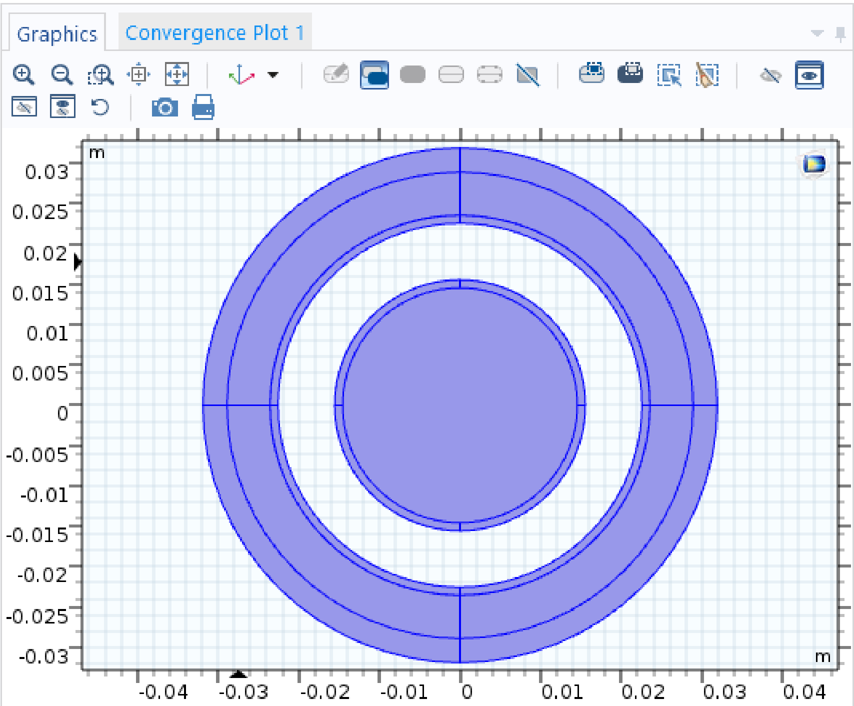


Figure 3.18: Selecting the geometry of Cable 1

3. All the geometry of the Cable 1 will be stored in the input section as and locate Displacement section, in the x, y text field and type 0.065 and 0 as shown in Figure 3.19.

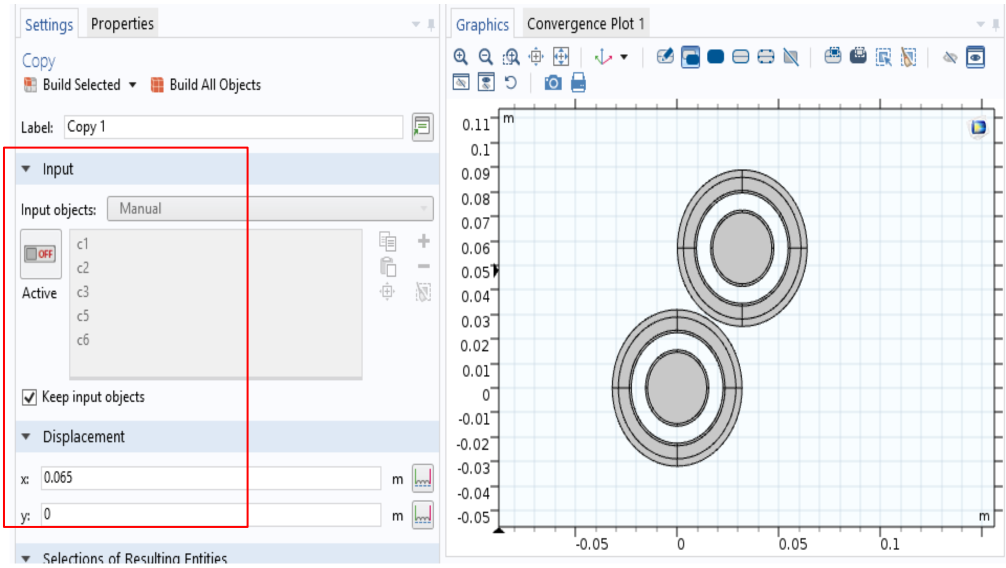


Figure 3.19: Storing the input geometric of Cable 1

4. Click Build Selected on the Settings window the geometry of the Cable 3 was plotted.

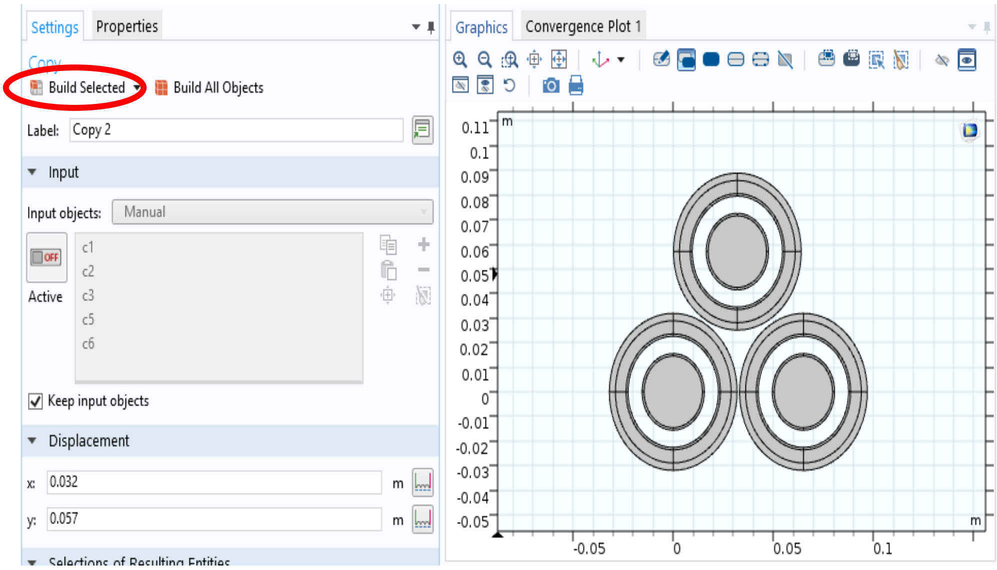


Figure 3.19: Graphic window designed for Cable 3

3.2.2.4 Designing the geometry for electromagnetic field and surrounding surface.

3.2.2.4.1 Electromagnetic field

1. On the Geometry toolbar and choose Circle.

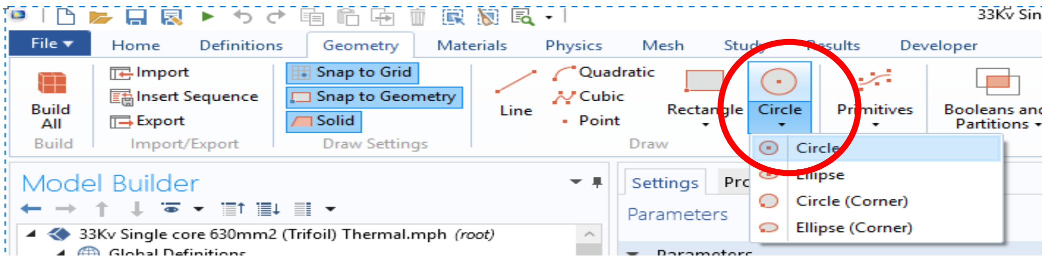


Figure 3.20: Choosing the circle geometry for Electromagnetic field

2. In the Setting window for Circle, locate the object type section and select solid.
3. Locate the Size and Shape section in the radius text field, type Dcon/2.
4. Locate the Position section, in the x, y text field and type 0.032 and 0.025.
5. Click the Build Selected and the geometry of the electromagnetic field was plotted.

All the steps above are shown in Figure 3.21.

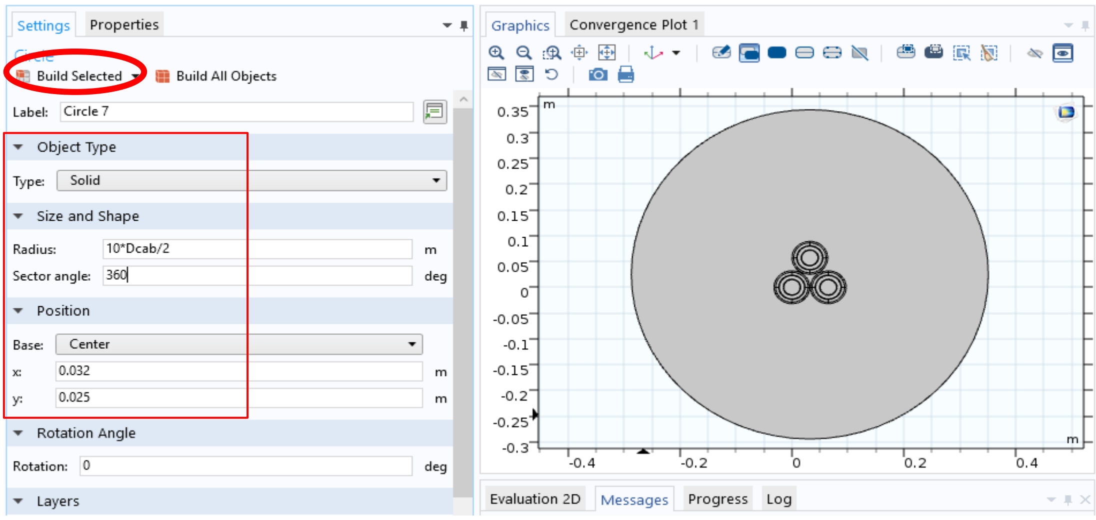


Figure 3.21: The Graphic designed for Electromagnetic Field

3.2.2.4.2 Surrounding Surface

1. On the Geometry toolbar and choose Rectangular.

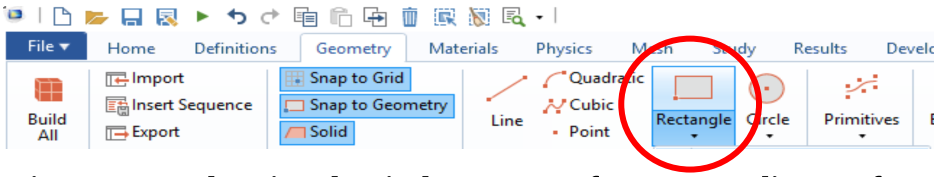


Figure 3.22: Choosing the circle geometry for Surrounding Surface

2. In the Setting window for Rectangle, locate the object type section and select solid.
3. Locate the Size and Shape section, under the width and height type 10[m] and 8[m].
4. Locate the Position section, in the x, y text field and type -5[m] and -4[m].
5. Locate the Layer section, under Layer 1 type 5[m] for the boundary between two section.
6. Click the Build Selected and the geometry of the surrounding surface was plotted.

All the steps above are shown in Figure 3.23.

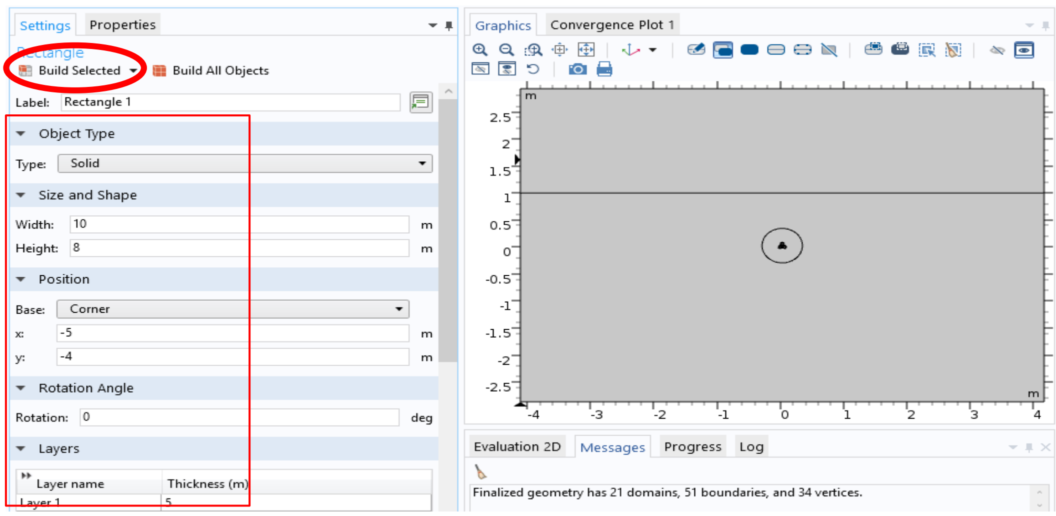


Figure 3.23: The graphic window designed of surrounding surface

3.2.2.5 Compiling the whole geometry by using Union.

On the Geometry toolbar, click Build All and the geometry has been built as shown in Figure 3.24.

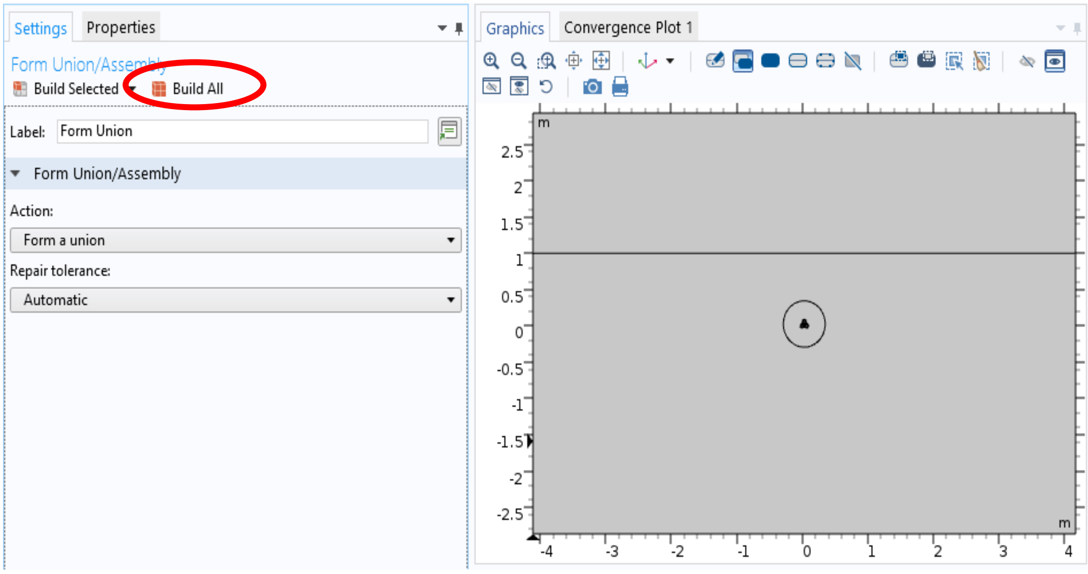


Figure 3.24: The Graphic window for Whole Cable Geometry by using Union function.

The geometry of the '33kV Single core 630mm² XLPE Cable' was assembled by using Union function.

3.2.3 Defining the Geometry of the Underground Power Cable (UPC)

Next, defining all geometry by characterization for every layer of the cable.

3.2.3.1 Defining for the Cables

1. On the Definitions toolbar, click Explicit.

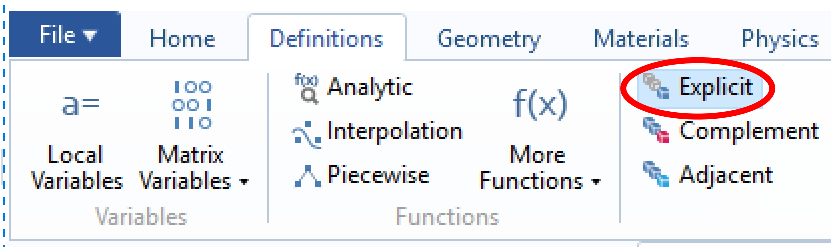


Figure 3.25: Choosing the Explicit for Cables.

2. Type Cable in the Label text field under the Settings window for Explicit.
3. Click on the cables geometry to highlight the cable and the geometry entities are stored in Input Entities.
4. The definition for the Cables is completed.

All the steps above are shown in Figure 3.26.

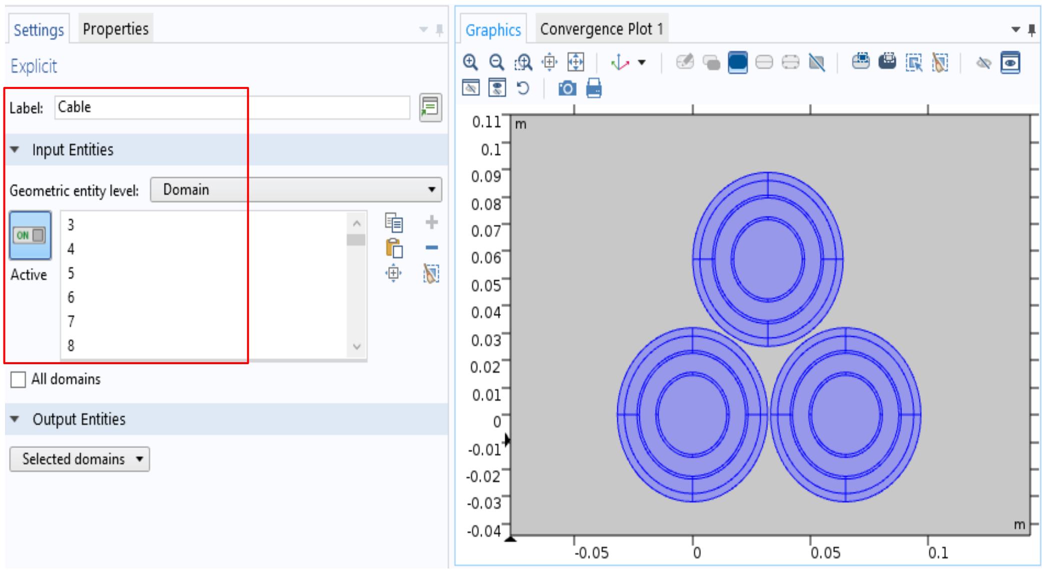


Figure 3.26: The Graphic window for the Definition of the Cables

3.2.3.2 Defining for the Metal Internal

1. On the Definitions toolbar, click Explicit.

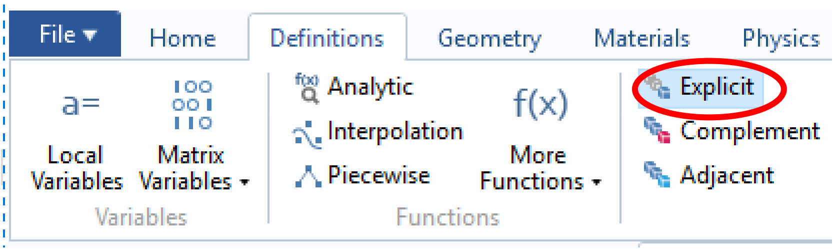


Figure 3.27: Choosing the Explicit for Metal Internal.

2. Type Metal internal in the Label text field under the Settings window for Explicit.
3. Click on the geometry to highlight the metal part which is conductor and armoured wire and the geometry entities stored in Input Entities.
4. The definition for the Metal internal is completed.

All the steps above are shown in Figure 3.28.

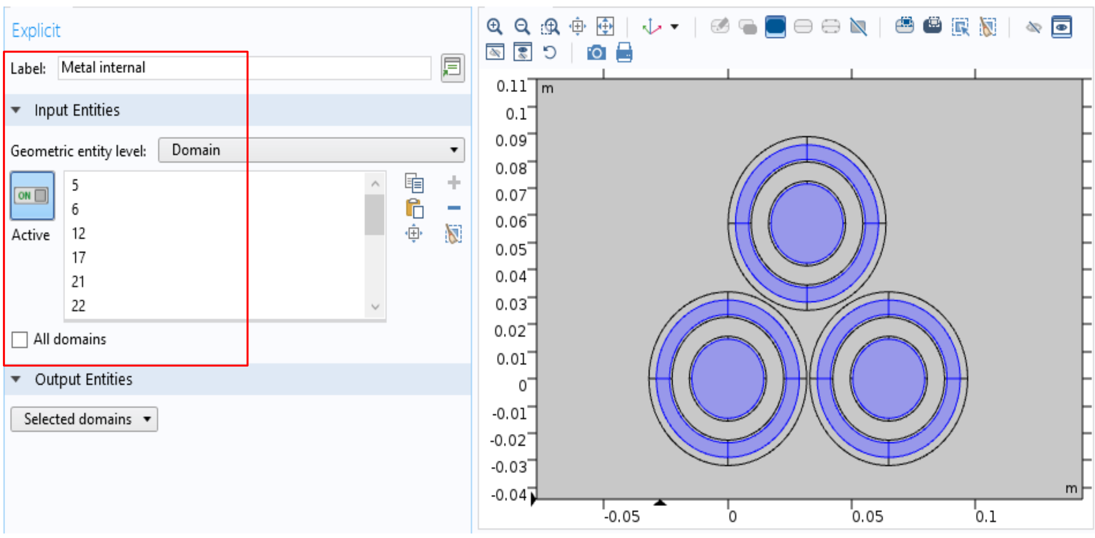


Figure 3.28: The Graphic window for the Definition for the Metal Internal.

3.2.3.3 Defining for the Aluminium Conductor

1. On the Definitions toolbar, click Explicit.

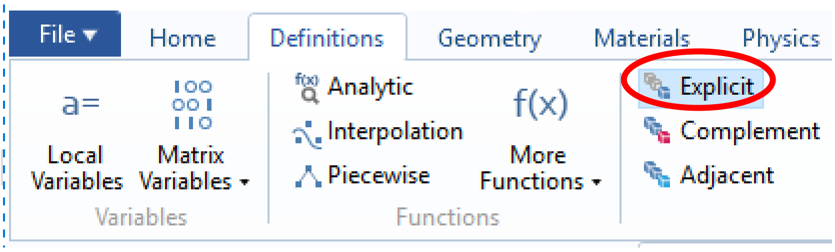


Figure 3.29: Choosing the Explicit for Aluminium Conductor.

2. Type Conductor in the Label text field under the Settings window for Explicit.
3. Click on the geometry to highlight the metal part which is Conductor and the geometry entities stored in Input Entities.
4. The definition for the Conductor is completed.

All the steps above are shown in Figure 3.30.

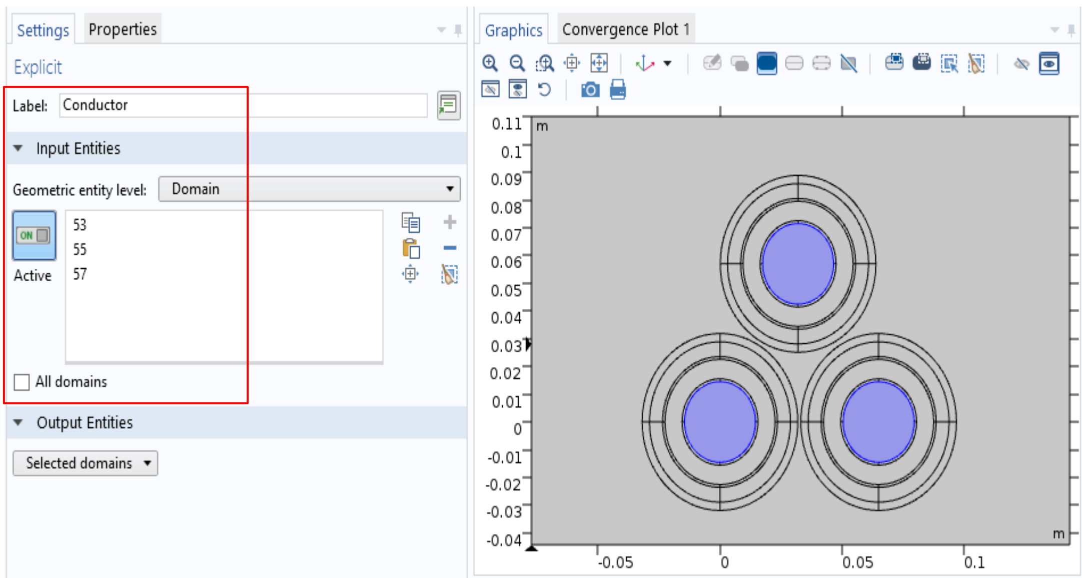


Figure 3.30: The Graphic window for the Definition for the Aluminium Conductor.

3.2.3.4 Defining for the Insulation Internal (XLPE)

1. On the Definitions toolbar, click Explicit.

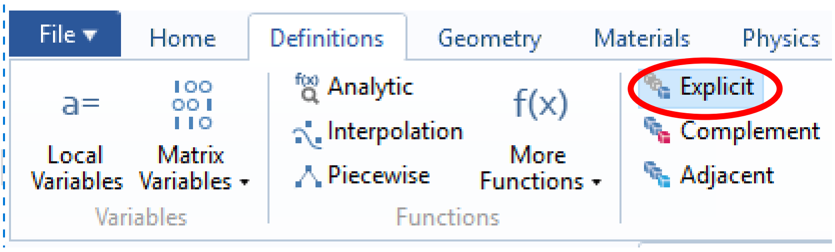


Figure 3.31: Choosing the Explicit for Insulation internal (XLPE).

2. Type Insulation internal in the Label text field under the Settings window for Explicit.
3. Click on the geometry to highlight the insulation layer which is insulation (XLPE) and the geometry entities stored in Input Entities.
4. The definition for the Insulation internal is completed.

All the steps above are shown in Figure 3.32.

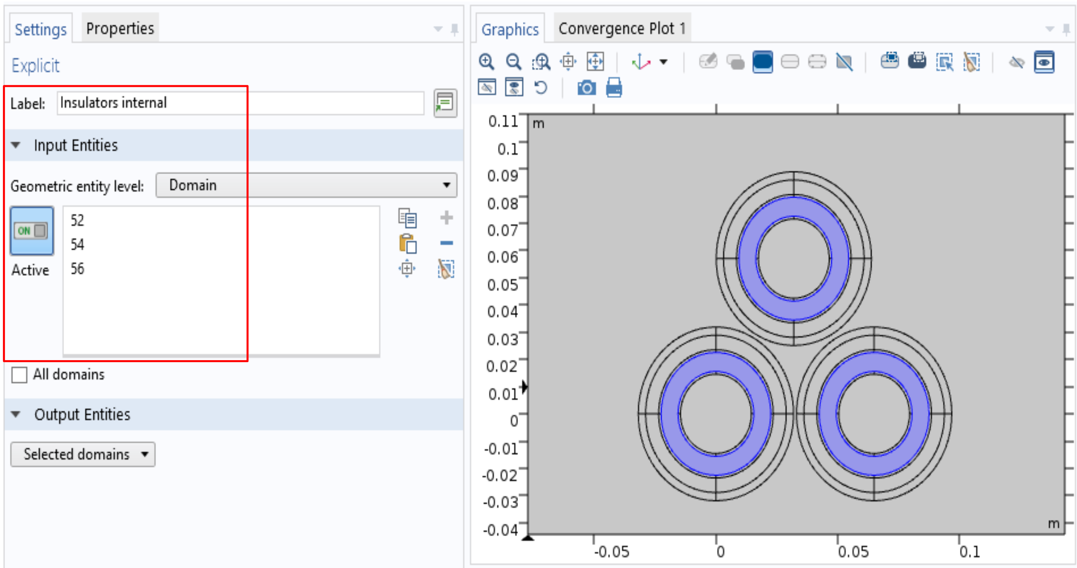


Figure 3.32: The Graphic window for the Definition for the Insulation Internal.

3.2.3.5 Defining for the Semi-conductive compound

1. On the Definitions toolbar, click Explicit.

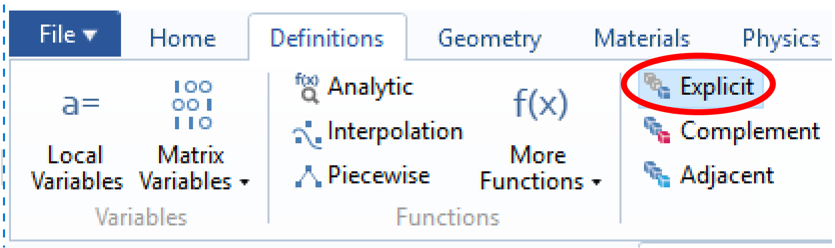


Figure 3.33: Choosing the Explicit for Semi-conductive compound.

2. Type Semiconductor in the Label text field under the Settings window for Explicit.
3. Click on the geometry to highlight the semi conductive layer which is Semi-conductor and the geometry entities stored in Input Entities.
4. The definition for the Semiconductor is completed.

All the steps above are shown in Figure 3.34.

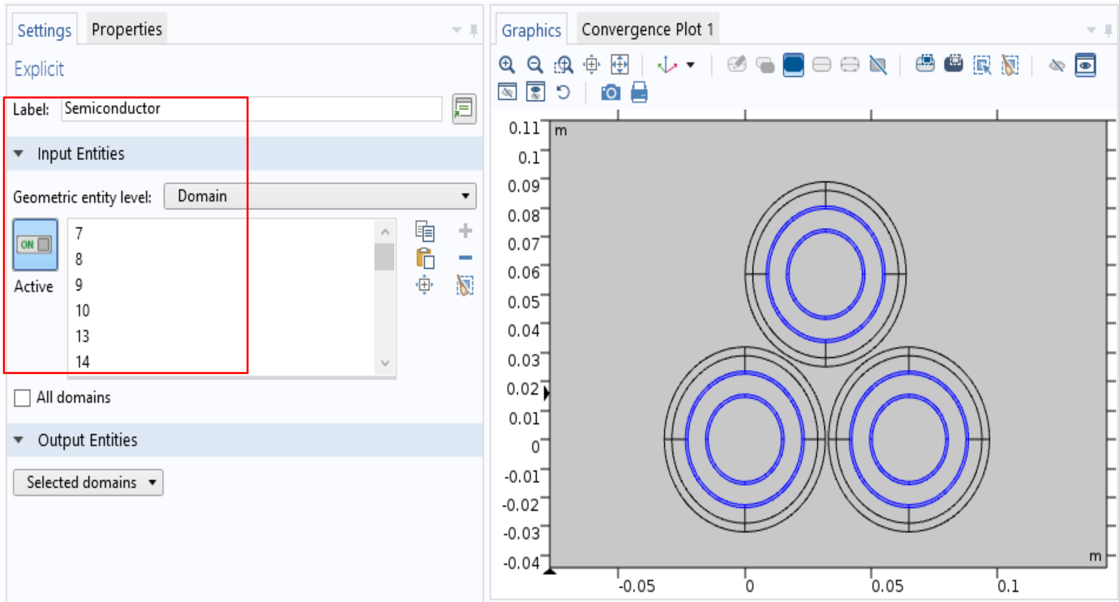


Figure 3.34: The Graphic window for the Definition for the Semi-conductive compound.

3.2.3.6 Defining for the Polyvinyl Chloride (PVC) Insulation

1. On the Definitions toolbar, click Explicit.

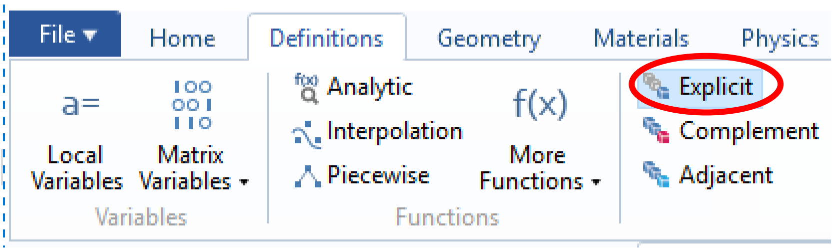


Figure 3.35: Choosing the Explicit for PVC Insulation

2. Type Polyvinyl chloride (PVC) in the Label text field under the Settings window for Explicit.
3. Click on the geometry to highlight the outer layer of the cable which is PVC and the geometry entities stored in Input Entities.
4. The definition for the Polyvinyl Chloride (PVC) is completed.

All the steps above are shown in Figure 3.36.

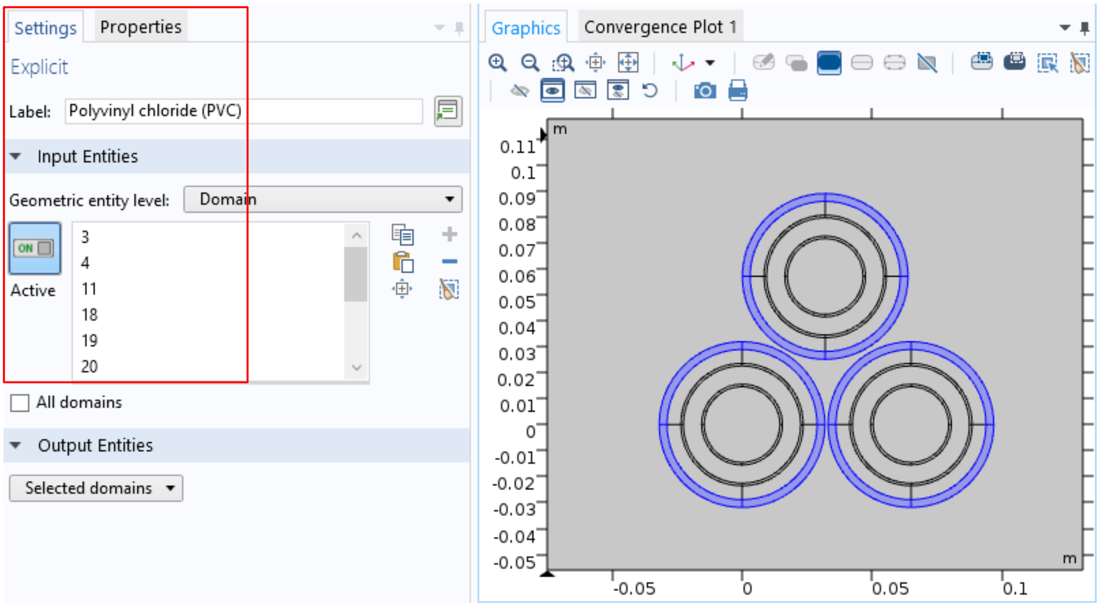


Figure 3.36: The Graphic window for the Definition for the PVC Insulation

3.2.3.7 Defining for the Armoured Wires

1. On the Definitions toolbar, click Explicit.

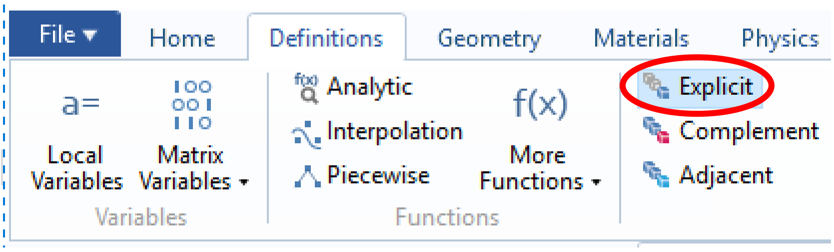


Figure 3.37: Choosing the Explicit function for Armoured Wires

2. Type Armoured Wires in the Label text field under the Settings window for Explicit.
3. Click on the geometry to highlight the metal part of the cable which is Armoured Wire and the geometry entities stored in Input Entities.
4. The definition for the Armoured Wire is completed.

All the steps above are shown in Figure 3.38.

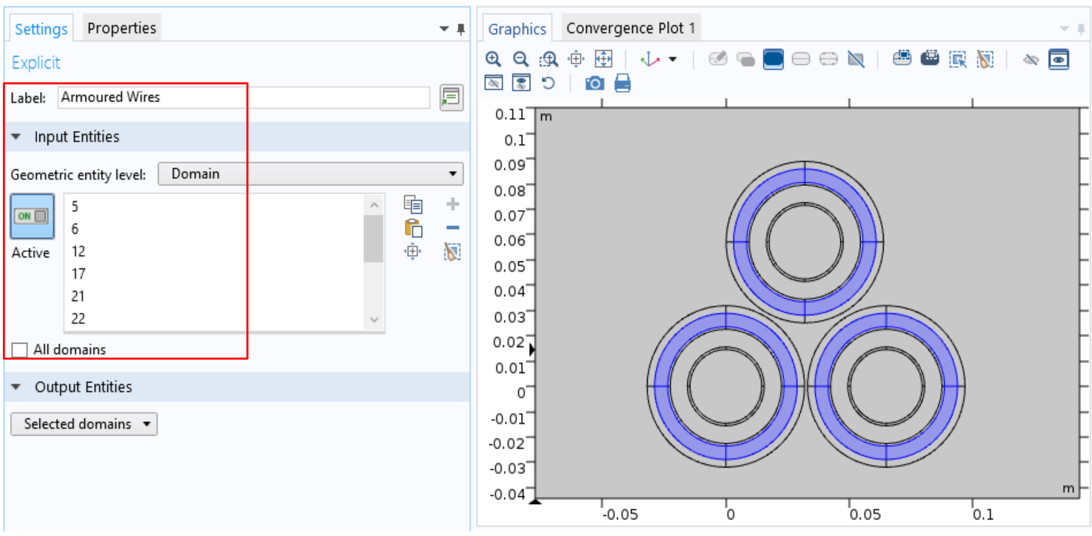


Figure 3.38: The Graphic window for the Definition for the Armoured Wires

3.2.3.8 Defining the Metal Internal and Armoured Wire in one Union

1. Click Union on the Definitions toolbar.

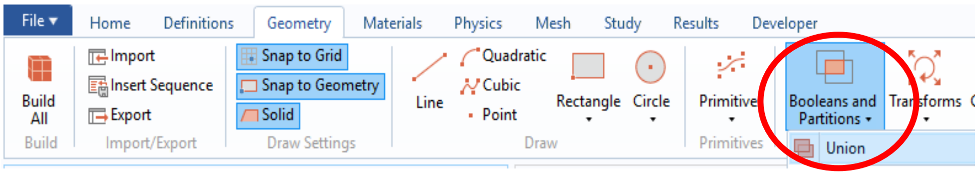


Figure 3.39: Choosing the Union function for Metal Internal and Armoured Wires

2. Type Metals in the label text field in the Settings window for Union.
3. Locate the Input Entities section, click Add under Selections to add.
4. Choose Metals internal and Armoured wire in the Add dialog box, in the Selections to add list.
5. Click Ok

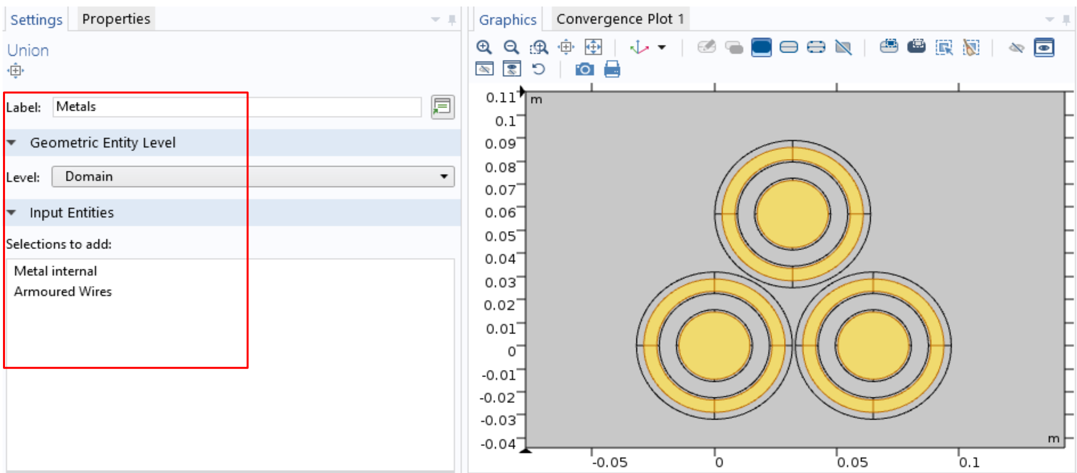


Figure 3.40: The Graphic window for the Metal Internal and Armoured Wires by using Union

Applying Union function for metal parts is because to handle it in one form when doing simulation in the coming sections.

3.2.4 Selecting the Material Type for the Underground Power Cable (UPC)

After completing defining the geometry of the cable, the next steps will be adding the material type to the cables. The material properties that was used for 33kV Single core 630mm² XLPE Cable are shown in Table 1. In addition, the parameters for thermal conductivity, density, for the following materials was used from the COMSOL where the values are all built-in the material section (Littmarck, 2015).

Material	Thermal conductivity, k (W/mK)	Density, Rho (kg/m³)	Heat Capacity, Cp (J/kg.K)
Air	k(T[1/K])	rho(pA[1/Pa], T[1/K])	Cp(T[1/K])
Soil	1	2020	2512
Water, liquid	k(T[1/K])	rho(T[1/K])	Cp(T[1/K])
Polyvinyl Chloride (PVC)	0.19	1760	1170
Cross-linked polyethylene (XLPE)	0.46	930	2302
Semi-conductive compound	10	1055	2405
Aluminium	Ntcon*238	2700	900
Copper	400	7850	475

Table 3.1: The Materials properties of the '33kV Single core 630mm² XLPE Cable"

3.2.4.1 Adding Materials to the Underground Power Cable

1. In the File menu, under Materials, click Add Material window.

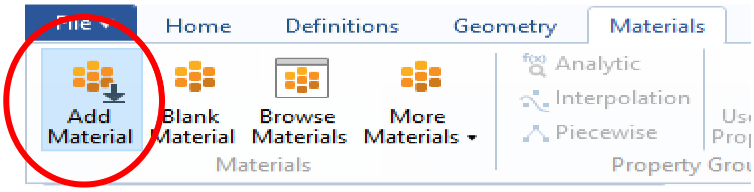


Figure 3.41: Choosing the Add Material for the cable

2. Under the Add Material window, select Built-In>Air.
3. Click Add to Component 1.

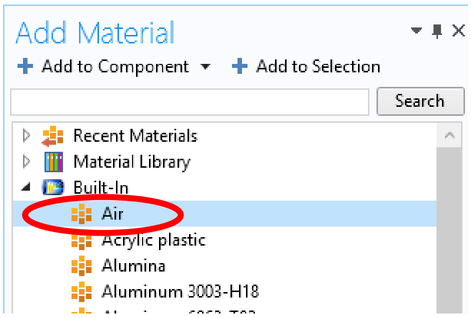


Figure 3.42: Selecting the Air material

4. The material Air will be added Model Builder section

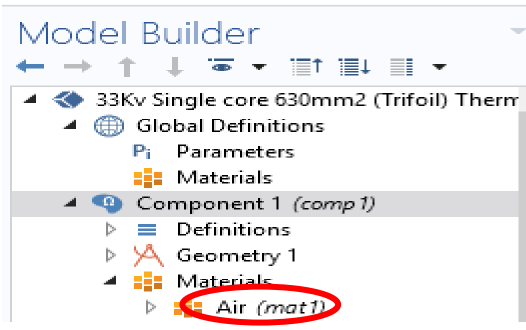


Figure 3.43: The material Air was added in the design

Basically, this Add Materials steps will be repeated for the remaining materials which need to be added and after all the materials added under model builder it was shown in Figure 3.44.

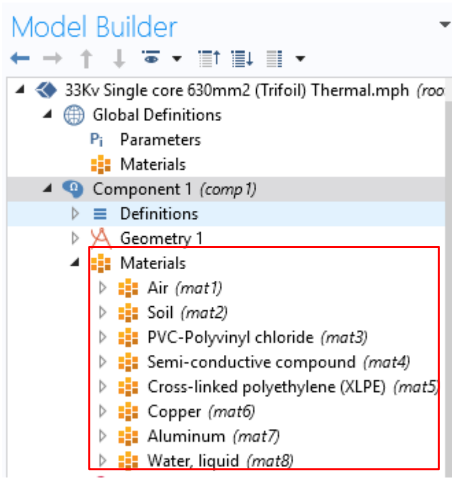


Figure 3.44: The All materials are added

3.2.4.2 Assigned materials for the Underground Power Cable

The final part for the material section is assigning the correct selection of the cable structure using correct material.

3.2.4.2.1 Assigning the Air Material

1. In the Model Builder window, under Component 1 (comp1)>Materials click Air.

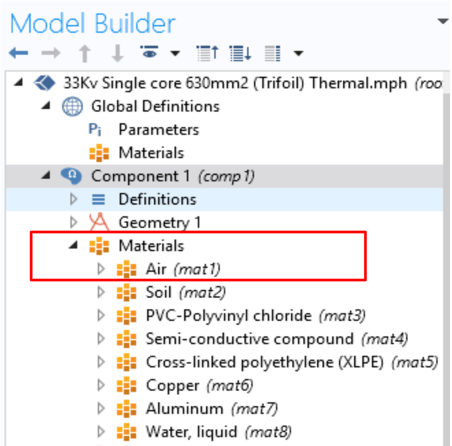


Figure 3.45: Selecting Air material to be assign

2. Click on the geometry to highlight the surrounding of the cable which is Air and the geometry entities are stored in Input Entities as shown in Figure 3.46.

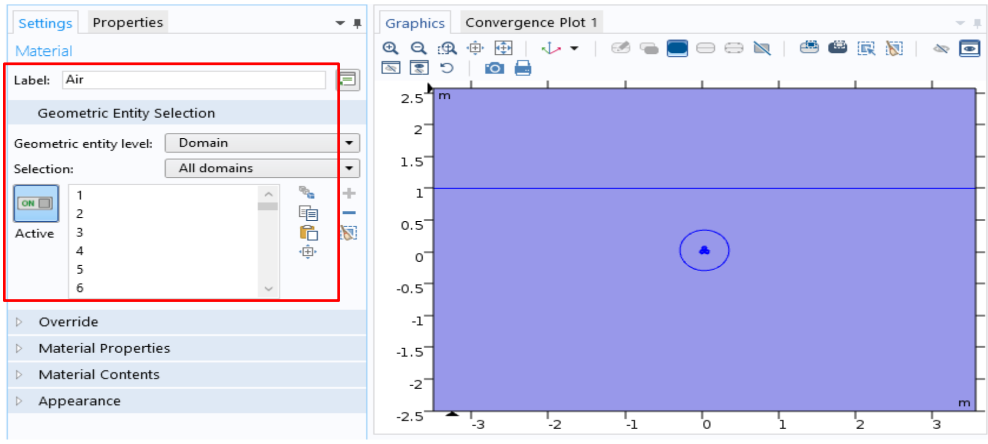


Figure 3.46: The Graphic window for the Air material assigned to surrounding of the cable.

3.2.4.2.2 Assigning the Soil or Water Material

1. In the Model Builder window, under Component 1 (comp1)>Materials click Soil or Water.

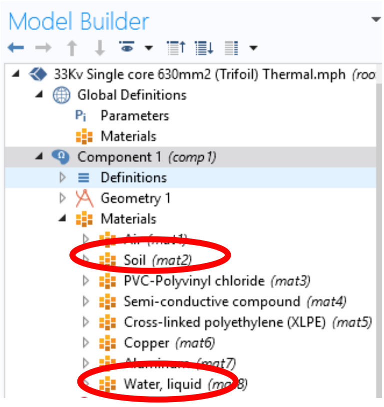


Figure 3.47: Selecting Soil or Water material to be assign

2. Click on the geometry to highlight the surrounding background of the cable which is Soil or Water and the geometry entities are stored in Input Entities as shown in Figure 3.48.

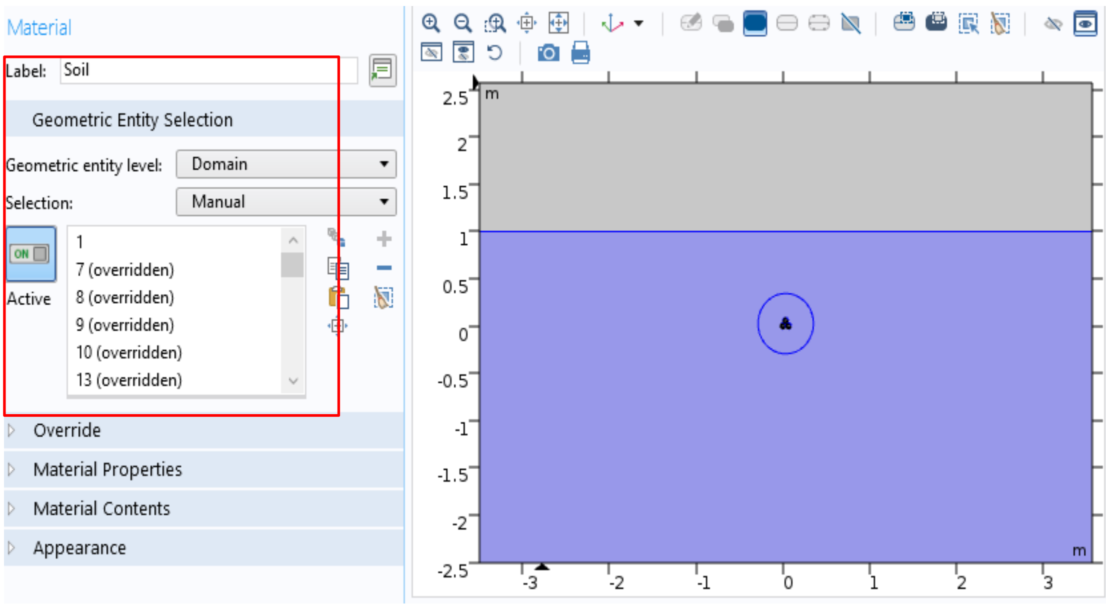


Figure 3.48: The Graphic window for the Soil or Water material assigned to surrounding of the cable.

3.2.4.2.3 Assigning the Polyvinyl Chloride (PVC) Material

1. In the Model Builder window, under Component 1 (comp1)>Materials click PVC.

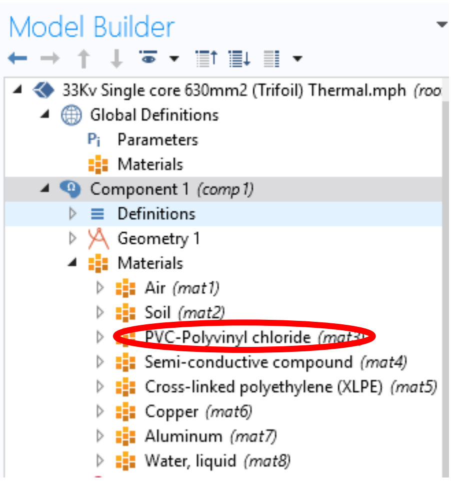


Figure 3.49: Selecting Polyvinyl Chloride (PVC) material to be assign

2. Click on the geometry to highlight the outer layer of the cable which is PVC and the geometry entities are stored in Input Entities as shown in Figure 3.50.

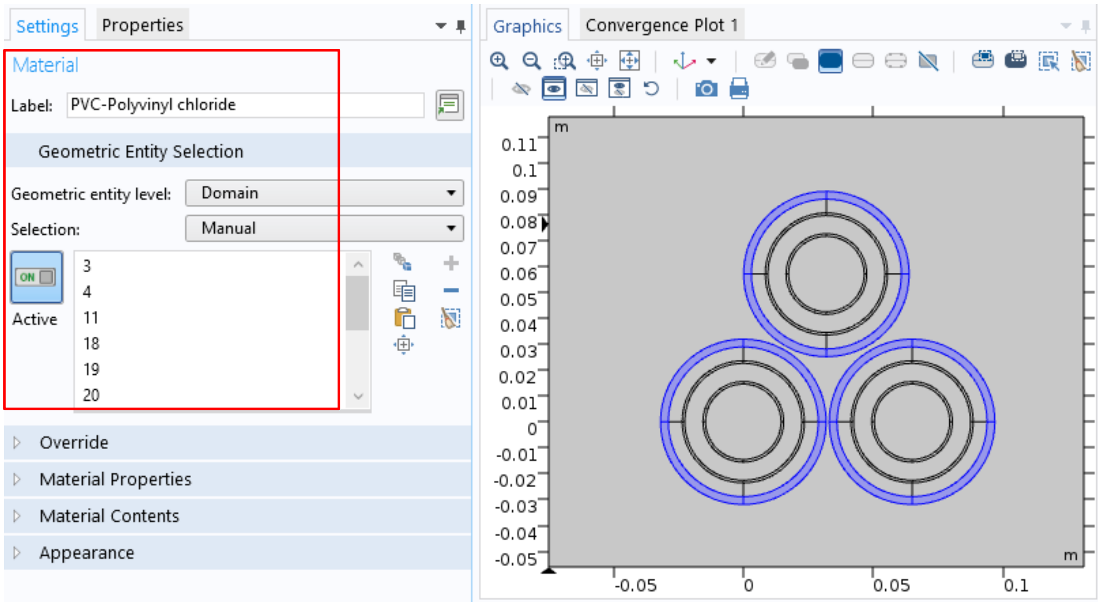


Figure 3.50: The Graphic window for Polyvinyl Chloride (PVC) assigned to the cable.

3.2.4.2.4 Assigning the Semi-conductive compound Material

1. In the Model Builder window, under Component 1 (comp1)>Materials click Semi-conductive compound.

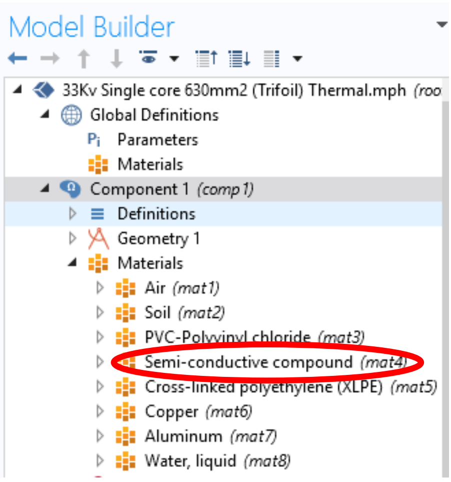


Figure 3.51: Selecting Semi-conductive compound material to be assign

2. Click on the geometry to highlight the Semiconductor of the cable which is Semi conductive compound and the geometry entities are stored in Input Entities as shown in Figure 3.52.

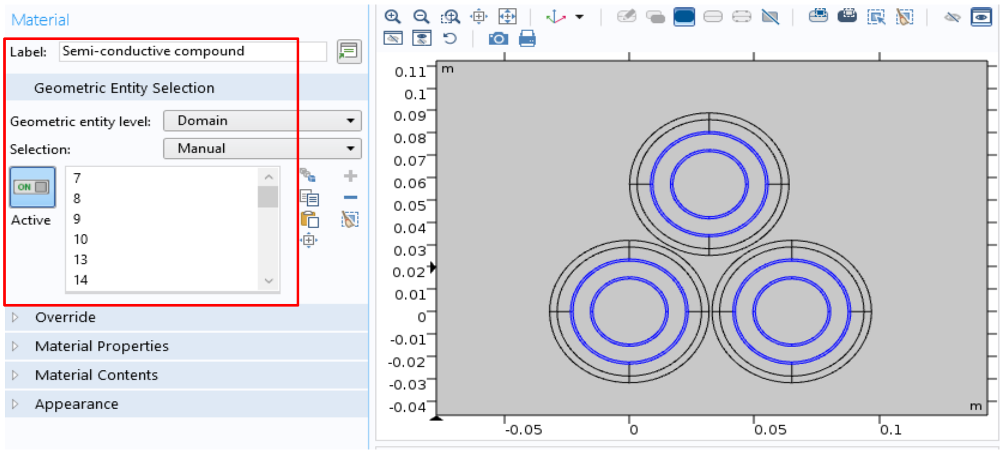


Figure 3.52: The Graphic window for Semi-conductive compound assigned to the cable.

3.2.4.2.5 Assigning the Copper Material

1. In the Model Builder window, under Component 1 (comp1)>Materials click Copper.

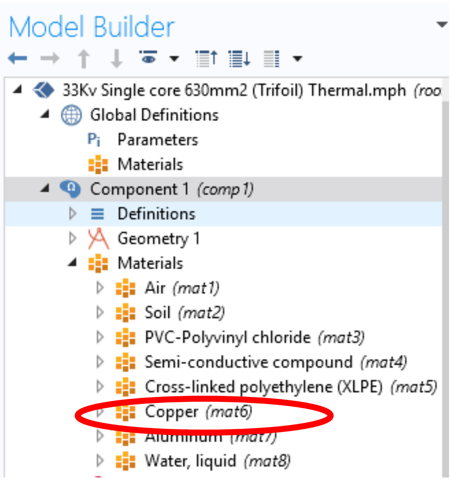


Figure 3.53: Selecting Copper material to be assign

2. Click on the geometry to highlight the armoured wires of the cable which is Copper and the geometry entities are stored in Input Entities as shown in Figure 3.54.

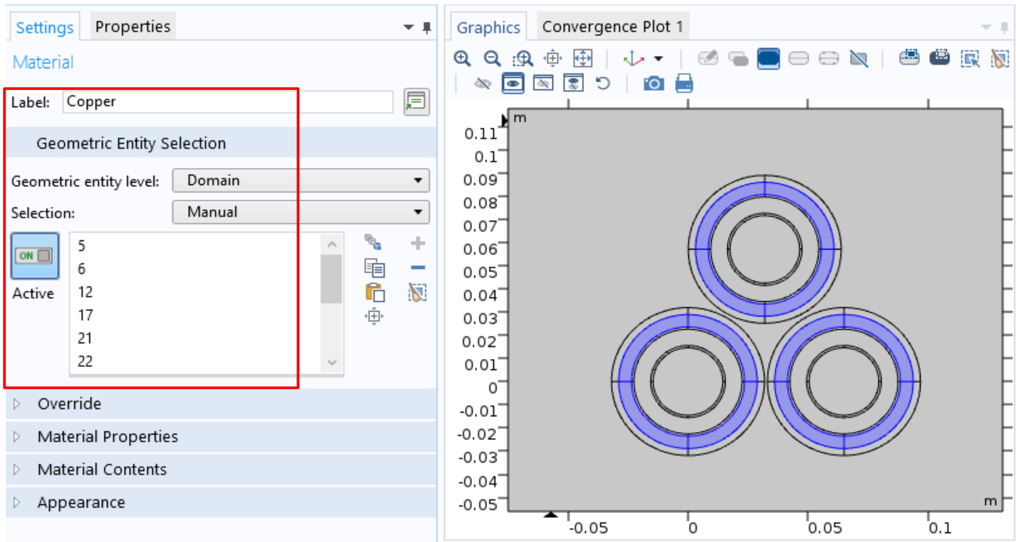


Figure 3.54: The Graphic window for Copper material assigned to the cable.

3.2.4.2.6 Assigning the Aluminium Material

1. In the Model Builder window, under Component 1 (comp1)>Materials click Aluminium.

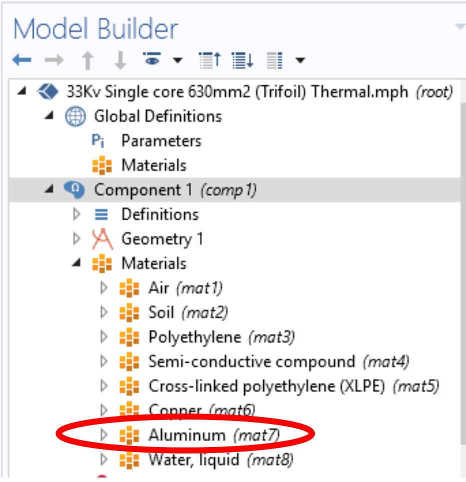


Figure 3.55: Selecting Aluminium material to be assign

2. Click on the geometry to highlight the Conductor of the cable which is Aluminium and the geometry entities are stored in Input Entities as shown in Figure 3.56.

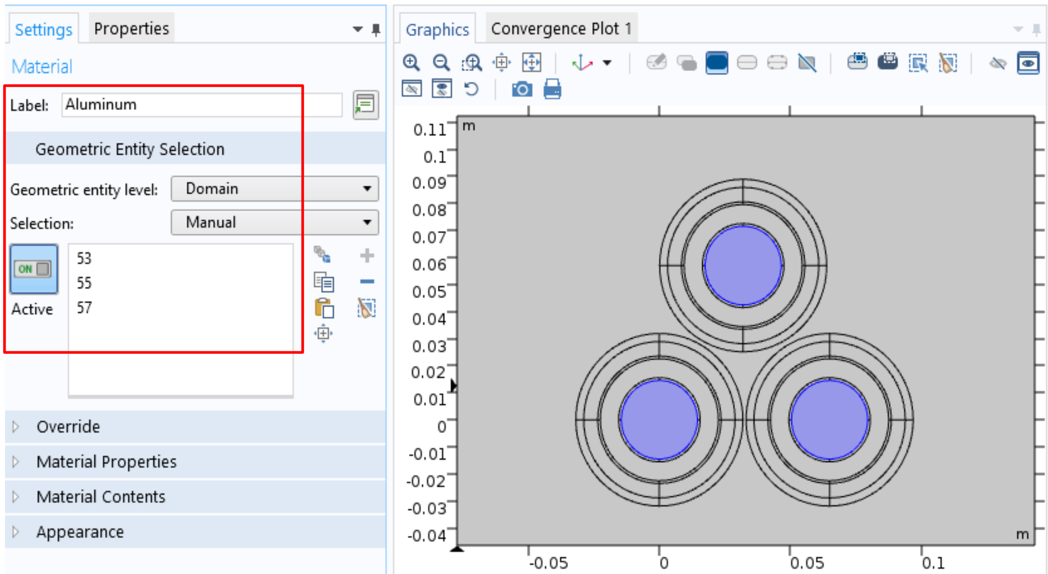


Figure 3.56: The Graphic window for Copper material assigned to the cable.

3.2.5 Meshing the '33kV Single core 630mm² XLPE Cable'

The last part of this whole geometry design for the cable is mesh. The purpose of meshing is to generate a polygonal or polyhedral that estimates the geometric domain of cable model.

1. In the Model Builder window, under Component 1 click Mesh 1.
2. Locate the Mesh Settings section in the Settings window for Mesh.
3. Click Build All

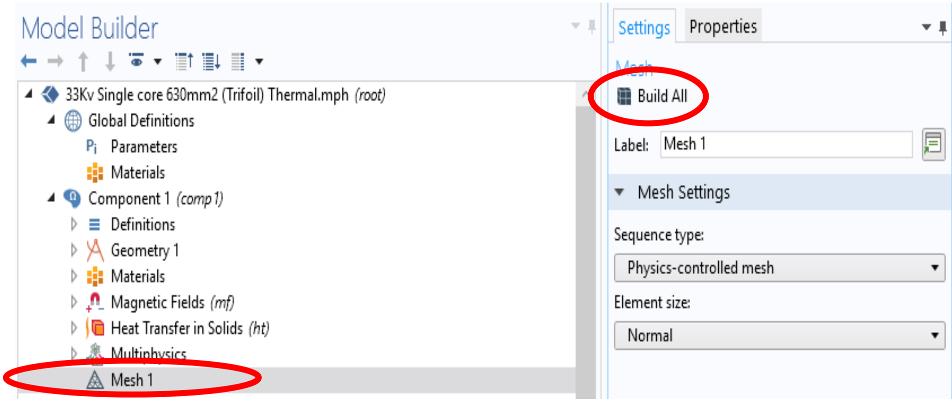


Figure 3.57: The Mesh setting for the cable

4. Finally the mesh of the cable is produced was shown in Figure 3.58.

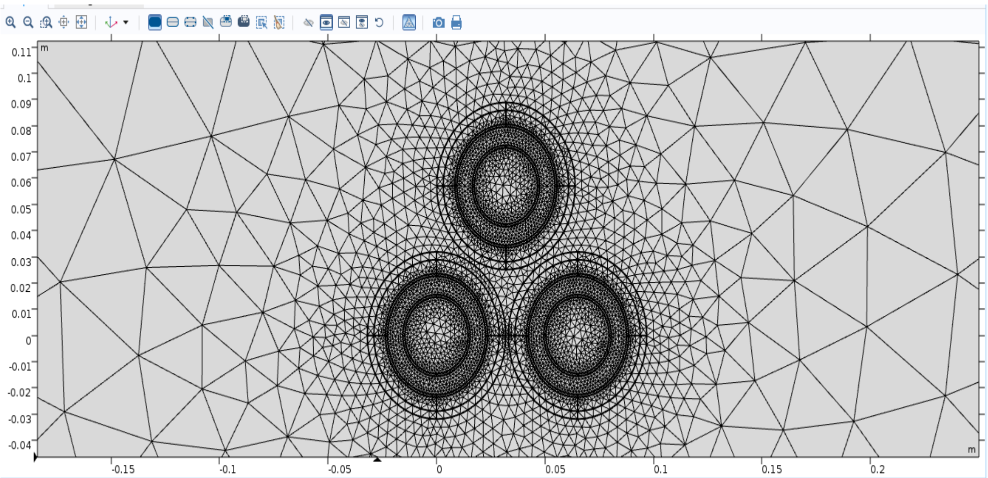


Figure 3.58: The Mesh Model of the '33kV Single core 630mm² XLPE Cable'

3.2.6 Adding Magnetic Field for the '33kV Single core 630mm² XLPE Cable'

1. Click Add Physics on the Home toolbar to open the Add Physics window.

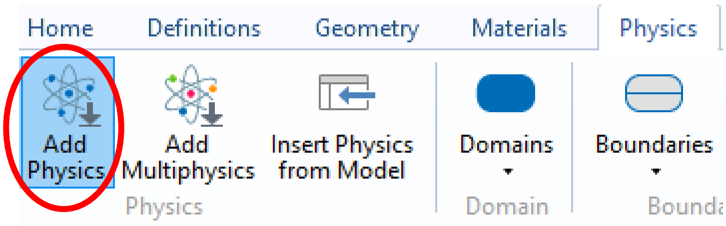


Figure 3.59: Choosing the Add Physics for the cable

2. Under the Add Physics window, select AC/DC>Magnetic Field (mf) and under the window toolbar click Add to Component.

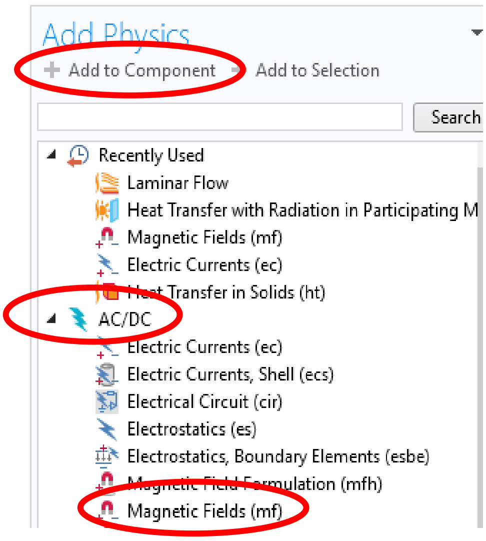


Figure 3.60: Selecting the Magnetic Fields for the cable

3. On the Settings window for Magnetic Fields, locate the Domain Selection section and from the Selection list choose Electromagnetic domains as shown in Figure 3.61.
4. The Electromagnetic domains are added to the cable.

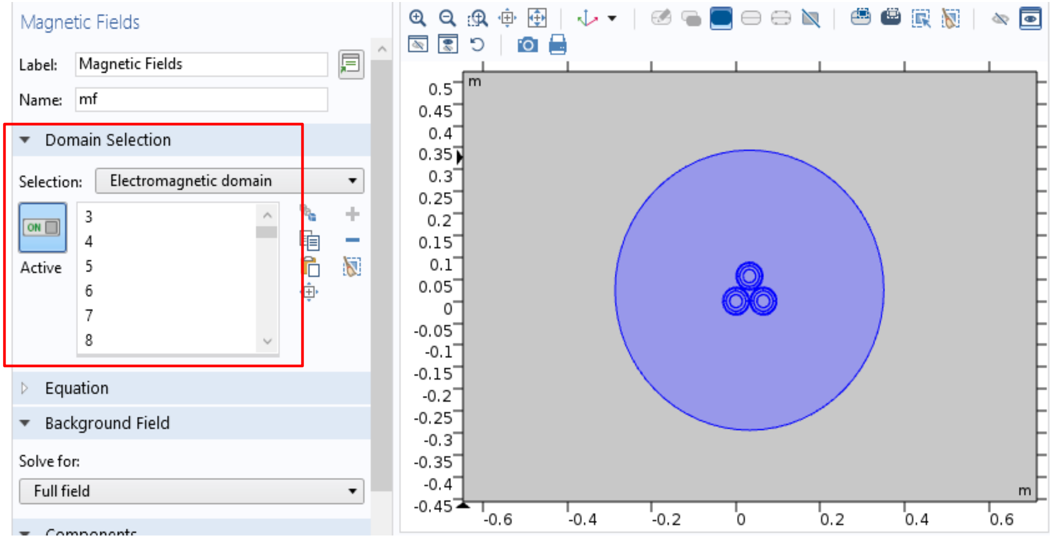


Figure 3.61: The Magnetic field was added to the cable.

3.2.7 Adding the Thermal effect to the '33kV Single core 630mm² XLPE Cable'

1. Click Add Physics on the Home toolbar to open the Add Physics window.

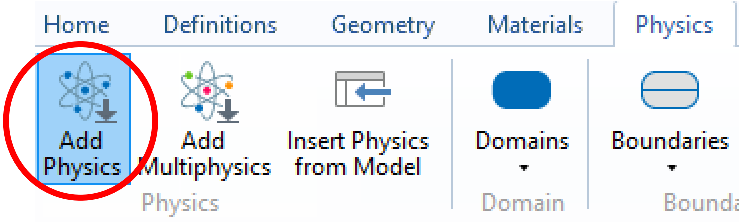


Figure 3.62: Choosing the Add Physics for the cable

2. Under the Add Physics window, select Heat Transfer>Heat Transfer in Solids (ht) and under the window toolbar click Add to Component.

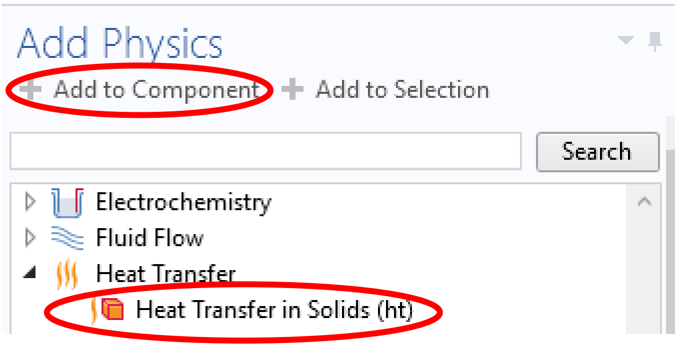


Figure 3.63: Selecting the Heat Transfer in Solids for the cable

3. On the Settings window for Heat Transfer in Solids, locate the Domain Selection section and from the Selection list choose Thermal domains as shown in Figure 3.64.
4. The Thermal domains are added to the cable.

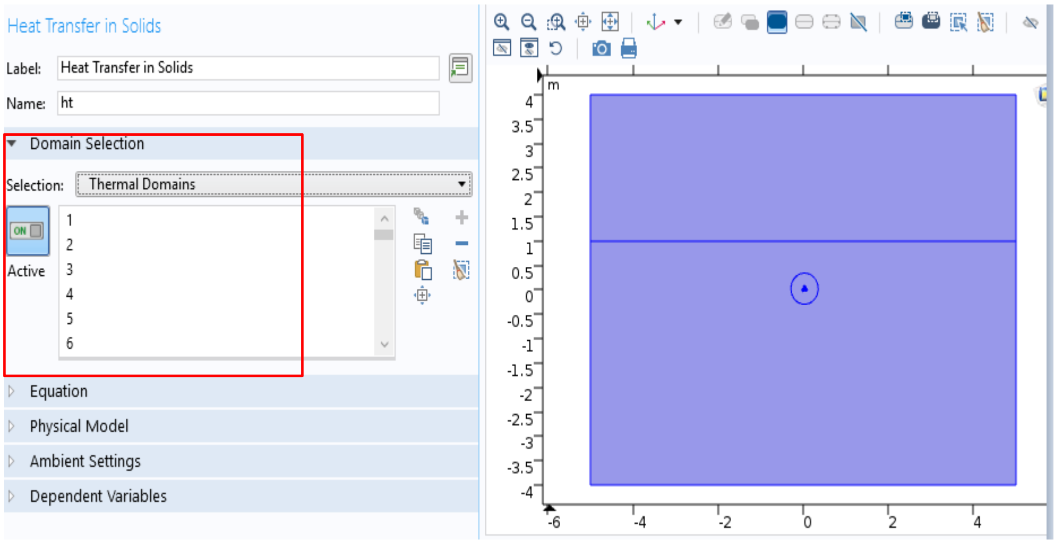


Figure 3.64: The Heat Transfer in Solid was added to the cable

3.2.8 Adding the Multiphysics Couplings to the '33kV Single core 630mm² XLPE Cable'

The next step is to use Multiphysics Couplings which is coupling method where it combines the Magnetic Flux and Heat Transfer in solid to form the Electromagnetic Heating. This method was used so that electromagnetic losses results in generation of heat. Therefore, it creates temperature dependent properties in the Magnetic Field boundary which are related to the temperature values determined by Heat Transfer in Solids (Kalenderli).

3.2.7.1 Adding the Electromagnetic Heating

1. Click Multiphysics Coupling on the Physics toolbar and choose Global>Electromagnetic Heating.

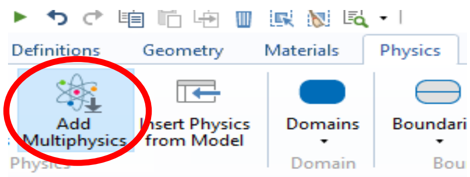


Figure 3.65: Choosing the Multiphysics Coupling for the cable

2. On the Settings window for Electromagnetic Heating, locate the Domain Selection section and from the Selection list, choose Electromagnetic domains as shown in Figure 3.66.
3. The Electromagnetic domains are added to the cable.

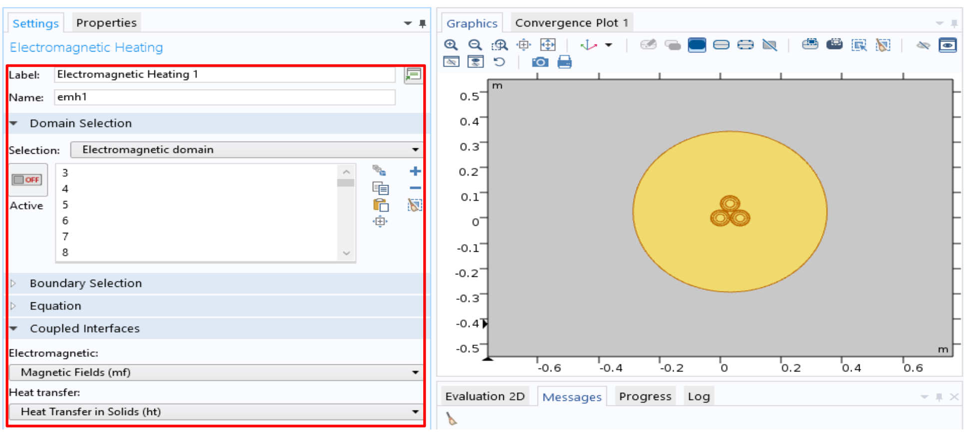


Figure 3.66: The Electromagnetic Heating was added to the cable

3.2.7.2 Adding the Temperature

The reason of Temperature is to study the thermal effect on cable.

1. Click Boundaries on the Physics toolbar and choose Temperature.
2. Under the Graphics toolbar select the Boundaries and the boundary entities will stored under the Boundary selection as shown in Figure 3.67.
3. Under the Settings window for Temperature, locate the Temperature section and in the *To* text field, type Text.

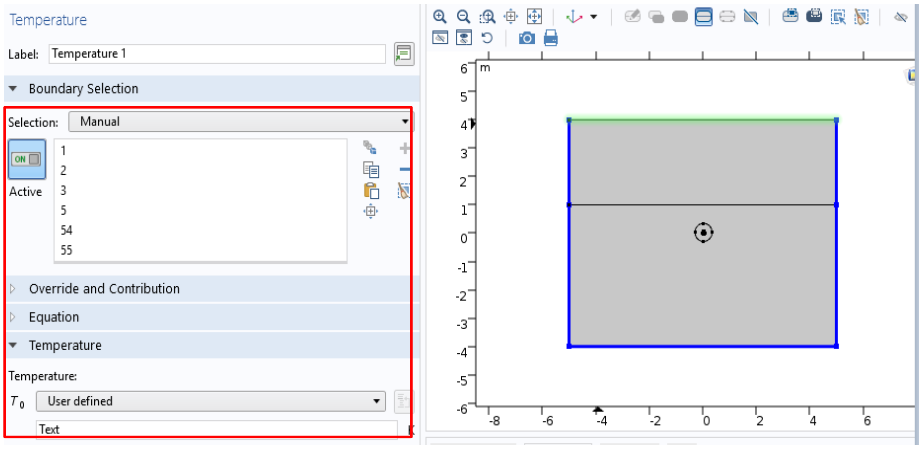


Figure 3.67: The Temperature was added to the cable

4. On the Home toolbar of Study, click Compute.

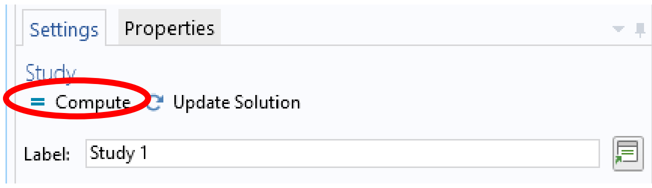


Figure 3.68: The setting for Study

Finally the simulation result can observed in the next section

3.2.7.3 The Result of the Temperature (ht)

1. In the Model Builder window, under Results click Temperature (ht).

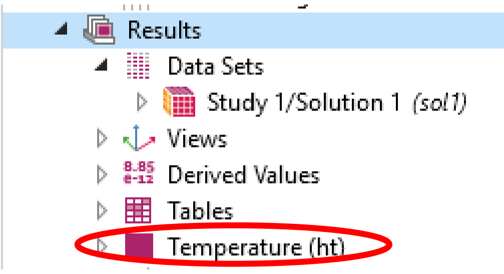


Figure 3.69: Selecting the Temperature (ht)

2. Locate the Plot Settings section the Settings window for 2D Plot Group, choose View 2D 2 from the View list.
3. Click Plot on the Temperature (ht) toolbar

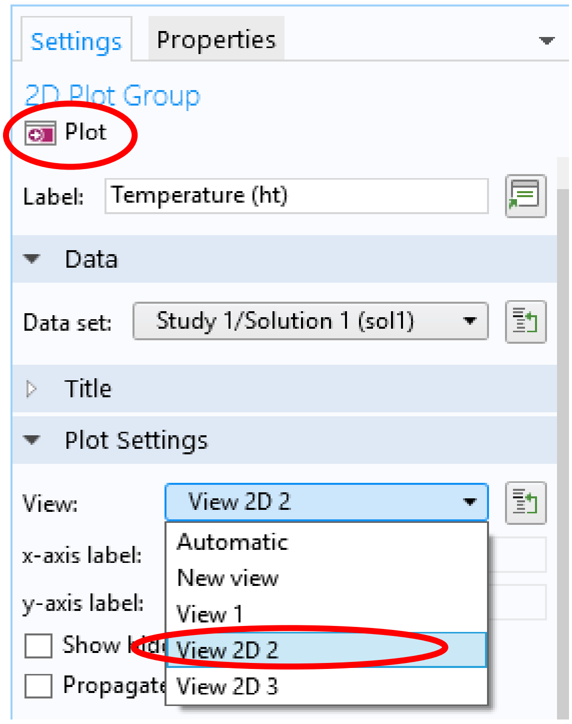


Figure 3.70: Choosing the result view

4. The design of the heat transfer on the cable will be displayed shown in Figure 3.71.

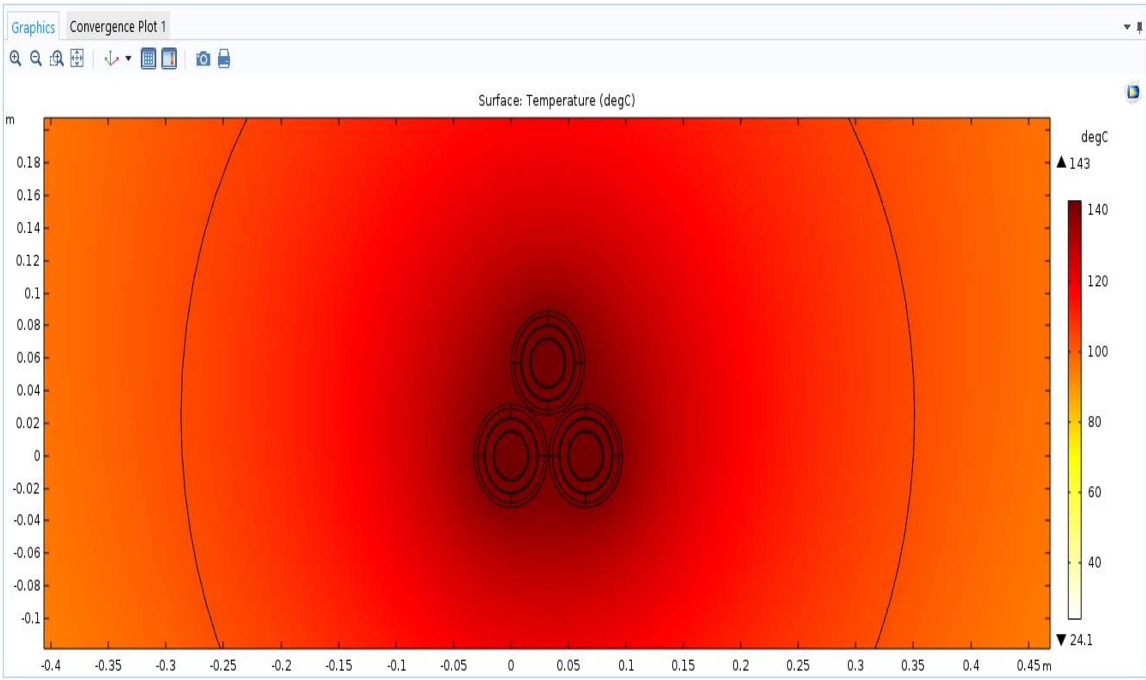


Figure 3.71: The heat transfer on the cable

3.2.8 Complete design of 33kV Single Core 630mm² Al XLPE Cable by using COMSOL software.

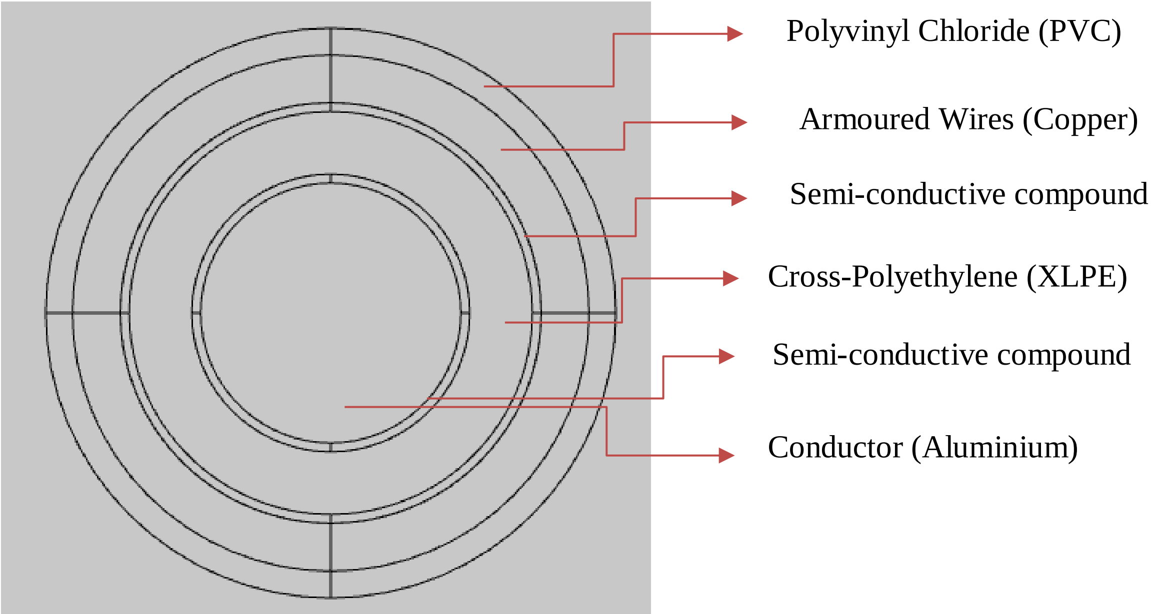


Figure 3.72: 33kV Single Core 630mm² Al XLPE Cable Structure

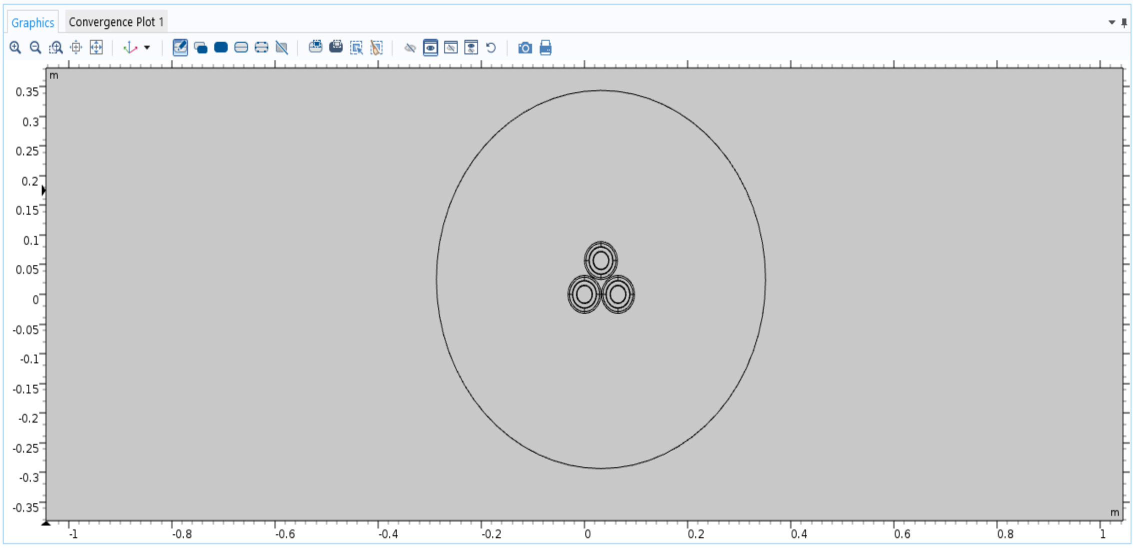


Figure 3.73: The Geometry of the '33kV Single Core 630mm² Al XLPE Cable'.

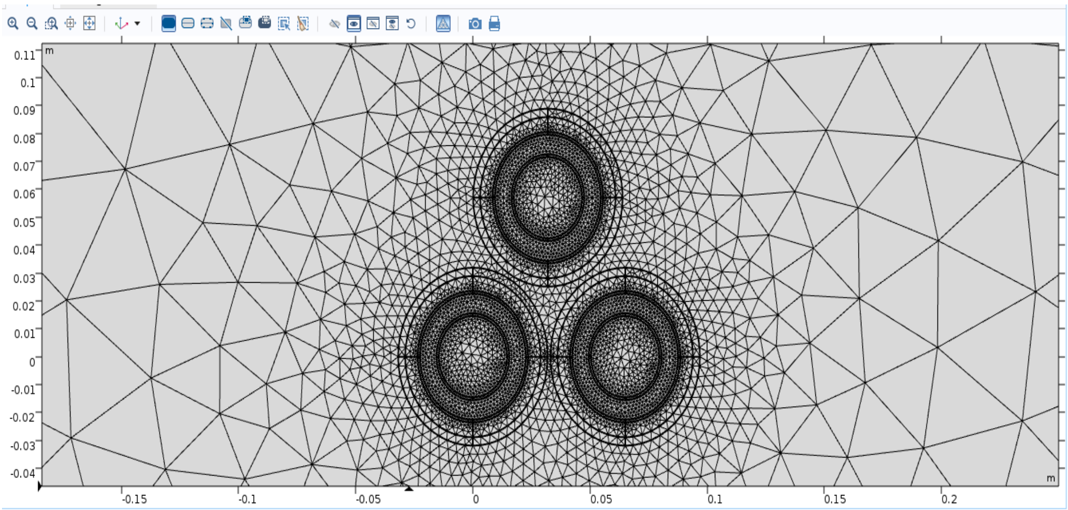


Figure 3.74: The Mesh Model of the ‘33kV Single core 630mm² XLPE Cable’

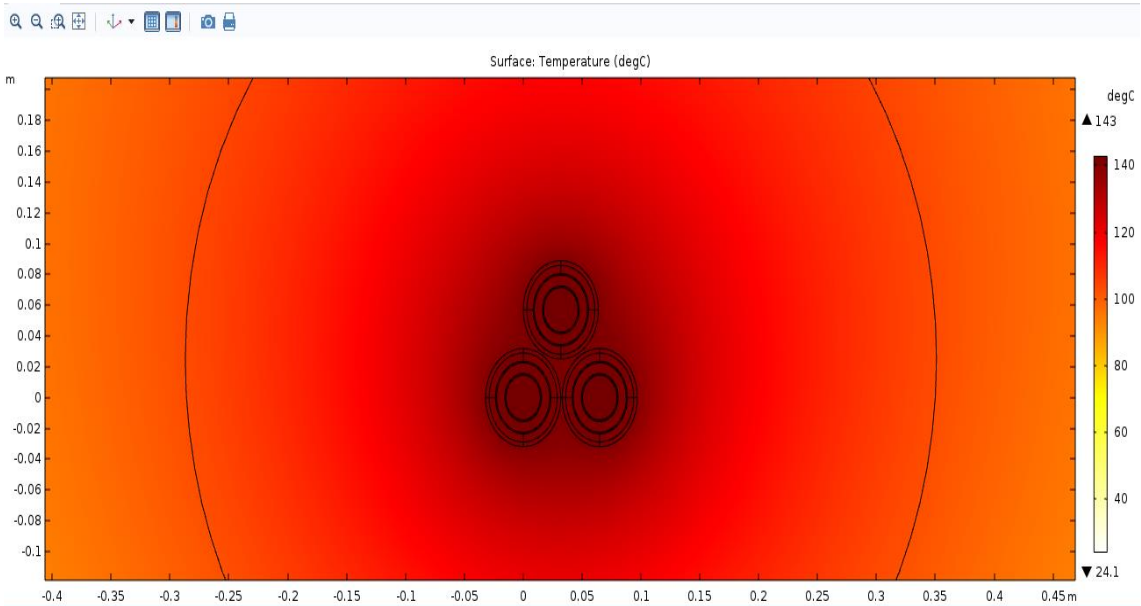


Figure 3.75: The Thermal Effect on 33kV Single Core 630mm² Al XLPE Cable’

3.3 Summary

In brief, the first step was designing the geometry of the selected power cable. Basically, three cables was constructed which are identical in parameters except for the position since it was set in trefoil position. After that, every structures of the selected power cables was designed based on the cable specification. The second step was need to define the geometry of the designed cable based on the cable structures. Once done with defining the cable structures, the materials for cable structures and surrounding surface was selected. In addition, the parameters for the thermal conductivity, density for the following materials was used from the software where values are all built-in in the material section. Furthermore, the electromagnetic heating has been added by coupling the magnetic flux and heat transfer on the solid in order to produce the heating effect on the chosen power cable.

CHAPTER 4

RESULT AND DISCUSSSION

4.1 Introduction

In this chapter, it shows that the thermal analysis has been conducted on the **'33kV Single Core 630mm² Al XLPE Cable'**. This simulation test was done in order to obtain the operating temperature with different soil conditions with the current correction factor (CF) and without the current correction factor (CF) by changing the soil temperature, different cable positions, different cable depth buried into the ground and also with water.

4.2 Thermal effect on single-core cable

In this work, the 33KV Single Core 1x630mm² XLPE Cable was used as mentioned before. Therefore, this cable has been used to analyse the thermal effect under two different depth burial of the cable under the soil which is 0.5 and 1 meter as shown in Figure 4.2 and 4.5. The soil condition which was used for this analysis are dry type. The ambient ground temperature was fixed at 35°C. In addition, the minimum current value that was used in this simulation test are the operating current value of the power cable from the data sheet which is $I_a = 685$A and this value was increased to the maximum current rating in order to obtain the maximum cables conductors operating temperature (°C) which is 90°C of the underground power cables (UPC) selected for this research.

4.2.1 The Single Cable Buried Cable Under 0.5 meter Depth

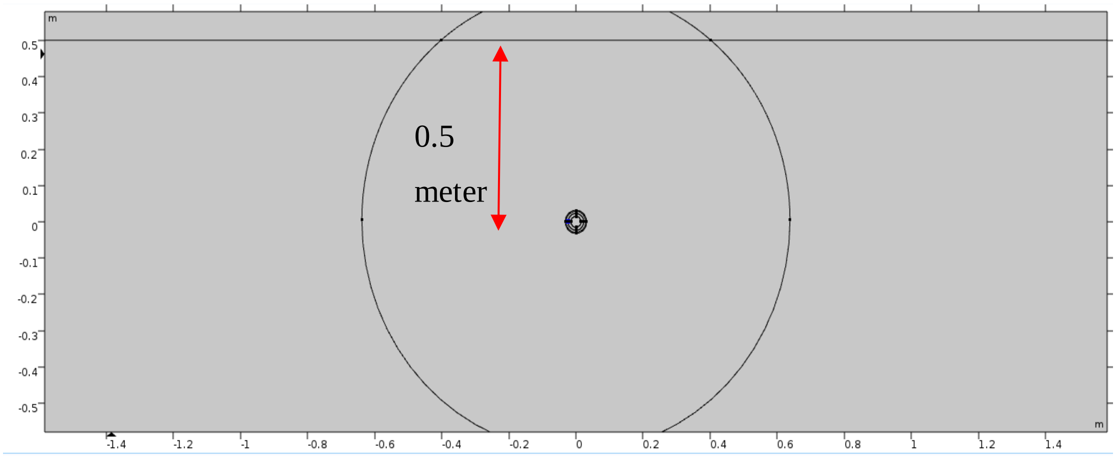


Figure 4.1: The single cable buried in depth of 0.5 meter.

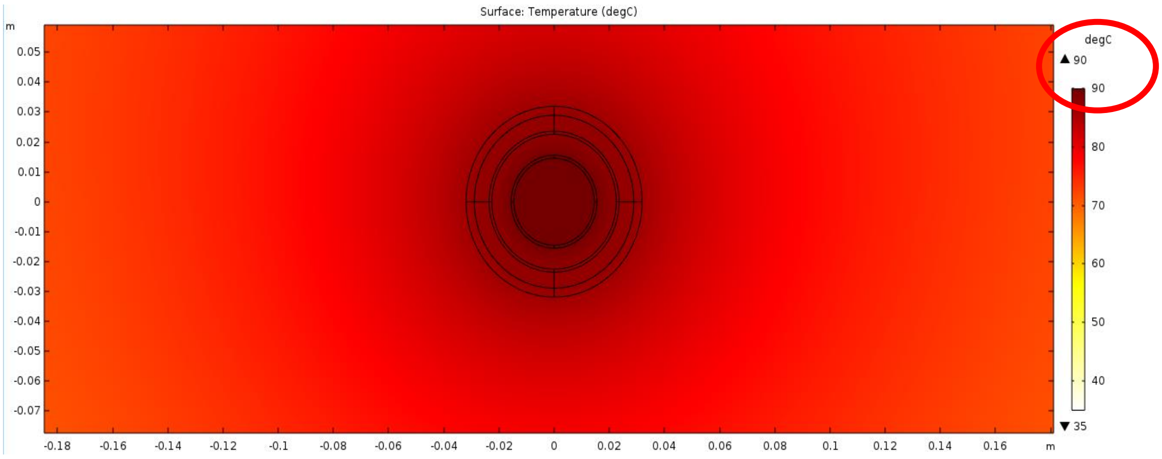


Figure 4.2: The operating temperature on underground power cables (UPC) buried in depth of 0.5 meter (Zoom in view).

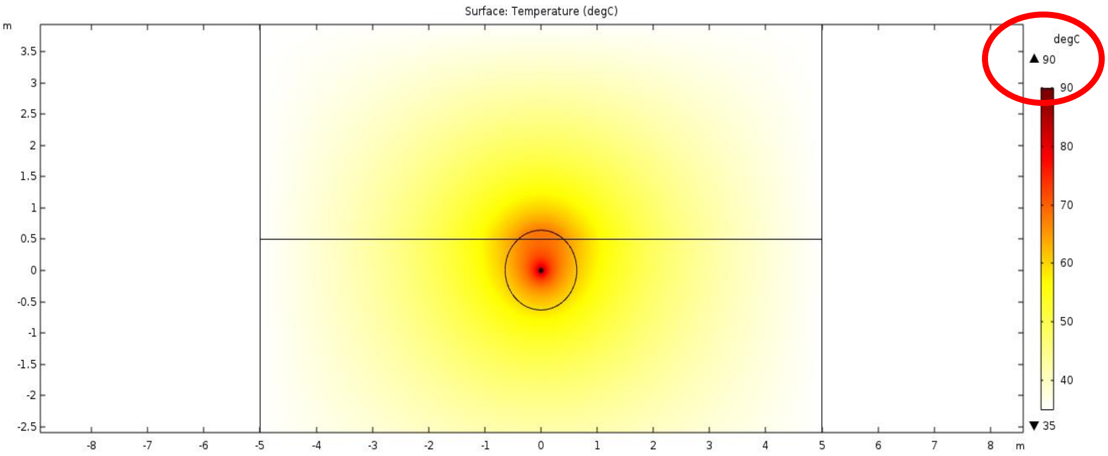


Figure 4.3: The operating temperature on underground power cables (UPC) buried in depth of 0.5 meter (Zoom out view).

Based on Figure 4.2 and 4.3, one of the six simulated results of operating temperature on single underground cables (UPC) in depth of 0.5 meter under dry soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is the maximum operating temperature of the cables conductor at 90°C with the ambient ground temperature was set at 35°C.

Ampacity (A)	Cable Conductor Temperature(°C)
685	52.3
735	71.9
785	77.1
835	82.6
885	88.5
898.1	90

Table 4.1: The cable conductor temperature of buried under 0.5 meter by changing the ampacity.

Based on Table 4.1, the current carry capacity of the cable was increased from lowest value to highest value which are 685A to 898.1A relatively affects the operating cables conductor temperature which has increase from 52.3°C to 90°C. Therefore, it has reach the maximum operating cable conductor temperature.

4.2.2 The Result of Buried Cable under 1 meter Depth

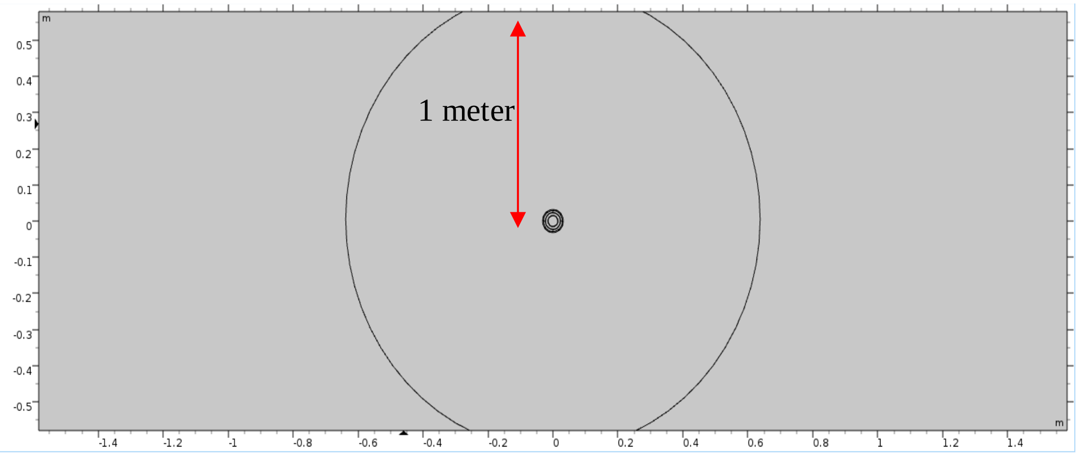


Figure 4.4: The single cable buried in depth of 1 meter.

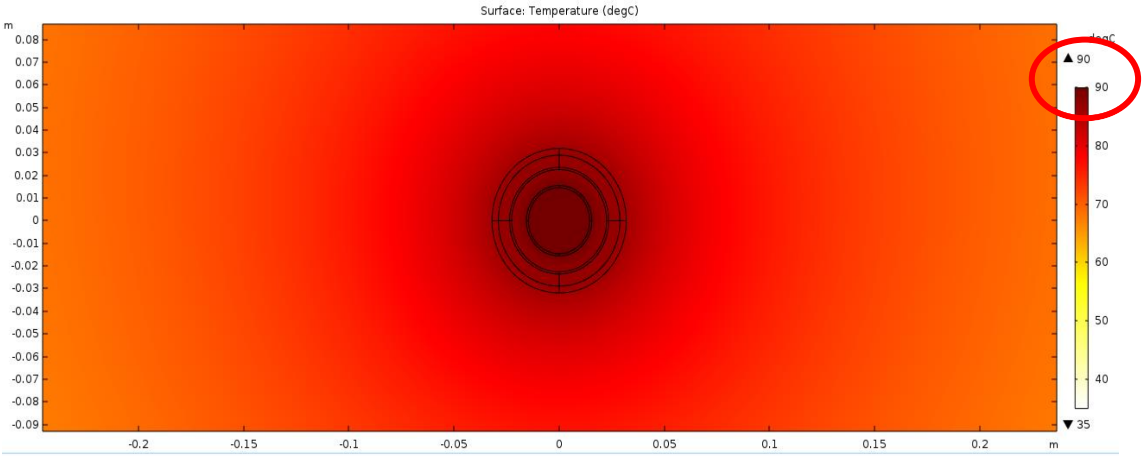


Figure 4.5: The operating temperature on underground power cables (UPC) buried in depth of 1 meter (Zoom in view).

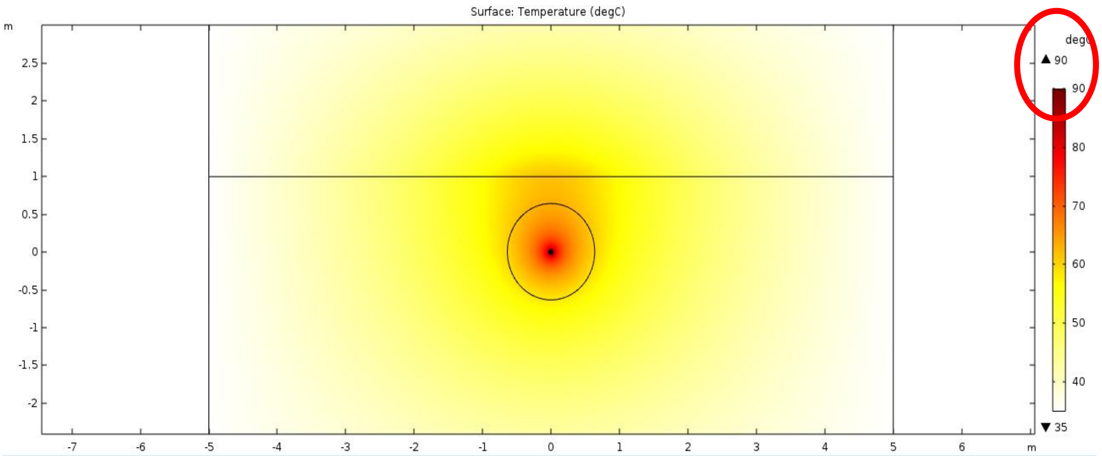


Figure 4.6: The operating temperature on underground power cables (UPC) buried in depth of 1 meter (Zoom in view).

Based on Figure 4.5 and 4.6, one of the six simulated results of operating temperature on single underground cables (UPC) in depth of 1 meter under dry soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is the maximum operating temperature of the cables conductor at 90°C with the ambient ground temperature was set at 35°C.

Ampacity (A)	Cable Conductor Temperature(°C)
685	64.7
735	69.2
785	74
835	79.2
885	84.6
932	90

Table 4.2: The cable conductor temperature of buried under 1 meter by changing the ampacity.

Based on Table 4.2, the current carry capacity of the cable was increased from the lowest value to the highest value which are 685A to 932A correspondingly affects the operating cables conductor temperature which has increase from 64.7°C to 90°C. Therefore, it has reach the maximum operating cable conductor temperature.

4.2.3 Comparison of the result of the two cable depth of the buried in 0.5 meter and 1 meter.

Ampacity (A) for 0.5 meter	Cable Conductor Temperature(°C) for 0.5 meter	Ampacity (A) for 1 meter	Cable Conductor Temperature(°C) for 1 meter
685	67.4	685	64.7
735	71.9	735	69.2
785	77.1	785	74
835	82.6	835	79.2
885	88.5	885	84.6
898.1	90	898.1	86.1
932	98.4	932	90

Table 4.3: The two cable depth of the buried in 0.5 meter and 1 meter.

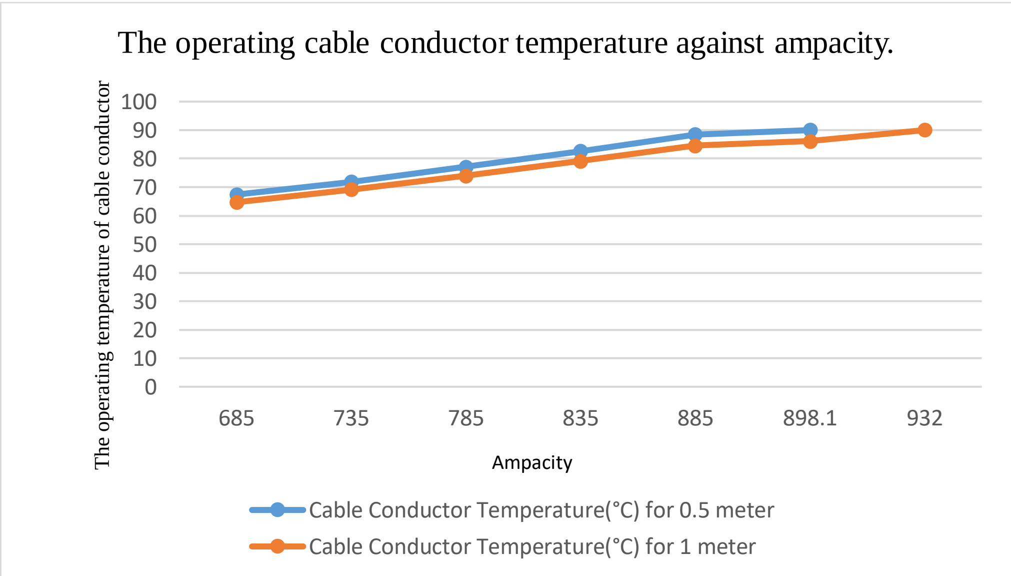


Figure 4.7: The two cable depth of the buried in 0.5 meter and 1 meter.

Based on the tabulated result on Table 4.3 and Figure 4.7, when the single core cable was buried under 0.5 meter depth, the operating temperature of the cable conductor which is 67.4°C is much higher than 1 meter depth of the buried single core cable temperature which is 64.7°C. This shows that the laying the cable closer to the ground surface increases the operating temperature of the cable conductor due to the heat transferred from the sunlight with the irradiance of 1000 W/m² which was set in the simulation. Therefore, the single core cable buried in depth of 0.5 meter will receive more heat than the single core cable buried in depth of 1 meter.

Other than that, the current carry capacity of the single core cable was buried under 0.5 meter depth being reduced to 898.1 A at the maximum operating temperature of 90°C which is less than the single core cable buried under 1 meter depth which is 932A at the same maximum operating temperature. Basically, the heat transferred from sunlight to the surface ground will not affect the single core cable buried under 1 meter depth as much as cable buried in depth of 0.5 meter because laying the cable further from the ground surface will reduce heat transferred on the cable and this are the reason behind it can carry more current.

In matter of fact, laying the single core cable in depth of 1 meter will be the preferred depth for the cable than the 0.5 meter depth and this was proven by comparing the results of the operating cable conductor's temperature in two different depth.

4.3 Effect of thermal conductivity of different types of soil on underground power cables with current rating correction factors.

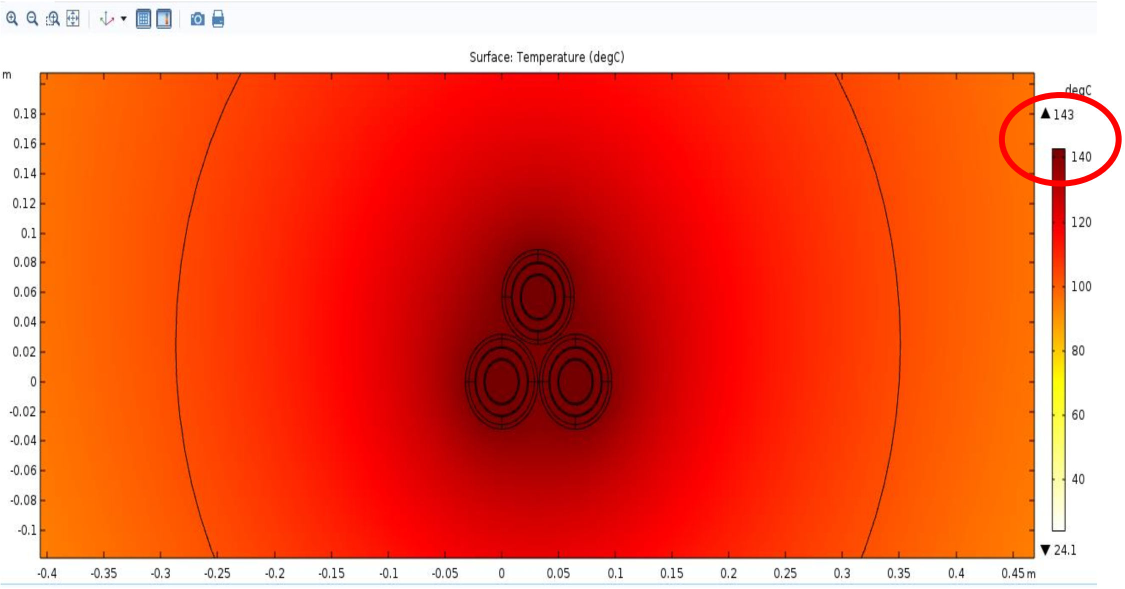


Figure 4.8: The operating temperature on underground power cables (UPC) buried in depth of 1 meter in Tre-foil position (Zoom in view).

For this section, four different types of soil with different thermal conductivity and thermal resistance which are Very Moist, Moist, Dry and Very Dry types as shown in Table 4.4 was used to analyse the thermal effect on the UPC (Kalenderli)**.** The parameters of soil thermal conductivity which was used are 1.4 W/K.m, 1 W/K.m, 0.5 W/K.m and 0.3 W/K.m with the parameters of soil thermal resistivity which are 0.7 K.m/W, 1 K.m/W, 2 K.m/W and 3 K.m/W. In addition, there was no measurement for moisture content of the soil since it was defined by the soil thermal conductivity and resistivity.

Soil Conditions	Soil Thermal Conductivity (W/K.m)	Soil Thermal Resistivity (K.m/W)
Very Moist	1.4	0.7
Moist	1	1
Dry	0.5	2
Very Dry	0.3	3

Table 4.4: The Soil Thermal Conductivity and Soil Thermal Resistivity Values

The simulation test was conducted on designed Underground Power Cable (UPC) with the trefoil position, cable was buried in ground depth of 1 metre which is displayed on laptop as shown in Figure 4.6 and this was simulated with different ambient ground temperature by increasing the temperature every 5°C from the range of 20°C to 45°C as shown in Table 4.5. In fact, this range was chosen based from the UPC cable specification.

Ambient Ground Temperature (°C)
20
25
30
35
40
45

Table 4.5: The Ambient Ground Temperature (°C)

Additionally, the current rating correction factors was included in this analysis thus there are three current rating correct factors was considered which are for ambient ground temperature, depth laying for direct buried cables, soil thermal resistivity (K.m/W) and soil thermal resistivity (K.m/W). By taking all this condition into the consideration, the Underground Cable Current Carrying Capacity (Ampacity) was calculated by using the following formula;

$$I_c = I_a . k_1 . k_2 . k_3$$

$I_c - The\ undeground\ Cable\ Current\ Carrying\ Capacity\ (Ampacity)$

$I_a - The\ operating\ current\ of\ the\ cable$

$K_1 - The\ Correction\ factor\ of\ ground\ ambient\ temperature$

$K_2 - The\ Correction\ factor\ of\ Soil\ Thermal\ Resistivity$

$K_3 - The\ Correction\ factor\ of\ depth\ of\ the\ buried\ cable$

Maximum conductor temperature °C	Ambient ground temperature °C							
	10	15	20	25	30	35	40	45
90	1.03	1.00	0.97	0.93	0.89	0.86	0.82	0.77

Table 4.6: Correction factor for ambient ground temperatures

Depth laying m	Single-core cables Nominal conductor size mm²	
	≤ 185 mm²	> 185 mm²
0.50	1.04	1.06
0.60	1.02	1.04
0.80	1.00	1.00
1.00	0.98	0.97
1.25	0.96	0.95
1.50	0.95	0.93
1.75	0.94	0.91
2.00	0.93	0.90
2.50	0.91	0.88
3.00	0.90	0.86

Table 4.7: Correction factor for depth laying for direct buried cables

Nominal area of conductor mm²	Values of soil thermal resistivity K.m/W (Moist ← → Dry)								
	0.7	0.8	0.9	1.0	1.2	1.5	2.0	2.5	3.0
≤ 16	1.23	1.17	1.12	1.07	1.00	0.91	0.80	0.73	0.67
25	1.24	1.18	1.12	1.07	1.00	0.91	0.80	0.73	0.67
35	1.24	1.18	1.12	1.07	1.00	0.91	0.80	0.72	0.66
50	1.25	1.18	1.13	1.08	1.00	0.91	0.80	0.72	0.66
70	1.25	1.19	1.13	1.08	1.00	0.91	0.80	0.72	0.66
95	1.25	1.19	1.13	1.08	1.00	0.91	0.79	0.72	0.66
120	1.26	1.19	1.13	1.08	1.00	0.91	0.79	0.72	0.66
150	1.26	1.19	1.13	1.08	1.00	0.91	0.79	0.71	0.66
185	1.26	1.19	1.13	1.08	1.00	0.90	0.79	0.71	0.65
240	1.26	1.20	1.13	1.08	1.00	0.90	0.79	0.71	0.65
300	1.27	1.20	1.14	1.08	1.00	0.90	0.79	0.71	0.65
400	1.27	1.20	1.14	1.09	1.00	0.90	0.79	0.71	0.65
500	1.27	1.20	1.14	1.09	1.00	0.90	0.79	0.71	0.65
630	1.27	1.20	1.14	1.09	1.00	0.90	0.79	0.71	0.65

Table 4.8: Correction factor for soil thermal resistivity (K.m/W)

4.3.1 The Result of Operating Cable Conductor Temperature using Different Soil Conditions with Correction Factor

4.3.1.1 Soil Moisturity (Very Moist)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under **very moist** soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 1.4
- Correction factor for soil thermal resistivity value 0.7 K.m/W = 1.27
- Correction factor for ambient ground temperature for every added 5°C from 20°C to 45°C is 0.97, 0.93, 0.89, 0.86, 0.82 and 0.77.
- Correction factor for depth of buried cables for 1 meter = 0.97

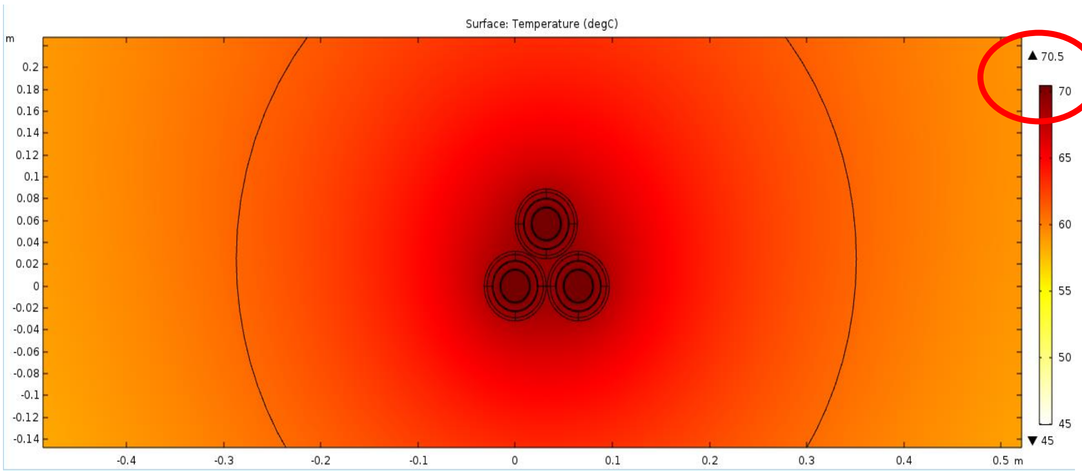


Figure 4.9: The operating temperature on underground power cables (UPC) under very moist soil condition (Zoom in view).

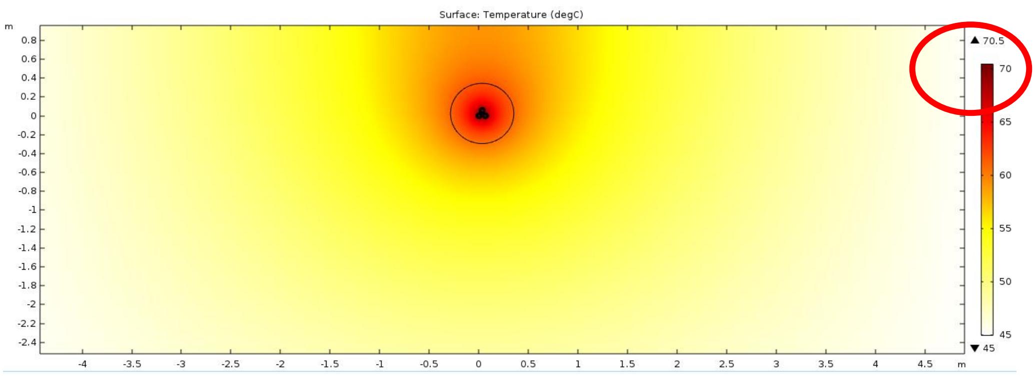


Figure 4.10: The operating temperature on underground power cables (UPC) under very moist soil condition (Zoom out view).

Based on Figure 4.9 and 4.10, one of the six simulated results of operating temperature on underground cables (UPC) with current rating correction factor under very moist soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 70.5°C with the ambient ground temperature was set at 45°C.

Ambient Ground Temperature (°C)	Ampacity (A)	Cable Conductor Temperature(°C)
20	818.5	60.5
25	784.78	62.2
30	751.03	64.1
35	725.71	66.8
40	691.96	68.9
45	649.77	70.5

Table 4.9: The Cable Conductor Temperature (°C) of Very Moist Soil Condition

Based on Table 4.9, the ambient ground temperature was increased from 20°C to 45°C and the ampacity for this temperature range decreases from the highest to lowest value which are 818.5A to 649.77A. The operating cables conductor temperature has increase from 60.5°C to 70.5°C respectively to the ambient ground temperature and ampacity of the UPC.

4.3.1.2 Soil Moisturity (Moist)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under **moist** soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 1
- Correction factor for soil thermal resistivity value 1 K.m/W = 1.09
- Correction factor for ambient ground temperature for every added 5°C from 20°C to 45°C is 0.97, 0.93, 0.89, 0.86, 0.82 and 0.77.
- Correction factor for depth of buried cables for 1 meter = 0.97

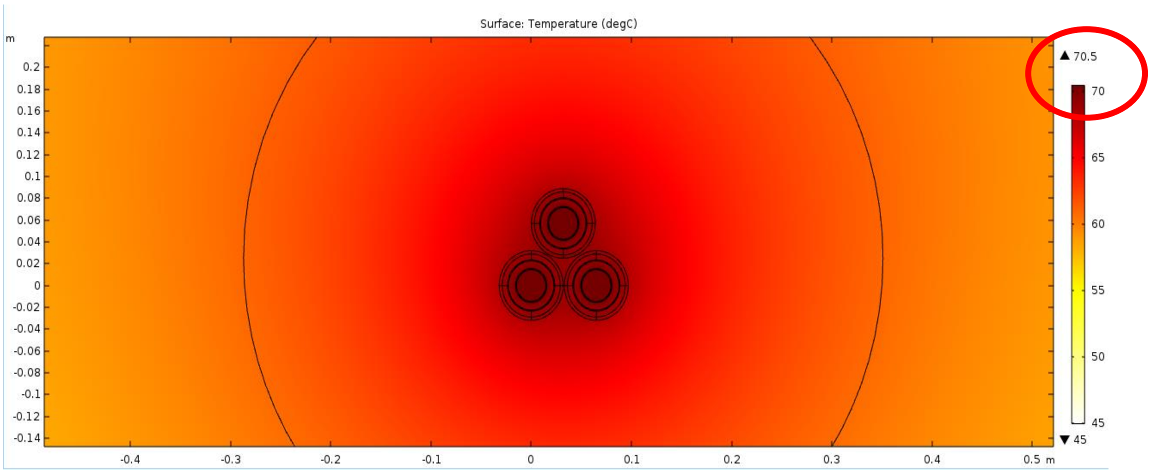


Figure 4.11: The operating temperature on underground power cables (UPC) under moist soil condition (Zoom in view).

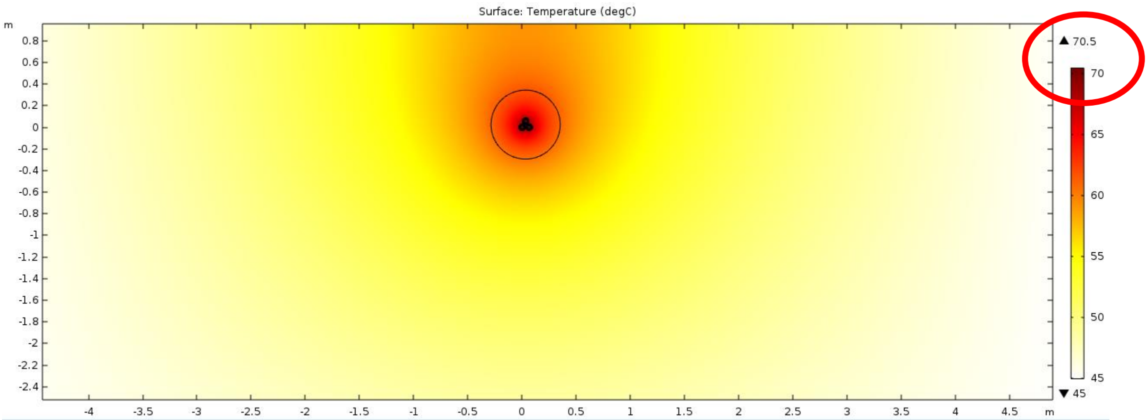


Figure 4.12: The operating temperature on underground power cables (UPC) under moist soil condition (Zoom out view).

Based on Figure 4.11 and 4.12, one of the six simulated results of operating temperature on underground cables (UPC) with current rating correction factor under moist soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 70.5°C with the ambient ground temperature was set at 45°C.

Ambient Ground Temperature (°C)	Ampacity (A)	Cable Conductor Temperature(°C)
20	702.52	60.5
25	673.55	62.2
30	644.58	64.1
35	622.86	66.8
40	593.89	68.9
45	557.67	70.5

Table 4.10: The Cable Conductor Temperature (°C) of Moist Soil Condition

Based on Table 4.10, the ambient ground temperature was increased from 20°C to 45°C and the ampacity for this temperature range decreases from the highest to lowest value which are 702.52A to 557.67A. The operating cables conductor temperature has increase from 60.5°C to 70.5°C respectively to the ambient ground temperature and ampacity of the UPC.

4.3.1.3 Soil Moisturity (Dry)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under **dry** soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 0.5
- Correction factor for soil thermal resistivity value 2 K.m/W = 0.79
- Correction factor for ambient ground temperature for every added 5°C from 20°C to 45°C is 0.97, 0.93, 0.89, 0.86, 0.82 and 0.77.
- Correction factor for depth of buried cables for 1 meter = 0.97

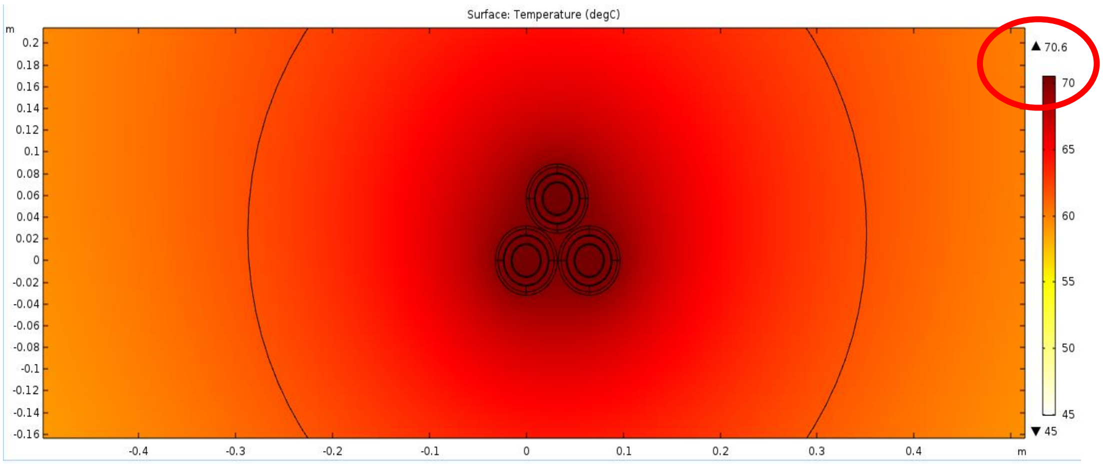


Figure 4.13: The operating temperature on underground power cables (UPC) under dry soil condition (Zoom in view).

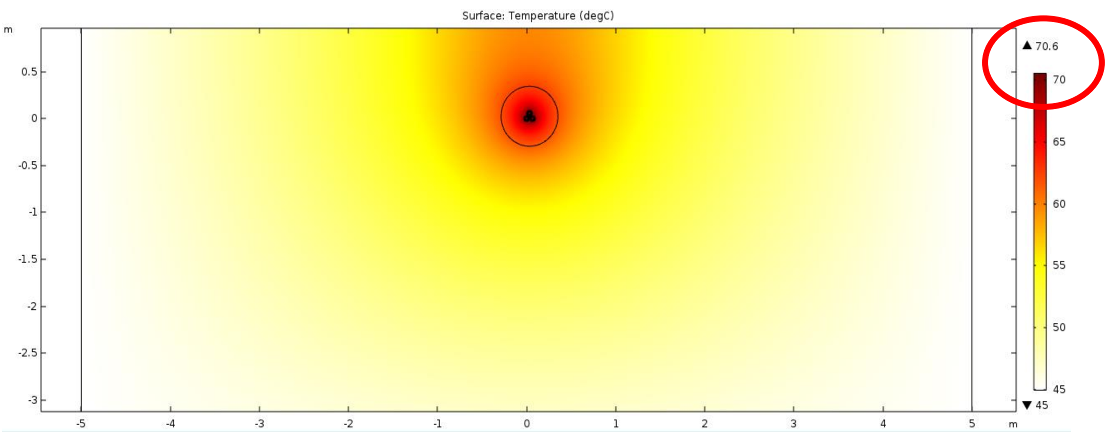


Figure 4.14: The operating temperature on underground power cables (UPC) under dry soil condition (Zoom out view).

Based on Figure 4.13 and 4.14, one of the six simulated results of operating temperature on underground cables (UPC) with current rating correction factor under dry soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 70.6°C with the ambient ground temperature was set at 45°C.

Ambient Ground Temperature (°C)	Ampacity (A)	Cable Conductor Temperature(°C)
20	509.17	60.6
25	488.17	62.3
30	467.17	64.2
35	451.4	66.9
40	430.43	69
45	404.18	70.6

Table 4.11: The Cable Conductor Temperature (°C) of Dry Soil Condition

Based on Table 4.11, the ambient ground temperature was increased from 20°C to 45°C and the ampacity for this temperature range decreases from the highest to lowest value which are 509.17A to 404.18A. The operating cables conductor temperature has increase from 60.6°C to 70.6°C respectively to the ambient ground temperature and ampacity of the UPC.

4.3.1.4 Soil Moisturity (Very Dry)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under **very dry** soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 0.3
- Correction factor for soil thermal resistivity value 3 K.m/W = 0.65
- Correction factor for ambient ground temperature for every added 5°C from 20°C to 45°C is 0.97, 0.93, 0.89, 0.86, 0.82 and 0.77.
- Correction factor for depth of buried cables for 1 meter = 0.97

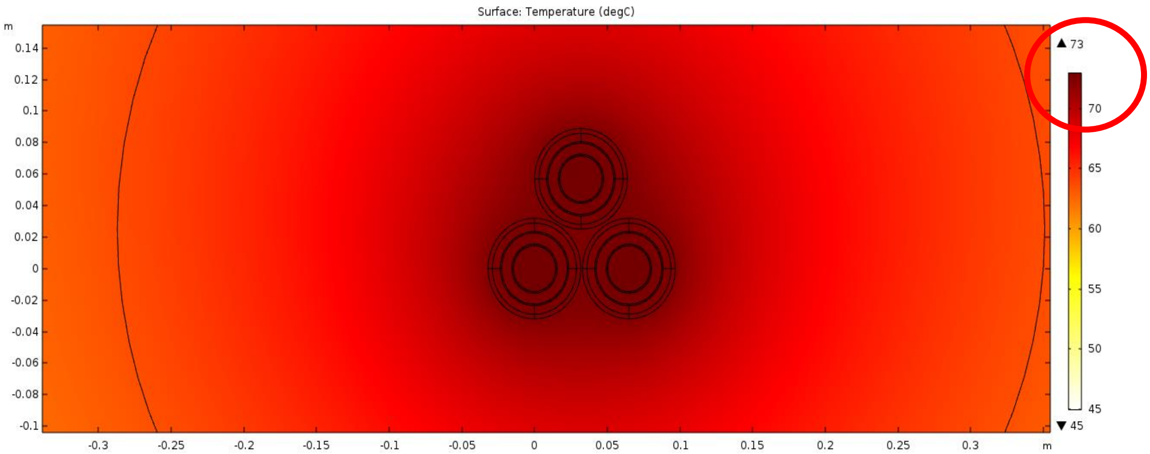


Figure 4.15: The operating temperature on underground power cables (UPC) under very dry soil condition (Zoom in view).

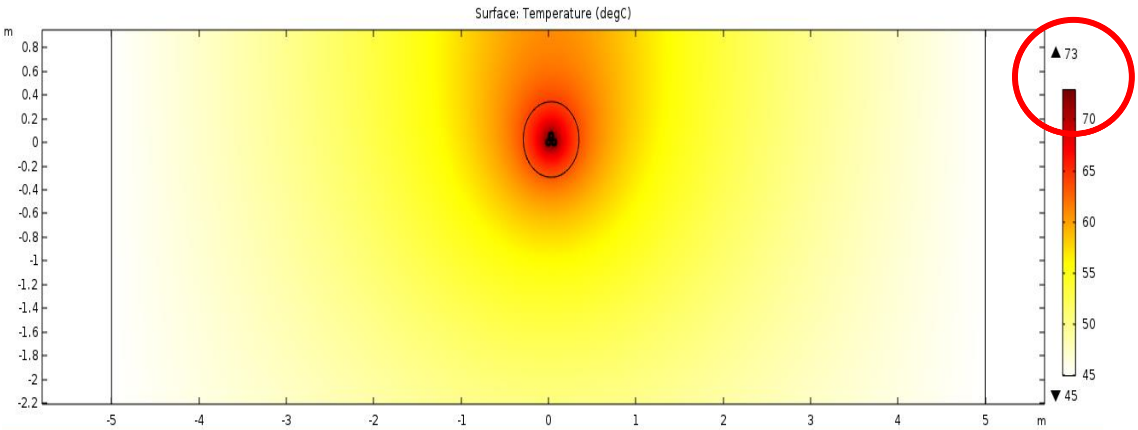


Figure 4.16: The operating temperature on underground power cables (UPC) under very dry soil condition (Zoom out view).

Based on Figure 4.15 and 4.16, one of the six simulated results of operating temperature on underground cables (UPC) with current rating correction factor under very dry soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 73°C with the ambient ground temperature was set at 45°C.

Ambient Ground Temperature (°C)	Ampacity (A)	Cable Conductor Temperature(°C)
20	418.94	64.5
25	401.66	65.9
30	384.38	67.5
35	371.43	70
40	354.15	71.8
45	332.56	73

Table 4.12: The Cable Conductor Temperature (°C) of Very Dry Soil Condition

Based on Table 4.12, the ambient ground temperature was increased from 20°C to 45°C and the ampacity for this temperature range decreases from the highest to lowest value which are 418.94A to 332.56A. The operating cables conductor temperature has increase from 64.5°C to 73°C respectively to the ambient ground temperature and ampacity of the UPC.

Ambient Ground Temperature(°C)	Operating cable conductor temperature (°C) at different soil conditions			
	Very Moist	Moist	Dry	Very Dry
20	60.5	60.5	60.6	64.5
25	62.2	62.2	62.3	65.9
30	64.1	64.1	64.2	67.5
35	66.8	66.8	66.9	70
40	68.9	68.9	69	71.8
45	70.5	70.5	70.6	73

Table 4.13: The operating cable conductor temperature (°C) at four different soil conditions was tabulated into one table.

Based on Table 4.13, the results of operating cable conductor temperature (°C) at four different soil conditions was tabulated into one table.

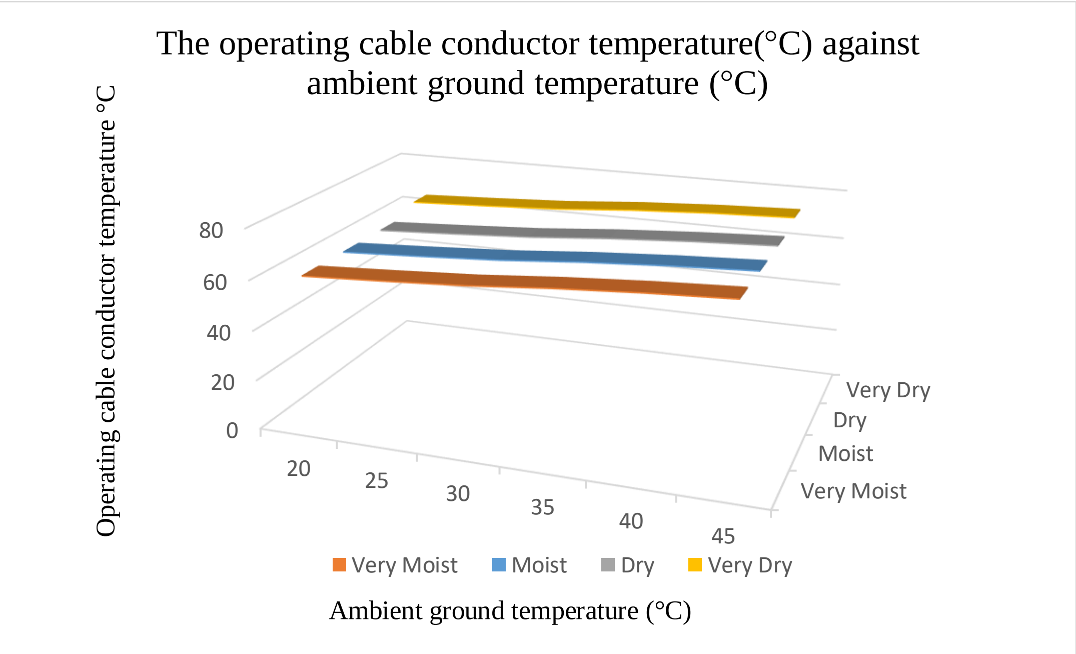


Figure 4.17: The operating cable conductor temperature (°C) at four different soil conditions was tabulated into one table.

Based on the Figure 4.17, it shows the results of operating cable conductor temperature (°C) with current rating correction factors at four different soil conditions by using thermal effect analysis.

Ambient Ground Temperature(°C)	Current carry capacity (Ampacity) of the cable at four type soil condition			
	Very Moist	Moist	Dry	Very Dry
20	818.5	702.52	509.17	418.94
25	784.78	673.55	488.17	401.66
30	751.03	644.58	467.17	384.38
35	725.71	622.86	451.4	371.43
40	691.96	593.89	430.43	354.15
45	649.77	557.67	404.18	332.56

Table 4.14: The Current carry capacity (Ampacity) of the cable at four different soil conditions was tabulated into one table.

Based on Table 4.14, the results of current carry capacity (Ampacity) of the cable at four different soil conditions was tabulated into one table.

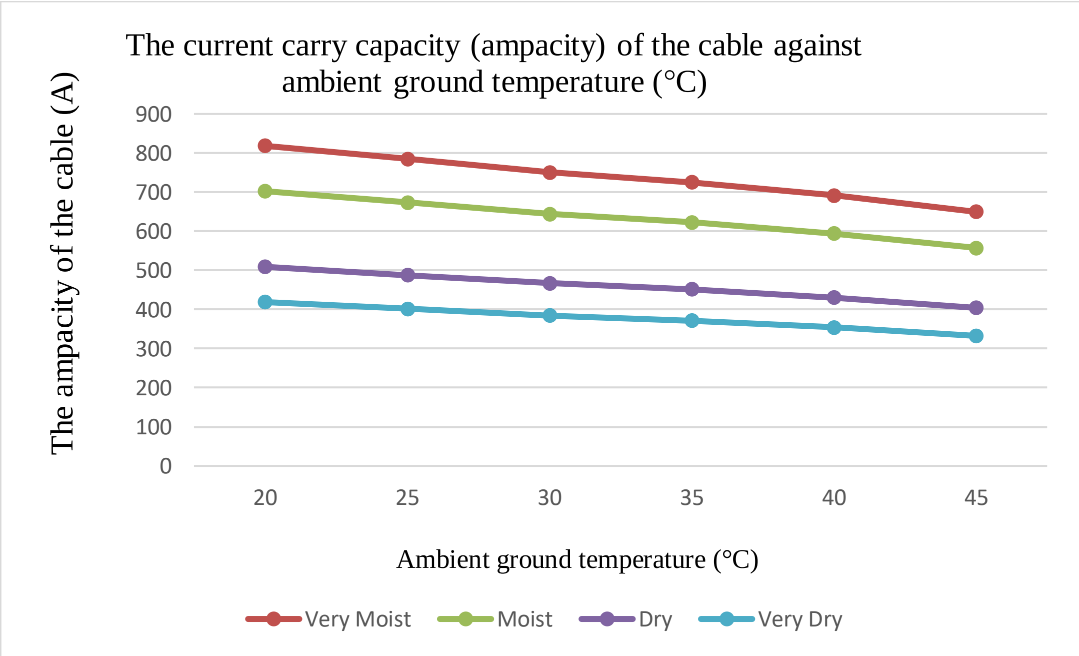


Figure 4.18: The Current carry capacity (Ampacity) of the cable at four different soil conditions was tabulated into one table.

Based on the Figure 4.18, the results of current carry capacity (Ampacity) of the cable at four different soil conditions by using thermal effect analysis.

4.3.2 Effect of thermal conductivity of different types of soil on underground power cables without current rating correction factors.

For this section, all the parameters and condition that was used are same as the **Section 4.3.1.** Except for this thermal analysis the current rating correction factor has been ignored and the current value that was used in this simulation test are the operating current value of the power cable from the data sheet which is $I_a = 685$A. This current rating was used to obtain the cables conductors operating temperature (°C) for all the four soil condition types which is Very Moist, Moist, Dry and Very Dry. Moreover, the ambient ground temperature was increased until the cables conductors operating temperature (°C) reach the maximum conductor temperature which is 90°C of the underground power cables (UPC) selected for this research.

4.3.2.1 Soil Moisturity (Very Moist)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under very moist soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 1.4
- The operating current rating, $I_a = 685$A
- The ambient ground temperature from 20°C to 60°C increased with every 5°C.

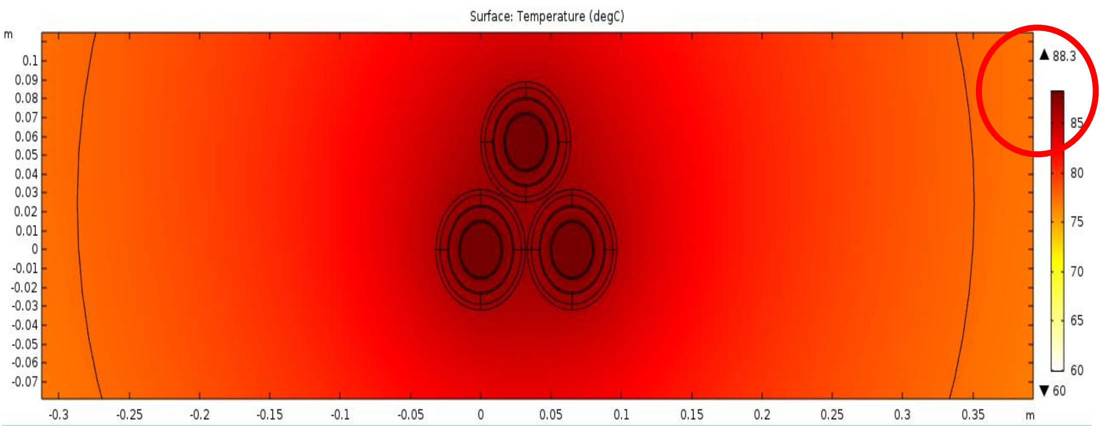


Figure 4.19: The operating temperature on underground power cables (UPC) under very moist soil condition (Zoom in view).

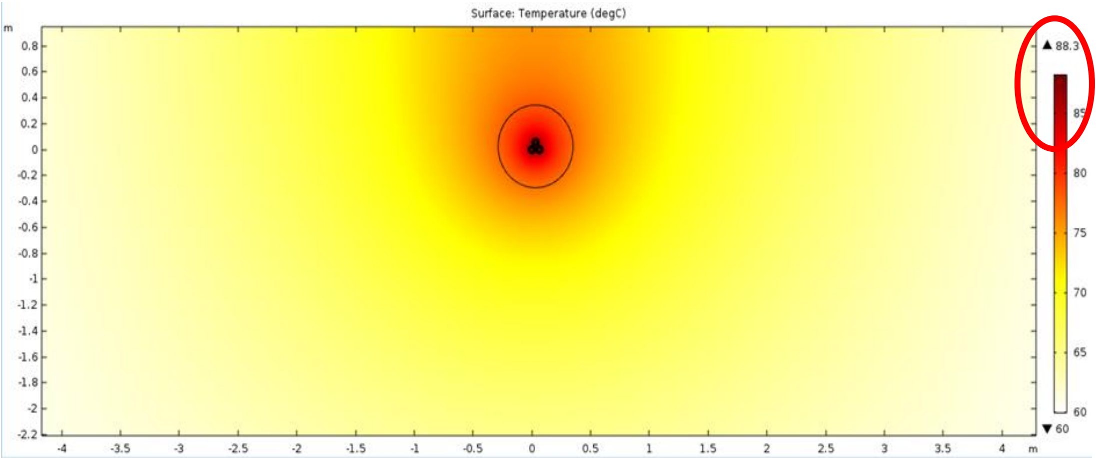


Figure 4.20: The operating temperature on underground power cables (UPC) under very moist soil condition (Zoom out view).

Based on Figure 4.19 and 4.20, one of the nine simulated results of operating temperature on underground cables (UPC) under very moist soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 88.3°C with the ambient ground temperature was set at 60°C.

Ambient Ground Temperature (°C)	Cable current rating (A)	Cable Conductor Temperature(°C)
20	685	48.3
25	685	53.3
30	685	58.3
35	685	63.3
40	685	68.3
45	685	73.3
50	685	78.3
55	685	83.3
60	685	88.3

Table 4.14: The Cable Conductor Temperature (°C) of Very Moist Soil Condition

Based on Table 4.14, the ambient ground temperature was increased from 20°C to 60°C and the operating cable current rating, I_a = 685A. The operating cables conductor temperature has increase from 48.3°C to 88.3°C respectively to the ambient ground temperature and cable current rating of the UPC. In this result, the operating cable conductor temperature which is 88.3°C value has reach close to the maximum conductor temperature which is 90°C.

4.3.2.2 Soil Moisturity (Moist)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under moist soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 1
- The operating current rating, $I_a = 685$A
- The ambient ground temperature from 20°C to 50°C increased with every 5°C.

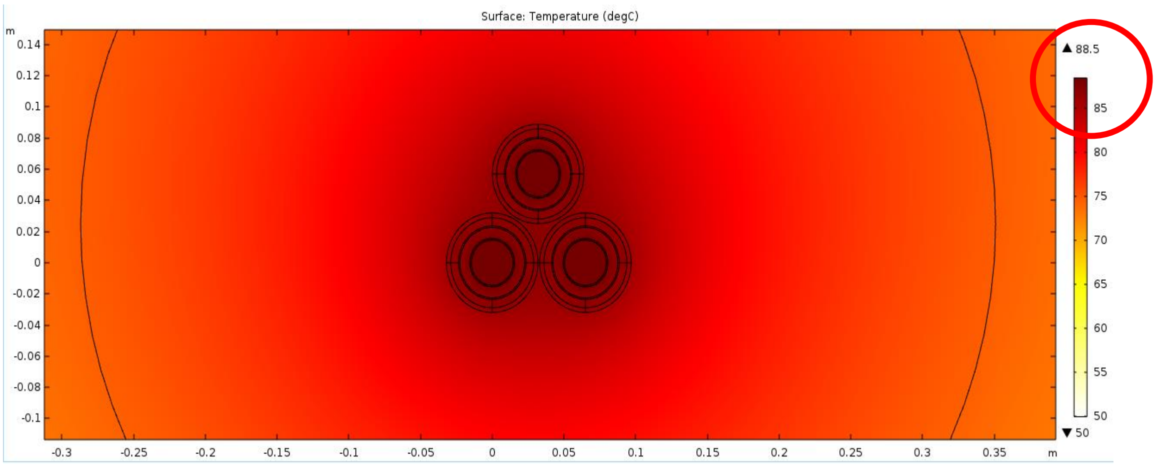


Figure 4.21: The operating temperature on underground power cables (UPC) under moist soil condition (Zoom in view).

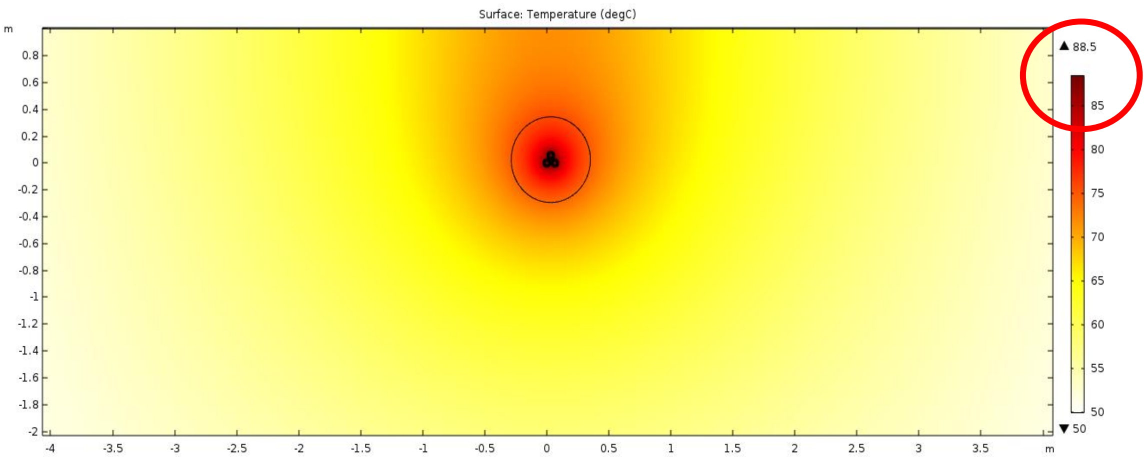


Figure 4.22: The operating temperature on underground power cables (UPC) under moist soil condition (Zoom out view).

Based on Figure 4.21 and 4.22, one of the seven simulated results of operating temperature on underground cables (UPC) under moist soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 88.5°C with the ambient ground temperature was set at 50°C.

Ambient Ground Temperature (°C)	Cable current rating (A)	Cable Conductor Temperature(°C)
20	685	58.5
25	685	63.5
30	685	68.5
35	685	73.5
40	685	78.5
45	685	83.5
50	685	88.5

Table 4.15: The Cable Conductor Temperature (°C) of Moist Soil Condition

Based on Table 4.15, the ambient ground temperature was increased from 20°C to 50°C and the operating cable current rating, I_a = 685A. The operating cables conductor temperature has increase from 58.5°C to 88.5°C respectively to the ambient ground temperature and cable current rating of the UPC. In this result, the operating cable conductor temperature which is 88.5°C value has reach close to the maximum conductor temperature which is 90°C.

4.3.2.3 Soil Moisturity (Dry)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under dry soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 0.5
- The operating current rating, $I_a = 685$A
- The ambient ground temperature from 20°C to 45°C increased with every 5°C.

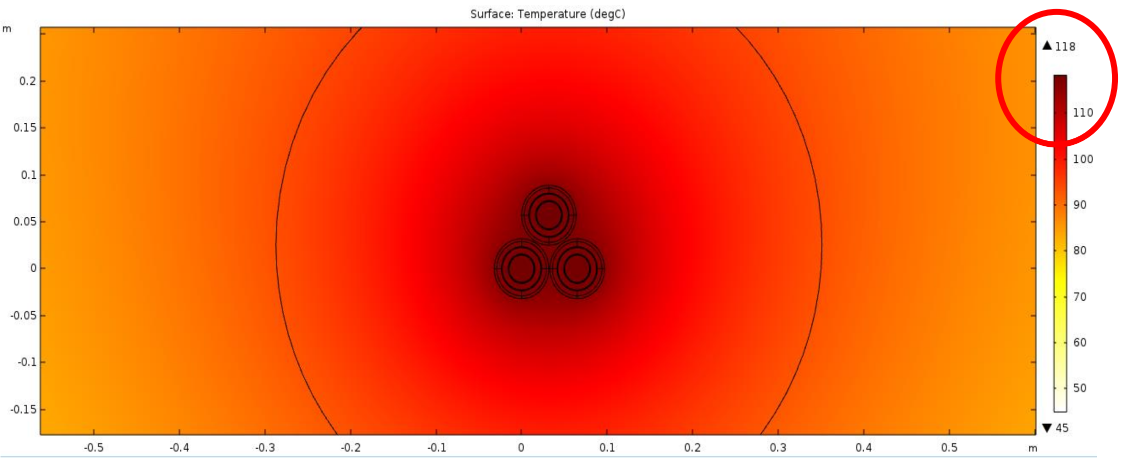


Figure 4.23: The operating temperature on underground power cables (UPC) under dry soil condition (Zoom in view).

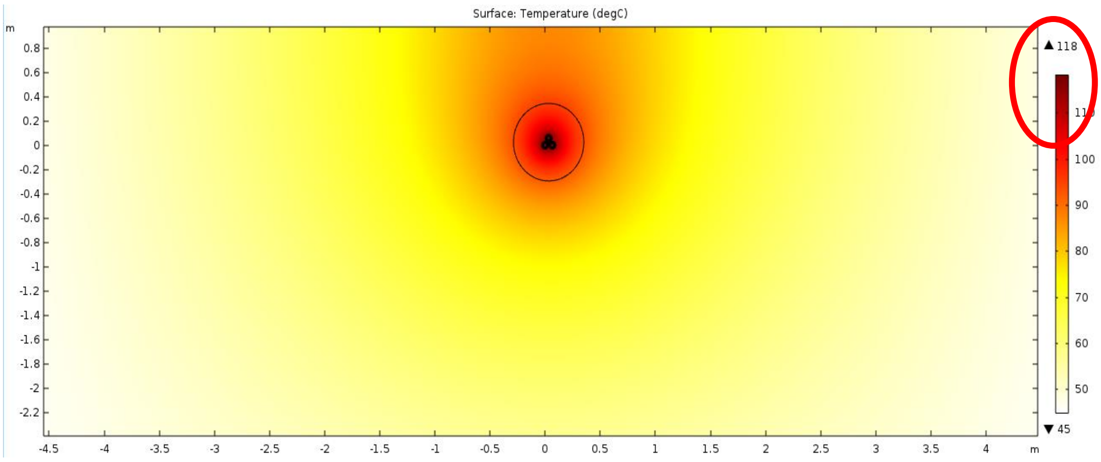


Figure 4.24: The operating temperature on underground power cables (UPC) under dry soil condition (Zoom out view).

Based on Figure 4.23 and 4.24, one of the six simulated results of operating temperature on underground cables (UPC) under dry soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 118°C with the ambient ground temperature was set at 45°C.

Ambient Ground Temperature (°C)	Cable current rating (A)	Cable Conductor Temperature(°C)
20	685	93.5
25	685	98.5
30	685	103
35	685	108
40	685	113
45	685	118

Table 4.16: The Cable Conductor Temperature (°C) of Dry Soil Condition

Based on Table 4.16, the ambient ground temperature was increased from 20°C to 45°C and the operating cable current rating, I_a = 685A. The operating cables conductor temperature has increase from 93.5°C to 118°C respectively to the ambient ground temperature and cable current rating of the UPC. In this result, the operating cable conductor temperature which is 118°C has cross the limit of maximum conductor temperature which is 90°C at the ambient ground temperature which is 45°C.

4.3.2.4 Soil Moisturity (Very Dry)

The parameters that are considered to simulate the thermal effect on underground power cables (UPC) under very dry soil condition such as:

- Soil Thermal Conductivity (W/K.m) = 0.3
- The operating current rating, $I_a = 685$A
- The ambient ground temperature from 20°C to 45°C increased with every 5°C.

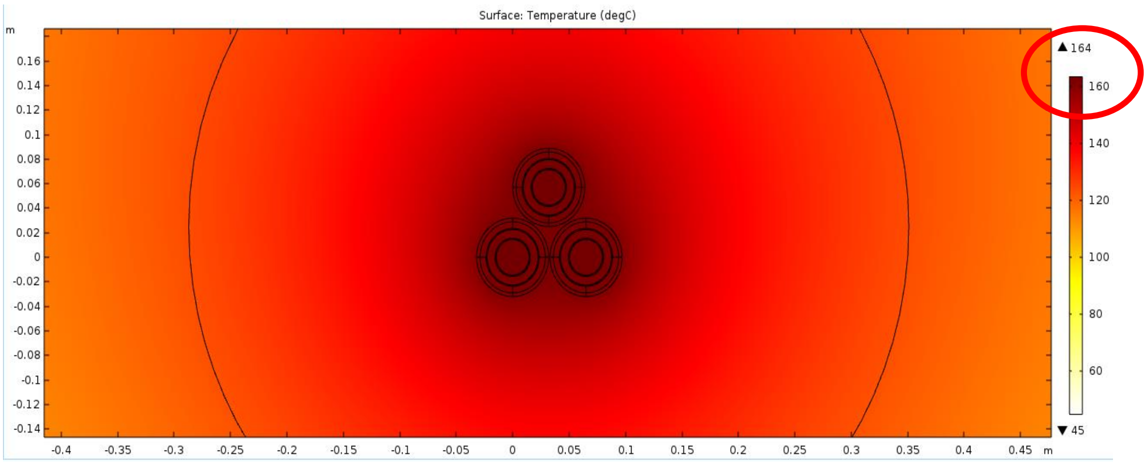


Figure 4.25: The operating temperature on underground power cables (UPC) under very dry soil condition (Zoom in view).

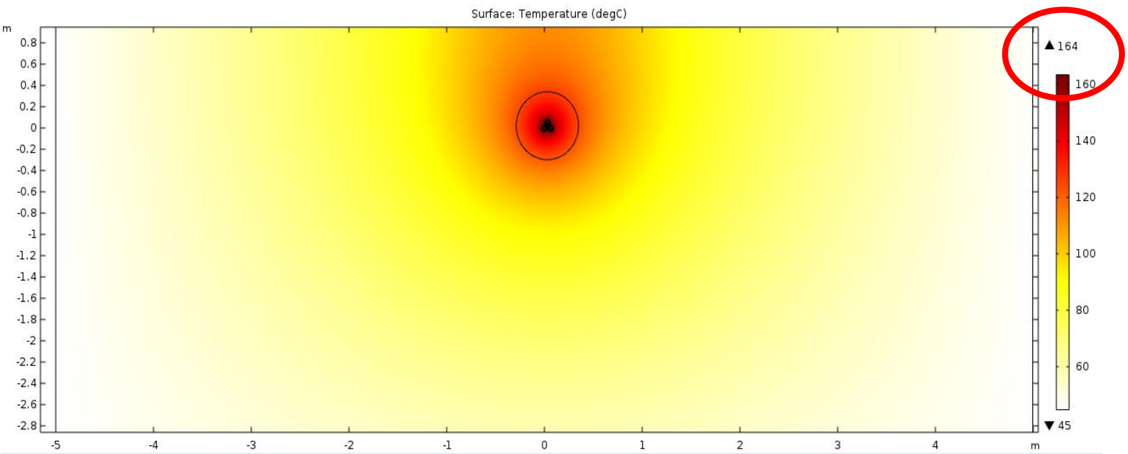


Figure 4.26: The operating temperature on underground power cables (UPC) under very dry soil condition (Zoom out view).

Based on Figure 4.25 and 4.26, one of the six simulated results of operating temperature on underground cables (UPC) under very dry soil condition. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is operating temperature of the cables conductor at 164°C with the ambient ground temperature was set at 45°C.

Ambient Ground Temperature (°C)	Cable current rating (A)	Cable Conductor Temperature(°C)
20	685	139
25	685	144
30	685	149
35	685	154
40	685	159
45	685	164

Table 4.17: The Result of Cable Conductor Temperature (°C) of Very Dry Soil Condition

Based on Table 4.17, the ambient ground temperature was increased from 20°C to 45°C and the operating cable current rating, I_a = 685A. The operating cables conductor temperature has increase from 139°C to 164°C respectively to the ambient ground temperature and cable current rating of the UPC. In this result, the operating cable conductor temperature which is 164°C has cross the limit of maximum conductor temperature which is 90°C at the ambient ground temperature which is 45°C.

Ambient Ground Temperature(°C)	Operating cable conductor temperature (°C) at different soil conditions			
	Very Moist	Moist	Dry	Very Dry
20	48.3	58.5	93.5	139
25	53.3	63.5	98.5	144
30	58.3	68.5	103	149
35	63.3	73.5	108	154
40	68.3	78.5	113	159
45	73.3	83.5	118	164
50	78.3	88.5	-	-
55	83.3	-	-	-
60	88.3	-	-	-

Table 4.18: The operating cable conductor temperature (°C) at four different soil conditions was tabulated into one table.

Based on Table 4.18, the results of operating cable conductor temperature (°C) at four different soil conditions without current rating correction factors was tabulated into one table.

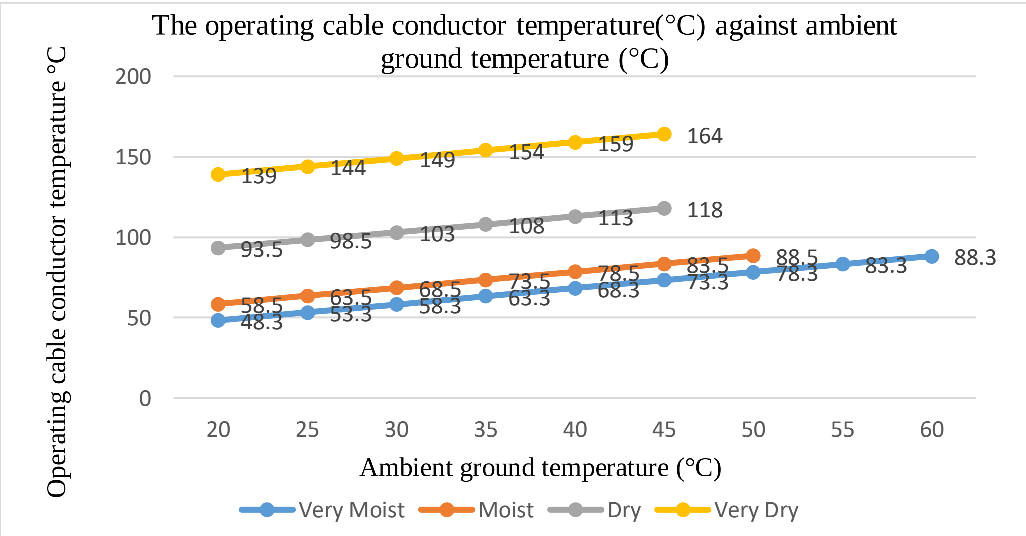


Figure 4.27: The operating cable conductor temperature (°C) at four different soil conditions without current rating correction factors

Based on the Figure 4.27, it shows the results of operating cable conductor temperature (°C) without current rating correction factors at four different soil conditions by using thermal effect analysis.

4.3.3 The discussion on the effect of thermal conductivity of different types of soil on underground power cables with and without current rating correction factors.

Throughout the research work, the designed **'33kV Single Core 630mm² Al Underground Power Cable'** was used to obtain the outcomes of the effect of thermal conductivity of different types of soil on underground power cables with and without current rating correction factors by using the heat transfer procedure as mentioned before. The performance of the cables with different thermal conductivity of the soil condition and the current carry capacity of the cable with and without current correction factor are shown in Table 4.19 and 4.20.

Ambient Ground Temperature(°C)	Operating cable conductor temperature (°C) and the ampacity at different soil conditions with correction factor							
	Very Moist		Moist		Dry		Very Dry	
	(A)	(°C)	(A)	(°C)	(A)	(°C)	(A)	(°C)
20	818.5	60.5	702.52	60.5	509.17	60.6	418.94	64.5
25	784.78	62.2	673.55	62.2	488.17	62.3	401.66	65.9
30	751.03	64.1	644.58	64.1	467.17	64.2	384.38	67.5
35	725.71	66.8	622.86	66.8	451.4	66.9	371.43	70
40	691.96	68.9	593.89	68.9	430.43	69	354.15	71.8
45	649.77	70.5	557.67	70.5	404.18	70.6	332.56	73

Table 4.19: The operating cable conductor temperature (°C) and the ampacity at different soil conditions with correction factor

Based on the conducted simulation test, the UPC with current correction factor was included in the current carry capacity (Ampacity) which affects the operating temperature of the cable conductor to maintain under four types of soil condition with the surrounding of different ambient ground temperature as shown in Table 4.19. As from the results, it shows the UPC at the minimum ambient ground temperature of 20°C for the four soil types which are very moist, moist, dry and very dry, the temperature are 60.5°C, 60.5°C, 60.6°C and 64.5°C. In addition, the maximum ambient ground temperature of 45°C are 70.5°C, 70.5°C, 70.6°C and 73°C.

This proves that the given correction factors from the cable datasheet are to prevent the operating temperature of the cable to reach the maximum operating temperature of conductor which is 90°C from any circumstances. Basically, when more conductors of the cables are energized, there will be high rate of heat will be produced so the excessive amount of heat generated within the conductors are compensated by using the current rating correction factors.

Ambient Ground Temperature(°C)	**Operating cable conductor temperature (°C) and the ampacity at different soil conditions without correction factor**							
	Very Moist		Moist		Dry		Very Dry	
	(A)	(°C)	(A)	(°C)	(A)	(°C)	(A)	(°C)
20	685	48.3	685	58.5	685	93.5	685	139
25	685	53.3	685	63.5	685	98.5	685	144
30	685	58.3	685	68.5	685	103	685	149
35	685	63.3	685	73.5	685	108	685	154
40	685	68.3	685	78.5	685	113	685	159
45	685	73.3	685	83.5	685	118	685	164

Table 4.20: The operating cable conductor temperature (°C) and the ampacity at different soil conditions without correction factor

After that, a second test was conducted on the UPC without including current rating correction factor and the current was fixed at 685A as shown in Table 4.20. This affects the operating temperature of the cable conductor to increase for the dry and very dry soil condition to extremely high by crossing the limit of the maximum conductor temperature of the cable with different ambient ground temperature. As from the result, it shows that the UPC at the minimum ambient ground temperature at 20°C for dry and very dry soil type, the temperature are 93.5°C and 139°C. In addition, the maximum ambient ground temperature at 45°C are 118°C and 164°C. Besides that, the operating temperature of cable conductor of the other two soil type very moist and moist are basically lower than the maximum temperature of the conductor at the minimum ambient ground temperature at 20°C, the operating cable conductor temperature are 48.3°C, 58.5°C and for maximum ambient ground temperature at 45°C, the operating cable conductor temperature are 73.3°C and 83.5°C.

This results shows that without implementing the correction factor into the cables, the operating temperature of the cable conductors will be affected by ambient ground temperature respectively with the soil thermal conductivity and soil resistivity. Since the soil thermal conductivity of the dry and very dry which is 0.5 W/K.m and 0.3 W/K.m, the heat from the operating cables will be dispersed slowly to surrounding ground so this will increase the temperature of the cable conductors. Basically, this are the main reasons behind where the cables temperature increases.

4.3.4 Effect of cable flat position on temperature distribution

For this section, the simulation test was conducted on designed Underground Power Cable (UPC) with the flat position, cable was buried under ground depth of 1 meter. The ambient ground temperature was fixed at 35°C. In addition, the current value that was used in this simulation test are the operating current value of the power cable from the data sheet which is $I_a = 685$A. This current rating was used to obtain the cables conductors operating temperature (°C) for the dry soil condition. Moreover, the current carrying capacity of the centre cable was decreased in order reduce the operating temperature of the cable from the maximum the conductor current which is 90°C of the underground power cables (UPC) selected for this research.

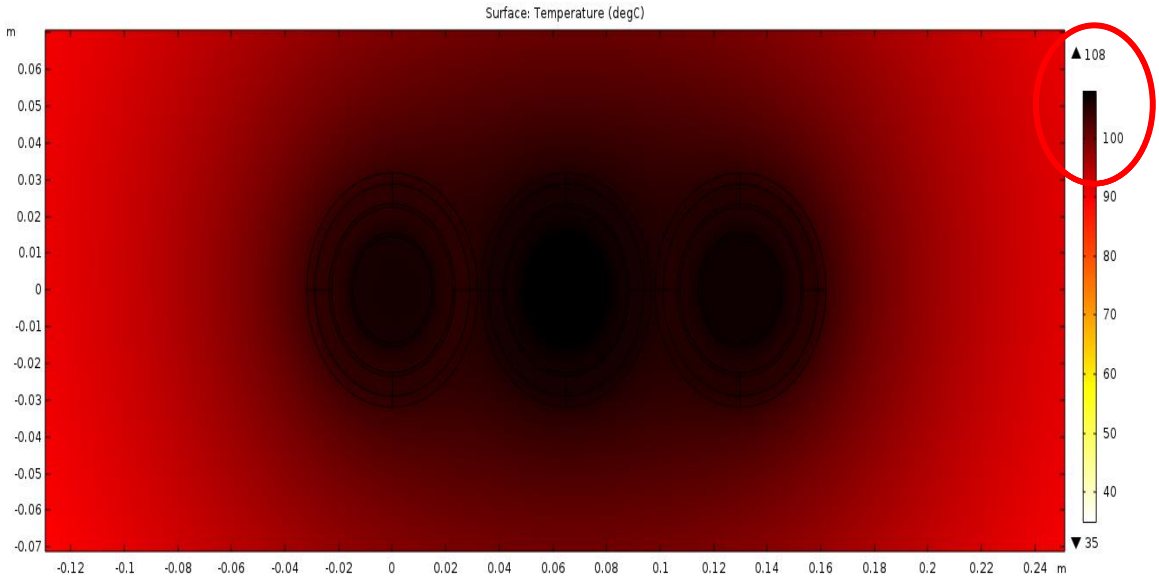


Figure 4.28: The operating temperature on underground power cables (UPC) in flat position under dry soil condition.

Based on Figure 4.28, one of the four simulated results of operating temperature on underground cables (UPC) in flat position under dry soil condition. Based on the thermal analysis, it shows that the centre cable conductor which more heated area in thermal black colour than other two cables and the operating temperature of the centre cables conductor at 108°C with the ambient ground temperature was set at 35°C. In fact, this result is not acceptable because the operating temperature around the three cables has to maintain around the same temperature and also should not exceed the maximum operating temperature of the cables conductor which is 90°C.

In order to solve this, the current carrying capacity of the centre cable was reduced from 685A to 412A and also without changing the current value of the other two cables. This has a great impact on the operating temperature of the conductor cable as shown in Table 4.21, where the temperature of the centre cable has drop from 108°C to 88.9°C and this also affects the other two cable to drop the temperature from 106°C to 88.8°C. In fact, now the operating temperature for the three cables are below the maximum operating temperature of the cables conductor which is 90°C. The result of these thermal effect analysis are shown in Figure 4.29.

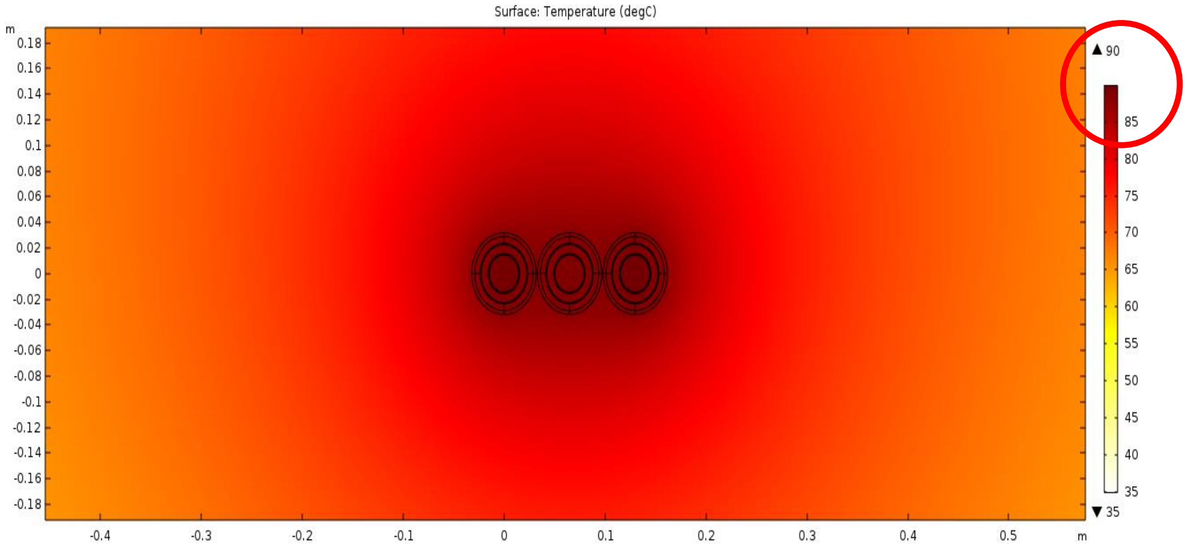


Figure 4.29: The operating temperature on underground power cables (UPC) in flat position after reducing the phase 2 cable ampacity under dry soil condition.

Ampacity (A)			Operating cable conductors temperature (°C)		
Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase3
685	685	685	106.4	108	106.3
685	645	685	103	104	103
685	565	685	99.2	100	99
685	412	685	88.8	88.9	88.8

Table 4.21: The Ampacity and Operating cable conductors' temperature (°C) of the three cables.

Based on the Table 4.21, the operating temperature of the centre cable exceed more than the other two cables because it was affected by the magnetic fields of the two other cables which was placed at two adjacent of sides of the cable as shown in Figure 4.28 and there was no contact between the first and the third cable. In addition, this can be the reason causing the operating temperature of the cable conductor to increase very high. Moreover, the soil condition are dry which will also make an impact in terms of soil conductivity which is low and the soil resistivity will be high, thus these causes slow heat dissipation to the soil surroundings from the cables. Therefore, these are main reasons the trefoil position are used so that the magnetic field and circulating currents are equivalent for each cable.

4.3.5 Effect of Water on Cable

In the conducted thermal analysis so far, the temperature distribution and current carrying capacity (Ampacity) of 33kV Single Core 630mm² XLPE Cable was simulated surrounded with different soil conditions. In this section, the water property was used as the backfilled for the UPC instead of soil, in order to obtain the temperature distribution and current carrying capacity. In this numerical model, it was assumed that the cable was immersed in water under depth of 1 metre. Basically, for the first part of the thermal analysis for this section, the operating temperature of the cable conductor was obtained by changing the water temperature. The current value that was used is the operating current value of the power cable from the data sheet which is $I_a = 685$A. The second part of the test is that the water temperature was fixed at 30°C and the result was obtained by changing ampacity of the cable.

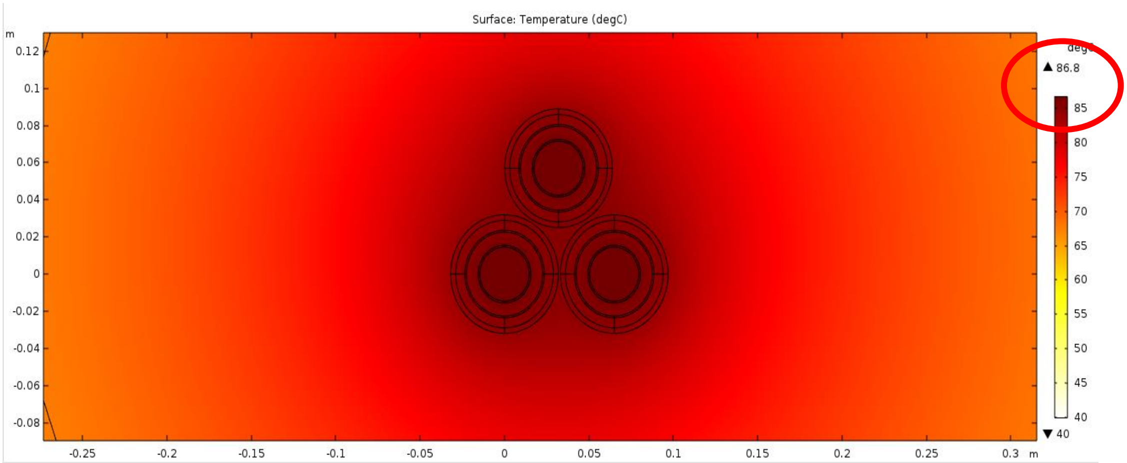


Figure 4.30: The operating temperature on underground power cables (UPC) in water by changing the water temperature.

Based on Figure 4.30, one of the five simulated results of operating temperature on underground power cables (UPC) in depth of 1 meter in water. On the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is the operating temperature of the cables conductor at 86.8°C with the water temperature was set at 40°C.

Water Temperature (°C)	Cable current rating (A)	Cable Conductor Temperature(°C)
20	685	68.4
25	685	72.9
30	685	77.5
35	685	82.1
40	685	86.8

Table 4.22: The Operating cable conductors' temperature (°C) in water by changing the water temperature.

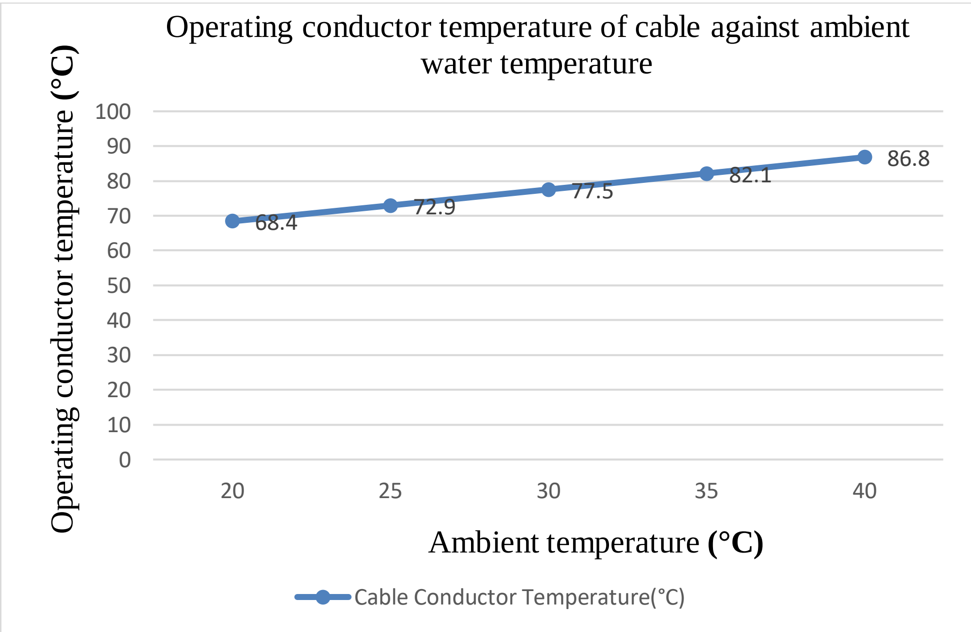


Figure 4.31: The Operating cable conductors' temperature (°C) in water by changing the water temperature.

Based on Table 4.22 and Figure 4.31, the ambient ground temperature was increased from 20°C to 40°C and the operating cable current rating, I_a = 685A. The operating cables conductor temperature has increase from 58.5°C to 88.5°C respectively to the water temperature and cable current rating of the UPC. In this result, the operating cable conductor temperature which is 86.8°C value has reach close to the maximum conductor temperature which is 90°C.

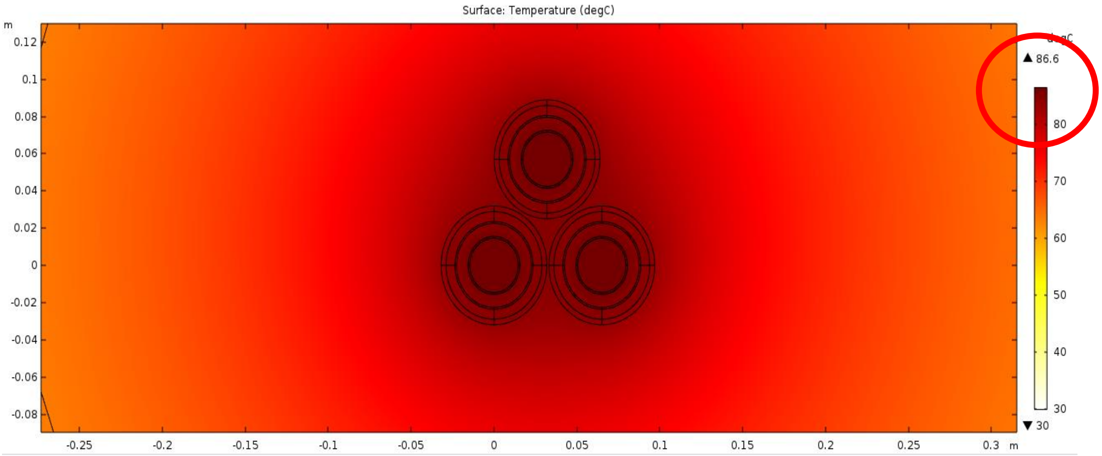


Figure 4.32: The operating temperature on underground power cables (UPC) in water by changing the ampacity.

Based on Figure 4.32, one of the six simulated results of operating temperature on underground power cables (UPC) in depth of 1 meter in water. Based on the thermal analysis, it shows that the most heated area on the cables are in thermal red colour, which is the operating temperature of the cables conductor at 86.6°C with the water temperature was set at 30°C.

Water Temperature (°C)	Cable current rating (A)	Cable Conductor Temperature(°C)
30	500	55.8
30	550	61
30	600	66.8
30	650	72.9
30	700	79.5
30	750	86.6

Table 4.23: The operating temperature on underground power cables (UPC) in water by changing the ampacity.

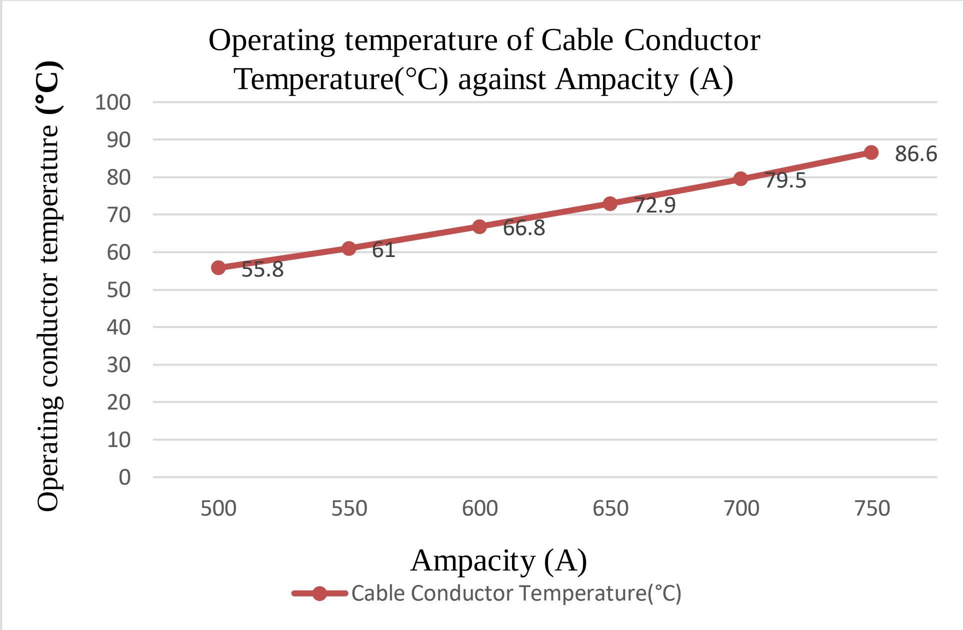


Figure 4.33: The operating temperature on underground power cables (UPC) in water by changing the ampacity.

Based on Table 4.23 and Figure 4.33, the water temperature was set at 30°C and the ampacity of the cable was increased from 500A to 750A. The operating cables conductor temperature has increase from 55.8°C to 86.6°C respectively to the water temperature and cable current rating of the UPC. In this result, the operating cable conductor temperature which is 86.6°C value has reach close to the maximum conductor temperature which is 90°C.

Basically, by comparing both simulation test result on the operating temperature of the cable conductor was obtained by changing the water temperature and current carrying capacity of the UPC which shows that the operating temperature of the cable conductor in water surrounding are higher than the soil surrounding. This factor can be experienced because the heat from the cables are dispersed slowly into the water surrounding than the soil surrounding. In fact, the thermal conductivity of the water can be one of the reason for the heating factor because it changes respectively with the water ambient temperature. Besides that, this selected 33kV XLPE Single Core Al 630mm² cable are not suitable to operate underwater. Basically, if there any deep damages occurs on the cable's PVC insulation, the water will flow into the cables which causes the temperature to rise and in result it will explode. In matter of fact, the most suitable cable to operate under water is the 'submarine cable' where it was specially made to carry the current in water surrounded area.

4.4 Summary

In brief, the thermal analysis was conducted on the "33kV Single Core 630mm² Al XLPE Cable. Firstly, the thermal effect on the single underground power cable (UPC) was studied and analysed by changing the buried depth of the cable thus laying the single core cable in depth of 1 meter will be the preferred depth for the cable than the 0.5 meter depth and this was proven by comparing the results of the operating cable conductor's temperature in two different depth. Secondly, the Trefoil position of UPC was studied and analysed in different soil condition, different ground ambient temperature and also with and without the current rating correction factor. In matter of fact, the given correction factors from the cable datasheet are to prevent the operating temperature of the cables from reaching the maximum conductor temperature which are 90°C. On the other hand, ignoring the correction factors from cables causes the operating temperature of the cable conductor to be affected by the ambient ground temperature respectively with the soil thermal conductivity and resistivity. Thirdly, the operating conductor temperature of UPC in flat position was studied and analysed by changing the ampacity of the cables thus the operating temperature of the centre cable exceed more than the other two cable because it was affected by the magnetic fields of the two other cables which was placed at two adjacent of sides of the cable. Finally, the operating conductor temperature of UPC in immersed in water was also studied and analysed. In fact, the operating temperature of the cable conductor was obtained by changing the water temperature and current carrying capacity of the UPC, which shows that the operating temperature of the cable conductor in water environment are higher than the of soil environment due to the heat from cable are slowly dispersed into the water surrounding than the soil surrounding due to the thermal conductivity of the water which can be the reason for the heating factor.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

In the nutshell, the purpose of this project has create a good progress on the combination section, succeeding the aim and objectives as stated in Section 1.3, which focused more on to designed and analysed the Thermal Effect on the Underground Power Cable, to do some studies on chosen 33KV Single Core 1x630mm² XLPE Cable, studied the FEM by using COMSOL software, studied the effect thermal conductivity of the soil condition on underground power cable (UPC), the cable laying position of the cables, effect of different burial depth of the cable and also studied the thermal effect on the cable by using water as surrounding material. The main purpose of this analysis was conducted in order to study and record the temperature distribution on the underground power cable (UPC) and also to determine the current passing through the cable with and without current rating correction factor. Through the reference and instruction accessible from online sources, learning and understand the COMSOL software, learn about the underground power cable were to a certain extent it's really challenging and lots of knowledge has been gain throughout the learning process.
In fact, by achieving all the aim and objective as stated in Section 1.3, there are number of benefits have been earned from this research such as:

- The effectiveness of using different material as backfill of the cable.
- The effect of laying the cable under the soil by choosing the best position of the cable.
- The operating temperature of the cable can be measured by using the software with sufficient information.
- The operating cable conductor temperature will be more stable by including the current rating correction factor.

5.2 Recommendations

In this project, there is room for improvements can make from this studies. Since, the finite element method (FEM) with the COMSOL software has been used to analyse and study the thermal effect on underground cable has been succeeded. The next step can be developed by using this knowledge is to study and analyse 'The Thermal Effect of Underground Cable Joints'. Usually, if the distribution line is more than 500 meters then there will be cable jointed for every 500 meters thus this will be very helpful to study the cause of the cable breakdown that occurs on the cable jointing part. Furthermore, the effect thermal conductivity of the soil condition on underground cable joints, the effect of cable joint position/arrangement, effect of different burial depth of the cable joint, immersed the cable joint under water can be studied and analysed by using the FEM with the COMSOL software.

REFERENCES

ANIXER. (2018). Retrieved from Copper vs. Aluminum Conductors: https://www.anixter.com/en_uk/resources/literature/wire-wisdom/copper-vs-aluminum-conductors.html [Accessed 11 April 2019].

BSE Border States-Supply Chain Solutions. (2014, May 29). Retrieved from Copper vs. Aluminum Cable and Copper Coatings: Their Best Use Cases: https://solutions.borderstates.com/copper-vs-aluminum-cable-and-copper-coatings-their-best-use-cases/ [Accessed 11 April 2019].

Edvard. (2010, December 12). *EEP-Electrical Engineering Portal*. Retrieved from Sheilding of Power Cables: https://electrical-engineering-portal.com/shielding-of-power-cables [Accessed 11 April 2019].

Edvard. (2014, November 12). *EEP-Electrical Engineering Portal*. Retrieved from Characteristics of XLPE insulated cables: https://electrical-engineering-portal.com/characteristics-of-xlpe-insulated-cables-with-reference-to-the-uk-standards [Accessed 11 April 2019].

ELAND CABLES. (2019). Retrieved from WHAT ARE THE BENEFITS OF PVC INSULATED CABLES?: https://www.elandcables.com/the-cable-lab/faqs/faq-what-are-the-benefits-of-pvc-insulated-cables [Accessed 11 April 2019].

Hwang, C. C. (2003). "Extensions to the finite element method for thermal. *Elsevier Electric Power Systems Research*, 159-164.

Igwe, O. E. (2016). Cable Sizing and Its Effect on Thermal and Ampacity Values in Underground Power Distribution. *University of kentuky UKnowledge*, 43.

Kalenderli, M. K. (n.d.). Coupled Electrical and Thermal Analysis of Power Cables Using Finite Element Method. *Heat Transfer – Engineering Applications*, pp. 206-227.

Kocar, I. E. (2004). Thermal analysis for determination of current carrying capacityof PE and XLPE insulated power cables using finite element method. *IEEE MELECON*, 905-908.

Littmarck, S. (2015, NOVEMBER 20). *COMSOL*. Retrieved from COMSOL MODELING SOFTWARE: https://www.comsol.com/ [Accessed 11 April 2019].

M. Rasoulpoor, M. M. (2016). Electromagnetic and thermal analysis of undergroundpower solid-conductor cables under harmonic andunbalancing currents based on FEM. *Wiley*, 1-17 .

Monika Rerak, P. O. (2017). The effect of soil and cable backfill thermal conductivity on the. *E3S Web of Conferences WTiUE 201 6*, 1-5.

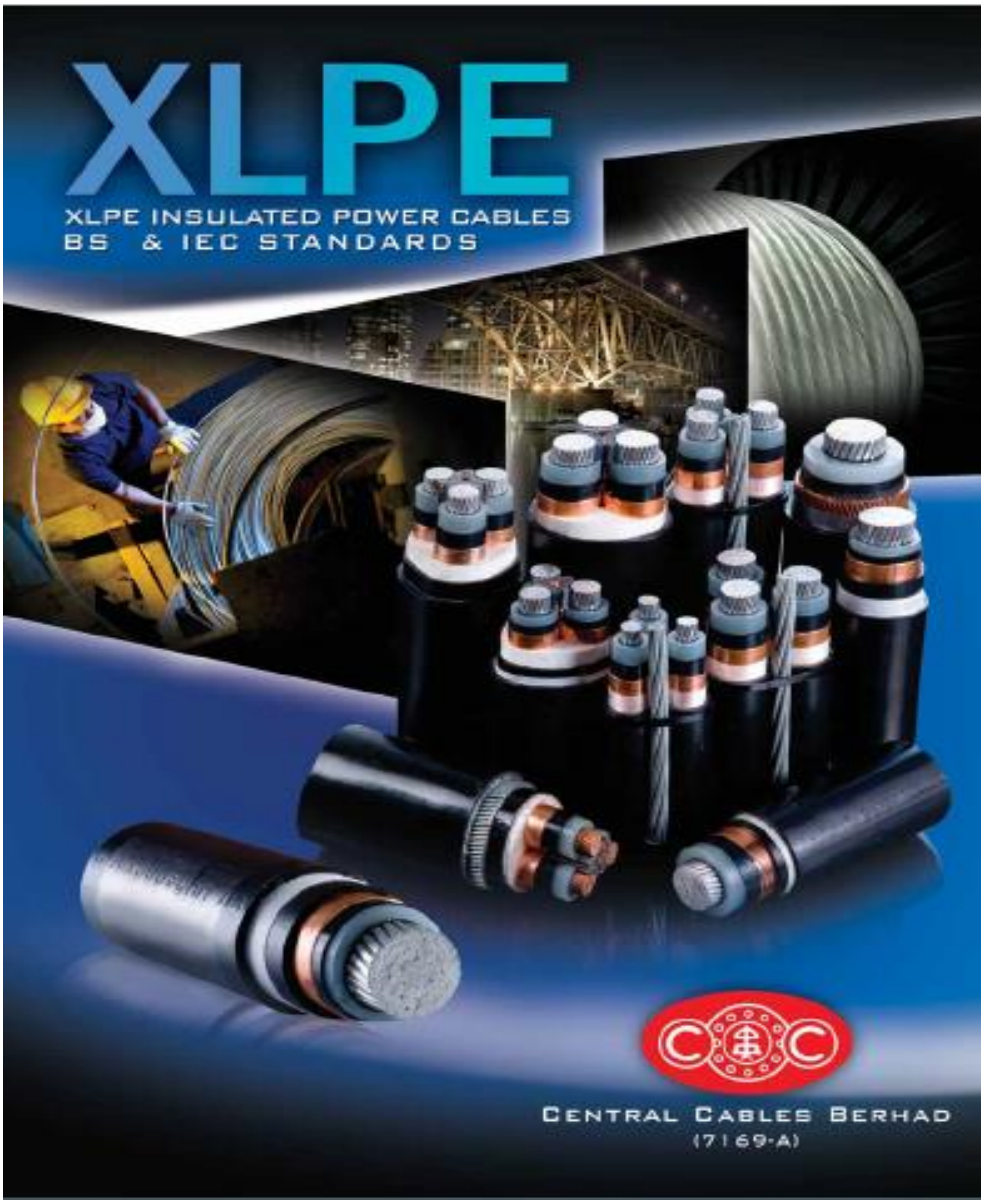
Murat Karahan, H. S. (2009). Thermal Analysis of Power Cables Using Finite Element Method and Current-carrying Capacity Evaluation. *International Journal of Engineering Education*, 2-7.

Parmar, J. (2016, April 7). *Electrical Notes & Articles*. Retrieved from Cable Construction & Cable Selection- Part:1: https://electricalnotes.wordpress.com/2016/04/07/cable-construction-cable-selection-part1/ [Accessed 11 April 2019].

Tedas (Turkish Electrical Power Distribution Inc.). (2005). *Assembly (application) principlesand guidelines for power cables in the electrical power distribution networks.* Retrieved from istanbul.meteor.gov.tr/marmaraiklimi.htm

APPENDICES

APPENDIX A: XLPE INSULATED POWER & IEC STANDARDS (CENTRAL CABLES BERHAD (7169-A)



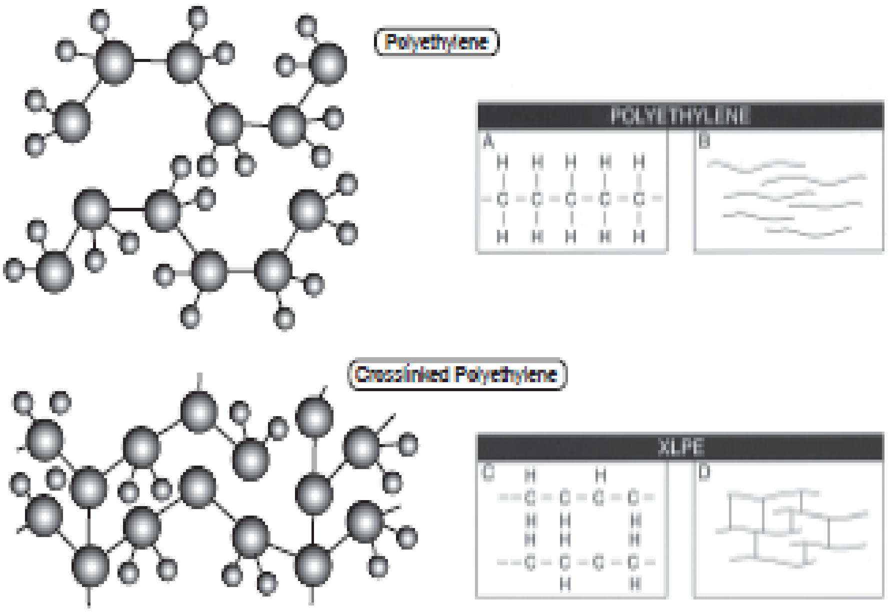
WHAT IS XLPE?

XLPE is an abbreviated designation of "cross-linked polyethylene". Polyethylene has a linear molecular structure as shown in A. Molecules of polyethylene not chemically bonded as shown in B are easily deformed at high temperature, while XLPE molecules bonded in a three dimensional network as shown in C and D, have strong resistance to deformation even at high temperatures.

Cross linked polyethylene is produced from polyethylene under high pressure with organic peroxides as additives. The application of heat and pressure is used to effect the cross linking. This causes the individual molecular chains to link with one another which in turn causes the material to change from a thermoplastic to an elastic material.

An important advantage of XLPE as insulation for medium and high voltage cables is their low dielectric loss. The dielectric loss factor is about one decimal power lower than that of paper insulated cables and about two decimal powers lower than that of PVC-insulated cables. Since the dielectric constant is also more favourable, the mutual capacitance of XLPE cables is also lower, thus reducing the charging currents and earth-leakage currents in networks without the rigid star-point earthing.

Structure of PE and XLPE



XLPE INSULATED ARMOURED SHEATHED CABLE 19/33 (36)kV

SINGLE CORE - AL / XLPE / CTS / PVC / AWA / PVC SHEATHED CABLE DIMENSION

Nominal cross-sectional area of conductor	Nominal diameter of conductor	Nominal insulation thickness	Metallic screening	Nominal thickness of separation sheath	Armouring wire diameter	Nominal thickness of PVC outer sheath	Approximate overall diameter	Standard packing length
			Nominal thickness of copper tape					
mm²	mm	mm	mm	mm	mm	mm	mm	m/drum
50	8.2	8.0	0.1	1.2	2.0	2.2	38.4	1000
70	9.8	8.0	0.1	1.2	2.0	2.2	40.1	1000
95	11.6	8.0	0.1	1.2	2.0	2.3	42.0	1000
120	13.0	8.0	0.1	1.2	2.0	2.3	43.4	1000
150	14.4	8.0	0.1	1.3	2.5	2.4	46.2	1000
185	16.2	8.0	0.1	1.3	2.5	2.5	48.2	1000
240	18.5	8.0	0.1	1.3	2.5	2.6	50.7	1000
300	20.7	8.0	0.1	1.4	2.5	2.5	53.1	1000
400	23.5	8.0	0.1	1.4	2.5	2.7	56.1	1000
500	26.5	8.0	0.1	1.5	2.5	2.8	59.6	1000
630	30.1	8.0	0.1	1.6	2.5	3.0	63.8	500

SINGLE CORE - AL / XLPE / CTS / PVC / AWA / PVC SHEATHED CABLE ELECTRICAL PROPERTIES

Nominal cross-sectional area of conductor	Maximum current rating per cable*			Maximum 3 phase voltage drop	Minimum charging current	Positive & negative sequence impedance at 25°C*	Zero sequence impedance at 25°C*
	Buried direct in ground	In single-way PE duct in ground	In tray in air (indoor)				
	Trefoil	Trefoil	Trefoil				
mm²	A	A	A	mV/A/m	A/km	ohm/km	ohm/km
50	171	162	205	1.451	0.7030	0.6541 + j0.1609	3.6312 + j0.0949
70	209	198	254	1.017	0.7859	0.4522 + j0.1492	3.2258 + j0.0842
95	250	236	308	0.752	0.8705	0.3268 + j0.1420	2.9698 + j0.0778
120	284	268	354	0.610	0.9841	0.2585 + j0.1359	2.7805 + j0.0725
150	318	301	402	0.513	1.0076	0.2107 + j0.1334	2.6258 + j0.0688
185	359	340	461	0.428	1.0901	0.1680 + j0.1288	2.4623 + j0.0648
240	415	392	542	0.351	1.2007	0.1285 + j0.1231	2.2775 + j0.0600
300	467	441	618	0.304	1.3031	0.1033 + j0.1189	2.1325 + j0.0565
400	533	501	717	0.265	1.4313	0.0812 + j0.1145	1.9770 + j0.0529
500	606	568	831	0.236	1.5736	0.0641 + j0.1105	1.8304 + j0.0496
630	685	638	956	0.215	1.7392	0.0510 + j0.1068	1.6864 + j0.0464

*Note : Electrical properties are calculated base on conditions in appendix B.

APPENDIX B
TECHNICAL DATA

(B) CURRENT RATING INFORMATIONS.

The Current rating of the cables given in the tables are based on the assumption shown below :

1) Maximum conductor temperature : -- 90°C

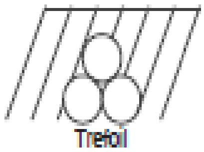
2) Ambient temperature : Ground -------------------------------- 15°C
Air ------------------------------------ 30°C

3) Soil thermal resistivity : -- 1.2 K.m/W

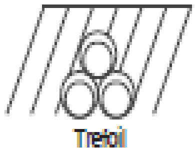
4) Laying depth in ground : -- 800mm

5) Screen bonding : Single core cables ------------------- Bonded at both ends
Three core cables ------------------- Single point or Cross-bonded

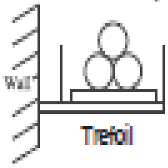
6) Installation method : 1 core cables in ground



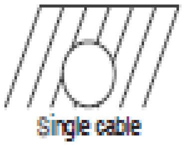
1 core cables in duct



: 1 core cables in tray in air

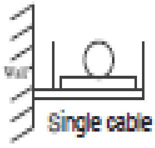


Multi-core cable in ground



: Multi-core cable in duct

Multi-core cable in tray in air



All the ratings for cables install in duct in ground are assumed to be polyethylene(PE) duct type having an inside diameter of 1.5 times the outside diameter of the cable and a wall thickness equal to 6% of the duct inside diameter. The ratings are based on the assumption that the ducts are air filled.

All the ratings for cables install in tray in air are calculated for indoor use only without any solar radiation taken into account. The cables are assumed to be spaced at least 0.5 times the cable diameter for single core cables and 0.8 times the cable diameter for three-core cables from any vertical surface such as wall and installed in non-magnetic cable tray.

All the rating shown in the tables are calculated base on single circuit and maximum current flowing in one conductor.

APPENDIX C
TECHNICAL DATA

(C) CURRENT RATING CORRECTION FACTORS.

Table 1 Correction factors for ambient air temperatures.

Maximum conductor temperature °C	Ambient air temperature °C							
	20	25	30	35	40	45	50	55
90	1.08	1.04	1.00	0.96	0.91	0.87	0.82	0.76

Table 2 Correction factors for ambient ground temperatures.

Maximum conductor temperature °C	Ambient ground temperature °C							
	10	15	20	25	30	35	40	45
90	1.03	1.00	0.97	0.93	0.89	0.86	0.82	0.77

Table 3 Correction factors for depth laying for direct buried cables.

Depth laying m	Single-core cables Nominal conductor size mm²		Three-core cables
	≤ 185 mm²	> 185 mm²	
0.50	1.04	1.06	1.04
0.60	1.02	1.04	1.03
0.80	1.00	1.00	1.00
1.00	0.98	0.97	0.98
1.25	0.96	0.95	0.96
1.50	0.95	0.93	0.95
1.75	0.94	0.91	0.94
2.00	0.93	0.90	0.93
2.50	0.91	0.88	0.91
3.00	0.90	0.86	0.90

Table 4 Correction factors for depth laying for cables in duct in ground.

Depth laying m	Single-core cables Nominal conductor size mm²		Three-core cables
	≤ 185 mm²	> 185 mm²	
0.50	1.04	1.05	1.03
0.60	1.02	1.03	1.02
0.80	1.00	1.00	1.00
1.00	0.98	0.97	0.99
1.25	0.96	0.95	0.97
1.50	0.95	0.93	0.96
1.75	0.94	0.92	0.95
2.00	0.93	0.91	0.94
2.50	0.91	0.89	0.93
3.00	0.90	0.88	0.92

APPENDIX C
TECHNICAL DATA

(C) CURRENT RATING CORRECTION FACTORS.

Table 5 Correction factors for soil thermal resistivities for direct buried single-core cables.

Nominal area of conductor mm²	Values of soil thermal resistivity K.m/W — Moist ← → Dry								
	0.7	0.8	0.9	1.0	1.2	1.5	2.0	2.5	3.0
≤ 16	1.23	1.17	1.12	1.07	1.00	0.91	0.80	0.73	0.67
25	1.24	1.18	1.12	1.07	1.00	0.91	0.80	0.73	0.67
35	1.24	1.18	1.12	1.07	1.00	0.91	0.80	0.72	0.66
50	1.25	1.18	1.13	1.08	1.00	0.91	0.80	0.72	0.66
70	1.25	1.19	1.13	1.08	1.00	0.91	0.80	0.72	0.66
95	1.25	1.19	1.13	1.08	1.00	0.91	0.79	0.72	0.66
120	1.26	1.19	1.13	1.08	1.00	0.91	0.79	0.72	0.66
150	1.26	1.19	1.13	1.08	1.00	0.91	0.79	0.71	0.66
185	1.26	1.19	1.13	1.08	1.00	0.90	0.79	0.71	0.65
240	1.26	1.20	1.13	1.08	1.00	0.90	0.79	0.71	0.65
300	1.27	1.20	1.14	1.08	1.00	0.90	0.79	0.71	0.65
400	1.27	1.20	1.14	1.09	1.00	0.90	0.79	0.71	0.65
500	1.27	1.20	1.14	1.09	1.00	0.90	0.79	0.71	0.65
630	1.27	1.20	1.14	1.09	1.00	0.90	0.79	0.71	0.65

Table 6 Correction factors for soil thermal resistivities single-core cables in buried ducts.

Nominal area of conductor mm²	Values of soil thermal resistivity K.m/W — Moist ← → Dry								
	0.7	0.8	0.9	1.0	1.2	1.5	2.0	2.5	3.0
≤ 16	1.14	1.10	1.08	1.04	1.00	0.92	0.82	0.76	0.70
25	1.15	1.11	1.08	1.04	1.00	0.92	0.82	0.76	0.70
35	1.15	1.11	1.08	1.04	1.00	0.92	0.82	0.75	0.69
50	1.16	1.11	1.08	1.05	1.00	0.92	0.82	0.75	0.69
70	1.16	1.12	1.08	1.05	1.00	0.92	0.82	0.75	0.69
95	1.16	1.12	1.08	1.05	1.00	0.92	0.81	0.75	0.69
120	1.17	1.12	1.08	1.05	1.00	0.92	0.81	0.75	0.69
150	1.17	1.12	1.08	1.05	1.00	0.92	0.81	0.74	0.69
185	1.17	1.12	1.08	1.05	1.00	0.91	0.81	0.74	0.68
240	1.17	1.13	1.08	1.05	1.00	0.91	0.81	0.74	0.68
300	1.18	1.13	1.09	1.05	1.00	0.91	0.81	0.74	0.68
400	1.18	1.13	1.09	1.06	1.00	0.91	0.81	0.74	0.68
500	1.18	1.13	1.09	1.06	1.00	0.91	0.81	0.74	0.68
630	1.18	1.13	1.09	1.06	1.00	0.91	0.81	0.74	0.68

Recommended value of soil thermal resistivities are as follows:

Peat / Clay / Chalk soil	1.2 K.m/W	Very dry soil	3.0 K.m/W
Very stony soil	1.5 K.m/W	Dry soil	2.0 K.m/W
Sandy soil	2.5 K.m/W	Moist soil	1.0 K.m/W

The value for the all soils category may be reduced to 1.2 K.m/W if the soil is under impermeable cover such as asphalt or concrete.