

## Factors Affecting the Sheath Losses in Single-Core Underground Power Cables with Two-Points Bonding Method

Osama Elsayed Gouda, Adel Abd-eltwab Farag

Department of Electrical Power and Machines, Faculty of Engineering, Cairo University

South Cairo Electricity Distribution Company, Ministry of Electricity and Energy

Email: d\_gouda@yahoo.com, Adelfarag94@yahoo.com

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### ABSTRACT

Single-core underground power cables with two-points bonding induce currents in their metallic sheaths. The sheath induced currents are undesirable and generate power losses and reduce the cable ampacity. This paper has shown that the values of the sheath losses in some cases could be greater than conductor losses, depending on various factors. Such these factors are type of cable layouts, cable parameters, cable spacing, sheath resistance, phase rotation, conductor current and cable armoring. In this paper the above factors have been investigated. The calculations are carried out depending mainly on IEC 60287 by a proposed computer program using MATLAB.

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### Corresponding Author:

Osama Elsayed Gouda,

Department of Electrical Power and Machines,

Faculty of Engineering, Cairo University

Email: d\_gouda@yahoo.com

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## 1. INTRODUCTION

In a single-core power transmission cable, normally a metallic sheath is coated outside the insulation layer to prevent the ingress of moisture, protect the core from possible mechanical damage, serve as an electrostatic shield (the electric field is enclosed in between the conductor and the sheath), and act as a return path for fault current and capacitive charging currents [1].

When an isolated single conductor cable carries alternating current, an alternating magnetic field is generated around it. If the cable has a metallic sheath, the sheath will be in the field, the sheath of a single-conductor cable for A.C service acts as a secondary of a transformer; the current in the conductor induces a voltage in the sheath. When the sheaths of single-conductor cables are bonded to each other, the induced voltage causes current to flow in the completed circuit. This current causes losses in the sheaths [2]. Dry zone may be formed around the underground cable and leading to thermal failure of cable insulation [3]. Much work has been done, for the purpose of minimizing sheath losses by introducing various methods of bonding and other solutions as has shown in [2, 4, 5, 6, 7, and 8]. Due to the importance of sheath losses in single-core underground power cables with two-points bonding, the factors affecting them are investigated.

## 2. SHEATH BONDING ARRANGEMENTS

The IEEE Standard 575 [3] introduces guidelines into the various methods of sheath bonding. The most common types of bonding are single point, two-points or multiple points and cross bonding.

### 2.1. Sheath bonded at two-points

In which the sheaths of three separate cables will be connected together at both ends of the run. For safety reasons one end of the sheaths must also be earthed. This system doesn't allow high values of the induced voltages in the metallic sheaths. In this situation, sheath circulating currents appear because of there is a closed circuit between the sheath and the return path through the ground. This scheme is studied in this paper.

### 2.2. Sheath bonded at one end only

In which the sheaths of three separate cables will be connected together and earthed at one point only along their length. At all other points, a voltage will appear from sheath to ground that will be a maximum at the farthest point from the ground bond. Since there is no closed sheath circuit current no sheath circulating current loss occurs, but sheath eddy loss will still be present.

### 2.3. Sheath cross bonded

Cross bonding of single-core cable sheaths is in use for many years. In which, each sheath circuit contains one section from each phase such that the total voltage in each sheath circuit sums to zero. If the sheaths are then bonded and earthed at the end of the run, the net voltage in the loop and the circulating currents will be zero and the only sheath losses will be those caused by eddy currents.

## 3. FACTORS AFFECTING THE SHEATH LOSSES IN SINGLE-CORE UNDERGROUND POWER CABLES WITH TWO-POINTS BONDING

Sheath losses are current dependent, and can be divided into sheath eddy loss due to the voltage difference between external and internal sides of metallic sheath and circulating loss when both ends of the sheath are grounded [1, 9].

The study is carried out by using single-core cable made of a stranded copper conductor with 800 mm<sup>2</sup> insulated by XLPE and covered by a lead screens,  $f = 50$  Hz, 66 kV, which its parameters [10] are listed in table I. The calculations of sheath circulating and eddy current losses have been carried out by using IEC Standard 60287 [11], [12].

Table 1. Single-core cables 800 mm<sup>2</sup> CU with lead screen parameters

Cable parameters		
Conductor size (mm <sup>2</sup> )		800
Diameter of the conductor (mm)		34
Mean sheath diameter (mm)		62.6
Outer diameter of cable (mm)		80
DC Resistance of the copper conductor at 20 °C	Ω/km	0.0221
Lead electrical resistivity at 20°C	Ω.m	$21.4 \times 10^{-8}$
Copper electrical resistivity at 20°C	Ω.m	$1.7241 \times 10^{-8}$
Temperature coefficient of copper per K at 20 °C		$4 \times 10^{-3}$
Temperature coefficient of lead per K at 20 °C		$3.93 \times 10^{-3}$

The cable data in Table 1 are given at:

Ground temperature	20°C
Laying depth	1.0 m
Ground thermal resistivity	1.0 Km/W
Assuming the sheath temperature equals to	70 °C
Current rating (A) for copper conductor	995 A
Distance "S" between cable axes laid in flat formation De	(De: the external diameter of the cable)

### 3.1. Cable layouts formation

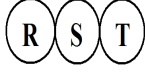
Trefoil and flat formations are usually used in practice, so they are used in this paper.

Table II shows the values of sheath currents and their losses factors for touch trefoil and touch flat, where:

$\lambda_{CS}$  : The circulating sheath loss factor percentage of conductor loss

$I_{CS}$  : The circulating current in the sheath in A  
 $\lambda_{SE}$  : The sheath eddy loss factor percentage of conductor loss  
 $I_{SE}$  : The eddy current in the sheath in A

Table 2. Sheath currents and their losses factors with lead screen

Phase no.	Touch trefoil				Touch flat 			
	$\lambda_{CS}$ %	$I_{CS}$ (A)	$\lambda_{SE}$ %	$I_{SE}$ (A)	$\lambda_{CS}$ %	$I_{CS}$ (A)	$\lambda_{SE}$ %	$I_{SE}$ (A)
R	21.32	116 A	2.82	42.1 A	47.38	172.9 A	1.41	29.8 A
S	21.32	116 A	2.82	42.1 A	12.18	87.7 A	5.64	59.6 A
T	21.32	116 A	2.82	42.1 A	52.79	182.5 A	1.41	29.8 A

From Table 2, it is noticed that: For trefoil layout the eddy losses are equal in all cable phases sheath, while for flat layout the eddy losses in the outer cable sheaths are equal and usually smaller than the value of the middle cable sheath, But it must be notice that, the total sheath eddy losses per circuit in trefoil are equal that in flat formation.

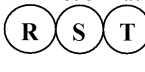
For trefoil layout the circulating losses are equal, while for flat layout the sheath circulating losses have unequal magnitude, the least value occurs in the sheath of the middle cable, values in sheaths of outer cables are of unequal magnitude too. Thereby, the cable sheath of the lag phase has a higher value. In general the trefoil formation has lower total sheath losses than flat formation.

### 3.2. Cable conductor resistivity

Copper and Aluminum of metals are commonly used for cables conductors, so the effect of conductor resistivity on the sheath losses is examined by calculating the sheath losses for aluminium and copper cables with the same dimensions.

Table 3 shows the values of sheath currents and their losses factors for touch trefoil and touch flat in two single-cores cables, one of them is made of a stranded copper conductor and the other is made of a stranded aluminium conductor.

Table 3. Sheath currents and their losses factors in single-core cables for copper and aluminium conductors

Conductor material	Cable layout arrangement								Phase no.
	Touch trefoil				Touch flat 				
	$\lambda_{CS}$ %	$I_{CS}$ (A)	$\lambda_{SE}$ %	$I_{SE}$ (A)	$\lambda_{CS}$ %	$I_{CS}$ (A)	$\lambda_{SE}$ %	$I_{SE}$ (A)	
CU	21.32	116 A	2.82	42.1 A	47.38	172.9A	1.41	29.8 A	R
	21.32	116 A	2.82	42.1 A	12.18	87.7A	5.64	59.6 A	S
	21.32	116 A	2.82	42.1 A	52.79	182.5A	1.41	29.8 A	T
AL	13.78	92.6 A	1.82	33.7 A	30.62	138.1A	0.91	23.8 A	R
	13.78	92.6 A	1.82	33.7 A	7.87	70 A	3.64	47.6 A	S
	13.78	92.6 A	1.82	33.7 A	34.11	145.8A	0.91	23.8 A	T

From table 3, it is noticed that: Both sheath circulating loss factors and sheath eddy loss factors decrease as the conductor resistivity increase, i.e. the sheath losses factors ( $\lambda_{SE}$  &  $\lambda_{CS}$ ) are inversely proportional to the conductor resistivity, so when the advantages of copper are mentioned as its conductor loss is lower than aluminium loss for the same cable size, its disadvantages in sheath losses must be mentioned also.

### 3.3. Cable spacing

The effect of spacing on the sheath circulating losses and sheath eddy losses in single-core cable can be shown in Figs 1, 2, 3 and 4.

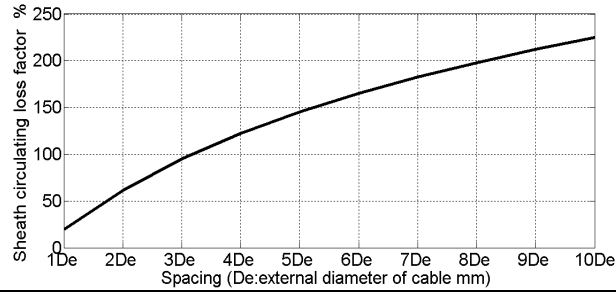


Fig. 1 Sheath circulating loss factor vs. conductor spacing- trefoil formation

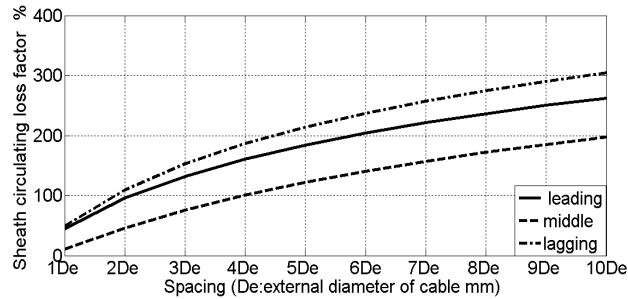


Fig. 2 Sheath circulating loss factor vs. conductor spacing- flat formation

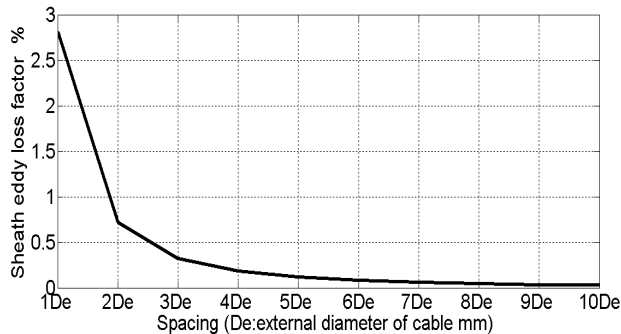


Fig. 3 Sheath eddy loss factor vs. conductor spacing- trefoil formation

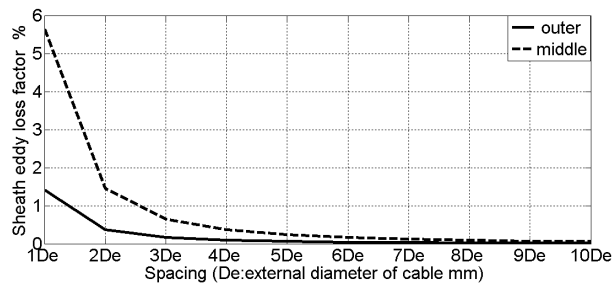


Fig. 4 Sheath eddy loss factor vs. conductor spacing - flat formation

From Figs 1 and 2 it can be seen that: The sheath circulating losses are proportional to the spacing between phases. The sheath circulating losses could be reached to more than two times the conductor losses

depending on the spacing between phases. The sheath circulating losses could be reached to more than its double values with duplicating the spacing between phases.

From Fig.s 3 and 4 it is clearly appearing that: The sheath eddy losses are inversely proportional to the spacing between phases, so it can be deduced that for large cables the effect of spacing on total sheath losses is much less than that on the sheath circulating losses alone. The sheath eddy losses reduce rapidly at lower spacing, while reduce very slowly at large spacing. The sheath eddy losses can be neglected at large spacing.

**3.4. Sheath resistance**

The effect of sheath resistance on the sheath circulating losses and sheath eddy losses in single-core cable can be shown in Fig.s 5, 6, 7 and 8.

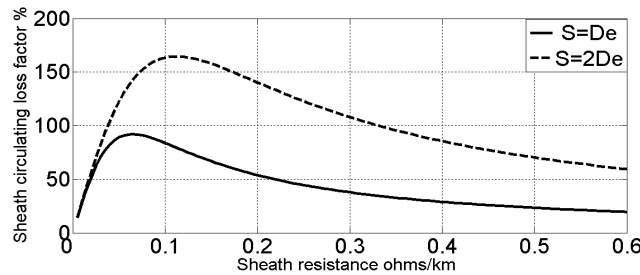


Fig. 5 Sheath circulating loss factor vs. sheath resistance in trefoil formation with De and 2De spacing between cables

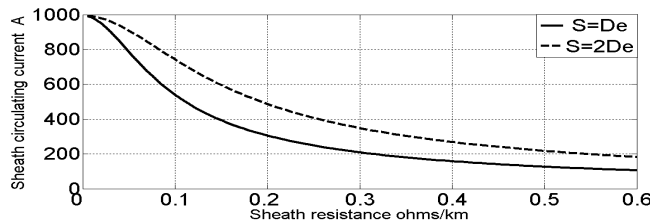


Fig. 6 Sheath circulating current vs. sheath resistance in trefoil formation with De and 2De spacing between cables

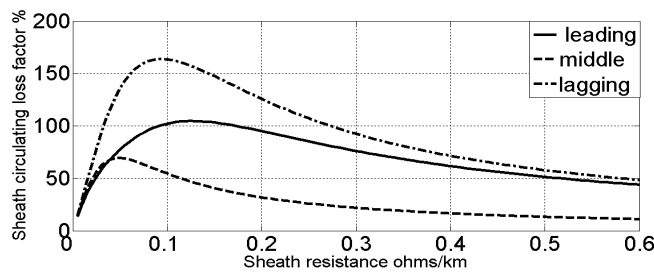


Fig. 7 Sheath circulating loss factor vs. sheath resistance in flat formation

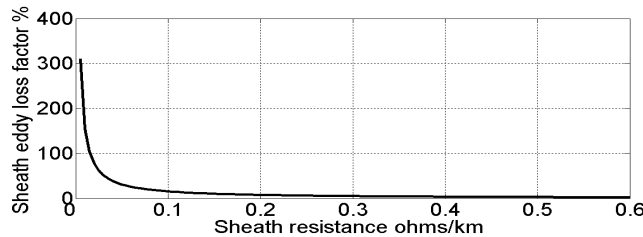


Fig. 8 Sheath eddy loss factor vs. sheath resistance in trefoil formation

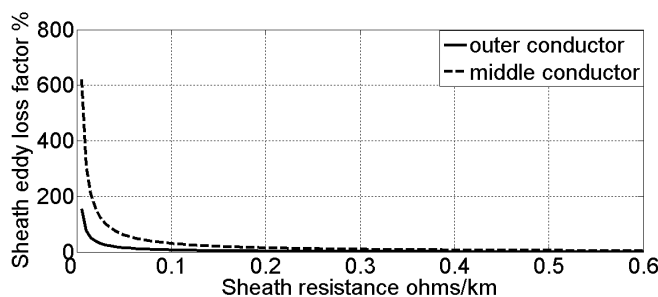


Fig. 9 Sheath eddy loss factor vs. sheath resistance in flat formation

From Figs 5, 6 and 7 which indicate the effect of sheath resistance on the sheath circulating losses it is seen that: At the maximum sheath current, equal to full conductor current, (i.e., for the case of zero sheath resistance), the circulating-current loss is obviously zero. While the sheath current falls with increasing sheath resistance, i.e. the sheath current is inversely proportional to the sheath resistance, the sheath circulating loss first rises to a maximum, and then falls again approaching zero at infinite sheath resistance, so the sheath circulating loss would be eliminated when the sheath resistance tends to either zero or infinity, so it can be said that the sheath resistance plays a great role in controlling the values of sheath losses. The sheath circulating losses could be reduced by large increase in sheath resistance or large reduce in the sheath resistance. By increasing the sheath resistance the sheath current and sheath circulating losses are decreased, this can be achieved by using a suitable metal having a resistivity several times that of lead such as stainless steel ( $\rho_{\text{stainless-steel}} = 3.27\rho_{\text{lead}}$ ) or reducing the sheath size as using copper tape or copper wire, while reducing the sheath resistance can be achieved by one of the two ways: 1. Adding nonmagnetic armouring material (it will be investigated later), the sheath circulating losses could be less than the sheath circulating losses with no armouring. On another hand armor increases the cable cost. 2. Using aluminium as metallic sheath. But in two previous ways, the sheath circulating current will approach the conductor current in magnitude. The value of sheath resistance which gives maximum-sheath circulating-current loss is called critical sheath resistance, values of sheath resistance higher or lower than this critical value will give lower circulating-current losses than those for the critical sheath resistance, so the cable designer must be aware to avoid this value.

Attention is also called to the fact, indicated in Fig. 11, that the critical sheath resistance for a given cable is diminished when the spacing between phases is reduced. The critical value of sheath resistance in flat formation differs from conductor to other in flat formation as shown in Fig. 7.

From Figs 8 and 9 which indicate the effect of sheath resistance on the sheath eddy losses it can be seen that: The sheath eddy losses are inversely proportional to the sheath resistance. The sheath eddy losses can be neglected at large values of sheath resistances. Sheath eddy losses could be reached to undesirable values at lower sheath resistance values.

### 3.5. Phase rotation

The above calculations are carried out on flat arrangement with phase rotation R-S-T. To examine the effect of phase rotation on sheath circulating losses for two-points bonding, calculations are carried out using S-T-R and S-T-R configurations. The results are shown in table 4. In this table the sheath circulating losses in each phase of single-core cable are calculated with corresponding to three different phase rotation arrangements of the cable.

From the obtained results in table 4, it is noticed that: Always the central conductor has the lowest sheath circulating loss value due to magnetic cancellation. The sheath circulating losses of the outer conductors are depending on the phase rotation and its arrangement.

### 3.6. Conductor current

To examine the effect of conductor current on the sheath losses, the sheath losses are calculated at two different values of conductor current (full & half conductor rating). The results are shown in Table 5.

From table 5, it is noticed that: The sheath currents (eddy and circulating) duplicate with duplicating the conductor current. The sheath losses factors (eddy and circulating) did not changed because the ratio of sheath current and conductor current is fixed.

Table 4. Sheath circulating losses factors for different configuration in flat formation

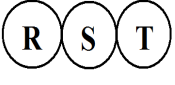
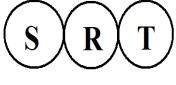
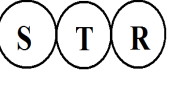

SHEATH CIRCULATING LOSS FACTOR (%)	CABLE CONFIGURATION		
			
$\lambda_{CS-R}$	47.38	12.18	52.79
$\lambda_{CS-S}$	12.18	52.79	47.38
$\lambda_{CS-T}$	52.79	47.38	12.18

Table 5. Sheath current and their losses factors for single-core cables with full rating current and its half value

Current	Cable layout arrangement								Phase no.
	Touch trefoil				Touch flat 				
	$\lambda_{CS}$ %	$I_{CS}$ (A)	$\lambda_{SE}$ %	$I_{SE}$ (A)	$\lambda_{CS}$ %	$I_{CS}$ (A)	$\lambda_{SE}$ %	$I_{SE}$ (A)	
Full rating	21.32	116 A	2.82	42.1 A	47.38	172.9 A	1.41	29.8 A	R
	21.32	116 A	2.82	42.1 A	12.18	87.7 A	5.64	59.6 A	S
	21.32	116 A	2.82	42.1 A	52.79	182.5 A	1.41	29.8 A	T
Half rating	21.32	58 A	2.82	21 A	47.38	86.4 A	1.41	14.9 A	R
	21.32	58 A	2.82	21 A	12.18	43.8 A	5.64	29.8 A	S
	21.32	58 A	2.82	21 A	52.79	91.2 A	1.41	14.9 A	T

### 3.7. Cable armoring

In order to protect cables from mechanical damage cable armoring is employed [13]. Armored single-core cables for general use in A.C systems usually have nonmagnetic armor. This is because of the very high losses that would occur in closely spaced single-core cables with magnetic armor [14]. To calculate the sheath and armour losses for single-core cables with nonmagnetic armor, IEC 60287 is used [11], but with using the parallel combination of sheath and armour resistance in place of single sheath resistance and the root mean square value of the sheath and armour diameter replaces the mean sheath diameter, i.e

$$R_e = \frac{R_S R_A}{R_S + R_A} \quad (1)$$

$$d = \sqrt{\frac{d_S^2 + d_A^2}{2}} \quad (2)$$

So

$$I_S = (R_e/R_S)I_{SA} \quad (3)$$

$$I_A = (R_e/R_A)I_{SA} \quad (4)$$

Where:

$R_e$ : The equivalent resistance of sheath and armour in parallel ( $\Omega/m$ )

$R_A$ : The resistance of armour per unit length of cable at its maximum operating temperature ( $\Omega/m$ )

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

$d_S$ : The mean diameter of sheath (mm)

$d_A$ : The mean diameter of 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

Table 6. Armored single-core cable 800 mm<sup>2</sup>, 66 kV CU with lead covered and aluminium wire armored parameters

Outer diameter of cable (mm)	93
Mean armour diameter (mm)	82.5
Mean sheath diameter (mm)	62.6
DC Resistance of the copper conductor at 20°C Ω/km	0.0221
diameter of the conductor (mm)	34
Thickness of lead (mm)	2.6
No. of armour wires	50

Thus the addition of the armour is at least equivalent to lowering of the sheath resistance, so from discussion in clause (3.4), if  $R_e$  is lower than the critical value of sheath resistance, the addition of the armour may tend to reduce or increase the combined sheath-armour circulating losses, if  $R_e$  is higher than the critical value of sheath resistance, the addition of the armour, tends to increase the combined sheath-armour circulating losses, while for combined sheath-armour eddy loss as well as combined sheath-armour current it is expected increasing them because they are inversely proportional to sheath resistance.

Fig. 10 shows the effect of armour resistance on the sheath and armour currents, if the armour resistance equals the sheath resistance,  $I_{SA}$  is equally divided between sheath and armour resistance i.e. the armour current will be equal the sheath current (intersection point in Fig. 10), and if the armour resistance is lower than the sheath resistance, the armour current will be higher than the sheath current and vice versa. The cable data used in these calculations is listed in table 6.  $R_S = 0.5 \Omega / \text{km}$ ,  $R_A = 0.39 \Omega / \text{km}$  and  $R_e = 0.22 \Omega / \text{km}$ .

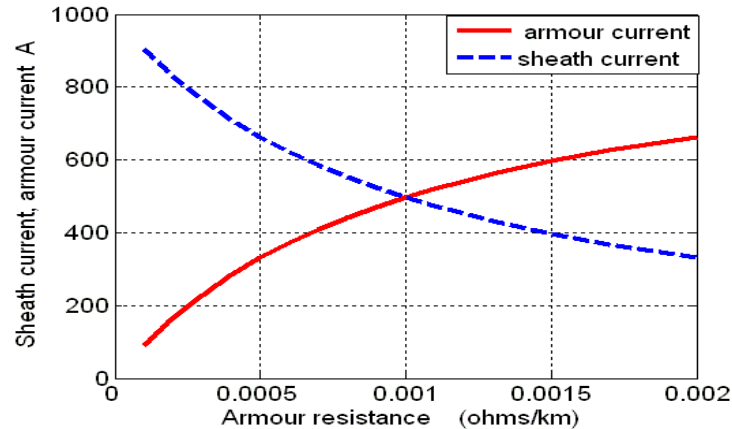


Fig. 10 Sheath, armour current vs. armour resistance

Table 7. shows the values of sheath currents and armor currents with their corresponding losses for armored single-core cable in case of touch trefoil and touch flat.

Where:

$I_{CS-R}, I_{CS-S}, I_{CS-T}$  : Circulating current in sheath of phase no. R,S and T respectively

$\lambda_{CS-R}, \lambda_{CS-S}, \lambda_{CS-T}$  : Circulating loss factor in sheath of phase no. R,S and T respectively

$I_{SE-R}, I_{SE-S}, I_{SE-T}$  : Eddy current in sheath of phase no. R,S and T respectively

$\lambda_{SE-R}, \lambda_{SE-S}, \lambda_{SE-T}$  : Eddy loss factor in sheath of phase no. R,S and T respectively

$I_{AC-R}, I_{AC-S}, I_{AC-T}$  : Circulating current in armor of phase no. R,S and T respectively

$I_{AE-R}, I_{AE-S}, I_{AE-T}$  : Eddy current in armor of phase no. R,S and T respectively

$\lambda_{AE-R}, \lambda_{AE-S}, \lambda_{AE-T}$  : Eddy loss factor in armor of phase no. R,S and T respectively

$I_{AC-R}, I_{AC-S}, I_{AC-T}$  : Circulating current in armor of phase no. R,S and T respectively



From the obtained results with using armored single-core cable instead of unarmored single-core cable which its results are listed in Table 7, it can be noticed that: The combined sheath-armour circulating losses ( $\lambda_{CS} + \lambda_{AC}$ ) and the combined sheath-armour eddy ( $\lambda_{SE} + \lambda_{AE}$ ) increased due to  $R_c$  is higher than the critical value of sheath resistance. The sheath circulating losses and the sheath eddy losses are lower than the armour circulating losses and the armour eddy losses respectively because the armour resistance ( $R_A = 0.39\Omega/\text{km}$ ) is lower than the sheath resistance ( $R_S = 0.5\Omega/\text{km}$ ). The sheath current value in armored single-core cable is depending mainly on the ( $R_c/R_S$ ) ratio.

Table 7. Sheath, armour currents and their losses factors for nonmagnetic armored single-core cable

Parameters	Cable layout arrangement	
	Touch trefoil	Touch flat
$\lambda_{CS-R} + \lambda_{AC-R}$	46.01	87.35
$\lambda_{CS-S} + \lambda_{AC-S}$	46.01	26.8
$\lambda_{CS-T} + \lambda_{AC-T}$	46.01	110.76
$\lambda_{SE-R} + \lambda_{AE-R}$	6.59	3.30
$\lambda_{SE-S} + \lambda_{AE-S}$	6.59	13.19
$\lambda_{SE-T} + \lambda_{AE-T}$	6.59	3.30
$I_{CS-R}$	112.1 A	154.4 A
$I_{CS-S}$	112.1 A	85.5 A
$I_{CS-T}$	112.1 A	173.9 A
$\lambda_{CS-R}$	20.10	38.16
$\lambda_{CS-S}$	20.10	11.71
$\lambda_{CS-T}$	20.10	48.39
$I_{SE-R}$	42.4 A	30 A
$I_{SE-S}$	42.4 A	60 A
$I_{SE-T}$	42.4 A	30 A
$\lambda_{SE-R}$	2.88	1.44
$\lambda_{SE-S}$	2.88	5.76
$\lambda_{SE-T}$	2.88	1.44
$I_{AC-R}$	144.5 A	199.1 A
$I_{AC-S}$	144.5 A	110.2 A
$I_{AC-T}$	144.5 A	224.2 A
$\lambda_{AC-R}$	25.91	49.19
$\lambda_{AC-S}$	25.91	15.09
$\lambda_{AC-T}$	25.91	62.37
$I_{AE-R}$	54.7 A	38.6 A
$I_{AE-S}$	54.7 A	77.3 A
$I_{AE-T}$	54.7 A	38.6 A
$\lambda_{AE-R}$	3.71	1.86
$\lambda_{AE-S}$	3.71	7.43
$\lambda_{AE-T}$	3.71	1.86

#### 4. CONCLUSION

The following are briefly analyzing the main conclusions of this paper:

1. It must pay attention to sheath losses in single-core cables with two-points bonding as their values could be reached to more than the conductor losses.
2. The sheath eddy losses could be neglected w.r.t the sheath circulating losses at high sheath resistance values and high conductors spacing
3. Sheath eddy losses are inversely proportional to sheath resistance, cable conductor resistivity and conductors spacing, while they are proportional to conductor current.
4. Sheath circulating losses are proportional to the conductors spacing, and conductor current and can be reduced by large increase in sheath resistance or large reduce in the sheath resistance but the later leading to high circulating current.
5. Phase rotation plays a great role in determination of the sheath circulating losses in flat layout.
6. Trefoil formation introduces symmetrical values of losses in its sheathes than flat formation addition to the total sheath losses in the trefoil are lower than flat layout.

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## BIBLIOGRAPHY OF AUTHORS



Prof. Dr. Ossama El-Sayed Gouda is the professor of electrical Power engineering and high voltage in the Dept. of electrical power and machine, Faculty of Engineering, Cairo University since 1993. He teaches several courses in Power system, High voltage, Electrical machine, Electrical measurements, Protection of electrical power system & Electrical installation. He is a consultant of several Egyptian firms. He conducted more than 100 papers in the field of Electrical power system and high voltage engineering. He supervised about 60 M.Sc. & Ph.D. thesis. He conducted more than 150 short courses about the Electrical Power, Machine & High voltage subjects for the field of Electrical Engineers in Egypt & abroad. He is the head of high voltage group, Cairo University.



Eng. Adel Abd-eltwab Farag is an electrical engineer in the South Cairo Electricity Distribution Company, Ministry of Electricity and Energy, Cairo, Egypt. He received the B.Sc. degrees in Electrical Power & Machines Engineering, Faculty of Engineering, Cairo University, Cairo, Egypt, 2001. He obtained higher Diploma in High Voltage with a grade of Very Good from Cairo University. He is now working towards the Master degree at the same University.