International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING

ISSN:2147-6799 www.ijisae.org Original Research Paper

Analysis of Induced Sheath Voltage and Current within Underground Power Cables

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Submitted: 25/01/2024 **Revised**: 07/03/2024 **Accepted**: 15/03/2024

Abstract: In this article, past researches related to the generation of induced sheath voltage and current were theoretically analyzed. The findings of seven different cable conditions that contribute to voltage and current induced in cable sheaths which include type of earthing methods, laying arrangement of cables, thermal resistivity of soil, material of pipe ducts, method of burying cables, spacing between cable ducts, and depth of buried cables were observed, obtained, and analyzed with the aid of CABLEIZER software. By comparison, an optimal cable condition was deduced. Furthermore, the dielectric and ohmic losses due to circulating currents in sheath, cable ampacity and cross section of underground cables according to Tenaga Nasional Berhad (TNB) standards were also discussed. A variety of software used for the study of induced sheath voltage and current were also compared and synthesized. By identifying the optimal cable condition, induced sheath voltage and current generation can be minimized and unwanted thermal breakdown within underground cables can be avoided.

Keywords: *Energy, Circulating current, Induced sheath voltage, Thermal breakdown, Underground power cables.*

1. Introduction

The utilization of medium-voltage (MV) and high-voltage (HV) underground power cables for distribution and transmission lines are rapidly surging in order to meet consumer demand. The implementation of underground cables is preferred over overhead lines (OHL) due to several reasons. However, underground cables can also contribute to higher feeder loss compared to OHL due to its weak ability to dissipate heat [1]. In regard to underground distribution systems, feeder loss is the combination of dielectric losses and ohmic losses of a cable [2].

This paper presents the distinctive nature of the adverse effects of induced sheath voltage that occurs within underground power cables. MV and HV power cables are mainly applied for safety reasons and protection against several environmental drawbacks. However, these power cable conductors contribute to the generation of induced sheath voltage and must be accounted for proper permissible sheath voltage maintenance [1].

1.1. Dielectric Losses and Ohmic Losses

Dielectric and polarization losses are known to be the main factors of dielectric losses which will contribute to evident form of dielectric heating [3]. Polarization losses are generated due to the polarization of dielectric in the presence of an alternate electric field which induces an orientation and disorientation of poles, producing internal friction which heats the dielectric [3]. Even so, dielectric loss can be disregarded in 33kV and 11kV medium voltage underground (MVUG) cables [1]. The dielectric loss of a cable and the cylindrical capacitance per unit length of a single core can be expressed as follow:

$$P_{dielectric} = 2\pi f C U_f^2 tg\delta \qquad (1)$$

$$Q_{dielectric} = P_{dielectric} \times tg\delta \qquad (2)$$

$$C = \frac{55.7\varepsilon * 10^{-12}}{\ln\left(\frac{D_C + 2\Delta}{D_C}\right)} F/m \qquad (3)$$

where Uf is phase voltage, f is net frequency, D_C is the diameter of cable, δ is dielectric losses angle, Δ is insulation thickness of cable, and ε is relative dielectric constant of XLPE material with a value of about 2.5.

On the other hand, the ohmic loss in the cable core and other metallic parts of the cable are due to induced currents creating cable ohmic loss. Ohmic losses caused by induced currents in the sheath can be separated into two categories: eddy currents and circulating currents. The flow of sheath eddy currents is due to the unequal voltages on the sides of the sheath. The non-uniform

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current density of cable conductors will make the outer surface of the sheath smaller than the inner surface due to their convergence onto each other [5].

Meanwhile circulating currents are formed due to transformer coupling of the conductor and sheath / screen / armor of the cable system [1] and are commonly found in both ends grounding systems. The eddy and circulating current phenomenon which occur in underground metallic sheaths are as shown in **Fig. 1** and **Fig. 2** respectively. These losses will generate heat which is then released into the cable's surrounding space through thermal resistivity of the individual layers and result in unwanted cable thermal breakdown [6].

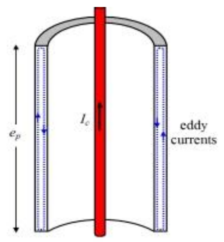

Fig. 1. Eddy currents in underground metallic sheath [5]

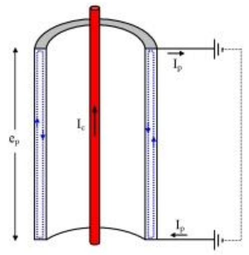

Fig. 2. Circulating currents in underground metallic sheath grounded at both ends [5]

1.2. Cable Ampacity

One of the ways to identify whether a cable is able to withstand thermal heat and avoid unnecessary breakdowns is by determining the current carrying capacity (ampacity) of a cable [7].

Cable ampacity is the maximum allowable current that can circulate through a conductor without damaging the insulation of the cable [8] and is limited by the maximum permissible temperature of the core and the shield [9]. Hence, temperature control of the cable is important to prevent rapid cable aging, and the assessment of heat dissipation process from underground power cables to external environment is utmost necessary [10].

The commonly used method for cable ampacity calculations can be found in the basis of IEC 60287 [11] which follows equations founded by Neher-McGrath. In reliance with the simulations executed by F. D. Leon et al. [12], cable ampacity is affected by similar major factors affecting the value of induced voltage and circulating current in a cable sheath, as they correspond to one another.

Additionally, a large variation on the soil thermal resistivity and different bonding types will affect more than 50% of cable ampacity value. As referred to B. Perovic et al. [13], electricity transmission bottlenecks at crossing areas of the system can be reduced with the increment in cable ampacities. This simple approach acts as an indicator that by decreasing the line ampacity with thermal environment, an optimal solution which corresponds particularly to the axial spacing between cables can be achieved.

1.3. Cross Section of Underground Cables

An electric cable is made up of several parts which consists of the conductor, conductor shield, insulation, insulation screen, metallic sheath, and jacket [14]. The metallic sheaths of underground cable can help to suppress the penetration of moisture in cables while acting as a protection layer against mechanical damage, electromagnetic interface, and fault return path for unbalanced systems [15].

The outer jacket of the cable ensures safeguard of the sheath from corrosion due to galvanic or electrolytic action whilst acting as a barrier against ingress of moisture [16]. **Table 1** below shows the different MV cable components, materials, and functions as depicted in TNB's underground cable system design manual [17].

Table 1. MV cable components, materials, and functions [17].

Component	*Material*	*Function*
Conductor	Copper, Aluminum	To carry the design rated current
Conductor Screen	Semiconducting material	To smooth out any irregularities over the stranded conductors' contours, reduce the probability of protrusions into the insulating layer in order to avoid localized stress that may exceed breakdown strength of the insulation
Insulation	XLPE, Paper	To provide insulation between conductors and earth to preclude dielectric failure
Insulation Screen	Semiconducting material	To provide a uniform earth potential layer to enable symmetrically spaced electrostatic flux lines and concentric equipotential lines in the insulation
Metallic Sheath	Copper wire, Copper tape, Lead sheath, Laminated aluminum foil	To provide return path for faults current, keep moisture out of the cable, contain a pressuring medium, function as a reference

		Ground for the whole length of the cable
Outer sheath / Jacket	PVC, MDPE	To provide mechanical and environmental protection and act moisture barrier

Cross linked polyethylene (XLPE) cables are often used as the insulation layer because they have higher allowable conductor temperature. Hence, more compact cables can be employed in the same power rating [16]. TNB has also been introduced to XLPE cables and resin filled joint technology to improve MVUG cable performances in Malaysia [18].

In addition, the cable insulation screen acts as an essential element of tree retardant to prevent moisture containment in a production process and throughout outer jacket of cable during any field operations [19]. The advantages and disadvantages of different types of metallic sheath design are as described in **Table 2** [20].

1.4. Induced Sheath Voltage and Current

The circulating currents in the metallic sheaths will contribute to the generation of induced sheath voltage and current losses along with reducing the current loading capacity of cables [20]. According to Faraday's law, the induced sheath voltage is due to the change in cable current, and it depends on its rate of change of current [16].

Table 2. Different metallic sheath types and implementations [20]

Type of metallic sheath	***Advantages***	***Disadvantages***	***Implementation***
Cu-wires screen with Aluminum laminated sheath	Light weight, small cable diameters, easily made longitudinally watertight (LWT)	Limited protection against mechanical damage	Polymer insulated cables for HV and MV cables
Lead alloy sheath / Hybrid sheath with additional copper wires	No corrugation, proven technology, easily made, LWT	Heavy in weight, environmental issues	Polymer / paper insulated cables, EHV & MV cables
Corrugated Aluminum sheath	Light weight, good mechanical protection, and high short circuit current capacity	Large cable diameter (corrugated), LWT difficult, slightly higher sheath losses compared to lead sheathed cables	Polymer / paper insulated cables, EHV cables
Smooth Aluminum sheath longitudinal welded	Light in weight, good mechanical protection, small diameter, easily made, LWT, high short circuit capacity, cost effective	Slightly higher sheath losses compared to lead sheathed cables	Polymer insulated cables in EHV range

The calculation methods of induced sheath voltage for cables are initially proposed in IEEE Std. 575 [21] which cannot exceed the maximum limit of 50V, in accordance with IEEE Std. 80-2000. Although, the maximum limit of induced sheath voltage may vary according to different countries [22]. The permissible operating temperature of conductor must also not exceed 90°C to avoid the occurrence of cable insulation meltdown [10].

According to past assessments of induced sheath voltage and current executed by [1], [3], [4], [8], [21], [23 – 28], induced sheath voltage and current calculation methods are mainly categorized into two: trefoil formation and flat formation. These formations identify as the laying arrangements of underground cables with commonly used configurations consisting of trefoil, flat and triangular formations. However, this project would only focus on the calculations for trefoil and flat formation.

A trefoil configuration is made up of three single-core wires that are arranged out like the angles of a triangle. Two single-core cables are arranged in this configuration closely together, with one cable forming an upward apex. Conversely, a flat configuration consists of three single-core wires with the center cable evenly spaced from the outer two cables and all three cables laid out in the same horizontal plane as shown in **Fig. 3** and **Fig. 4** respectively.

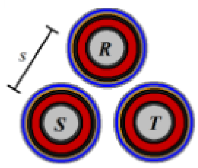

Fig. 3. 3-Core cables in trefoil formation [1]

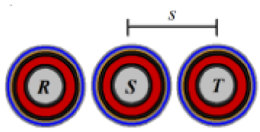

Fig. 4. 3-Core cables in flat formation [1]

The induced sheath voltages for flat formation of phase a, b, and c are as expressed below:

$$V_S = -j\omega L_S I \tag{4}$$

$$L_{SA} = \ln \frac{S^2(D^2+S^2)(4D^2+S^2)}{D_S^2 D^4} + \tag{5}$$

$$a \ln \frac{(D^2+S^2)(4D^2+S^2)}{4(D^2+S^2)(4D^2+4S^2)}$$

$$L_{SB} = \ln \frac{S^2(D^2+S^2)(4D^2+S^2)}{D_S^2 D^4} \quad (6)$$

$$L_{SC} = \ln \frac{S^2(D^2+S^2)(4D^2+S^2)}{D_S^2 D^4} + a^2 \ln \frac{(D^2+S^2)(4D^2+S^2)}{4(D^2+S^2)(4D^2+4S^2)} \quad (7)$$

$$a = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \quad (8)$$

where D is distance between cables, Ds is cable diameter, and S is spacing between adjacent cables.

On the contrary, the induced sheath voltages for trefoil formation of phase a, b, and c can be represented with the equations below:

$$V_A = j\omega I_b(2.10^{-7})\left(-\frac{1}{2}\log\left(\frac{2S_{ab}^2}{dS_{ac}}\right) + j\frac{\sqrt{3}}{2}\log\left(\frac{2S_{ac}}{d}\right)\right) \quad (9)$$

$$V_B = j\omega I_b(2.10^{-7})\left(\frac{1}{2}\log\left(\frac{4S_{ab}S_{bc}}{d^2}\right) + j\frac{\sqrt{3}}{2}\log\left(\frac{S_{bc}}{S_{ab}}\right)\right) \quad (10)$$

$$V_C = j\omega I_b(2.10^{-7})\left(-\frac{1}{2}\log\left(\frac{2S_{ab}^2}{dS_{ac}}\right) - j\frac{\sqrt{3}}{2}\log\left(\frac{2S_{ac}}{d}\right)\right) \quad (11)$$

where Sab is axial spacing between phase “a” and “b”, Sbc is axial spacing between phase “b” and “c”, and Sac is axial spacing between phase “a” and “c”.

The induced current in sheaths can be obtained by dividing the inductive voltage in sheaths with the total impedance in the circuit loop [4]. The total impedance in the circuit loop is the combination of grounding resistance, resistance of sheath, and contact resistance at the middle connection of circuit. Nevertheless, in-depth calculations should be executed for each case using proper simulations regarding the general formulas, as clearly stated in IEEE Std 575-1988 [21]. More importantly, the values of sheath voltage during steady state, under phase-to-ground fault and under phase-to-phase fault are not equal which is similar to the results of induced sheath voltage occurring during transient conditions as provided in [20].

1.5. Effects of Induced Sheath Voltage and Current

Induced voltage produced within the sheath of underground cables would then lead to the generation of hotspot regions. Hot spots are regions where the conductor temperature may be larger than most remaining parts on the cable [13].

These regions would later experience unwanted thermal stresses which can cause premature cable breakdown if the condition prolongs. Moreover, power consumers would also be affected due to disruptions and power outages as a result of premature cable failure along with a rather time-consuming rectification process. Cable puncture may also occur if the voltage differential between sheath and earth exceeds the cable jacket’s withstand [29]. Sheath currents induced in cable can also influence the conductor currents by proximity effects [15].

Long term dielectric and other failure issues might arise due to moisture ingress as a consequence of the cable puncture. A significant magnitude of surge voltage with moderate current may also travel into the cable during the occurrence of lightning on overhead transmission lines. Dry zones may be formed around the underground cable and lead to thermal failure of cable insulation [30].

The circulating current losses and sheath voltage induced due to lighting strikes would also result in energy loss, power transmission capacity reduction, and increase in cable temperature, among many other effects. As mentioned in [31], the outer sheath of the cable has a higher tendency to burn from the increment of conductor temperature and current that causes stronger current ablation ability of cable.

2. Factors Affecting Induced Sheath Voltage and Current

The fundamental issues that contribute to unwanted induced voltage and circulating currents in cable sheath such as the influence of different types of earthing methods, laying arrangement of cables, variation of thermal soil resistivity, material of pipe ducts, material of backfills, spacing between conductors, and depth of buried cables [32] have been studied by many researchers.

In addition, J. Lee et al. [19] have also proven that cable parameters are the only factors that can influence the outcome of voltage and circulating currents induced in cable sheath as XLPE implementation can omit the common root distribution causes in MVUG cables.

2.1. Earthing Methods

The sheath of one point of a distribution or transmission line needs to at least be grounded to ensure optimization of any XLPE cable operation. In terms of bonding schematics, they may vary according to the different system voltage bonding principles used.

Solid-bonding design is commonly applied in low voltage (LV) systems, medium voltage (MV) systems, and submarine cable installations where no other choices exist while sectionalized cross bonding design is typically used in long cable systems such as high (HV) systems and extra high-voltage (EHV) systems [29]. Bonding leads are utilized at both ends of a cable circuit for solid-bonding systems and can be considered as a simple, low-cost option. However, solid-bonding systems will cause cable sheath heating due to the circulating current and cable thermal capacity reductions [26].

Additionally, circulating currents on the metal sheaths for solid-bonding may occur and generate Joule losses which will increase the cable temperature. Thus, there are various methods of system grounding that can be implemented in a system, all of which aim to reduce the induced voltage and current circulating generated in cable sheath. Furthermore, the three most frequently used grounding methods in MVUG cable installations include single-end (or single-point) bonding, both ends sheath bonding, and cross bonding. Single-end bonding is commonly used when the cable line length is 500 meters or less.

In terms of installation, the cable sheaths in a single-end bonding system are directly grounded at one end and grounded at the other end through the protector [34], as shown in **Fig. 5.**

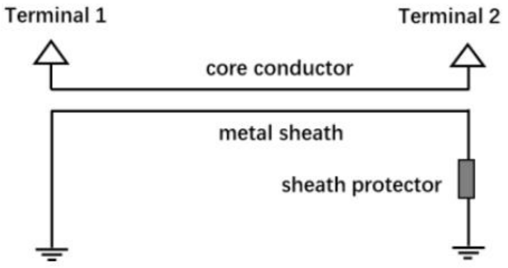

Fig. 5. Single-end bonding method [34]

Fig. 6 illustrates a system that implements both ends bonding. The two ends of the cable sheaths are directly grounded to the ground, causing a loop to be formed between the sheath and the earth. This bonding results in a loop appearance under induced voltage and is rarely used in 100kV and above HV single core cable lines. Both ends bonding are widely used in systems for cable lengths exceeding 500 meters.

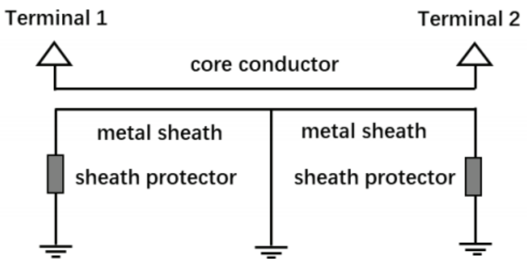

Fig. 6. Both-ends bonding method [34]

Cross bonding has been around for many years and has been deemed as a very common earthing technique to reduce circulating currents and excessive sheath voltages in cables [28]. This earthing method is achieved by dividing the cables into three equal lengths (called minor sections) along with breaking the sheath continuity at each joint.

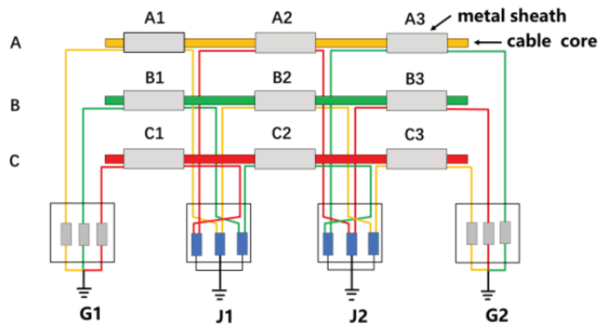

Fig. 7. Cross-bonding method [28]

The three separated equal lengths will produce nine minor sections in all respectively A1, A2, A3, B1, B2, B3, C1, C2, and C3. The cross-bonding system is formed when the segmented interlayers are connected by the order of A1-B2-C3, B1-C2-A3, C1-B2-A3, and line to grounding individually, as shown in **Fig. 7** [35]. This aids the superimposition of segmented interlayers when they are connected according to the respective sequence.

In theory, the induced sheath voltage and current are almost zero when the load is completely symmetrical and cross interconnection is segmented uniformly. Unfortunately, real life power engineering is bound to be limited by construction of geographical conditions and space location restrictions [35] which will not result in the theory of an ideal situation. In addition, cables are often transposed [36], [37] and cross bonded simultaneously to decrease induced sheath voltages and circulating current as maximum sheath voltage is induced when sheath is cross bonded [26].

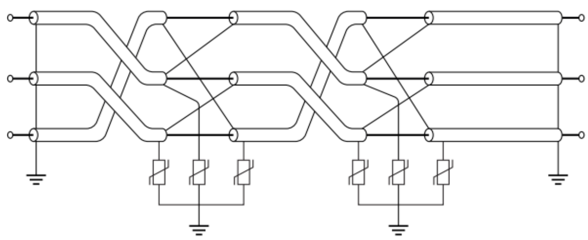

Fig. 8. Cross-bonding of cables with transposition [36]

Transposed conductors are described as conductors which are divided into three parts and the sheaths are interconnected at their respective joints [38]. **Fig. 8** illustrates an example of cross bonding sheath over three sections with 120° phase shifted in each section and transposed [21].

Moreover, it is impossible to achieve the exact induced sheath voltage balance without transposition for long cable installations [25]. Therefore, the cable sheaths must be transposed and cross bonded at each section's joint position regardless of cable formation to neutralize the induced sheath voltage produced. Even so, transposition methods possess minimal to no effect on any trefoil/triangular cable formation of single core cables [25] as the three phase sheath currents balance each other out despite being transposed or un-transposed. Furthermore, **Table 3** below explains the differences, advantages, and disadvantages of single-end bonding, both ends bonding, and cross bonding.

Table 3. Comparison of different types of grounding methods [4],[16],[28],[29],[35], [39-40].

Grounding Method	***Advantage***	***Disadvantage***
Single-end	No circulating current as there is no closed circuit for the sheath, resulting in no sheath circulating loss, lower losses from creating induced voltage at open end of cables	Eddy losses are still present, adequate for short lines only, faulty power cable system can cause additional losses
Both-ends	No induced voltage at the ends of cables as currents are divided into two that can cause reduction of fault losses, eddy current losses can be ignored because they are small	Significant power loss, generates large circulating current, additional losses at steady-state condition due to circulating currents in metallic sheaths
Cross-bonding	Decreases circulating sheath currents and	Implementation is expensive, requires

[41]	induced voltage, total voltage in each part is equal to zero, reduction of losses and thermal ageing, prevents risk of failures due to overheating of screen connections, allows cable to be transposed and further reduce induced sheath current	skilled workers, complicated installation as compared to single-end bonding, and both ends bonding

In regard to previous papers, many researchers have been able to obtain results for the three earthing methods as mentioned above. Z. L. Wei et al [42] proposed a formula that can be applied to asymmetrical systems and decouple the product matric of impedance and admittance. The calculations for terminal circulating currents of three-phase cables were executed and simulation results were compared using PSCAD/EMTDC software.

The research tackles the difficulty in obtaining accurate calculation of metal sheath circulating current and proves that significant reduction of induced circulating current in sheath can be observed by implementing both ends grounding method as compared to single-end bonding. However, in a more recent study by T. Kangro et al. [40], the sheath current and voltage levels for both ends bonding and cross bonding are discussed. It shows how sheath current losses for cross bonded were reduced to 93% at network power flow and fault situation if compared to both ends bonding earthing method.

Discussions in [28] also proved that single-end bonding and cross bonding earthing method produce lesser sheath current losses than both ends bonding, suggesting that single-end and cross bonding both generate equal amounts of sheath losses. L. Li et al. [43] mentioned that IEEE Standards 575 [44] requires a ground continuity conductor (GCC) for any single-point bonding schemes. As a result, a dedicated GCC will increase the cost of the project due to it being financially overpriced and can be considered a financial burden.

Studies in [26], [45], [46] also examined the comparison of three main earthing methods stated above and concluded that cross bonding would be the most effective earthing method available as it can suppress currents effectively, reduce risk of electric shock, and provides transposition to compensate induced voltages in sheath.

2.2. Laying Arrangements

In the aspect of cable formations, various configurations exist. Most common formations are of trefoil, flat, and triangular arrangement, as shown in **Fig. 9.**

According to the comparison between M. Shaban et al. [24] and W. Voon et al. [25], the calculations of voltage and current induced in cable sheaths are heavily influenced by the configuration of cable arrangements as both trefoil and flat formations utilizes different equations, as stated in section V.

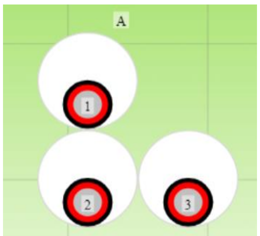

Fig. 9. Triangular formation of MVUG cables

Other relative research conducted by [1], [3], [5], [28], [29], [47]–[49] also provide equations utilized for trefoil and flat arrangements. From past research, we can deduce that trefoil formation will produce a lower amount of voltage and circulating currents induced in cable sheaths as compared to flat formation. The most obvious reason is due to symmetrical form of trefoil which produces zero induced voltage, in a given ideal system.

Supporting this, M. Rasoulpoor et al. [15] states that the values obtained from FEM simulations have lower error difference than IEC standards for trefoil than flat formations. This is due to the fact that IEC assumes symmetric position to form the related induced sheath voltage equation which is more reasonable for a symmetric trefoil arrangement. This FEM simulation, which utilizes the Ansoft Maxwell simulator in 2D steady state domain also provides findings on temperature increment for flat and trefoil configurations, stating that the latter is better, and is also supported by O. Gouda et al [30]. On an important note, the conductor temperature value does not reach the maximum 90°C for all cases.

2.3. Thermal Resistivity of Soil

The difference in degrees centigrade between opposite faces of a centimeter cube of soil caused by the transference of one watt of heat is what defines the thermal resistivity of soil and is measured through the moisture of soil [50]. Different types of soil consist of different thermal resistivity values [51].

As soil moisture increases, the thermal resistivity also increases but heat transfer capability of cables decreases. This indicates the significant influence that thermal resistivity of soil has on the current-carrying capacity of power cables, as previously stated by S. Czapp et al. [50] and D. Georgiev et al. [9]. S. Bustamante et al. [8] also emphasized how crucial different scenarios of soil moisture can affect cable ampacity calculations.

Table 4. Common thermal resistivity, conductivity, and density of soil [53].

Type of soil	*Density (g/cm3)*	*Thermal Conductivity (W/Mk)*	*Thermal Resistivity (˚Ccm/W)*
Quartz	2.66	8.8	11
Soil Minerals	2.65	2.5	40
Granite	2.64	3.0	33
Organic Matter	1.30	0.25	400
Water	1.00	0.58	172
Ice	0.92	2.5	40
Air	0.0012	0.026	3846

Additionally, the heat transfer along the distance between the cables can achieve high intensity due to the increment of current-carrying capacity, often caused by low thermal soil resistivity value. This will lead to unnecessary thermal breakdown and cable heat dissipation caused by underestimated soil thermal properties [9]. Any large variation of thermal resistivity of soil can also affect the ampacity of cables by more than 50% [12].

Although the effect of thermal resistivity of soil on the temperature distribution of cables can be acknowledged beforehand, they are usually chosen based on national standards, such as IEC 60387 and IEC 835 [52]. The thermal resistivity value of the most commonly used types of soil are as presented in **Table 4** as well.

2.4. Material of Pipe Ducts and Backfills

MVUG cables in Malaysia are installed directly underground, according to TNB regulations and specifications [54]. However, they can also be installed underground within pipe ducts under special circumstances, such as for under bridges and situations where the condition of the soil is too wet or contains excess substances.

With the installation of pipe ducts, an extra layer of protection is provided, and it can help reduce the voltage and circulating currents induced in cable sheaths. Pipe ducts can vary from PVC, aluminum, cement, steel, etc. and different ducts are implemented to different systems. By changing the type of pipe ducts that are used in MVUG cable installations, different heat dissipation properties can be observed.

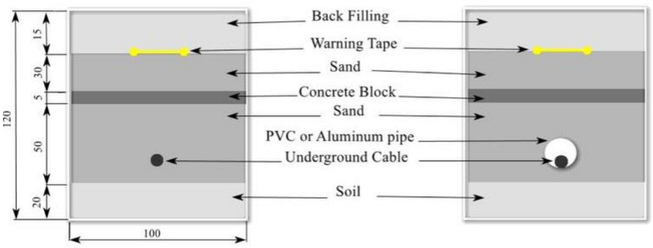

Fig. 10. MVUG cable laying conditions [10]

This observation can be seen clearly as executed by I. Al-Badawi et al. [10], which is an experimental evaluation of an underground cable of 12/20 (24 kV) single core cable with a copper conductor and XLPE insulation, as illustrated in **Fig. 10** above. The cable was placed inside the box by burying the cable in 3 different designs/models which includes directly buried in sand, aluminum pipe in sand, PVC pipe in sand. The current being loaded into the MVUG cables were at a steady temperature condition and the cable temperature was recorded every hour using a thermometer. The final findings after 5 experimental hours are as shown in **Table 5.**

Table 5. Final findings after 5 hours [10]

Model	*Burial depth (cm)*	*Current (A)*	*Conductor (˚C)*
Directly buried in sand	80	200	67.1
Aluminum pipe in sand	80	200	78.6
PVC pipe in sand	80	200	73.7

The performed experiments [10] state that directly burying the MVUG cables in sand will generate the lowest conductor temperature, followed by cables installed in aluminum pipe, and PVC pipes. When the heat dispersion from the cable to the outer soil surroundings is low, the current-carrying capacity is also affected. If the current-carrying capacity of cable is too high, the cable becomes overheated and vice versa. Thus, by lowering the temperature generated by conductor, we can minimize the induced voltage and currents in cable sheaths as they correspond to each other.

Nevertheless, P. Ocùoñ et al. [55] has made it evident that the configuration of the soil layers (amongst many other factors) have a prominent effect on the temperature distribution in soil. The maximum allowable electrical load along with the amount of heat dissipated from cables can also be increased by replacing native soil around cable with a thermal backfill material that possesses much higher thermal conductivity.

2.5. Spacing between Conductors

Temperature distribution of MVUG cables are also influenced by the spacing between conductors, which is defined as the distance of adjacent cable axes measured [1].

In most cases, the sheath circulating current losses are proportional to the spacing between phases whereas sheath eddy loss are inversely proportional to the adjacent distance of cable axes, as proven by O. Gouda et al. [30]. With respect to previous findings [1], [30], [48], we can deduce that as spacing between the cables increases, the sheath and armor circulating current loss also increases in both flat and trefoil configurations. However, sheath eddy losses can also be minimized rapidly at shorter conductor spacing and reduces fairly slowly at large conductor spacings.

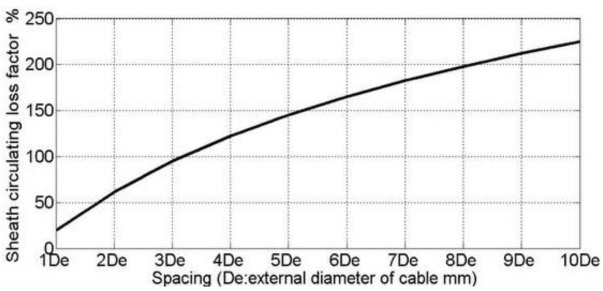

Fig. 11. Sheath circulating loss factor vs. conductor spacing (trefoil) [30]

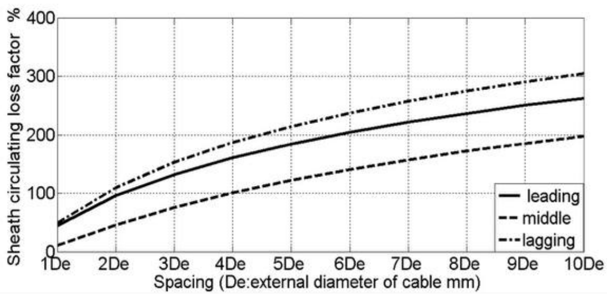

Fig. 12. Sheath circulating loss factor vs. conductor spacing (flat) [30]

Additionally, the sheath circulating loss factor versus conductor spacing for both trefoil and flat formation can be observed in **Fig. 11** and **Fig. 12** respectively. Hence, these papers show the importance of identifying the adequate distance between conductor spacing of cables to allow control of the temperature distribution within MVUG cables. When the control of conductor temperatures is accessible, the amount of voltage and current induced in cable sheaths generated can be reduced according to relevant system needs.

2.6. Depth of Installation

In most cases, the sheath voltage and circulating current induced are affected by the depths of installation. According to TNB's underground cable system design manual [17], the variation of cable ampacity produced is strongly influenced by the depths of cable system. When cable ampacity changes, the amount of induced sheath voltage and current also varies accordingly.

Producing a range of temperature distribution within the cables. **Table 6** shows how the number of cables in the same trench and depths of cable laying affect the cable ampacity, presented by TNB research [17].

Table 6. Typical TNB cable laying practices and their cable ampacity variation [17].

Voltage Level	***Laying Depth (mm)***	***Cable size (mm2)***	***Ampacity (Cable)***		
			1	***2***	***3***
11kV	1200	95	200	155	135
		150	240	190	165
		240	350	300	200
		500	550	460	400
		120	200	160	130
		185	250	200	170
		300	330	265	220
22kV	1200	150	250	200	170
		240	340	260	230
		185	275	230	200
		400	420	345	300
33kV	1500	630	525	450	380

3. Comparison of Software Used

Furthermore, temperature distribution within underground power cables due to induced sheath current leading to thermal breakdown can be analyzed using various simulation software such as Finite Element Method (FEM), CYMCAP, MATLAB, COMSOL, ANSYS, PSCAD, and others. **Table 7** below describes the difference in method of simulation implementation along with their advantages and disadvantages regard to previous papers and additional software guidelines [60], [61].

Table 7. Different simulation software and implementation methods [1], [5], [12], [13], [15], [31], [35], [39], [56]– [59]

Software	***Advantage***	***Disadvantage***
FEM	Allows for easier modeling of complex geometrical and irregular shapes	Large amount of data is required as input for the mesh used in terms of nodal connectivity and other parameters depending on the problem
CYMCAP	Provides increased confidence when upgrading existing power cable installations and designing new ones, thus maximizing the benefits from the considerable capital investment associated	Complex calculations with sensitive software computations
MATLAB	Implement and test algorithms easily, develop the computational codes easily, use a large database of built-in algorithms	It is an interpreted language and, therefore, may execute more slowly than compiled language, time consuming
COMSOL	Enables simulation of electromagnetics, structural mechanics, acoustics, fluid flow, heat transfer, and chemical phenomena in one environment	Difficult to use, complex formulations
ANSYS	Ergonomic and user-friendly criteria are introduced as standard, with the overall aim of developing more resistant, lightweight, and affordable structures	Requires basic mechanical engineering knowledge there for not much suitable for beginners.

Software	*Advantage*	*Disadvantage*
PSCAD	A flexible, powerful, and relatively cheap simulation program, maximize speed and provide memory efficient storage	Supports only time plots, not able to plot harmonic magnitude or phase versus frequency, graphs plotted could not be exported as a picture files

According to B. Perović et al. [13], it is quite difficult to solve problems using FEM or any FEM-based software including those mentioned in **Table 7** above due to the number of common restrictions addressed. A software called CABLEIZER for instance, can produce valid results and reasonings for the temperature distribution within underground power cables [62] due to induced sheath current leading to thermal breakdown analyzation, along with reducing errors obtained by other researches.

4. CABLEIZER Simulations

The study of different cable conditions' effect on the thermal distribution analysis of MVUG cables can be considered to be quite complex and tedious when simulated on an individual basis. Additionally, the generation of induced sheath voltage and current within MVUG cables will also heavily impact the thermal dissipation of cables produced. Hence, these variation limitations should be studied extensively using the appropriate application software made available to minimize errors and help ease the simulation process.

The analysis executed will provide us with constructive knowledge regarding the consequences of induced sheath voltage and current within MVUG cables along with the comprehension of thermal heat distribution analysis. Thus, acting as an advantageous and useful user-oriented application software for the investigation of voltage and current induced within sheath of MVUG cables.

4.1. Modelling of MVUG Power Cables

This study will focus specifically on medium voltage (MVUG) cables for distribution levels. Hence, 11kV TNB standard cables are used as reference [54]. MVUG cables are chosen fundamentally due to their existence and induced sheath voltage and current effects are more prominent as compared to LV/HV cables.

Fig. 13 shows the cross section of an 11kV MVUG cable conductor while **Table 8** describes the cable conductor specifications according to TNB guidelines. The cross section of a typical MVUG cable includes a metal conductor, conductor shield, insulation layer and screen, cable outer sheath, and conductor jacket.

Fig. 13. Cross section of an 11kV MVUG cable conductor

Table 8. Single core 11kV unarmored cable

Cable Parameter	*Quantity*
Nominal Area of Conductors (sqmm)	500
Thickness of Insulation (mm)	3.4
Thickness of Outer Sheath (mm)	4.0
Overall Diameter (mm)	46.7
Approx. Weight (kg/km)	2740

4.2. Modelling of MVUG Cable Configuration

Moreover, this study will concentrate on the effects of induced sheath voltage and current for MVUG cables with trefoil and flat formation only. Although these different laying arrangements are considered to be one of the most influential parameter for induced sheath voltage and current, we will also investigate the effects of other varying parameters such as type of earthing methods, thermal resistivity of soil, material of pipe ducts, method of cable burying, spacing between pipe ducts, method of burying cable and depths of buried cables.

To further evaluate the solemnity each parameter has on the generation of induced voltage and current of cable sheathes, each of the varying parameter will be examined individually. Other contributing factors will be kept at a constant value whilst the focused parameter varies in terms of value or intensity.

However, non-contributing factors of induced sheath voltage and current are maintained at a uniform value throughout the study. These include the system length of cables, temperature of soil, operating voltage and system frequency of cable configuration, and type of surrounding soil.

4.3. Description of Cable Configuration Variation

By identifying which MVUG cable parameter needs to be varied, it can help distinguish their effects on the induced sheath voltage and current generated within underground power cable sheaths. There are seven different parameters that we can discuss and analyze further as shown in the next sections. The results obtained from the simulations includes the conductor current and conductor temperature. Hence, the induced sheath voltage and current would be the results acquired from calculations of the obtained results.

5. Results and Discussions

5.1. Different Types of Earthing Methods

The burying method, system length, ambient temperature, thermal resistivity of soil, material of pipe duct, type of backfill, laying arrangements, and length of buried cables are kept at constant while the earthing methods are varied to single ends, both ends and cross bonding. The conductor current and temperature are obtained.

Table 9. Single core 11kV unarmored cable

Cable Condition	***Variation/Quantity***		
Laying Arrangement	Flat		
System Length (Buried)	1km		
Depth of Buried Cables (m)	1		
Type of Backfill	Directly Buried		
Operating Voltage	11kV		
Ambient Temperature (Soil)	25°C		
Material of Pipe Ducts	Polyvinyl Chloride (PVC)		
Spacing between Cable Ducts (cm)	0 (No Spacing)		
Thermal Resistivity of Soil (Km/W)	1.786 (Sand soil dry)		
Earthing Method	Single Ends (SE)	Both Ends (BE)	Cross Bonding (CB)
Result of Conductor Current (A)	521.80	413.40	522.20
Result of Conductor Temperature	A: 90°C B: 85.3°C C: 85.3°C	A: 77.9°C B: 90.0°C C: 85.1°C	A: 90.0°C B: 85.4°C C: 85.4°C
Temperature of Screen/Sheath	A: 87.7°C B: 83°C C: 83°C	A: 76.5°C B: 88.5°C C: 83.6°C	A: 87.7°C B: 83.1°C C: 83.1°C

In reference to the equations in Section 1.4, the induced sheath voltage and current are obtained and as shown in **Table 10** and **Table 11** respectively.

Table 10. Induced sheath voltage of different earthing methods (V/km)

Earthing Method	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
SE	221.402	187.624	221.398
BE	175.407	148.647	175.404
CB	221.571	187.768	221.568

Table 11. Induced sheath current of different earthing methods (A/km)

Earthing Method	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
SE	0.488	0.420	0.495
BE	0.401	0.327	0.392
CB	0.489	0.420	0.496

Induced sheath voltage generated for single ends and cross bonding are of similar values but are greater than both ends. Both ends produces the lowest induced sheath voltage generated. Hence, both ends produces the smallest value of induced sheath current, followed by a tie for single ends and cross bonding. Thus, both ends method is the best for generating the lowest amount of induced sheath current of an 11kV system.

5.2. Different Thermal Resistivity of Soil

The burying method, system length, ambient temperature, laying arrangement, material of pipe duct, type of backfill, earthing method, and length of buried cables are kept at constant while the thermal resistivity of soil are varied according to **Table 12**. The conductor current and temperature are also obtained.

Table 12. Single core 11kV unarmored cable

Cable Condition	***Variation/Quantity***		
Laying Arrangement	Flat		
System Length (Buried)	1km		
Depth of Buried Cables (m)	1		
Type of Backfill	Directly Buried		
Operating Voltage	11kV		
Ambient Temperature (Soil)	25°C		
Material of Pipe Ducts	Polyvinyl Chloride (PVC)		
Spacing between Cable Ducts (cm)	0 (No Spacing)		
Thermal Resistivity of Soil (Km/W)	1.786 (Sand soil dry)	1.047 (Sand soil moist)	0.463 (Sand soil soaked)
Earthing Method	Cross Bonding (CB)		
Result of Conductor Current (A)	521.8	628.7	780.3
Result of Conductor Temperature	A: 90°C B:85.3°C C: 85.3°C	A: 90°C B: 86°C C: 86°C	A: 90.0°C B: 87.4°C C: 87.4°C
Temperature of	A: 87.7°C	A: 86.6°C	A: 84.8°C

Screen/Sheath	B: 83°C	B: 82.7°C	B: 82.2°C
	C: 83°C	C: 82.7°C	C: 82.2°C

In reference to the equations in Section 1.4, the induced sheath voltage and current are obtained and as shown in **Table 13** and **Table 14** respectively.

Table 13. Induced sheath voltage of different thermal resistivity of soil (V/km)

Thermal Resistivity of Soil	*Cable Phase A*	*Cable Phase B*	*Cable Phase C*
1.786	221.402	187.624	221.399
1.047	266.760	226.062	266.756
0.463	331.084	280.573	331.080

Table 14. Induced sheath current of different thermal resistivity of soil (A/km)

Thermal Resistivity of Soil	*Cable Phase A*	*Cable Phase B*	*Cable Phase C*
1.786	0.488	0.420	0.495
1.047	0.590	0.506	0.597
0.463	0.737	0.630	0.743

As the amount of water present in soil increases, the thermal resistivity decreases. The induced sheath voltage and current generated is inversely proportional to the soil's thermal resistivity, meaning that as thermal resistivity of soil decreases, the induced sheath voltage, and current generated increases. Hence, the higher the thermal resistivity, the better. Thus, dry sand soil condition (1.786Km/W) produces the least induced sheath current, followed by moist sand soil and soaked sand soil (highest). Hence, dry sand soil condition will produce the lowest induced sheath current.

5.3. Different Laying Arrangements

The burying method, system length, ambient temperature, thermal resistivity of soil, material of pipe duct, type of backfill, earthing method, and length of buried cables for both conditions are kept at constant while the laying arrangements are varied to flat and trefoil. The conductor current and temperature are also obtained as stated in **Table 15.**

Table 15. Single core 11kV unarmored cable

Cable Condition	*Variation/Quantity*	
Laying Arrangement	Flat	Trefoil
System Length (Buried)	1km	
Depth of Buried Cables (m)	1	
Type of Backfill	Directly Buried	
Operating Voltage	11kV	
Ambient Temperature (Soil)	25°C	
Material of Pipe Ducts	Cement	
Spacing between Cable Ducts (cm)	0 (No Spacing)	
Thermal Resistivity of Soil (Km/W)	1.786 (Sand soil dry)	
Earthing Method	Both Ends (BE)	
Result of Conductor Current (A)	413.1	436
Result of Conductor Temperature	A: 78°C B: 90°C C: 85.1°C	A: 88.9°C B: 90.0°C C: 90°C
Temperature of Screen/Sheath	A: 76.6°C B: 88.5°C C: 83.7°C	A: 87.2°C B: 88.4°C C: 88.4°C

In reference to the equations in Section 1.4, the induced sheath voltage and current are obtained and as shown in **Table 16** and **Table 17** respectively.

Table 16. Induced sheath voltage of different laying arrangement (V/km)

Laying Arrangement	*Cable Phase A*	*Cable Phase B*	*Cable Phase C*
Flat	175.280	148.539	175.277
Trefoil	26.220	21.910	10.960

Table 17. Induced sheath current of different laying arrangement (A/km)

Laying Arrangement	*Cable Phase A*	*Cable Phase B*	*Cable Phase C*
Flat	0.400	0.327	0.391
Trefoil	0.058	0.048	0.024

Induced sheath voltage and current is highly influenced by the type of cable laying arrangement. When the cables are arranged in trefoil as compared to flat, they manage to cancel each other out and reduce the induced sheath voltage and current produced. The pattern obtained for both flat and trefoil is also unalike due to its arrangement. Hence, we can conclude that trefoil arrangement will produce, and much lower induced sheath current as compared to flat.

5.4. Different Material of Pipe Ducts

The burying method, system length, ambient temperature, thermal resistivity of soil, type of backfill, laying arrangement, earthing method, and length of buried cables are kept at constant while material of pipe ducts are varied as stated in **Table 18.**

Table 18. Single core 11kV unarmored cable

Cable Condition	***Variation/Quantity***			
Laying Arrangement	Flat			
System Length (Buried)	1km			
Depth of Buried Cables (m)	1			
Type of Backfill	Directly Buried			
Operating Voltage	11kV			
Ambient Temperature (Soil)	25°C			
Material of Pipe Ducts	Without Ducts (WD)	(PVC)	Cement (C)	Steel (S)
Spacing between Cable Ducts (cm)	0 (No Spacing)			
Thermal Resistivity of Soil (Km/W)	1.786 (Sand soil dry)			
Earthing Method	Single Ends (SE)			
Conductor Current (A)	471.4	521.8	521.5	548.5
Result of Conductor Temperature	A: 90°C B: 88.3°C C: 88.4°C	A: 90°C B: 85.3°C C: 85.3°C	A: 90.0°C B: 85.3°C C: 85.3°C	A: 90.0°C B: 89.8°C C: 89.8°C
Temperature of Screen/Sheath	A: 88.1°C B: 86.4°C C: 86.5°C	A: 87.7°C B: 83°C C: 83°C	A: 87.7°C B: 83°C C: 83°C	A: 87.4°C B:87.3°C C: 87.3°C

In reference to the equations in Section 1.4, the induced sheath voltage and current are obtained and as shown in **Table 19** and **Table 20** respectively.

Table 19. Induced sheath voltage of different material of pipe ducts (V/km)

Material of Pipe Ducts	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
WD	200.017	169.502	200.014
PVC	221.402	187.624	221.398
C	221.274	187.516	221.271
S	232.730	197.225	232.727

Table 20. Induced sheath current of different material of pipe ducts (A/km)

Material of Pipe Ducts	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
WD	0.441	0.375	0.443
PVC	0.488	0.420	0.495
C	0.488	0.420	0.495
S	0.514	0.435	0.514

Different material of pipe ducts will result in varying induced sheath voltage and current. Hence, in this pipe duct material configuration, induced sheath voltage generated will be at the lowest when there is no presence of pipe ducts, followed by cement, PVC, and steel. However, induced sheath current is influenced by the electrical sheath resistance of pipe ducts. Thus, making the condition where steel pipe ducts are implemented produces the highest induced sheath current, followed by cement (a tie with PVC) and steel.

Even though the induced sheath current generated is the lowest with the absence of pipe ducts, it is not really an ideal implementation in real life conditions as pipe ducts are needed to avoid physical damage caused by natural sources. Thus, making conditions where PVC or cement pipe ducts are implemented most ideal for real life situations. However, PVC is often opted as it is more affordable.

5.5. Different Type of Backfills

The burying method, system length, ambient temperature, thermal resistivity of soil, material of pipe duct, laying arrangement, earthing method, and length of buried cables are kept at constant while type of backfills are varied as shown in **Table 21.**

Table 21. Single core 11kV unarmored cable

Cable Condition	***Variation/Quantity***		
Laying Arrangement	Flat		
System Length (Buried)	1km		
Depth of Buried Cables (m)	1		
Type of Backfill	Directly Buried (DB)	In Concrete (IC)	In Sand (IS)
Operating Voltage	11kV		
Ambient Temperature (Soil)	25°C		
Material of Pipe Ducts	Cement (C)		
Spacing between Cable Ducts (cm)	0 (No Spacing)		
Thermal Resistivity of Soil (Km/W)	1.786 (Sand soil dry)		
Earthing Method	Single Ends (SE)		

Result of Conductor Current (A)	513.2	531.2	531.2
Result of Conductor Temperature	A: 90°C B: 85.4°C C: 85.4°C	A: 90°C B: 84.6°C C: 84.7°C	A: 90.0°C B: 84.6°C C: 84.7°C
Temperature of Screen/Sheath	A: 87.8°C B: 83.2°C C: 83.2°C	A: 87.6°C B: 82.2°C C: 82.3°C	A: 87.6°C B: 82.2°C C: 82.3°C

Although the conductor current values are similar, the induced sheath voltage and current is also affected by the electrical sheath resistance obtained, as shown in **Table 22.**

In reference to the equations in Section 1.4, the induced sheath voltage and current are obtained and as shown in **Table 23** and **Table 24** respectively.

Table 22. Electrical sheath resistance, Rsh (Ω/m)

Cable Phase	***Electrical Sheath Resistance (Ω/m)***
A_DB	4.536E-04
B_DB	4.472E-04
C_DB	4.472E-04
A_IC	4.534E-04
B_IC	4.458E-04
C_IC	4.459E-04
A_IS	4.534E-04
B_IS	4.458E-04
C_IS	4.459E-04

Table 23. Induced sheath voltage of different type of backfills (V/km)

Type of Backfills	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
DB	221.402	184.532	217.750
IC	225.390	191.004	225.387
IS	225.390	191.004	225.387

Table 24. Induced sheath current of different type of backfills (A/km)

Type of Backfills	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
DB	0.480	0.413	0.487
IC	0.497	0.428	0.505
IS	0.497	0.429	0.743

The induced sheath voltage generated is the lowest when the cables are directly buried into the ground rather than in both type of backfills (concrete & sand). This is due to the additional heat coming from the backfill surrounding the cables. Similar to induced sheath current, directly buried cables generates the lowest induced sheath current as compared to cables buried in backfills (concrete & sand). However, due to the uneven heat dissipation of the sand, it will cause an uneven induced sheath current production as shown in the figure above. Hence, it is more ideal to directly bury the cables into the ground without any backfill, depending on the suitability of the configuration.

5.6. Different Spacing between Cable Ducts

The burying method, system length, ambient temperature, thermal resistivity of soil, material of pipe duct, laying arrangement, earthing method, type of backfills, and length of buried cables are kept at constant while spacing between cable ducts are varied as shown in **Table 25**.

Table 25. Single core 11kV unarmored cable

Cable Condition	***Variation/Quantity***		
Laying Arrangement	Flat		
System Length (Buried)	1km		
Depth of Buried Cables (m)	1		
Type of Backfill	Directly Buried (DB)		
Operating Voltage	11kV		
Ambient Temperature (Soil)	25°C		
Material of Pipe Ducts	Cement (C)		
Spacing between Cable Ducts (cm)	0 (No Spacing)	10 cm (10)	50 cm (50)
Thermal Resistivity of Soil (Km/W)	1.786 (Sand soil dry)		
Earthing Method	Both Ends (BE)		
Result of Conductor Current (A)	412.1	403	395.5
Result of Conductor Temperature	A: 78°C B: 90°C C: 85°C	A: 78.1°C B: 90°C C: 84.1°C	A: 79.4°C B: 90°C C: 83.3°C
Temperature of Screen/Sheath	A: 76.6°C B: 88.6°C C: 83.6°C	A: 76.7°C B: 88.6°C C: 82.7°C	A: 78.1°C B: 88.7°C C: 82.0°C

In reference to the equations in Section 1.4, the induced sheath voltage and current are obtained and as shown in **Table 26** and **Table 27** respectively.

Table 26. Induced sheath voltage of different spacing between cable ducts (V/km)

Spacing between Cable Ducts	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
No Spacing	174.855	148.180	174.853
10	170.994	144.907	170.992
50	167.812	142.210	167.810

Table 27. Induced sheath current of different spacing between cable ducts (A/km)

Spacing between Cable Ducts	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
No Spacing	0.400	0.326	0.391
10	0.390	0.319	0.383
50	0.381	0.313	0.377

The effects created from varying the spacing between ducts is similar to varying the spacing between cables. When the spacing between ducts increase, the induced sheath voltage and current generated decreases. Hence, deducing the relation that spacing between cables is inversely proportional with the induced sheath voltage and current produced. Thus, when the duct spacing is the furthest (50 cm), induced sheath voltage and current generated is the lowest. Proving that it is more ideal to increase the space between the ducts to decrease the induced sheath current of cable system.

5.7. Different Depth of Buried Cables

The burying method, system length, ambient temperature, thermal resistivity of soil, material of pipe duct, laying arrangement, earthing method, type of backfills, spacing between cable ducts, and length of buried cables are kept at constant while depths of the buried cables are varied as shown in **Table 28.**

Table 28. Single core 11kV unarmored cable

Cable Condition	***Variation/Quantity***		
Laying Arrangement	Flat		
System Length (Buried)	1km		
Depth of Buried Cables (m)	1	1.2	1.5
Type of Backfill	Directly Buried (DB)		
Operating Voltage	11kV		
Ambient Temperature (Soil)	25°C		
Material of Pipe Ducts	Cement (C)		
Spacing between Cable Ducts (cm)	0 (No Spacing)		
Thermal Resistivity of Soil (Km/W)	1.786 (Sand soil dry)		
Earthing Method	Cross Bonding (CB)		
Result of Conductor Current (A)	413.1	402.9	391.3
Result of Conductor Temperature	A: 78.0°C B: 90.0°C C: 85.1°C	A: 77.8°C B: 90.0°C C: 85.1°C	A: 77.6°C B: 90.0°C C: 85.0°C
Temperature of Screen/Sheath	A: 76.6°C B: 88.5°C C: 83.7°C	A: 76.5°C B: 88.6°C C: 83.7°C	A: 76.3°C B: 88.7°C C: 83.8°C

In reference to the equations in Section 1.4, the induced sheath voltage and current are obtained and as shown in **Table 29** and **Table 30** respectively.

Table 29. Induced sheath voltage of different depth of buried cables (V/km)

Depth of Buried Cables	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
1	175.280	148.539	175.277
1.2	170.952	144.871	170.950
1.5	166.030	140.700	166.028

Table 30. Induced sheath current of different depth of buried cables (V/km)

Depth of Buried Cables	***Cable Phase A***	***Cable Phase B***	***Cable Phase C***
1	0.400	0.327	0.391
1.2	0.391	0.319	0.382
1.5	0.380	0.310	0.371

As depth of buried cables increase, induced sheath voltage and current generated decrease. The depth of buried cables is inversely proportional to the induced sheath current produced. Hence, we must increase the depth of buried cables to decrease induced sheath current generated. However, considering the situation on site, the further the buried cables are to the surface of the burial, it is more difficult to dig and costs more for extra labor work. When the buried cables are closer to the surface, it is more prone to damage such as external digging works and accidents. Thus, 1.2m is ideal for an 11kV burial system, as practiced by TNB.

6. Conclusion

The basics of MVUG cables which consist of dielectric and ohmic losses, cable ampacity, and cross section of MVUG cables are presented along with the fundamentals of induced sheath voltage and current. The factors of induced voltage and circulating currents in cable sheath are also comprehensively discussed in order to fully recognize and design simulations of crucial parameters.

As considered from the literature, the fundamental factors affecting induced sheath voltage and current generated can be divided into several categories such as the earthing method of the system, laying arrangements of cable configurations, thermal resistivity of soil, material of pipe ducts and backfills, spacing between the cable ducts in any arrangements, and cable depths installations. The general description, advantages, disadvantages, and previous research according to the specific elements were also analyzed, compared, and reconstructed.

Cable losses due to heat can be reduced by identifying the important cable conditions which also contribute to the increment of induced sheath voltage and current. In terms of performance evaluation, the optimal cable condition for a single core 11kV unarmored cable is by implementing both ends earthing methods, trefoil cable laying arrangement, directly burying cables into the ground, and a cable depth of 1.2m. Furthermore, increasing the space between cable ducts along with the usage of dry sand soil and PVC ducts.

In conclusion, the theoretical analysis of induced sheath voltage and current cable condition factors were identified and simulated with the use of CABLEIZER software. However, the temperature distribution within MVUG cables should be verified with other software such as FEM to further discuss the actual temperature induced within cable sheaths.

6.1. Acknowledgements

Works were carried out under the Institute of Power Engineering Universiti Tenaga Nasional, in collaboration with TNB Research Sdn. Bhd, Universiti Teknologi MARA, and Universiti Malaya. The authors would like to thank the Ministry of Higher Education Malaysia (MOHE) for funding this study under the Fundamental Research Grant Scheme (FRGS) of Grant No. FRGS/1/2021/TK0/UNITEN/02/1.

Author Contributions

Nur Faqihah Abdul Halim: Data collection, Interpretation of Data, Writing-Original Draft Manuscript Preparation, Conception Design and Editing. **Suhaila Sulaiman, Azrul Mohd Ariffin:** Critical Revision Process for Intellectual Content, Writing-Reviewing, Software Validation, Editing and Final Approval of Manuscript. **Nik Hakimi Nik Ali, Huzainie Shafi Abd Halim, Hazlee Azil Illias:** Final Approval of Manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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