https://doi.org/10.24191/jeesr.v24i1.002

Analysis of Underground Transmission Cable Ampacity for On-site Applications

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***Abstract*—Temperature poses a primary concern that must be addressed before installing power cables under the ground. This is due to the temperature increase at greater depths, which can impact the cable's ampacity. The higher the temperature, the higher the thermal resistance, resulting in a lower ampacity current being transmitted to the consumers, thus affecting electricity services. Therefore, this study aims to analyze the ampacity of underground transmission cables for on-site cable installation, considering different layout buried depths. The 132 kV underground transmission power cable was designed and simulated using COMSOL Multiphysics at varying burial depths for tarmac roads and horizontal direct drilling (HDD), with different conductor sizes. Additionally, the cable was arranged in a trefoil formation within the surrounding surface for both single and double circuits. Finally, the simulation displayed the cable condition, which is the cable's temperature. Results indicated that the cable temperature increased when the buried depth for the tarmac and HDD layout increased. About 3% of the temperature is increased with the depth of the buried cable. Besides, the cable temperature increased by about 17% when the cable was placed next to each other as a double circuit arrangement. As a result, the ampacity analysis on the underground transmission cable at different layouts and circuits depicts the deeper installation depth, and the closest number of circuits may cause the higher temperature. Hence, this study may provide valuable insight to electrical engineers by offering temperature data before the installation of 132 kV underground power cables in both layouts at a later stage.**

***Index Terms*—Ampacity, transmission, the temperature underground**

I. Introduction

The power system is a network of electrical components that transmit electricity to light up the world and run electrical equipment and machines in people's daily life. Every power system has three major features: power source generation with a specified voltage and frequency, load or demand that consumes power with a constant resistive value and transmission system that transmits power as a perfect conductor to the load [1-3].

For transmission power, the power cable is essential to transmit the electricity to the customer. In this study, an underground power cable is chosen to protect power delivery in the urban area, avoid appearance issues and ensure safety for the surrounding life since it is buried underground [4,5]. However, the installation and maintenance of underground power cables are more expensive than overhead lines due to the cost incurred at the installation process, making it imperative to use its full capacity. Hence, reliability power delivery shall be a further concern, as power cables buried underground experience losses when they become heated due to the surrounding environment [6,7].

Heat production in the cable is due to the flow of electrons through a substance. Energy is conserved to move the electrons forward, and at the same time, the electrons collide, generating heat. According to [6,8], the cable ampacity or the maximum amount of current can be delivered through a conductor is limited by the internal heat dissipation. The heat generation is also a key factor in the operation of power cable as it may affect the rated insulation capability of power cables. It is known as cable ampacity. The cable's ampacity is limited based on the cable temperature, which does not exceed 90^0C for Cross-linked polyethylene (XLPE) cables and controls the cable lifetime. That is why the cable temperature needs to be controlled in optimum value to maintain its operation, especially for the underground buried power cable.

Moreover, few literatures have shown that the ampacity of XLPE power cable reacts with the temperature whereby the ampacity is depended on the conductor size [4,6,9,10], installation type and the surrounding condition. Although many studies have been conducted in this area, more studies need to be conducted that take into account the layout of the on-site application, specifically on the direct buried underground on the transmission power cable 132 kV. Therefore, this study is deemed necessary to ensure that installing the 132 kV underground power cable is considered optimal. It is designed to meet the increasing electrical current demand in Malaysia by examining the thermal conditions of cables when placed underground, considering different layouts and the number of circuits.

In this study, a 132 kV underground transmission power cable is designed and simulated according to the layout of the on-site application by using COMSOL Multiphysics software. The simulation is run to achieve the cable temperature for each application. Further investigation and analysis of the results are performed.

This manuscript is submitted on 4 August 2022, revised on 16 October 2023, accepted on 31 October 2023 and published on 30 April 2024. Khairul Ikhwan Rosdi is with the Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia, 71800, Nilai, Negeri Sembilan (e-mail: khairulikhwanrosdi@gmail.com).

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II. CABLE STRUCTURES

Underground power cables play a crucial role in urban electricity supply networks, necessitating the protection of these buried cables as a fundamental principle. Ampacity signifies the maximum electric current capacity a cable can handle without experiencing immediate or gradual degradation. Hence, details on the underground power cable structures have to be reviewed as fundamental structure [8, 11] to understand the ampacity. Fig.1 shows the structure of the power cable consisting of multiple layers such as electrical conductor (first layer), electrical conductor shield (second layer), insulator (third layer), insulator shield (fourth layer), armoured wires (fifth layer) and the last one is an overall shield (outer layer).

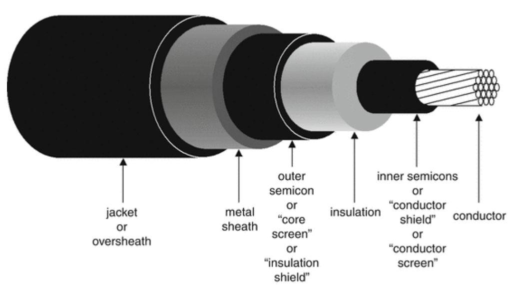


Fig. 1. Power Cable Structure [12].

A. Electrical Conductor

The electrical conductor is one of the most important components of power, and selecting the proper type of conductor for underground cables is as crucial as choosing the economic conductor size and transmission voltage. Copper and aluminium are the types of conductors used in electrical power cables. Copper has characteristics such as high electrical conductivity, greater tensile strength, and a smaller cross-sectional area, reducing weight and pressure. Similarly, aluminium possesses some desirable characteristics: it has 61% of the electrical conductivity of copper but weighs 30% less than copper at the same electrical resistance. Copper was preferred, but copper is rarely used nowadays due to its high cost. Aluminium has become more popular because it can reduce the cost and weight of the conductor compared to copper conductors over the same resistance. However, the current carrying capacity of copper is higher than aluminium [12,13].

B. Shield

An electrical conductor shield is a layer between the conductor and the insulator. An insulation shield is another layer between the insulation and armoured wires. The primary function of the electrical conductor and insulation shield is to maintain a uniformly divergent electric field and encircle the electric field within the cable core. Furthermore, the goal is to create an electric field that is symmetrical in all directions around the cable core, which is the electrical conductor, and to smooth out the irregular surface of the electrical conductor. The shield is made of a semiconductive compound because it does not conduct electricity. The materials consist of carbon distributed within a polymer matrix to ensure adequate and constant conductivity [12, 13].

C. Insulation

Insulation is of considerable importance in power cable structures as it helps to prevent leakage current and electrical breakdown of the cable. An excellent insulating material must possess the following properties: high insulation resistance, high dielectric strength, and high mechanical strength. The XLPE is used as the insulation material for underground power cables due to its low dielectric loss properties. The dielectric loss factor is approximately one decimal power lower than - insulated cables and about two decimal controls lower than Polyvinyl chloride (PVC) insulated cables. Because of its favourable dielectric constant, XLPE also exhibits lower mutual capacitance, reducing charging and earth-leakage currents in networks lacking rigorous star-point earthing [14]. However, XLPE insulation may face challenges when exposed to high temperatures. This is because individual molecular chains combine under pressure and heat, affecting the cross-linking chain and causing the material to transform from a thermoplastic to an elastic state. This transformation can result in a pathway for electric current to flow from the conductor to the insulation.

D. Armoured Wires

The armoured wires serve as an additional protection layer following the insulator shield layer. Their primary function is to provide mechanical strength and safeguard the inner layer of power cables against external damage, such as chemical corrosion, that can erode the surface of the inner layer.

E. Overall Shield

The overall shield is the final layer covering the entire power cable structure. It serves as an additional insulation layer to protect the underlying conductor against cable failures caused by any external electrical charges or mechanical damage. Several non-metallic materials can be used for the overall shield of the cable, such as PVC, Polyethylene (PE) and Ethylene Propylene Rubber (EPR). PVC is widely used in various applications because it is cost-effective and can be combined with plasticizers for electric cables.

III. CABLE AMPACITY

A. Cable Ampacity

Ampacity is the maximum current-carrying capacity of a cable, and this defining parameter is influenced by various cable properties, installation conditions and the surrounding environment. In other words, cable ampacity represents the highest current capacity through a conductor that may besafely transported without exceeding the insulation-rated limit. It is important to note that the ampacity of the underground cables depends on the rate of heat generated within the line and the heat dissipated from the cable into the surrounding environment. The limiting factor for cable ampacity is the withstanding temperature of the insulating material, which determines the maximum electric current that can be carried safely. For example, the operating temperature for thermal performance of XLPE is 90^0C [8,15].

B. *Cable Installation Geometry*

Cable installation geometry is a 2D schematic that represents the underground cross-section where the cable is installed. According to [10], there are several types of underground cable installation: 1) direct burial of the cable underground, 2) cable laid inside duct bank, 3) cable laid inside cable trench and 4) cable laid inside tunnel. Note that the cable directly buried underground can also be classified as the open-cut method for tarmac roads and HDD method. Different materials inside the geometry that cover the underground power will give a different result to the cable. The material's presence can increase the heat dissipation rate from the cable to the outer surroundings and, in return, increase the maximum allowable conductor current. It is important since it will affect the cable ampacity.

C. *Multiphysics Simulation Software*

COMSOL Multiphysics is a cross-platform finite element analysis, solver, and Multiphysics simulation software. It provides an Integrated Development Environment (IDE) and a uniform workflow for electrical, mechanical, fluid, and chemical applications. It supports traditional physics-based user interfaces and coupled partial differential equations (PDEs) systems. Application Programming Interface (API) for Java and Live Link for MATLAB are utilized with the same API via the Method Editor to control the software externally. COMSOL also includes an App Builder for developing separate domain-specific apps with bespoke user interfaces and a Physics Builder from the COMSOL Desktop with the same background as the built-in physics interfaces for creating new physics interfaces [16].

IV. METHODOLOGY

The investigation is performed using COMSOL Multiphysics software to simulate underground cables' temperature distribution with different sizes and layouts. The heat distribution within the cables and their surrounding at the respective depth is mainly governed by the conduction mode; hence the heat transfer module is adopted.

The dimension of each structural layer of the tested cables are properly modelled according to the Tenaga Nasional Berhad (TNB) 132 kV single core 630 mm², 1200 mm², and 1600 mm² aluminium XLPE cable as presented in Table I to ensure appropriate heat transfer analysis of the cables. In addition to the cables' structural design and layout modelling, the thermal conductivity property of each structural layer and soil are defined accordingly. Note that, TNB is the largest electricity provider in Malaysia.

Moreover, the work simulation begins with the design of cable structure specification, installation layout and COMSOL multiphysic consideration, as shown in Fig.2.

TABLE I. TNB 132 KV XLPE CABLE SPECIFICATION [14]

Nominal Cross-sectional area of conductor (mm^2)	Diameter of Conductor, AL (mm)	Nominal Thickness of XLPE Insulation (mm)	Nominal Thickness of HDPE Sheath (mm)	Approx. Overall Diameter of Cable (mm)
630	29.8	20	4.0	93
1200	43.4	20	4.0	109
1600	50.0	20	4.0	116

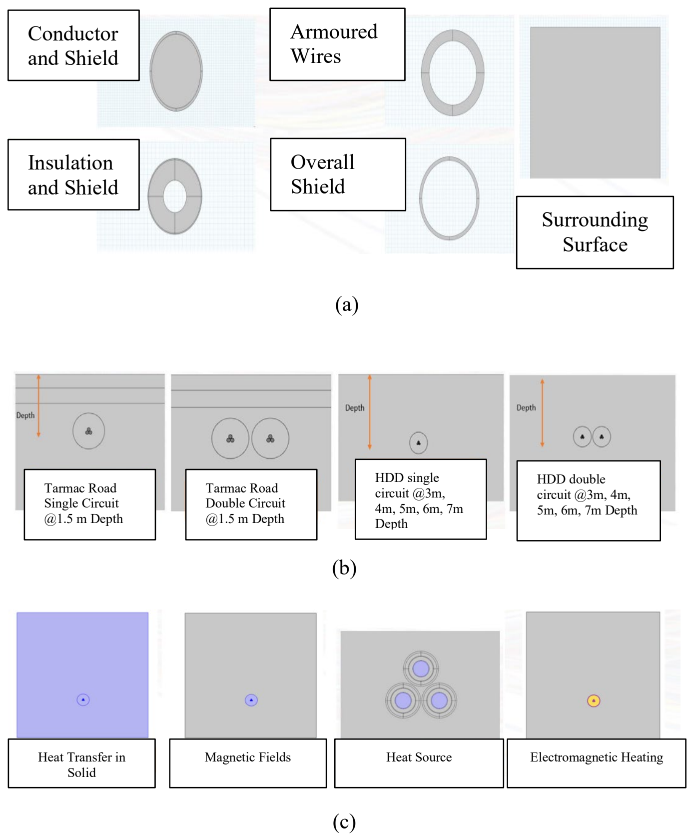


Fig. 2. Design layout of the cable (a) cable structure, (b) installation layout and (c) COMSOL multiphysic consideration.

For the cable structure specification in Fig.2 (a), each cable layer is drawn using the geometry function in COMSOL, followed by data as given in Table I. The cable core known as the conductor is geometry, with the diameter of the core is 29.8 mm. The second layer is the semiconductive layer of the conductor. The thickness of this layer is about 1 mm. Next is the insulation with a thickness of 20 mm. The third layer is again the semiconductive layer, but for the insulation layer it also has a thickness of 1 mm. Next are armoured wires, which have a thickness of 11.6 mm, and the outermost layer is an overall shield designed with a thickness of 4 mm. Also, the installation layout of the cables has been simulated according to the tarmac road (open cut method) and HDD method as presented in their specification depths in Fig. 2 (b) and Fig 2. (c) for the heat transfer module simulation. Table II shows the specification condition of the layout and Fig. 3 shows the buried underground power cable with the trefoil arrangement.

TABLE II. LAYOUT SPECIFICATION [9, 10]

Parameter	Specification Value
System Frequency	50 Hz
Aluminium conductor thermal conductivity	237 W/m.K
Soil thermal conductivity	1.0 W/m.K

(a) Material specification

Parameter	Tarmac road layout level from ground level
Tarmacadam material	75 mm
Gravel stone material	300 mm

(b) Level height of depth for tarmac road layout

Parameter	HDD layout level from ground level
Native soil thermal resistivity	6000 mm (as per study interest, the minimum level is 3000 mm)

(c) Level height of depth for HDD layout

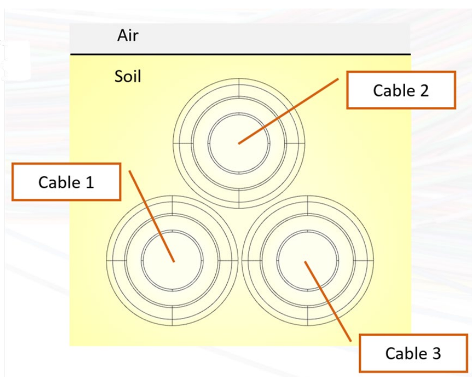


Fig. 3. The completed cable construction using the geometry function in COMSOL Multiphysics.

V. RESULTS AND DISCUSSIONS

The 132 kV single-core XLPE underground transmission power cable has been designed using COMSOL Multiphysics software. In total, 36 simulations were conducted for further analysis, which considered 3 conductor sizes (630 mm², 1200 mm², and 1600 mm²), 2 types of circuit (single and double circuit) and 6 different depth levels (1.5 meters, 3 meters, 4 meters, 5 meters, 6 meters, and 7 meters). The depth was simulated under tarmac road and HDD.

The appropriateness of the developed power cable modelling in COMSOL is first being confirmed by comparing the cable temperature according to the operational conditions of single core 1x630mm² XLPE cable in 33kV system as presented by Subramaniam [4]. The comparison is made possible as similar number of core is used and the cables are constructed in trefoil arrangement as shown in Fig. 3. Table III summarizes the appropriateness of the developed model as maximum percentage difference of less than 10% are obtained in the tested surroundings. The difference is recorded to be lower with the increased of depth. For example, at 0.5 meters depth, the temperature difference is 4.1 °C which indicates an 8.08% percentage difference. Meanwhile, at 1 meter depth, the difference is reduced to 1.1 °C or 1.94 % difference from the last literature.

TABLE III. CABLE TEMPERATURE COMPARISON BETWEEN PREVIOUS STUDY AND PRESENT STUDY

Type of Result	Cable Ampacity (A)	Depth (m) 0.5	1.0
		Cable Temperature (°C)	
Subramaniam [4]	607	46.3	57.3
Present Study	607	50.2	56.2
Difference		4.1°C (8.08%)	1.1°C (1.94%)

Next, the verified COMSOL model are modelled to replicate 630 mm², 1200 mm² and 1600 mm² conductor size in: single and double tyoes of circuit under tarmac roads and HDD. Table IV shows the overall thermal cable condition in different layouts and different number of circuits.

TABLE IV. ANALYSIS OF RESULTS CONCERNING DIFFERENT LAYOUTS AND DIFFERENT NUMBERS OF CIRCUIT

Conductor Size (mm²)	Type of Circuit	Tarmac Road	Horizontal Direct Drill (HDD)					Method Percentage Difference
		Installation Depth (m)						
		1.5	3	4	5	6	7	
		Cable Temperature (°C)						
630	Single	49.3	64.8	66.7	68.0	68.9	69.5	23.9%
	Double	54.1	78.5	82.2	84.8	86.5	87.8	31.1%
1200	Single	56.3	77.5	80.2	82.0	83.3	84.1	27.4%
	Double	63.3	96.6	101.9	105.5	108.0	109.7	34.5%
1600	Single	61.2	86.0	89.3	91.4	92.8	93.9	28.8%
	Double	69.5	108.7	115.0	119.3	122.3	124.3	36.1%

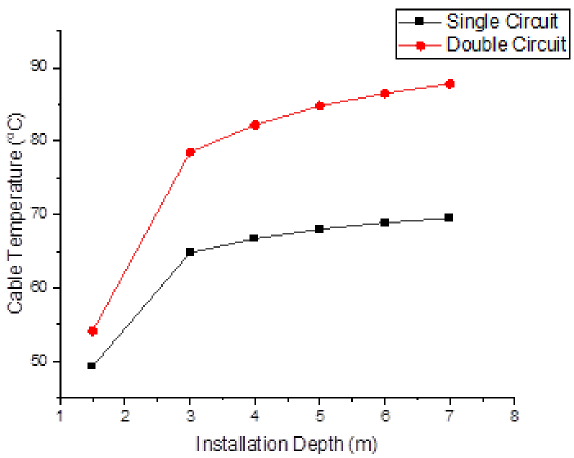
The temperature below than 70°C
The temperature in between 70°C to 89°C
The temperature is more than 90°C

For a single circuit cable with a 630 mm² conductor size, the temperature achieved for tarmac road and HDD is expected since it is below 90 °C. The temperature increased slightly at the double circuit cable due to multiple heat sources from two circuits that sit together. But the cable is still in normal condition because the temperature is below 90 °C.

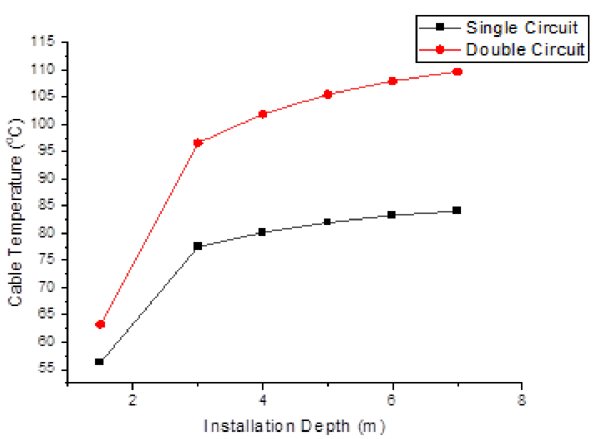
For a single circuit cable with a 1200 mm² conductor size, the temperature achieved for tarmac road, and HDD is normal since it is below 90 °C but increased slightly compared to 630 mm² conductor size due to bigger conductor size and inject current. However, at double circuit cable under HDD layout, the temperature achieved is not normal since it exceeded the limit of 90 °C due to multiple heat sources from two circuits that sit together. The temperature can still be managed below 90 °C by increasing the distance between both circuits because the temperature is not too far above 90 °C but will allocate more space area.

For single circuit cable with 1600 mm² conductor size, the temperature achieved for tarmac road, and HDD is normal since it is below 90 °C until, at 5 meters depth and deeper for HDD, it increased and exceeded 90 °C. Thus, this type of cable is unsuitable to be installed at this level. Moreover, at double circuit cable under HDD layout, the temperature achieved is not average at all installation depths since it exceeded the limit of 90 °C due to multiple heat sources from two circuits that sit together.

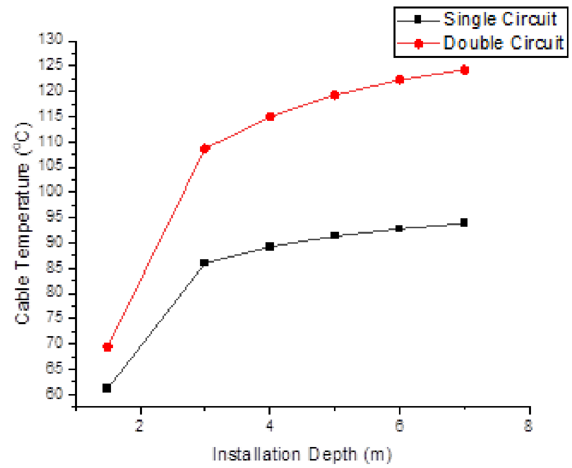
Lastly, Fig. 4 shows the cable temperature trend increasing linearly with installation depth. However, there is a considerable increment in the transition from tarmac road to HDD method. The overall method percentage difference for these 3 types of conductor size shows the difference percentage between 20% and 40%. Thus, these 2 methods must be appropriately analyzed to ensure the cable is installed optimally.



(a)



(b)



(c)

Fig.4. The trending of the cable temperature on the (a) 630mm² cables, (b) 1200mm² cable, and (c) 1600mm² cable.

VI. Conclusion

In conclusion, the structure of the underground transmission power cable, including installation geometry using COMSOL Multiphysics software, was successfully designed. The design includes underground power cable structures like a conductor, insulation, armoured wires, and overall shield and installation geometry surrounding the surface. The simulation evaluation found that the temperature in different layouts and circuits depicts the deeper installation depth, the more significant number of circuits, and the higher the temperature becomes. The temperature is also enormously dependent on the on-site application. However, futher improvements in research work shall be done where the experiemnetal work on a smaller scale is proposed to produce more reliable results. Besides, the result from the analysis can benefit the electrical engineers by providing roughly basic references to installing 132 kV underground power cables for both layouts later.

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