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Medium Voltage Single-Core Cable Armoring, Induced Currents, and Losses: A Research

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Abstract

Insulated underground cables have the potential to reduce maintenance expenses, transmission losses, and power outages as compared to overhead lines. However, because they are buried underground, they are susceptible to a number of threats and physical harm. The cables provide mechanical protection, tensile strength, and other advantages in addition to carrying earth fault currents adequately despite being armoured. This paper's primary goals are to introduce insulated underground cables, describe the armouring process, and analyse the induced currents that occur in metallic components like sheaths and armour and result in ohmic losses. These currents can be broadly divided into two groups: circulating current and eddy current. This paper provides an overview of analytical techniques for calculating losses in cable armour, analysing the impact of magnetic fields, and proposing strategies and solutions for armour loss reduction.

Keywords

Single-Core Cable, Armour, Armour Loss, Eddy Current, Circulating Current, Hysteresis Losses

1. Introduction

Using subterranean cables in distribution networks has become a crucial strategy to lower the danger of substantial storm-related outages on overhead conductors as the reliability of the power supply has become an increasingly critical aspect. Compared to overhead lines, insulated underground cables offer the potential to reduce outages, maintenance costs, and transmission losses.

Medium voltage (MV) cables are widely used for power distribution between high voltage mains power supply and low voltage applications. The main purpose of choosing a cable is to safely provide adequate electrical power, with continuous, trouble-free operation, in a system that can withstand unexpected demands and overload conditions.

A medium voltage insulated cable circuit consists of three single-core cables or one three-core cable with terminations at each end to connect to the transformer or switchgear within the network. The main differences between single-core and three-core cables are the thickness and approximate outer diameter of the cable, and the cable's weight which is less in single-core cable than the three-core type of the same section. Besides, in order to solve the problem of phase insulation, a single-core type is usually adopted. Although single-core cables are not quite suitable for multi-circuit line engineering of substation's inbound and outbound lines. When single-core cables connect to indoor distribution devices, due to the space limitations, they easily collide with one another, making the installation of cable terminals challenging [1].

The components of these cables that essentially determine the electrical and thermal behavior of the cable mainly consist of the current-carrying conductor, inner and outer semi-conductive layers as the insulation part, and the metallic screen. Conductors primarily made from stranded copper (Cu) or Aluminum (Al). Even though copper has a long history as the material of choice for electrical products, the price developments led to an overall competition between copper and other potential alternative materials. The aluminum industry has therefore become the biggest threat of substitution for copper producers, compromising the monopoly position of copper as an electrically conductive material. In contrast to copper, abundant and low-cost deposits of aluminum were available with ore concentrations of 20% - 40%, while copper had already become scarce with ore concentrations of about 2%. Concerning its quality as an electrical conductor, aluminum features conductivity values that are almost as qualified as those of copper, whereas aluminum is clearly superior as far as density is concerned [2]. Some of the advantages and disadvantages of aluminum are mentioned in **Table 1**.

Table 1. Advantages and disadvantages of aluminum compared to copper.

Advantages	Disadvantages
Aluminum has a more than three times smaller specific weight compared to copper [3].	Aluminum's lower conductivity results in a lower current carrying capacity (CCC) and increased voltage drop, compared to a copper cable of the same size
The lighter weight of aluminum cable reduces the tensile force placed on wire and poles.	The larger diameter of aluminum strands with a density of 2703 kg/m^3 at 20˚C results in less flexible cables than copper which is denser (8890 kg/m^3 at 20˚C) and is available in very low cross-sections.
Aluminum is relatively inexpensive	
The greater availability of raw aluminum. Global bauxite as the world's main source of aluminum is estimated at 55 - 75 billion tons, while world copper resources are estimated at 2.1 billion tons [4].	Aluminum has a higher coefficient of thermal expansion than copper that increases the risks of sag and destructive forces in joints

Generally, a conductor is insulated with polymers or polyethylene materials and there is also at least one semiconductive or screen layer. These cables are often designed with an insulating layer placed between two semiconductive layers in order to provide an equipotential surface to make the electric field of the insulating material uniform. The semiconductive layer forming the outer covering can be placed either by extruding the semiconductive composition on the conductor which is coated with at least the insulating layer, or by helically winding a tape of semiconductive composition on the same unit [5].

The rated voltage of a medium voltage cable is determined by the thickness of the whole insulation part around the conductor, which is set at specified levels according to standards.

The armour is an optional layer consists of metal wires or strips that are set over the separation sheath or bedding and provides additional protection where mechanical stress has the potential to cause damages to the cable. The armour wires usually earthed without running a separate earth conductor [6]. For multicore cables, steel wire armour is used (SWA), whereas a layer of protective aluminum armour (AWA) is used for single-core cables. This is because a magnetic field is produced by the current which induces an electric current (eddy currents) in any ferromagnetic armour material, such as steel, which could lead to the cable overheating. The non-magnetic aluminum armour prevents this from happening.

This paper presents the analysis of armoured cables, their pertinent characteristics, and provides information on the strengths and drawbacks, as well as calculation methods for armour losses.

The paper is organized as follows:

- Section 2 describes the armour of the cable, its characteristics, and the materials that can be used for this purpose.
- Section 3 focuses on the occurrence of the armour losses and describes the types of the losses.
- Section 4 reviews the different methods for calculating cable armour losses.
- Section 5 reports the conclusions of the work.

2. Armour

To protect cables from mechanical damages, cable armouring is employed [7]. Armour provides mechanical protection from crushing forces while serving as an Earth Continuity Conductor (ECC) to provide effective conductance of earth fault currents.

The external magnetic field of a three-core cable carrying balanced load currents quickly decreases to zero, because the vectorial sum of the spatial and time-resolved components of the field is zero. Thus, a useful degree of ferromagnetic armouring is achieved for three-core cables by the application of steel wire armour, which allows to contain the flux [8].

Nevertheless, the possibility of armouring single-core cables has been considered from time to time with a wide variety of opinions as to the resulting loss values. The publication of promiscuous experimental data on armour losses, relating usually to the prohibitively great loss in low-tension cables of large current-carrying capacity, has recently directed the attention to minimize the losses, by careful design. As mentioned, if magnetic material is employed as armour for a three-core cable carrying a three-phase current, there is practically no trouble due to inductive effects, since the resultant magnetomotive force around the three cores is zero. In the case of single-core cables, however, the inductive effects may become so pronounced that armouring becomes impracticable. Thus, because of the very high losses that would occur in single-core cables with magnetic armour, nonmagnetic material has been used in recent years for armoured single-core cables in AC systems [9]. To reduce the losses in the cable armour using a different material for the armour, particularly using a non-ferromagnetic metal like copper, bronze, brass, or stainless steel, aluminum is possible [10]. **Table 2** indicates the electrical properties of the common metals used in cables [11].

Taking price into consideration, copper wire armour (CWA) and aluminum wire armour (AWA) are the best choices for armouring single-core XLPE cables as they are non-magnetic, and hence there is no need to take the effects of eddy currents and hysteresis loss into account. Copper is far more resistant to corrosion than aluminum, but due to the higher cost of copper, aluminum is preferred. Aluminum is prone to corrosion, especially when buried in the ground or in other situations where moisture is present. If water penetrates the outer sheath of an AWA cable the armour will rapidly corrode and the earth fault capability of the cable will be reduced or lost entirely depending on the degree of corrosion. The protection of aluminum against corrosion is of particular importance, so, it is most important to utilize protection over exposed metal right up to and over the termination. The corrosion of aluminum usually takes the form of local pits which may quickly penetrate a sheath, although general surface attack may be quite small. The mechanism of pitting is associated with the local breakdown of the protective oxide film, in conditions that do not allow its repair, followed by cell action due to differential conditions of electrolyte concentrations or aeration. The presence of other underground services containing metals anodic to aluminum, such as lead, steel, or copper, may accelerate the attack. While some soils, such as in the made-up ground, are worse than others, it

Table 2. Electrical properties of metals.

Metal	Relative conductivity	Electrical resistivity at 20˚C (Ω·m, 10^{-8})	Temperature coefficient of resistance (per ˚C)
Copper	100	1.724	0.0039
Aluminum	61	2.826	0.0040
Steel	12	13.80	0.0045

is always essential to consider that any ground is aggressive and to ensure that good protection exists [12].

As mentioned, the induced electric current in ferromagnetic armour material may result in losses and temperature rise in the cable and become a cause of concern. The relevant information for these losses is provided in the next section.

3. Armour Loss

When a conductor cable carries alternating current, an alternating magnetic field is generated around it, which is much stronger if the conductor is surrounded by an iron-rich material, like steel wire as armour or steel conduit. The currents in a twin cable, or two single-core cables feeding a single load, will be the same. They will exert opposite magnetic effects which will almost cancel so that virtually no magnetic flux is produced if they are both enclosed in the same conduit or armouring as shown in **Figure 1**. The same is true of three-phase balanced or unbalanced circuits provided that all three are within the same steel armouring or steel conduit. Hence, all conductors of a circuit must be contained within the same cable, or are in the same conduit if they are single-core types.

If the single-core cable has a metal sheath that is non-magnetic, less magnetic flux will be produced. However, there will still be induced EMF in the sheath, which can give rise to a circulating current and sheath heating [13]. Circulating losses are due to currents flow in metallic sheaths circuits of single conductor power cables that are bonding at both ends and create a closed path. Eddy currents losses are due to induced currents in sheaths which circulate radially as a result of skin effect and azimuthally as a result of proximity effect. So, grounding system types including single-point bonding, both ends bonding, and cross bonding, play a major role in the losses incurred. The advantage of single-point grounding systems is lower losses and its disadvantage is creating induced voltage at the unearthed end of cables which can be high enough to be hazardous. Although it should be mentioned that in a faulty power cable system, currents should pass all lengths of cable to the ground which may cause additional losses

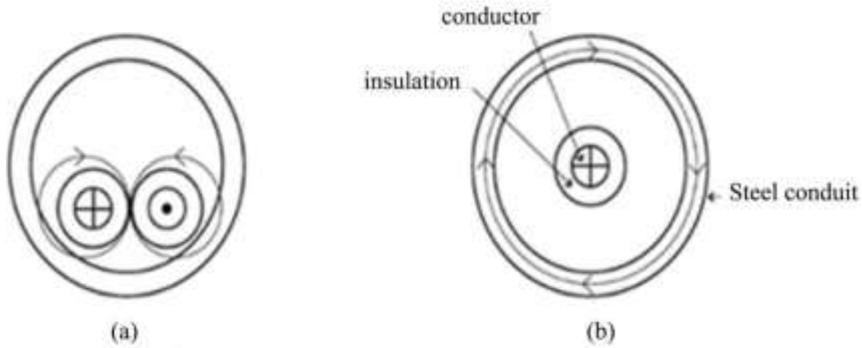

Figure 1. Iron losses in the steel surrounding a cable when it carries alternating current. (a) twin conductors of the same single-phase circuit, no losses; (b) single cone conductor high losses. (a) Near zero alternating flux; (b) strong alternating flux.

[14]. While in both ends bonding systems, there is no induced voltage at the ends of cables. In the failure situation of such systems, currents are divided into two portions that cause reduction of fault losses. But these systems have additional losses at steady-state conditions due to circulating currents in metallic sheaths. The cross-bonding method decreases circulating currents and high induced voltage as well. In this method, the cable system is consisting of three sections with repeating all three-phase sheaths in each part. In an ideal case, induced voltages in sheaths are equal in magnitude with 120˚ phase difference. Thus, the total voltage in each part is equal to zero. This method can be used only in cable systems with long lengths. Also, its implementation is expensive and needs skilled workers to run. Therefore, the cross-bonding method is not capable to perform in any situation.

It should be mentioned that eddy currents of sheaths occur in both mul- ticonductor and single conductor cables and also in single point or two ends bonding systems. But in the case of bonding sheaths at two ends these currents are small compared to circulating currents. Thus, eddy current losses can be ignored in cable analysis on both ends of grounding systems [15]. These losses are related to the magnetic field generated by AC current transported by the electric conductors, which causes eddy currents in the layers surrounding the cores (like, for example, the metal screen and the wires of the armour) and magnetic hysteresis of the ferromagnetic wires of the armour [16].

At present, IEC 60287 is used to calculate the sheath and armour losses for single-core cables with nonmagnetic armour [17], though this paper presents methods by different authors for calculating sheath and armour losses, in the next section.

4. Calculation of Armour Loss

Losses in protective armouring fall into several categories depending on the cable type, the material of the armour, and installation methods.

When magnetic armour such as steel is used for single-core cable, losses due to eddy currents and hysteresis in the steel must be considered. A method of calculating these losses is given by Bosone [18], and results agree with those obtained in the limited experimental work reported by Whitehead and Hutchings [19]. The latter work demonstrated that the losses in the sheath and armour combination could be several times the conductor losses, depending on the bonding arrangements of the sheaths and armour. The armour losses are lowest when the armour and sheath are bonded and grounded together at both ends of a run. AC cable's armour wire has three types of losses. Firstly, the Joule losses due to the armour's resistance and current flow in the longitudinal wire direction. This loss is well known as single-core cable loss and is caused when the single-core AC cable operates solidly bonded. Secondly, the eddy current loss is caused by induced currents by the magnetic flux in the armour wire formed by the conductor current [20]. If the flux density B_y is constant inside a wire with the diameter d, the eddy current loss P_a in the wire is according to Equation (1) given in [20].

$$P_a = \frac{\pi d^4 \sigma \omega^2 B_y^2}{64} \quad (1)$$

where d = the wire diameter, σ = wire conductivity, B_y = flux density, and ω = angular frequency.

The eddy current has its maximum value at the outer and inner parts of the wire. The equation gives the maximum power loss in an armoured single-core cable. Practically, the eddy current loss is lower than shown in Equation (1), since the skin effect will reduce the power loss inside the wire [21]. So, the eddy current varies due to the skin effects according to the properties of the ferro-magnetic materials [20]. The magnitude of the magnetic flux density depends on the conductor current and the relative permeability μ_e of the magnetic steel material. The wires are supposed to have no metallic contact since the relative permeability will be decreased in the φ-direction through the armouring wires and the wire gaps. The wire gap δ reduces the total permeability μ_t according to Equation (2) from [20].

$$\mu_t = \frac{d}{d + \mu_e \delta} \cdot \mu_e \quad (2)$$

For magnetic steel materials, IEC 60287 recommends $\mu_e = 400$, $\mu_t = 10$ when wires are in contact, and $\mu_t = 1$ where wires are separated.

$\mu_t = 10$ determines the wire gap δ to be around 0.4 mm for $d = 5$ mm. The permeability is then reduced about 40 times, compared to having the wires in direct metallic contact with each other. Instead of reducing the permeability of the magnetic steel material itself, the magnetic field intensity H is then reduced indirectly by the existing wire gaps in the cable. For example, a magnetic field intensity $H = 4000$ A/m originated from a conductor current $I = 1500$ A, is reduced to about 100 A/m (40 times) [21].

The third type of loss is hysteresis loss which is caused by the nonlinear characteristics of the ferromagnetic armour wires, that is relatively high for three-core combined cables, due to the low magnetic flux density in the armour [20].

For purposes of armouring single-core cables, there are special electrical requirements, such as low permeability and high resistivity which are difficult to obtain in conjunction with the mechanical requirements, and without raising the cost excessively.

In **Figure 2** some oscillograph records of the sheath, armour, and core currents are given for 66 kV cables with the lay of 68.2 cm [22].

It should be noted that on account of the variation of permeability of the armour, the induced voltages are not strictly proportional to the core currents. The effective permeability may be calculated from formula (3) stated in [22].

$$\mu = \left(\frac{10^8 l}{0.4\pi N^2 A} \right) L \quad (3)$$

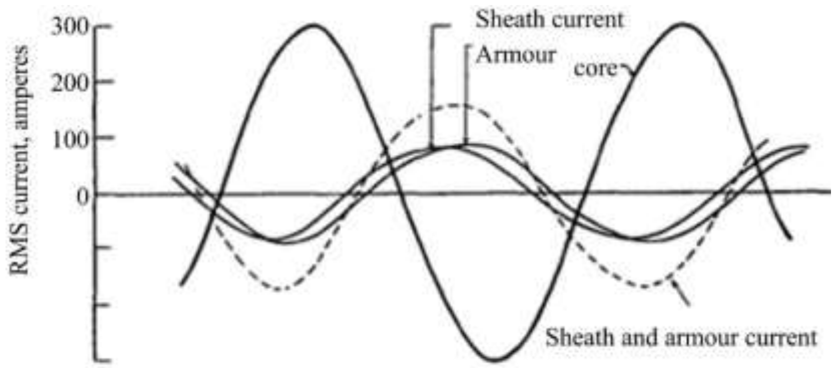

Figure 2. Oscillograph records of sheath and armour current when bonded.

where l is the length of the sample (cm), N is the number of turns on the magnetizing coil, A is the area of cross-section of iron of armour wire (cm^2), and L is the inductance of coil.

Tests taken on several samples of ordinary galvanized iron wires are given in **Figure 3** and **Figure 4**. A key to the numbering of the curves is given in **Table 3**.

The curve so obtained is shown in **Figure 5** and will be seen to be almost identical with those obtained from the tests on the wire samples 1 and 2 (**Figure 4**), except for small values of H, in which case the loss is rather higher in **Figure 5** [22].

To minimize the losses in the case of single-core cables armoured with magnetic material the wire should be applied with as long a lay as possible. An effective increase in lay, and hence a reduction in armour loss, is obtained by intertwisting cables as indicated.

Based on the tests performed by Brockbank and Webb [22] by utilizing bridging method on single-core, lead-covered armoured 66 KV cables, there is evidence that there are some ways to reduce armour loss when using magnetic materials for single-core cables. The external magnetizing force along the armour wires, causes a flux to alternate along the wires, which increases the losses due to eddy currents and hysteresis. The formula (4), stated in [22], shows that the only two variables are the core current and the length of wire per turn.

$$H = 0.4\pi \frac{I}{l_t} \tag{4}$$

In the above formula, H is magnetizing force and l_t is the length of one complete turn of armour as shown in Equation (5) from [22].

$$l_t = \sqrt{(2\pi r_a)^2 + l^2} \tag{5}$$

It is seen that by increasing the amount of r_a and l which are the mean radius through wires and the length of lay respectively, we can reduce the magnetized force. In the case of e.h.t. (Extra high tension) cables, the length of lay is larger than low-tension cables because of the greater diameter of the dielectric layer. It should be noted that the birdcage of the wire is a limit to the increment of lay length.

Table 3. Wire samples referred to in **Figure 3** and **Figure 4**.

Sample number	Diameter of wire (inch)
1	0.129
2	0.127
3	0.104
4	0.083
5	0.073
6	0.062

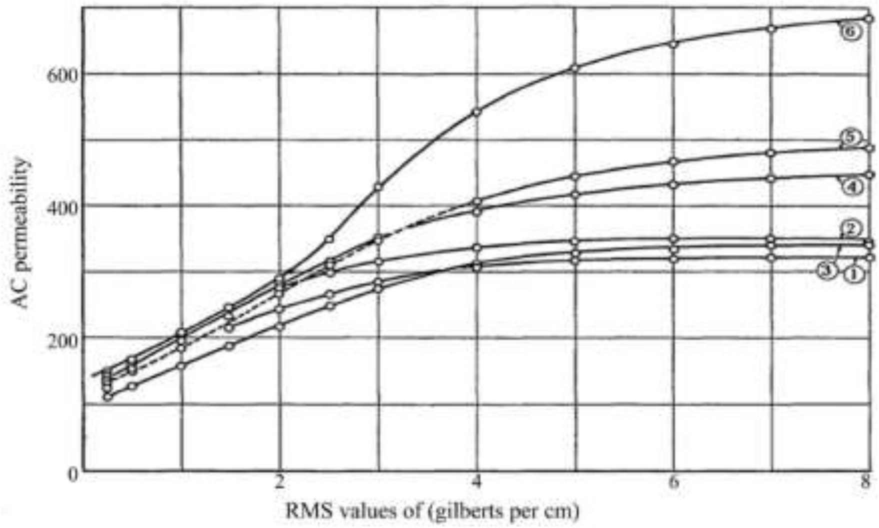

Figure 3. Magnetic tests on samples of armour wire at 50 cycles per sec.

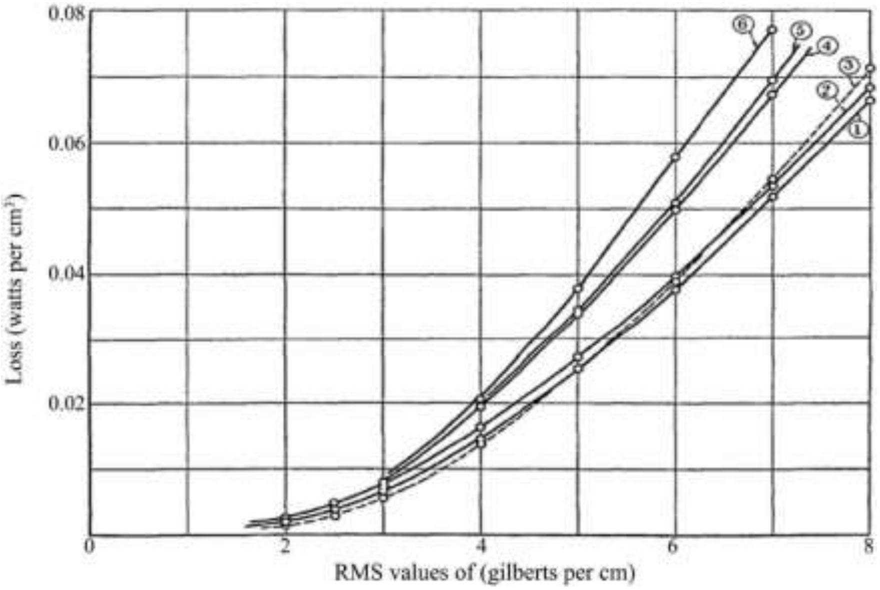

Figure 4. Magnetic tests on samples of armour wire at 50 cycles per sec.

Intertwisting cables in the same sense as the armour, as showed in **Figure 6**, can help to increase the effective lay.

Figure 5. Variation of loss with magnetizing force in 0.128-inch armour wire. Deduced tests on armoured cables.

Figure 6. The three cables of a 3-phase system intertwisted.

Therefore H' as magnetizing force along wires due to current in adjacent cables is equivalent to Equation (6) from [22].

$$H' = 0.4\pi \frac{I}{l_t'} \quad (6)$$

where l' is the length of armour wire encircled by one turn of adjacent cable (or cables) forming return path. Accordingly, the resultant magnetizing force acting along the wires is shown in Equation (7) given in [22]:

$$H + H' = \frac{}{l_t l_t' / (l_t' - l_t)} \quad (7)$$

π
I

The tests were performed by using the bridge method to measure the ratio of the AC to the DC loss on six groups of cables designed with 46/0.128-inch galvanized steel armour wire, with different lays as **Table 4**. The lays were measured by counting the number of complete twists of wire in a given length. For groups D, E, and F the cables were twisted together in the same sense as the armour wire. Throughout the tests, measurements were in general made at five different values of the current ranging from 50 to 300 amperes.

The tests on single-phase resulted in the curves in **Figure 7** and **Figure 8**, which shows the relationship between the loss per cm^3 and the root-mean-square value of H along the wire when lead and armour are bonded and cables are in contact. As can be seen in **Figure 7**, increasing the effective lay by twisting the cables reduces the losses [22].

From Harvey and Busby [23] experiment it has been shown that watt loss on a

Table 4. Group of cables designed with 46/0.128-inch galvanized steel armour wire, with different lays.

Group	Lay of wire on cable (cm), l	Lay of twist of two cables (cm), l'	Effective lay (cm), $ll'/(l'-l)$
A	54	-	
B	86.2	-	-
C	130.3	-	-
D	71	250	-
E	71	125	99
F	130.3	200	164.3

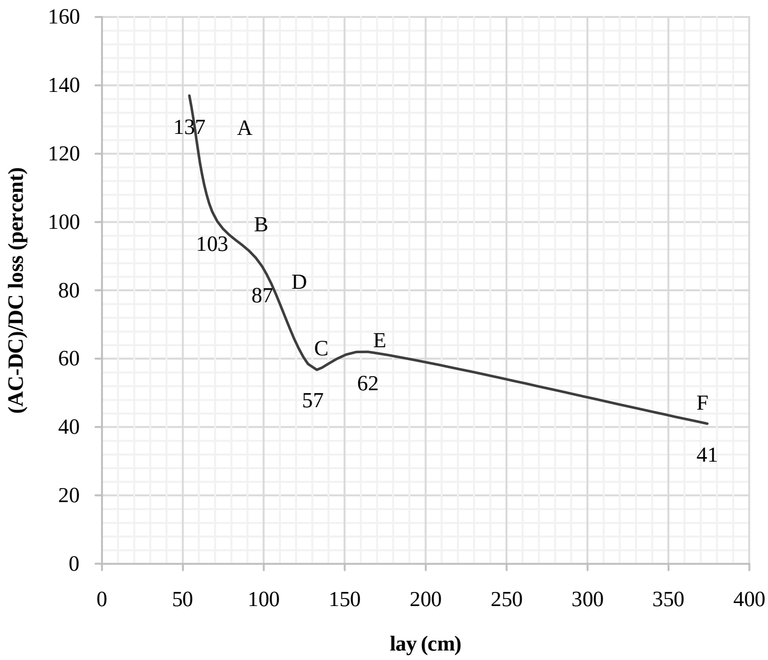

Figure 7. The variation of loss with the lay of 0.128 in. armour wire on 66 kV cable with I = 300 amps.

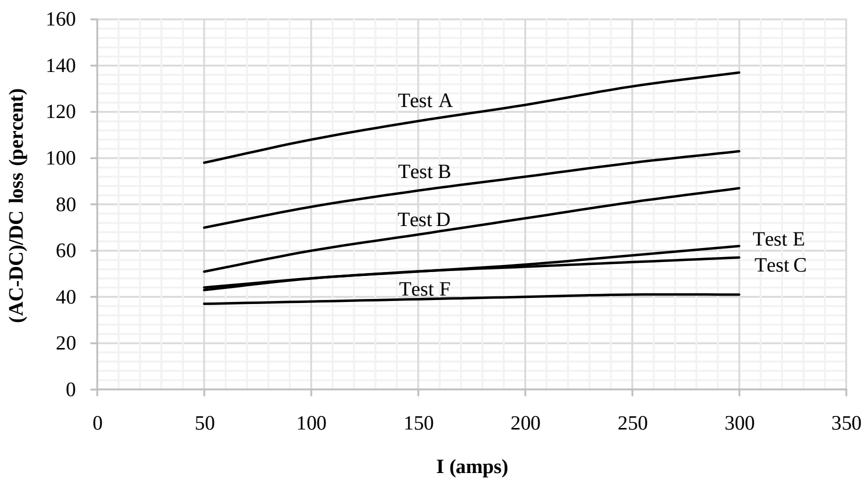

Figure 8. The variation of loss with the lay of 0.128 in. armour wire on 66 kV cable for different tests.

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500-volt circuit for the single-armoured cables [tests (E) and (G)] is 2.16 percent of the power input for every 100 yards of the circuit, and for the double-armoured cable [test (F)] 4.27 percent. In **Figure 9** the watts lost per ampere of the main current per 100 yards of the circuit are plotted, for each of the tests, against the main current as a percentage of the I.E.E. rating.

From the tests results as shown in **Table 5**, it has been determined that by decreasing the permeability and sectional area of the magnetic armour wire, the losses will be reduced [23].

However, in Cramp's review of the Harvey and Busby test G, it is shown that the flux density in the armour is far greater than that based upon the circumferential flux as given by Harvey and Busby.

Each armoured wire is a permeable conductive cylinder that is magnetized by an external force called H, which is parallel to the length of the wire, as shown in Equation (8) from [24]:

$$H = 0.2\sqrt{(2)\, I \cos\theta \sin 2\pi ft / r} \quad (8)$$

To calculate Eddy loss by means of the Kelvin functions $ber = \left[r_1 \sqrt{(\mu f)}/\rho \right]$ and $bei = \left[r_1 \sqrt{(\mu f)}/\rho \right]$ for test G with $\mu = 500$:

$ber = \left\lfloor r_1 \sqrt{(\mu f)}/\rho \right\rfloor = 0.8$ and $bei = \left\lfloor r_1 \sqrt{(\mu f)}/\rho \right\rfloor = 0.8$ approximately, the corresponding differential coefficients being 0.4 and 0.8 respectively.

Then the eddy losses per cm^3 of iron are 0.0046 watts at 100 percent of I.E.E. rating for the current in the core, corresponding to 0.0076 watts per cm length of cable.

Similarly, we can arrive at an approximate value for the hysteresis loss.

If we assume that:

$$r_1 \sqrt{(\mu f)}/\rho = x \quad (9)$$

$$r' \sqrt{(\mu f)}/\rho = x' \quad (10)$$

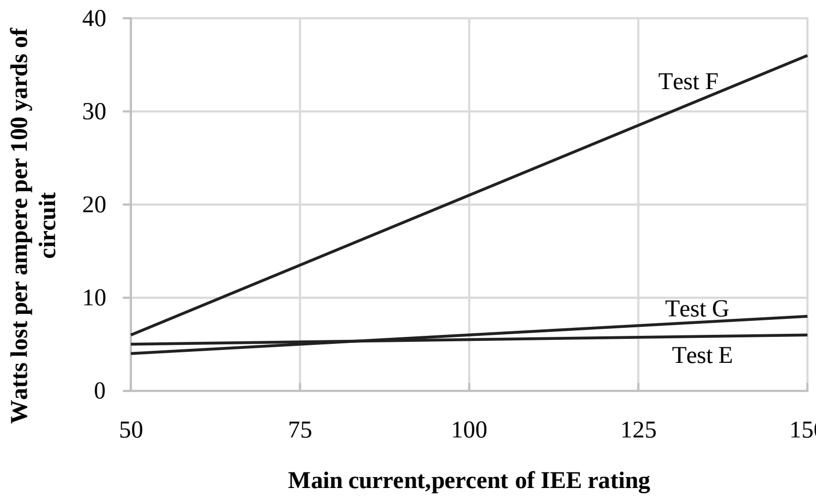

Figure 9. The watts lost per ampere of the main current per 100 yards of the circuit are for the tests E, F, G, against the main current as a percentage of the I.E.E. rating.

Table 5. Comparative table of results.

Test	Test (E)	Test (F)	Test (G)
Size of the main cable	37/0.092 in.	37/0.092 in.	19/0.072 in.
IEE rating (amperes)	214	214	97
Type of the sheath	Armour	Armour	Armour
Description of the sheath	Single	Double	Single
External diameter of the sheath	1.55 in.	1.77 in.	1.16 in.
Resistance of sheath per 100 yards of circuit, ohms	0.122	0.056	0.124
Permeability of sheath section	6	17	11
Sheath current for IEEE rating (main current), amps	0.5	0.46	0.33
Ratio: Sheath current/main current	0.0023	0.0021	0.0034
Percentage increase in sheath current for d = 12 in over that for d = 0	21.4	10.5	28.8
Percentage increase in sheath current for d = 48 in over that for d = 0	40	11.1	52
Impedance per 100 yards of circuit, ohms	0.125	0.157	0.177
Dead resistance per 100 yards of circuit, ohms	0.029	0.035	0.065
Effective resistance per 100 yards of circuit, ohms	0.0505	0.093	0.109
Ration: Impedance/Dead resistance	4.3	4.5	2.73
Ration: Effective resistance/Dead resistance	1.74	2.68	1.68
Watts loss per ampere of the main current per 100 yards of circuit	10.8	21.3	10.9
Voltage drop per 100 yards of circuit, volts	26.6	42.3	17.7

where r' is the radial distance measured from the center of the iron wire, the magnetic density in the wire at radius r' will be calculated from Equation (11) from [24]:

$$B = \frac{0.2\sqrt{(2)}\,\mu I \cos\theta}{r} \times \frac{\sqrt{\left[ber^2(x') + bei^2(x')\right]}}{\sqrt{\left[ber^2(x) + bei^2(x)\right]}} \quad (11)$$

from which the distribution of flux over the area of one wire, as seen in **Figure 10**, may be calculated.

To calculate hysteresis loss using the Steinmetz index with the coefficient of 0.003, 0.0064 watts dissipated in hysteresis per cm length of cable at 100 percent of I.E.E. rating for the current in the core. Adding these to the eddy losses already calculated, we obtain 0.0076 + 0.0064 = 0.014 watts in iron loss per cm of cable.

It is also showed that due to the larger ratio of diameter over armour to conductor's diameter, and thicker insulation layer in h.t cables, the eddy currents and hysteresis losses are smaller than l.t cables [24].

The comparison of the tests with μ = 500 and hysteresis coefficient h = 0.03 are shown in **Table 6**.

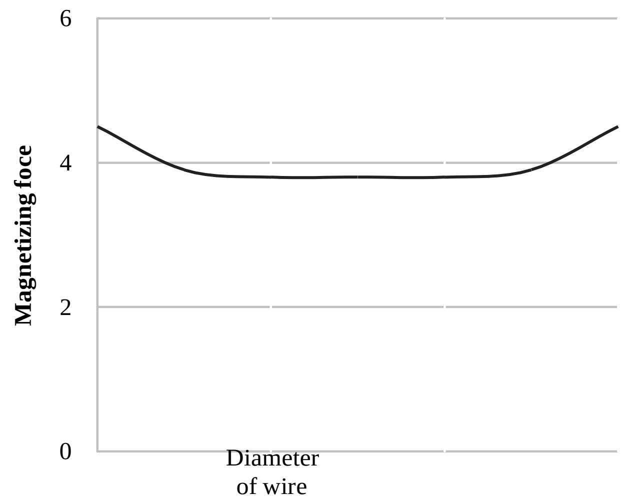

Figure 10. Variation of magnetizing force with the diameter of armour wire.

Table 6. Losses per cm length of cable [24].

Cable size	l.t cable	h.t cable	
	sq. in.	0.1 sq. in. (22,000 volts)	0.1 sq. in. (132,000 volts)
I.E.E rating	540 amperes	191 amperes	191 amperes
Armour wire thickness	=ht22000	=lt	0.104 in.
Core loss (copper loss)	0.16 watt	0.1 watt	0.01 watt
Eddy loss in the armour	0.17 watt	0.021 watt	0.008 watt
Hysteresis loss in the armour	0.08 watt	0.016 watt	0.009 watt
Total armour loss	0.25 watt	0.037 watt	0.017 watt
Ratio (armour loss)/(copper loss), percent	1%	37%	17%

In [25] to obtain sheath and armour loss factors, the total inductance between elements is calculated by the sum of internal and external inductances. For magnetic permeability of free space as μ_0($4\pi \times 10^{-7}$ H/m), the outer radius of the conductor r_c, the axial distance between conductors S, effective conductor radius αr_c, mean radius of the armour r_a, is the armour thickness t_a, complex relative longitudinal magnetic permeability μ_e, complex relative transverse magnetic permeability μ_t, helical lay length of the armour l_a, helical lay angle with respect to the cable axis β, and A_a as the sum of the wire or tape cross-sectional areas, the total conductor-conductor inductance L_{cc} is given by Equation (12) given in [25]:

$$L_{cc} = \frac{\mu_0}{2\pi}\ln\left(\frac{s}{\alpha r_c}\right) + \frac{\mu_0 t_a}{2\pi r_a}\left[\mu_t \cos^2(\beta) - 1\right] + \frac{\mu_0 \mu_e A_a}{2\pi r_a l_a}\sin\beta \tag{12}$$

Also, total conductor-sheath inductance L_{cs}, total sheath-sheath inductance L_{ss}, total conductor-armour and sheath-armour inductance L_{ca} and L_{sa}, and the armour-armour inductance L_{aa} is are given by (13), (14), (15) and (16) from [25]:

$$L_{cs} = \frac{\mu_0}{2\pi}\ln\left(\frac{s}{r_s}\right) + \frac{\mu_0\, t_a}{2\pi r_a}\left[\mu_t \cos^2(\beta) - 1\right] + \frac{\mu_0 \mu_e A_a}{2\pi r_a l_a}\sin\beta \tag{13}$$

$$L_{ss} = \frac{\mu_0}{2\pi}\ln\left(\frac{s}{r_s + t_s/6}\right) + \frac{\mu_0\, t_a}{2\pi r_a}\left[\mu_t \cos^2(\beta) - 1\right] + \frac{\mu_0 \mu_e A_a}{2\pi r_a l_a}\sin\beta \tag{14}$$

$$L_{ca} = L_{sa} = \frac{\mu_0}{2\pi}\ln\left(\frac{s}{r_a + t_a/2}\right) + \frac{\mu_0 \mu_t\, t_a}{2\pi r_a}\left[\frac{1}{2} - \sin^2(\beta)\right] + \frac{\mu_0 \mu_e A_a}{2\pi r_a l_a}\sin\beta \tag{15}$$

$$L_{aa} = \frac{\mu_0}{2\pi}\ln\left(\frac{s}{r_a + t_a/2}\right) + \frac{\mu_0 \mu_t\, t_a}{2\pi r_a}\left[\frac{1}{3\cos^2(\beta)} - \sin^2(\beta)\right] + \frac{\mu_0 \mu_e A_a}{2\pi r_a l_a}\sin\beta \tag{16}$$

For nonmagnetic armour the last two terms in Equation (13) and (14) are ignored and in Equation (15) the second term becomes $\mu_0 t_a / 4\pi r_a$ and the last term is ignored.

Additionally, for Equation (16) the second term becomes $\mu_0 t_a / 6\pi r_a$ and the last term is ignored with the presence of nonmagnetic armour.

As it can be seen in [25] by the use of nonmagnetic armour the inductances between elements can be reduced, thus, in order to prevent high losses in closely spaced single-core cables with magnetic armour, later studies have been conducted on nonmagnetic materials as armour. For this purpose, IEC 60287 is used to calculate the combination of sheath and armour losses for single-core cables with nonmagnetic armour [17]. With using the parallel combination of sheath and armour resistance R_e, and the root mean square value of the sheath and armour diameter d, shown in Equation (17) and (18) respectively, sheath current and armour current can be expressed as in Equation (19) and (20) given in [26].

$$R_e = \frac{R_s R_a}{R_s + R_a} \tag{17}$$

$$d = \sqrt{\frac{d_s^2 + d_a^2}{2}} \tag{18}$$

$$I_s = (R_e / R_s)\, I_{sa} \tag{19}$$

$$I_a = (R_e / R_a)\, I_{sa} \tag{20}$$

where:

R_e: The equivalent resistance of sheath and armour in parallel (W/m).

R_a: The resistance of armour per unit length of cable at its maximum operating temperature (W/m).

d: The mean diameter of sheath and armour (mm).

d_s: The mean diameter of the sheath (mm).

d_a: The mean diameter of the armour (mm).

I_s: Sheath current (circulating or eddy) in A.

I_a: Armour current (circulating or eddy) in A.

I_{sa}: Sheath-armour combination current in A.

Hence the total loss in the armour is calculated according to IEC 60287 as Equation (21) from [17]:

$$\lambda_2 = \frac{\left(R_s R_a\right)/\left(R_s + R_a\right)}{R} \frac{1.5}{1+\left(\left(\frac{R_s R_a}{R_s + R_a}\right)/X\right)^2} \quad (21)$$

where R is the AC resistance of conductor (Ω/m) and X is the reactance per unit length of cable (Ω/m) at their maximum operating temperature.

Armour currents and armour losses factors obtained from the investigation [26] for 800 mm^2 single-core cable at 66 kV, that armoured with 50 aluminum wires with mean armour diameter 82.5 mm, for touch trefoil and touch flat arrangement are given as **Figure 11** and **Figure 12** [26].

It can be seen that trefoil formation introduces symmetrical values of losses in its sheaths than flat formation addition to the total sheath losses in the trefoil are lower than flat layout [26].

In 2019 study of sheath and armour circulating current losses [27] for 11 kV, 400 mm^2 single-core cables with aluminum alloy armour (XLPE/LC/AWA/PVC) carried out for different cases with different laying configuration, conductor size, resistivity, and the number of armour wires. The calculated results for trefoil and

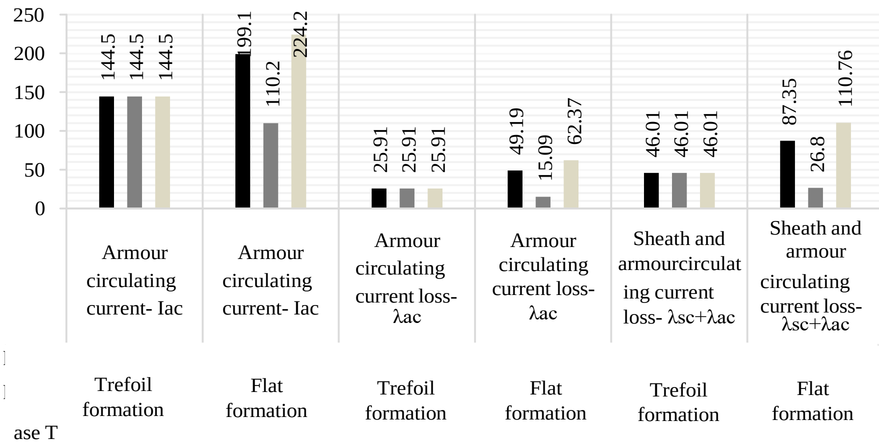

Figure 11. Armour circulating current loss for trefoil and flat arrangement.

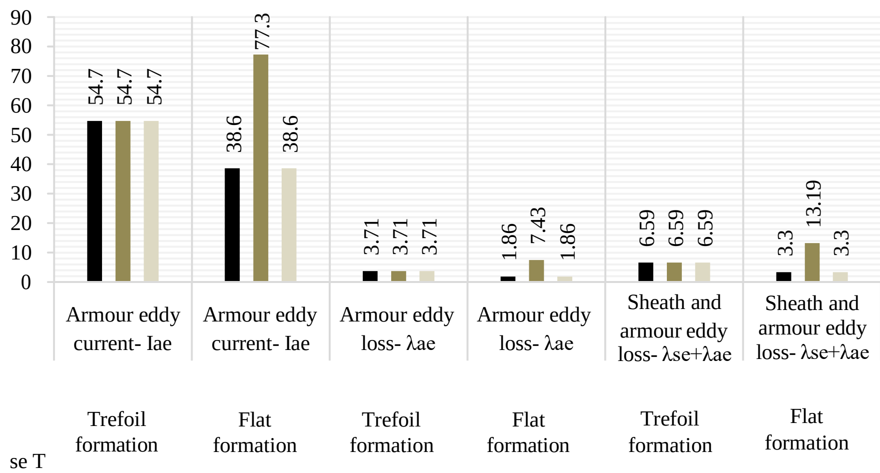

Figure 12. Armour eddy current loss for trefoil and flat arrangement.

flat configuration also showed that circulating current loss in trefoil configuration is equal in all three phases, but for flat configuration, it is minimum in the middle phase and maximum in the cable which has the lagging phase to the middle cable as illustrated in **Figure 13**.

To calculate the sheath and armour circulating current loss of a single-core cable with trefoil arrangement, I_{CS1}, I_{CS2}, I_{CS3} as phase 1, 2, and 3 sheath and armour circulating currents are considered equalas in Equation (22) stated in [27].

$$|I_{CS1}| = |I_{CS2}| = |I_{CS3}| = |I| \frac{\omega M}{\sqrt{R_S^2 + \omega^2 M^2}} \tag{22}$$

But for flat arrangement, sheath and armour circulating current loss varies with the cables as shown in (23)-(27) from [27]:

$$|I_{CS1}| = |I| \sqrt{\frac{Q^2}{4(R_S^2 + Q^2)} + \frac{3P^2}{4(R_S^2 + P^2)} + \frac{\sqrt{3}PQR_S(Q-P)}{2(R_S^2 + Q^2)(R_S^2 + P^2)}} \tag{23}$$

$$|I_{CS2}| = |I| \frac{Q}{\sqrt{R_S^2 + Q^2}} \tag{24}$$

$$|I_{CS3}| = |I| \sqrt{\frac{Q^2}{4(R_S^2 + Q^2)} + \frac{3P^2}{4(R_S^2 + P^2)} - \frac{\sqrt{3}PQR_S(Q-P)}{2(R_S^2 + Q^2)(R_S^2 + P^2)}} \tag{25}$$

$$P = X + X_m \tag{26}$$

$$Q = X - \frac{X_m}{3} \tag{27}$$

where I = The line current in A.

R_s = Resistance of sheath and armour per unit length, at its maximum operating temperature $\Omega \cdot m^{-1}$.

ω = Angular frequency in rad·s^{-1}.

R = Resistance of core conductor per unit length, at its maximum operating temperature $\Omega \cdot m^{-1}$.

M = Mutual inductance between core, sheath, and armour in H·m^{-1}.

X = Reactance per unit length of sheath and armour (ωM) in $\Omega \cdot m^{-1}$.

And

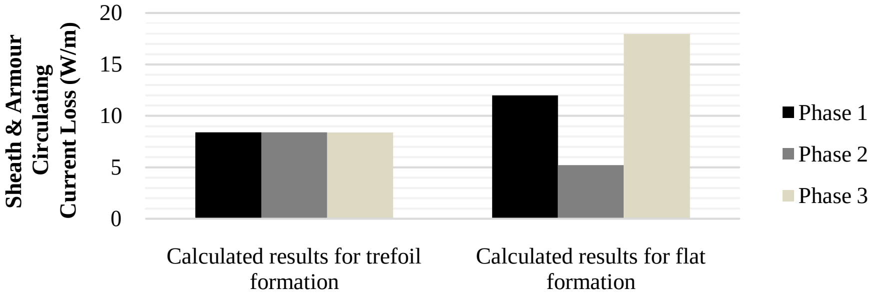

Figure 13. Variation of sheath and armour circulating current loss with trefoil and flat laying formations of cables.

$$X_m = \omega \times 2 \times 10^{-7} \ln 2 \quad (28)$$

Thus, sheath and armour circulating current loss per unit length of a single core cable W_{CS} in W·m^{-1} is calculated as Equation (30):

$$W_{CS} = I_{CS}^2 R_S \quad (29)$$

To investigate circulating current variation with different conductor sizes, they applied 315 A to all different sizes of conductors with trefoil and flat configuration that resulted in increment of the circulating current with greater sizes of the conductor as illustrated in **Figure 14** [27].

It's also showed that increasing the resistivity of the cable armour or decreasing the number of armour wires leads to circulating current loss reduction (**Figure 15** and **Figure 16**).

It should be noted that according to IEC 60502-2 and AS/NZS 1429-1 the diameter of the armour wire is not flexible, and nominal diameters of round armour wires shall be not less than the values given in **Table 7** [28] [29].

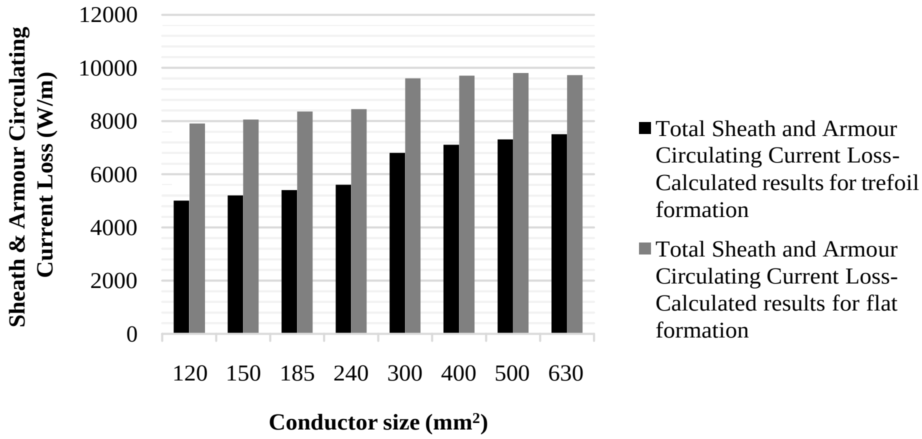

Figure 14. Variation of sheath and armour circulating current loss with conductor size.

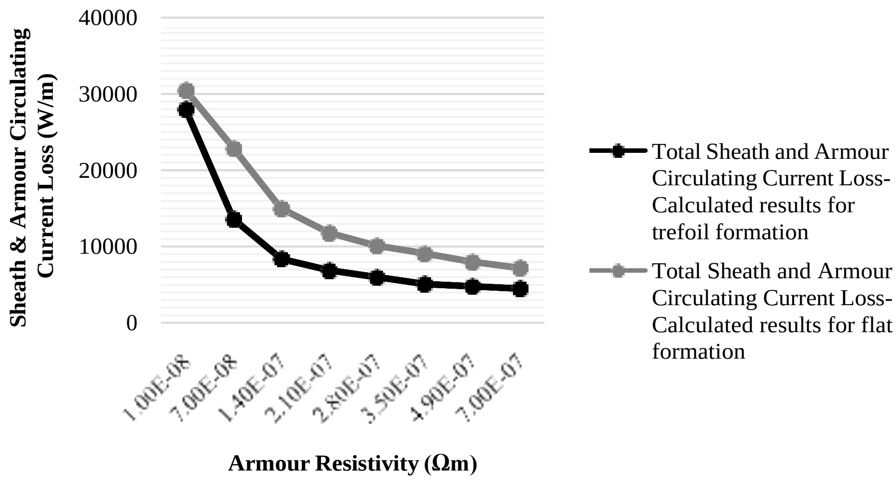

Figure 15. Variation of sheath and armour circulating current loss with the resistivity of the armour.

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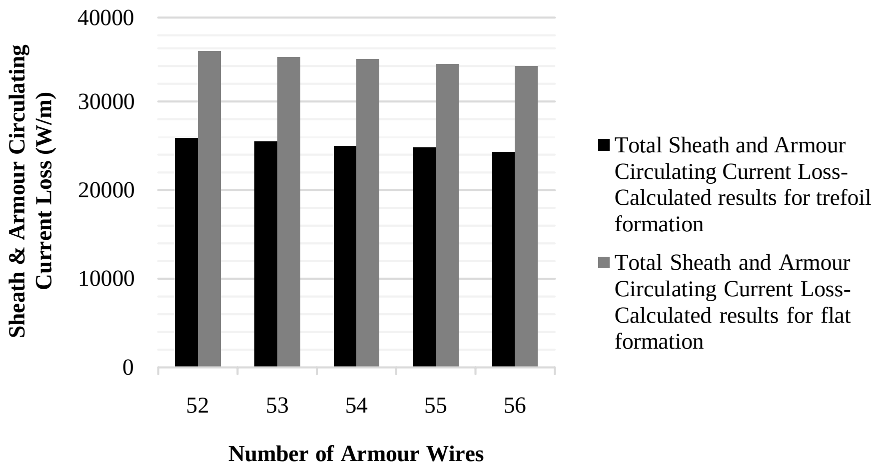

Figure 16. Variation of sheath and armour circulating current loss with quantity of armour wires.

Table 7. Nominal diameter of armour wire.

Fictitious diameter under the armour (mm) of armour wire (mm)	Nominal diameter	
	IEC 60502-2	AS/NZS 1429-1
<10	0.8	1.6
>10 - ≤15	1.25	1.6
>15 - ≤25	1.6	1.6
>25 - ≤35	2.0	2.0
>35 - ≤60	2.5	2.5
>60	3.15	3.15

5. Conclusions

In addition to introducing voltage and current in cable armour and discussing armour loss calculation methods, this paper evaluated the literature on cable armoring. This study shows that very significant losses can occur in single-core cables with magnetic armour. It has been demonstrated that using single-armoured cables with an effective improvement in armour lay by twisting the wires can lower magnetic armour losses. The losses and flux density in the magnetic armours, however, were too high to be of much value. In order to cut back on excessive losses, more research has been done on non-magnetic materials. It was shown that using armour made of aluminium rather than steel helped to reduce losses.

This paper also briefly described several techniques that can lead to reduction in circulating current loss, like different laying configurations, increasing the resistivity of the cable armour, or decreasing the number of armour wires. It was concluded that the trefoil formation is preferable to the flat formation, since this configuration distributes the losses evenly over the phases, resulting in a reduction in total sheath and armour circulating current loss. Further investigation of the properties of other potential alloys with higher strength and lower losses is required, which will be left to future work.

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