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ANALYSIS ON THREE-CORE LEAD-SHEATHED HVAC SUBMARINE CABLE WITH TWISTED MAGNETIC ARMOR BASED ON BONDING TYPES USING COMSOL MULTIPHYSICS

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ABSTRACT

As the appeal and stockpile of energy increases, the quest for natural energy becomes incredibly essential due to the rapid commercial growth of several developing countries worldwide. The three-core lead sheathed XLPE HVAC submarine cable became very familiar for the long transmission lines. However, it has some restrictions, such as the need for reactive power compensation and types of bonding used. This research is intended to demonstrate and discuss best practise in setting up models and running simulations on a three-core lead sheathed XLPE HVAC submarine cable on how the bonding types influenced the cable's ampacity. Submarine cable ampacity indicates the current-carrying capacity at the optimum working temperature in a steady-state condition, with the laying system and constant environmental exposure. Massive reactive power needs to be generated due to increased conductor capacitance, leading to higher cable current ratings, losses, and costly umbilical capacity. The bonding types must be considered when constructing the submarine cable because it is well-known to affect the power loss of the submarine power cables. The finite element method AC/DC used in this modelling of the submarine cable, which established respectively in the Comsol Multiphysics software to analyse the current build-up for various bonding types as well as the corresponding losses in the submarine cable screen. Based on the conducted simulation, the suitable type of bonding method used for the submarine power cable based on different lengths is the cross-bonding type. The charging current and losses per cable screen do not vary along the cable for each type of bonding type and its change with the cable length.

1.0 INTRODUCTION

The submarine three-core lead-sheathed XLPE HVAC submarine cable has played an essential role in the power system network because it transmits the power between countries and critical regions like bays, estuaries, and rivers [1]. There is a rising requirement for deep-water oil and gas production with the devaluation of existing oil and gas reserves, requiring long-distance power transmission and distribution from onshore power plants to numerous subsea electrical loads. A precise instrument is needed to simulate the complex physics and connections involved in three-core armoured cables as the experimental measurements and reconstruction of damaged submarine cables are expensive and only feasible for manufacturers [2]. Numerical models based on the finite element mechanism (FEM) used to construct the submarine power cable. The capacitance increase should not be neglected for long submarine cables. This capacitance is responsible for generating the reactive power, forcing the use of compensating equipment to prevent the occurrence of overvoltage and overcurrent problems [3].

The capacitive analysis is critical in the submarine power cable, which will be assumed to be compromised by the various bonding arrangements to assess power efficiency. Suppose the cable was

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constructed long enough, the cable's reactive power will take up the conductor's entire current-carrying capacity so that no operational power would be transmitted. Therefore, all these aspects must be considered during the design phase of the power supply system to allow verification of the technical feasibility of the HVAC transmission system [4]. The HVAC transmission poses problems for very long distances when issues inherent to AC systems depict significant effects, such as reactive power generation [3]. There are two basic types of cable, which are HVAC (High Voltage Alternating Current) and HVDC (High Voltage Direct Current) [5]. The transmitting distance is limited to HVAC cables, typically less than 80 km, whereas HVDC cables are used for longer distances and system interconnection [6].

However, with the increasing installed capacity and offshore distance, line loss of capacity and reactive power will be lager. By using simulation methods, it has been shown that for HVAC and HVDC offshore transmissions having the same capacity and distance, the efficiency of HVDC transmission is lower than for an HVAC system with the converter stations accounting for most of the additional loss [7]. Furthermore, AC transmission systems are far more manageable since paralleling multiple generators, voltage step-up and step-down for integration into national grid networks is much simpler. The three-core cables can be installed with HVAC submarine cable networks for transferring smaller volumes of three-phase electric electricity and all three shielded conductors are inserted into a single underwater cable [1]. The cable consists of core, sheath, armour and insulation, resulting in significant values of distributed capacitance, whose magnitude increases with the length [3]. The current-carrying conductors in submarine power cables are copper and aluminium. Compared to the current-carrying capacity, copper is more luxurious than aluminium, and most submarine power cables used copper conductors [7]. Copper makes a narrower cross-section and requires less material, such as lead and steel wires, for the outer layers. As the prices vary widely in a competitive metal market, there is no better option given. Aluminium's limited corrosion resistance is often cited in advance of copper for submarine power cables. Though seawater may induce corrosion of the conductor, the coating has already entered, and the cable must be fixed or exchanged, irrespective of the substance of the conductor [8].

Submarine cable ampacity refers to the current-carrying capacity at the optimum working temperature in a steady-state condition, with the laying system and constant environmental exposure. At present time, the ampacity of three-core armoured submarine cables is calculated according to IEC 60287. As problems inherent to AC systems reveal significant consequences, such as reactive electricity generation, the HVAC transmission presents issues for very long distances. The reactive power generated by submarine cables varies with the length of the cable [9]. The capacitance oversees producing reactive power, which involves the use of compensating equipment to avoid overvoltage and overcurrent problems from occurring [10]. The transmission potential of the HVAC system decreases with distance because of dielectric losses and reactive power.

For determining the cable's capacitive properties per phase in μF/km, oftentimes the analytical relation for coaxial capacitor is used in Eqn. 1 is given by:

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{In\left(\frac{R_2}{R_1}\right)} \tag{1}$$

where $\varepsilon_0\varepsilon_r$ refers to the insulator's permittivity, and R_1, R_2, refer to the insulator's outer, and inner radius, respectively. From the capacitance C and the applied voltage V_0, the charging current per phase in A/km can be derived as follows. In this case, the charging current I_C in A/km in Eqn. 2 is given by:

$$I_C = j\omega C V_0 \tag{2}$$

where C refers to the capacitance in μF/km, and V_0 to the phase-to-ground voltage of 127 kV. The value V_0 refers to the potential difference between the phase and the screen. Since the charging current barely depends on the screen voltage, it may be considered a constant and may follow reasoning where the currents are assumed to develop linearly along the cable’s length, reaching an upper limit at the bonded ends and the intersections. In addition, the current rises with the line capacitance, which is distributed along the cable. Therefore, the longer the length of the cable, the higher the charging current.

For protection purposes, submarine cable sheaths and armours are connected to the earth. For several bonding types, the build-up of charging currents and the screen's corresponding losses are analysed. IEEE

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Standard 575 introduces guidelines into the various methods of sheath bonding. The procedure for creating an electrical connection between the sheaths of cables is known as cable bonding. Such a sheath's electrical connection depends on the requirement whether performed at one end or both ends of the cable. Bonding techniques will influence power loss in submarine power cables, especially for the transmission of long-distance power [11]. The type of bonding used has a significant effect on waveforms [12]. Single-point bonding, solid bonding, and cross bonding methods are the three basic bonding methods presently in use, as shown in Fig.1 to 3, respectively.

In single-point bonding, it is bonded and connected to the ground at one end only, as shown in Fig. 1. Each screen is electrically paired in single-point bonding, with the same phase across the cable's entire length. The phase potential will force a constant charging current that accumulates inside the screen. The display currents build up linearly along the cable, reaching a maximum at the bonded end [13].

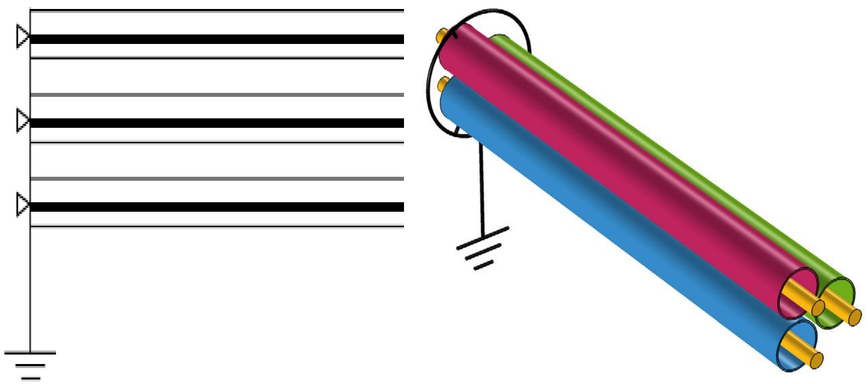

Fig. 1. Arrangement for single-point bonding

In solid bonding, each screen is bonded and connected to the ground at both ends, as shown in Fig. 2. The solid bonded cable can be considered two single-point bonded cables of half the total length, and floating ends meet in the middle. The screen currents will build up in both directions, starting from zero at the centre. The maximum screen potential will occur in the middle.

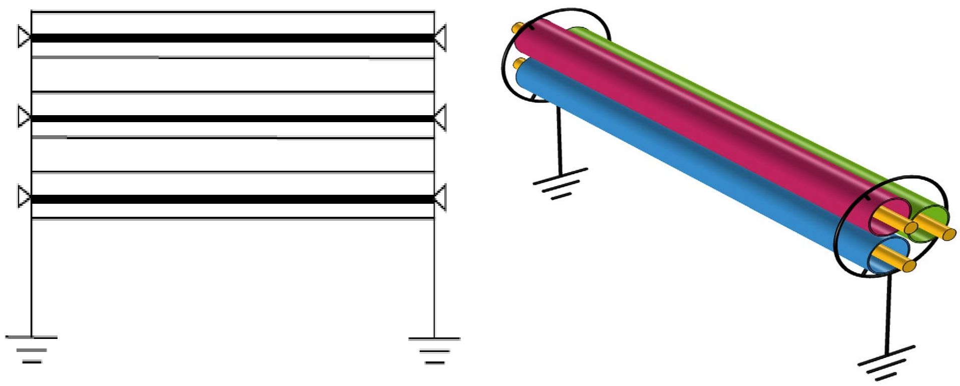

Fig. 2. Arrangement for solid bonding

In cross bonding, the total length of the cable is separated into three parts of equal size. From the electrical point of view, the screen is paired with a different phase for each section, as shown in Fig. 3. As the charging currents for the three sections show a 120° phase shift, it is not the norm of the screen current that will change linearly along the cable [14]. Since the currents at these three locations are 120° out of phase, the three points of maximum current form an equilateral triangle on the complex plane cantered around zero.

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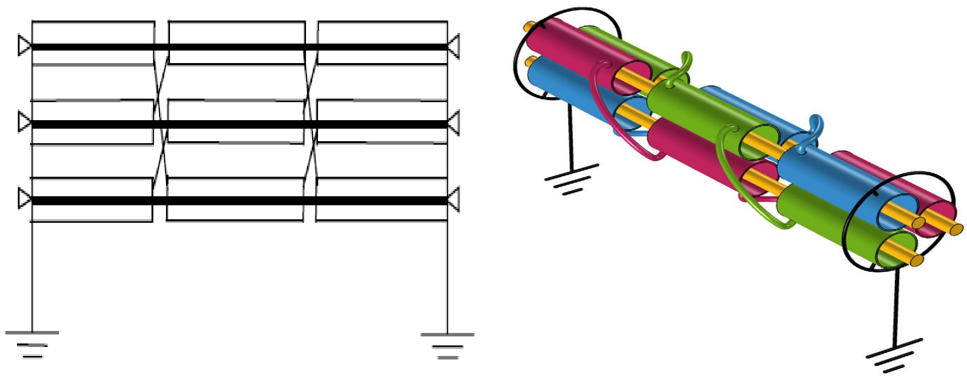

Fig. 3. Arrangement for cross bonding

Bonding types are known to influence power loss in the submarine power cable. Long-distance offshore power transmission needs to quantify the impact of capacitive in a power cable to determine power quality, which would be expected to be influenced by the different bonding arrangements and cable length. The cable impedances and admittances are dependent upon the method of bonding types being used. The cable will experience different induced voltages, circulating currents, frequency response, and harmonic resonances are depending upon the cable's bonding method [11].

2.0 MOTIVATION

Numerical analysis of cable systems is an active field of research. It is dominated not only by scientific knowledge but also by engineering experience and numerical consideration. A precise instrument is needed to simulate the complex physics and connections involved in three-core armoured cables as the experimental measurements and reconstruction of damaged submarine cables are expensive and only feasible for manufacturers [2]. Numerical models based on the finite element mechanism (FEM) will be used for this purpose. By using Comsol Multiphysics software, geometry handling, meshing, resolution, and post-processing are all achieved within the user-friendly desktop environment for the cable models. The capacitance increase should not be neglected for long submarine cables. This capacitance is responsible for generating the reactive power, forcing the use of compensating equipment to prevent the occurrence of overvoltage and overcurrent problems [3].

The cable capacity simulation measurement can be used as an essential guide before the test. The capacitive analysis is critical in the submarine power cable, which will be assumed to be compromised by the various bonding arrangements to assess power efficiency. The bonding type must be considered because it is well-known to affect the power loss of the submarine power cables. Suppose the cable was constructed long enough, the cable's reactive power will take up the conductor's entire current-carrying capacity so that no operational power would be transmitted. Therefore, during the design phase of the power supply system, several aspects must be considered to verify the technical feasibility of the HVAC transmission system [4].

3.0 METHODOLOGY

In this study, COMSOL Multiphysics software is used to design the geometry of single-phase HVAC submarine cable configuration to analyse the current build-up and maximum voltage potential for various bonding types as well as the corresponding losses in the submarine cable screen. This project starts with identifying problems related to the effectiveness of the HVAC submarine cable in transmitting power for long distances. To achieve the objectives, a study has been conducted to discover more about the suitable bonding arrangement for build the HVAC submarine cable. Comsol Multiphysics software used as the main software to demonstrate and model the cable's geometry for one phase. To solve the parameter and equation, Comsol Multiphysics software uses finite element analysis. Thus, sufficient knowledge about the software is required and needs to be explored.

This software includes the main important database to design a model: geometry, material, physic, study, and mesh sequence. Comsol Multiphysics is a simulation platform that encompasses all steps in the modelling workflow from the definition of geometry, material properties, study and physics that describe

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specific phenomena for the resolution and post-processing of models to produce accurate and reliable results. This software can simulate and analyses dynamic physics and relations involving three-core armoured cables, as laboratory measurements are expensive [15]. Its main purpose is to provide a suitable method for studying and designing three-core armoured cables and virtualise costly experimental configurations that allow essential data to be obtained earlier to help with the laboratory's accuracy tests [16].

In the initial steps of the software setup for Comsol Multiphysics, Model Wizard is chosen to set the space dimension, select the physics and the study type. The space dimension that is selected for the model component for the submarine cable is 2D Axisymmetric design, as shown in Fig. 4.

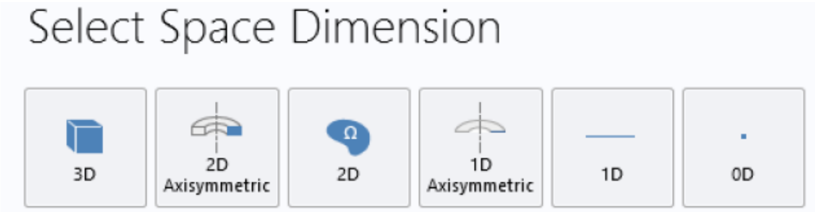

Fig. 4. GUI of the Comsol **multiphysics** software

Several physics contains specialized studies for specific functions. The present study types and other specialized studies available depend on the physics that is added. The physics database stores all physical and geometrical domains, and the user can specify the properties, as shown in Fig. 5. In this project, the submarine cable physics interface under AC/DC is selected to determine the electric currents.

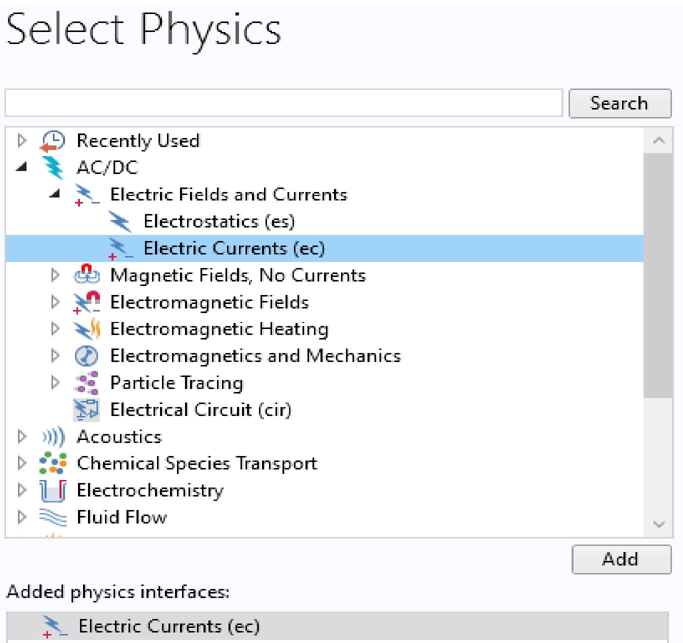

Fig. 5. GUI for physics database

When creating a model, the study must be included to compute it. The study mode automatically defines a simulation solution sequence based on selected physics and study type. The study used in this simulation is the frequency domain, as shown in Fig. 6. Frequency Domain physics interface, based on the electric field vector, solves the wave equation.

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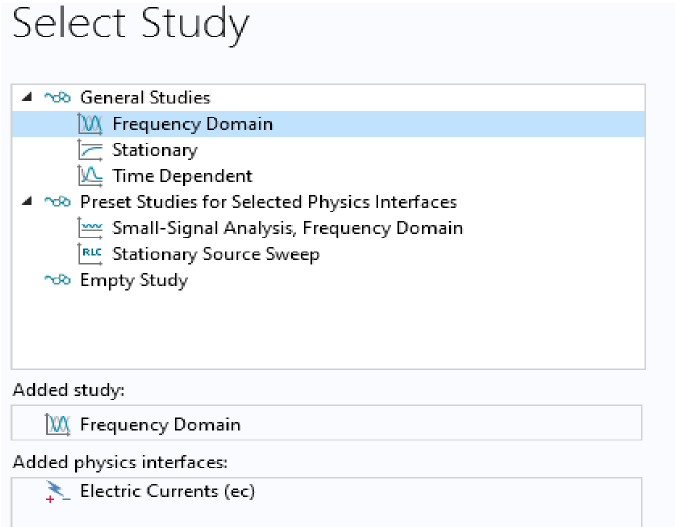

Fig. 6. GUI for study database

Table 1 shows the parameter setup for the single-phase HVAC submarine cable in the Comsol Multiphysics. The parameter of the submarine cable used is load from the library file in the Comsol Multiphysics software and it is the common parameter in the manufacture based on the International Electrotechnical Commission datasheet. It contains the geometric and electromagnetic parameters in constructing the submarine cable.

Table 1. Parameter of HVAC submarine cable

Parameters	Values
Diameter of main conductors (phase)	26.2 mm
Insulation thickness (XLPE)	24.0 mm
Diameter over insulation (XLPE and SCC)	77.6 mm
Semi-conductive compound thickness	0.85 mm
Lead sheath thickness	2.9 mm
Polyethylene sheath thickness	2.9 mm
Diameter over phase	89.2 mm
Diameter over three phases combined	65.3 mm
Diameter of fibre optic core	2.5 mm
Steel helix thickness (fibre)	0.5 mm
Diameter over fibre optic cable	9.2 mm
Outer diameter of submarine cable	219.0 mm
Central diameter of armour ring	142.2 mm
Armor thickness (wire diameter)	5.6 mm
Number of armour wires in ring	110
Filler margin	0.5 mm
Armor margin	4.3 mm
Cross sectional area of conductors	500 mm^2
Conductor packing density (phase)	0.93
Cross sectional area of lead sheath	733.4 mm^2
Relative length cross bonding section 1	1/3
Relative length cross bonding section 2	1/3
Relative length cross bonding section 3	1/3
Total length of submarine cable	10 km
Geometric scale factor (2Daxi model)	1e5
Operating frequency	50 Hz
Angular frequency	314.2 rad/s
Phase to ground voltage (amplitude)	127 kV
Rated current (amplitude)	926.3 A
Copper conductivity, at 20°C	5.96e7 S/m
Lead sheath conductivity, at 20°C	4.55e6 S/m

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Parameters	Values
Armor wire conductivity, at 20°C	4.03e6 S/m
Relative permeability, copper	1
Relative permeability, lead sheath	1
Relative permittivity XLPE	2.5
Capacitance per phase	0.17 μF/km
Charging current per phase	4.7 A/km

The geometric and electromagnetic parameters was added inside global definitions based on the Table 1. The geometry is simple, and it contains only one phase. Initially, the length unit is set to meter to use in fields for lengths and visualization of the geometry, and the angular unit is set to the degree. Two rectangles added in the geometry toolbar, as shown in Fig. 7. This geometry allows currents to circulate along the "tube" armour so that armour losses may be necessary.

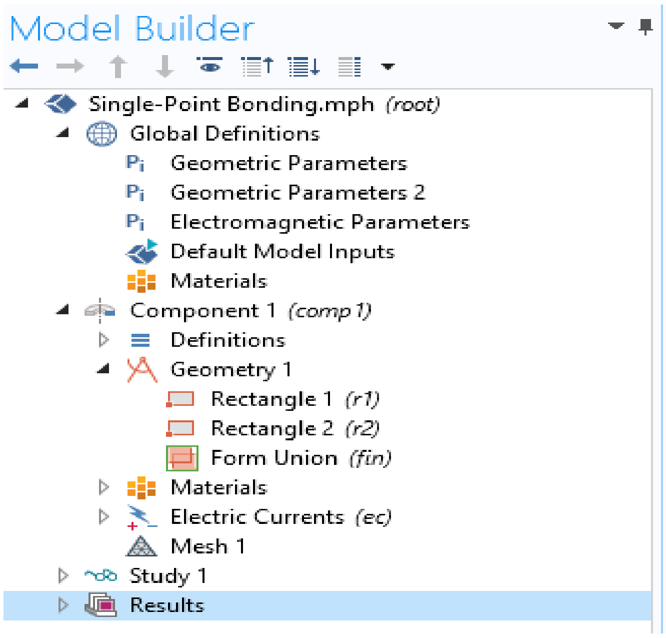

Fig. 7. Geometry database

The model contains the insulators and screen surrounding the main conductor for the one phase, as shown in Fig. 8. The yellow colour region is the screen of the conductor. The white colour shows the cross-linked polyethene (XLPE) of the cable, which acts as the insulator, the black colour is the semi-conductive compound, and the purple one is the lead sheath. Then, we set the arrangement and boundaries for modelling the cable by using single-point bonding, solid bonding, and cross bonding.

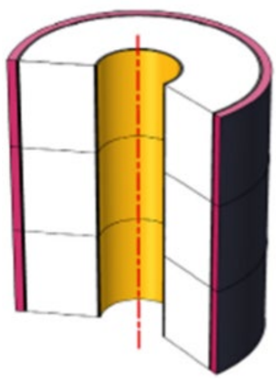

Fig. 8. The cable's 2D axisymmetric geometry

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In the model builder window, under component 1, the added materials are semi-conductive compound, cross-linked polyethene (XLPE), and lead, as shown in Fig. 9. Thus, all the submarine cable parameters and material properties for one phase are set up in the software.

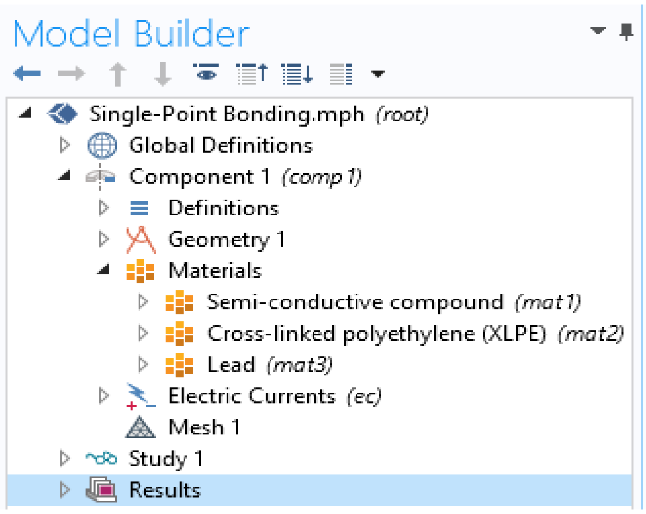

Fig. 9. Material database

Fig. 10 shows the 2D geometry of cable bonded and connected to the ground at one end only for the single-point bonding method. The model is simulated by applying a phase voltage to the innermost boundary. The screen is electrically paired with the same phase across the entire length of the cable.

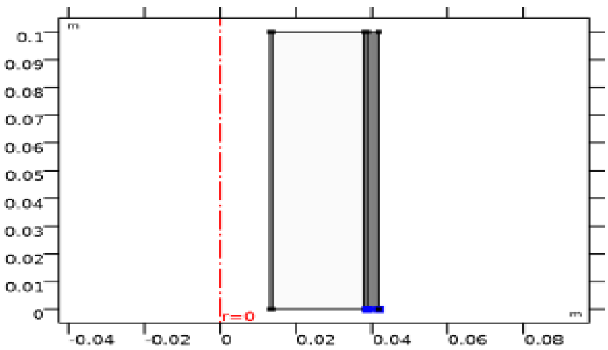

Fig. 10. 2D Geometry of single-point bonding method

Fig. 11 shows the 2D geometry of cable bonded and connected to the ground at both ended for the solid bonding method. The model is simulated by applying a phase voltage to the innermost boundary same as the single-point bonding method. The screen is electrically paired with the same phase across the entire length of the cable.

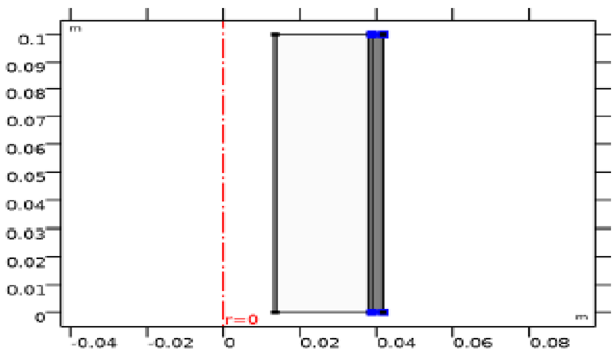

Fig. 11. 2D Geometry of solid bonding method

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Fig. 12 shows the 2D geometry of cable bonded and connected to the ground at both ends for the cross-bonding method. The cable is divided into three equal sections and applied a different phase potential to each of them. The model represents three separate phases.

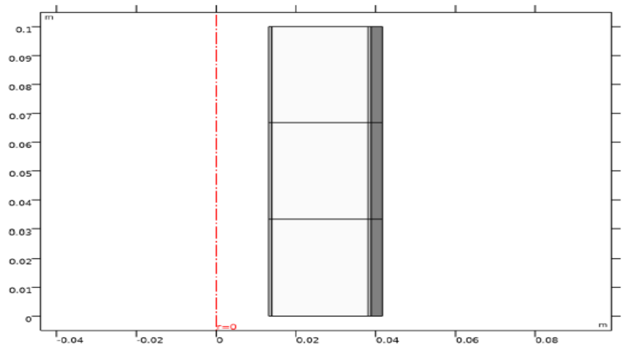

Fig. 12. Geometry of cross bonding method

The flow chart in Fig. 13 shows the steps for the model development of the study. This project starts with cable modelling by using the geometry parameters for different types of bonding. The physic features and materials properties are set up based on the geometry induced selections. The boundaries and the grounding of the cable set in the physic toolbar based on the three different types of bonding method, as shown in Fig. 10 to 12, respectively. The electric potential applied at the different phase based on the bonding method at the cable boundaries. Obtained graph plots based on the simulations to analyse the charging currents, maximum voltage potential, and corresponding losses in the cable using different cables for 10 km, 30 km, and 50 km. The simulation shows the impact of different types of bonding on different lengths. This study will determine the suitable type of bonding method used for the submarine power cable based on different lengths for good efficiency.

4.0 RESULTS AND DISCUSSION

The results that have been obtained based on the conducted simulation on the different types of bonding methods used for the different submarine cable lengths.

4.1 Charging Currents

A higher voltage rated cable would have a greater charging current and a shorter cut-off length for cables of the same ampacity [17]. The line charging current depends on the transmission frequency as the lower the frequency, the lower the charge's current. The phase potential will force a constant charging current that accumulates inside the screen [18]. The screen currents build up linearly along the cable, reaching a maximum at the bonded end for single-point bonding. At the floating end, the screen currents are zero, and the screen potential reaches a maximum. The maximum charging current through lead sheath (A) for single-point bonding as shown in Fig. 14 for 10 km length of the cable is about 55.00 A while for the 30 km length of cable is 167.00 A and for 50 km length of the cable is about 267.00 A. The maximum charging current occurs at the farthest point from the ground bond. The current carried in the cable proportional to the length of the cable.

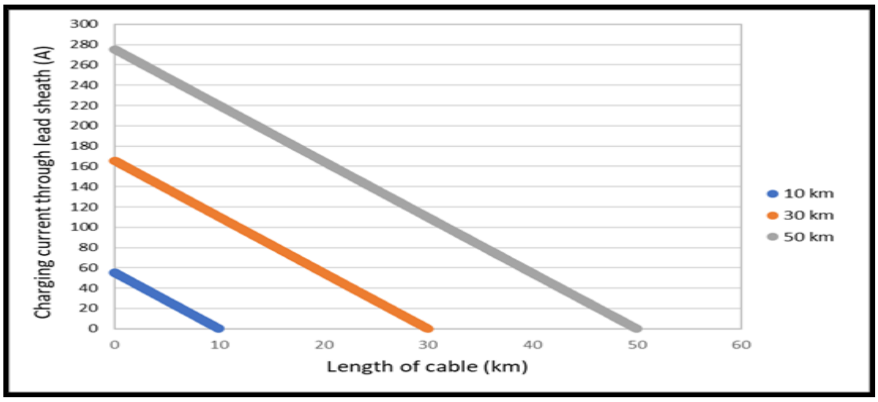

Fig. 13. Charging current through lead sheath (A) for single-point bonding

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The charging currents build up in both directions, starting from zero at the centre. At both ends, they reach a level that is one-half times the maximum screen current found for the single-point bonding configuration. The maximum charging current through lead sheath (A) for solid bonding as shown in Fig. 15 for 10 km length of the cable is about 27.60 A while for the 30 km length of cable is 83.00 A and for 50 km length of the cable is about 138.00 A. It provides a path for circulating current in the cable. The circulating current in the cable is proportional to the length of the cable and the magnitude of the load current.

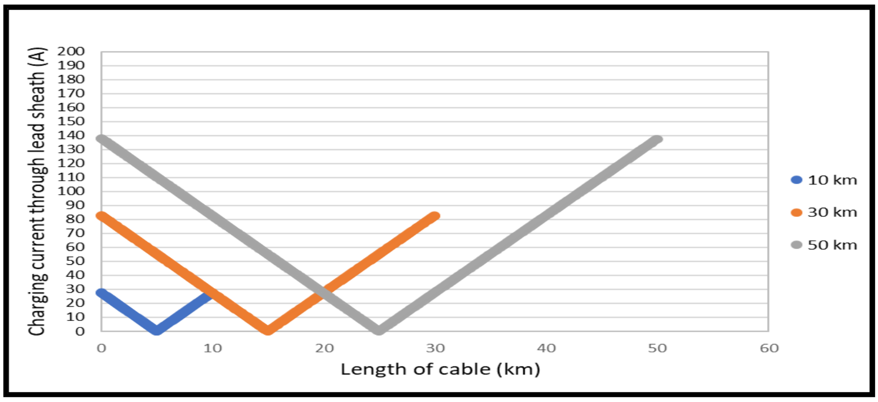

Fig. 14. Charging current through lead sheath (A) for solid bonding

As the charging currents for the three sections show a 120° phase shift, it is not the norm of the screen current that changes linearly along the cable. The charging current graph for the cross-bonding method formed three U shaped because the cable's geometry is modified by splitting the cable into three equal sections. The maximum charging current through lead sheath (A) for cross bonding as shown in Fig. 16 for 10 km length of the cable is about 10.70 A while the 30 km length of cable is 32.00 A and for 50 km length of the cable is about 53.20 A. This current occurs at the two intersections and the bonded ends.

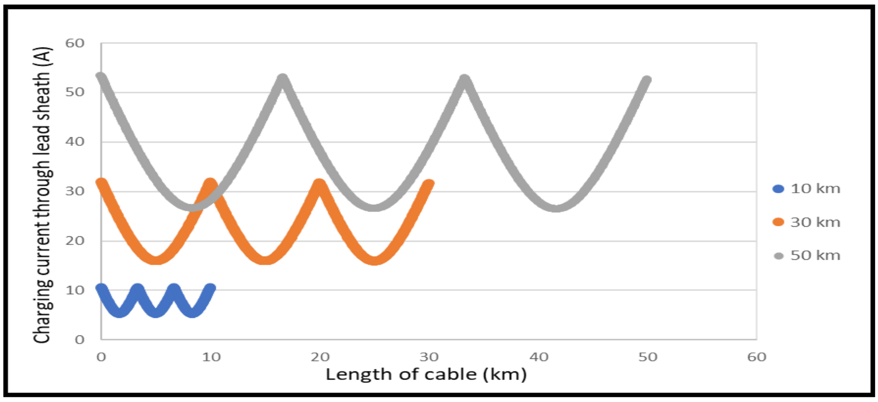

Fig. 15. Charging current through lead sheath (A) for cross bonding

The conducted simulation has concluded that the cross bonding has the lowest charging current compared with the single-point bonding and solid bonding method.

4.2 Maximum Voltage Potential

The magnitude of the standing voltage is depended on the magnitude of the current flows and the cable length. An induced voltage proportional to the length of the cable. In general, it accepted that the screen voltage potential limits the length. An analysis of the graph illustrates the voltage potential for the single-point bonding method formed zero volts with respect to the earth grid voltage at the earthed end, while the standing voltage at the unearthed end. The maximum voltage potential rise across lead sheath (V) for single-point bonding as shown in Fig. 17 for 10 km length of the cable is about 83.00 V while for the 30 km length of cable is about 745.00 V and for 50 km length of the cable is about 2060.00 V. If the cable screen is single point bonded, no electrical continuity and magnetic potential generate a voltage.

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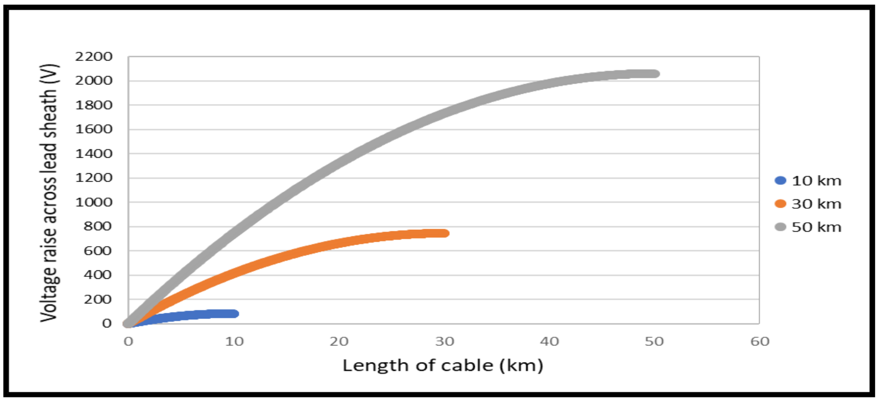

Fig. 16. Voltage raises across lead sheath (V) for single-point bonding

The voltage potential graph for the solid bonding method formed inverted U shaped because the cable was grounded at both ends. To eliminate the induced voltages in the cable screen is to bond the sheath at both ends of the cable circuit [19]. The maximum screen potential occurs in the middle. The maximum voltage potential rise across lead sheath (V) for solid bonding as shown in Fig. 18 for 10 km length of the cable is about 21.00 V while for the 30 km length of cable is about 185.00 V and for 50 km length of the cable is about 520.00 V.

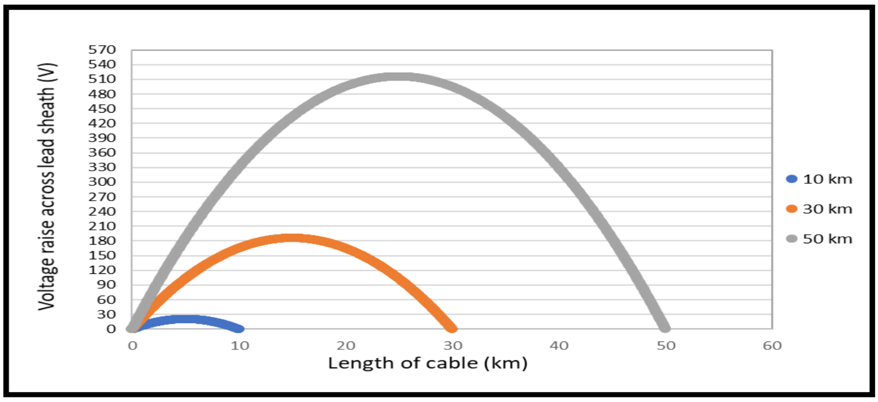

Fig. 17. Voltage raises across lead sheath (V) for solid bonding

The maximum induced voltage will appear at the link boxes for the cross-bonding method. The maximum voltage potential rise across lead sheath (V) for cross bonding as shown in Fig. 19 for 10 km length of the cable is about 6.90 V while for the 30 km length of cable is about 63.00 V and for 50 km length of the cable is about 172.00 V. The summation of the phase-shifted voltages reduces the overall induced voltage [20].

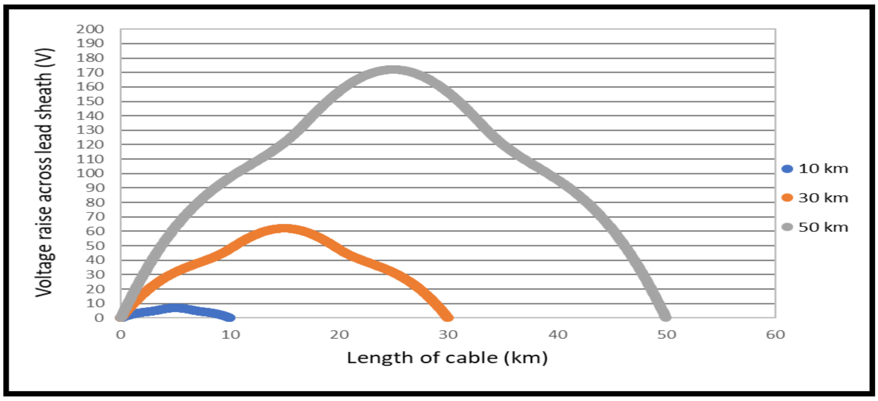

Fig. 18. Voltage raises across lead sheath (V) for cross bonding

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From the conducted simulation, it has been concluded that the Cross Bonding method has the lowest maximum voltage potential compared with the single-point bonding and solid bonding method from the simulation.

4.3 Total Losses Per Screen

The cable screen consists of an extruded layer of semiconducting compounds. Screen losses play a significant role as they are in the same order of magnitude as the losses in the conductors. The current flowing causes screen losses through a conductor. The total losses per phase in the conducted simulation shown about the value deviates from the analytical result due to scaling the r-component of the lead conductivity. The total losses per screen (W) for single-point bonding as shown in Fig. 20 for 10 km length of the cable is about 1531.20 W per screen while for the 30 km length of cable is about 41089.00 W per screen and for 50 km length of the cable is about 189030.00 W per screen. The total losses per screen are the highest for the 50 km cable.

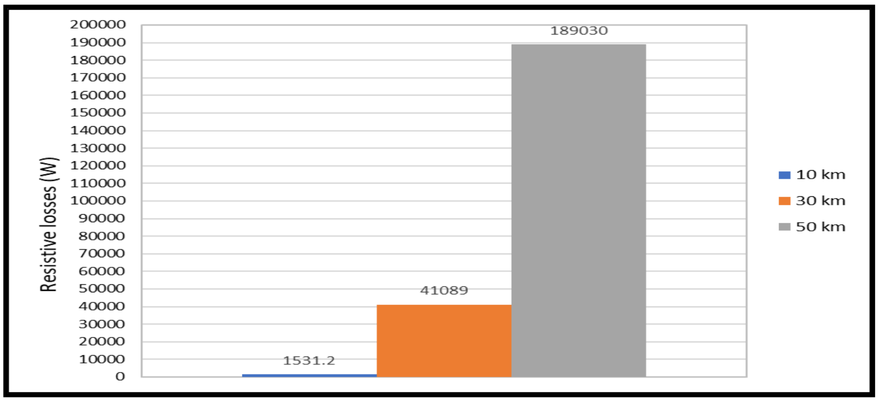

Fig. 19: Corresponding losses per screen (W) for single-point bonding

The total losses per screen (W) for solid bonding, as shown in Fig. 21, for 10 km length of the cable is about 383.04 W per screen, while for the 30 km length of cable is about 10291.00 W per screen and for 50 km length of the cable is about 47412.00 W per screen. The total losses per screen are the highest for the 50 km cable.

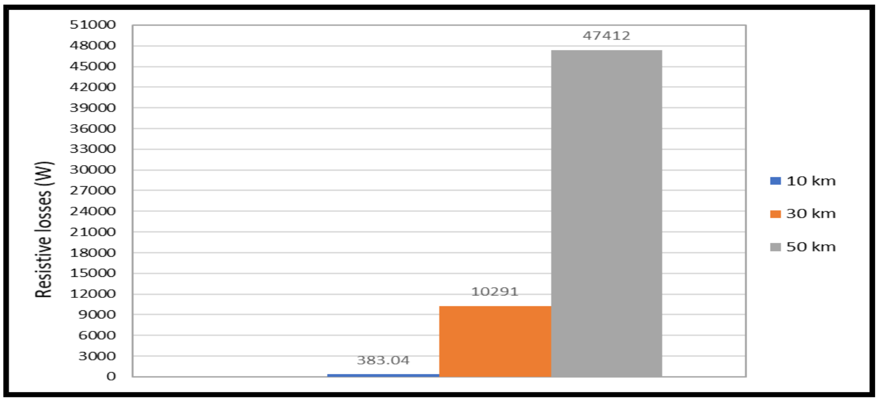

Fig. 20: Corresponding losses per screen (W) for solid bonding

The total losses per screen (W) for cross bonding, as shown in Fig. 22 for the 10 km length of the cable, is about 85.12 W per screen, while for the 30 km length of cable is about 2287.00 W per screen and for 50 km length of the cable is about 10536.00 W per screen. The losses per screen are the highest for the 50 km cable.

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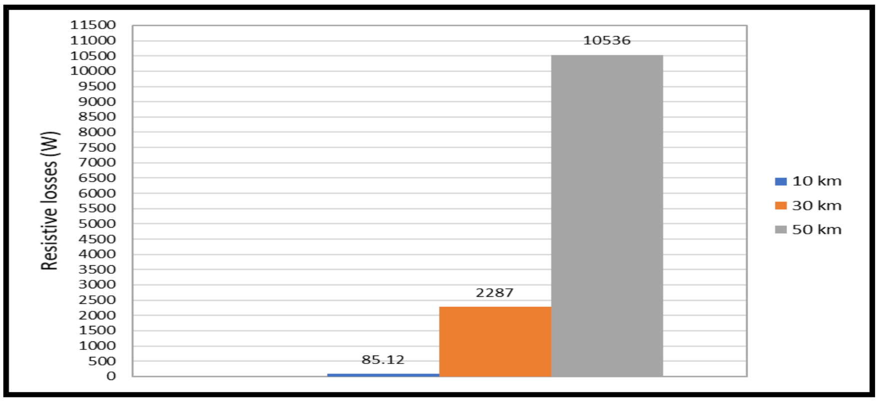

Fig. 21: Corresponding losses per screen (W) for cross bonding

From the conducted simulation, it has been concluded that the cross-bonding method has the lowest losses per screen compared with the single-point bonding and solid bonding method.

5.0 CONCLUSION

In conclusion, all objectives defined at the beginning of this project are achieved successfully. Based on the experiment that has been carried out, the design of the submarine cable is modelled and functioning properly using Comsol Multiphysics software. The type of bonding for cable is the most important things that should be considered when constructing a cable. The bonding methods affect the cable sheath circulating current and cable total losses. The simulation validates the assumption that the high phase potential induces a uniform charging current that barely depends on the screen potential and cable length. The simulation conducted shown that the cross-bonding method is the most effective method to be chosen when constructing the submarine cable for long distances rather than the single-point bonding and solid bonding method. The cross-bonding method has the lowest effect on the charging current, voltage potential, and losses per screen. Its accuracy is compared with experimental measurements and the International Electrotechnical Commission (IEC) standard. The results show a very good agreement between simulations and measurements. Upon completion of the project, there are some recommendations for future research to find better solutions. Firstly, the grounding method must be considered for designing a cable. If grounded at only one end, any possible fault current must traverse the length from the fault to the grounded end, imposing a high current on the usually very light shield conductor. Multiple grounding, rather than just grounding at both ends, is simply the grounding of the cable shield or sheath at all access points, such as manholes or pull boxes [21]. The multiple grounding also limits possible shield damage to only the faulted section, whether the cable shield should be grounded at both ends or only one end. Moreover, new materials and technological advancement of power system and material science technology need to be explored, promising significant advances in conductor and insulation materials in the future. This will bring a more effective tool for saving time and computational resources in cable design and developing new analytical expressions to improve the IEC standard. Advances in manufacturing technology would allow the development of longer and more efficient cables. As a result, longer distances and greater depths may be exploring.

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