Electrical and Thermal Analysis of Single Conductor Power Cable Considering the Lead Sheath Effect Based on Finite Element Method

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Abstract: This paper investigates the effect of metallic sheaths on losses and temperature of medium voltage power cables. Two grounding methods of sheaths, including both ends bonding and single point bonding that causes different situations on cable ampacity, are considered. Electrical losses of cables that are main sources of heat are calculated in both conductor and metallic sheath of the cables. Sheathed and unsheathed medium voltage single conductor cables in flat and trefoil formations with different distances are considered, while calculated losses are compared in different constructions. Calculations of resistive losses are performed based on Finite Element Method (FEM) and IEC standard formulations. The results of two methods are compared and analyzed. Moreover, the effects of eddy currents and circulating currents of sheath on total resistive losses are evaluated. Finally, thermal analysis based on FEM is executed to achieve maximum temperature of cable in different constructions. Simulation results show the importance of metallic sheaths and grounding system effects in power cable ampacity analysis.

Keywords: Medium Circulating Current Loss, Eddy Current Loss, Thermal Analysis, Voltage Cable.

1 Introduction

Power transmission cables are basically composed of conductors and insulations. Some metallic layers such as sheath, armour and shield are used in power cables. Metallic sheaths of power cables prevent penetration of moisture in cables. Moreover, metallic sheaths are protective layers against mechanical damage, creation electromagnetic interface and are return path for fault and unbalanced current in three phase systems [1]. Single point bonding, bonding at both ends and cross bonding are the main methods of grounding systems in power cables [2]. Each of the grounding system methods creates currents in metallic sheaths that affect the total resistive losses. Besides the metallic sheath losses based on grounding types, sheath currents can influence the conductor currents by proximity effect. By these notifications it is obvious that considering and analysis of metallic sheath is an important factor in computation of heat losses and temperature in cables.

Sheath losses in different cables arrangements, conductors resistivity, and sheaths resistance are computed in [3] by standard formulas. In [4] a theoretical method is used for the calculation of conductor and sheath losses with sheath bonding at both ends. Losses calculation of high voltage cables in sinusoidal currents are performed in [5] for determination of volumetric heat source in thermal analysis. Calculation of sheath induced voltage is performed in [6] with considering phase current variations, distances and radiuses of cables. Influence of cross bonding cables on losses with transposed and non-transposed conductors are investigated in [7]. In this method basic matrix impedance and Kron reduction method are used to determine of positive sequence impedance matrix and losses. Sheath loss study based on improved coupled line model to calculation of admittance matrix is performed in [8]. The paper studies on connecting impedance in cross bonding joints to reduce the sheath loss. In the study of [9] an integral equation method is used for sheath losses calculation of three phase cables in triangular construction. Analytical study is performed in [10] on the cable conductor losses without metallic sheaths in multi circuits system inside duct bank. Losses distributions are considered symmetrical which is not valid for asymmetric

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configurations and cables close to each other. Standard and theoretical formulations are used to losses computations in all of mentioned studies. Standard formulations are straight forward for conductor and sheath losses calculations in some predefined constructions that are presented for engineers. But these formulas can not be used for precise losses computations with considering the skin and proximity effect in all complicated cables constructions.

On the other hand FEM can be used for electrical and thermal analysis of power cables in different formation and various constructions [11, 12]. Although this method is precise, deep computation is needed by computer. Also simulation results are sensitive to accurate modeling of region, boundary conditions and meshing of system. The loss attribute of HTS DC model cable using FEM is presented in [13]. In the study the effects of HVDC converter on DC power cable is studied. Authors in [14] investigate electrical resistive losses of low voltage cables by FEM where there are no metallic layers in power cables. A thermal analysis is performed in [15, 16] for underground cables. Finite elements simulations are performed in [17] for underground transmission line that are buried in multilayer soil. But none of the mentioned studies are performed on the computation of sheath losses and cable temperature by FEM.

In this study a new analysis is performed on determination of total resistive losses of power cables. A thorough investigation is performed on the computation of cable conductor and lead sheath losses separately. Different constructions are considered. Sheathed and unsheathed cables in both flat and trefoil formations are investigated. Also calculations are performed in different distances between cables. Calculations of conductor and sheath losses are performed by IEC standard equations and FEM for single point bonding and both ends bonding grounding systems. Resistive losses in each profile are calculated and results are analyzed. For investigation of the effects of each profile on cable temperature raising a thermal analysis by FEM is performed. Electrical and thermal simulation results show cable sheaths can increase or reduce the cable ampacity which has not been studied before. Also analysis results indicate the importance of considering the sheaths, grounding method and cable formation in power cable losses and ampacity analysis.

2 Determination of Resistive Losses

2.1 Conductor Losses

Cable conductor losses are calculated by analytical method as standard formulations and FEM as differential equations.

2.1.1 Analytical Method

Main sources of heat in power cables are central conductors resistive losses. Total resistive conductor losses in power cables can be calculated as [18]:

$$w_c = n.R_{ac}.I^2 \tag{1}$$

where I is effective current of cable, R_{ac} is ac resistance of conductor in operating temperature and n is the number of loaded conductors in power cable. Ac resistance of power cables is a function of DC resistance, proximity and skin effects of conductors. In IEC-60287, ac resistance of conductor is calculated as:

$$R_{ac} = R_{dc}(1 + Y_s + Y_p) \tag{2}$$

where R_{dc} is DC resistance of conductor in operating temperature, Y_s and Y_p are skin and proximity effect factors, receptively. These factors are dependent to conductor diameter, axial distances of concoctors and frequency. Skin and proximity effect factors are defined as:

$$Y_s = \frac{x_s^4}{192 + 0.8.x_s^4} \tag{3}$$

$$x_s^2 = \frac{8\pi f}{R_{dc}}.10^{-7}.K_s \tag{4}$$

$$Y_p = \frac{x_p^4}{192 + 0.8.x_p^4}\left(\frac{d_c}{s}\right)^2. \left[0.0312.\left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{x_p^4}{192 + 0.8.x_p^4} + 0.27}\right] \tag{5}$$

$$x_p^2 = \frac{8\pi f}{R_{dc}}.10^{-7}.K_p \tag{6}$$

where d_c is conductor diameter, s is axial distance of conductors, K_s, K_p are constant factors that are presented in IEC tables. Equations (1-6) are used to calculation of conductors losses in some predefined formations and constructions of power cables. These relations give accurate results for simple constructions and are unusable for complicated systems or exact considering of proximity effect between conductors. Computations based on FEM are required in these cases.

2.1.2 Finite Element Method

Finite element is a mathematical method for solving ordinary and partial differential equations. It is a numerical method with ability to solve complex problems that can be represented in differential equations form. The method in electrical applications is described by Maxwell's equations. In this concept, electric and magnetic fields are defined as force, that is inserted at a test charge (q), if it were introduced at speed v and stated as:

$$f = q.(E + v \times B) \tag{7}$$

where E and B are electric field and magnetic density, respectively. Linear diffusion equation is:

$$\frac{1}{\mu}\left(\nabla \times \nabla \times \vec{A}\right) = -j\omega\sigma\vec{A} - \sigma\nabla\varphi \tag{8}$$

where $A, \varphi, \omega, \sigma$ and μ are magnetic vector potential, magnetic flux, angular frequency, conductivity and magnetic permeability, respectively. FEM considers total current density in a specific conductor or region as below [19]:

$$\vec{J} = \vec{J}_e + \vec{J}_s \quad (9)$$

where J_e and J_s are related to the magnetic vector potential and electric potential, respectively. Current densities are calculated in finite element equations as:

$$\vec{J}_e = -j\omega\sigma\vec{A} \quad (10)$$

$$\vec{J}_s = -\sigma\nabla\varphi \quad (11)$$

By solving for unknown values of A and J_s, current flowing in the conductor with cross section of S can be determined as:

$$I_{rms} = \iint_S J.ds \quad (12)$$

In this way, FEM can solve equations for determination of losses in sections of cables with different current densities.

2.2 Sheath Losses

Sheaths losses are divided to circulating current and eddy current losses based on grounding system type. Circulating losses are due to currents flow in 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. Three types of grounding systems are: I. Single point bonding, II. Both ends bonding, III. Cross bonding.

The advantage of single point grounding systems is lower losses and its disadvantage is creating induced voltage at open end of cables. Although it should be mentioned that in faulty power cable system, currents should pass all length of cable to ground which may cause additional losses [1].

There is not any induced voltage at the ends of cables, in both ends bonding systems. In the fault situation of such systems, currents are divided in two portions where causes reduction of fault losses. But these systems have additional losses at steady- state condition due to circulating currents in metallic sheaths. Cross bonding method decreases circulating sheath currents and high induced voltage as well. In this method, cable system is consisting of three sections with repeating all three phase sheaths in each part. In ideal case, induced voltages in sheaths are equal in magnitude with 120º phase difference. Thus total voltage in each part is equal to zero. This method can be used only in cable systems with long length. Also its implementation is expensive and needs skilled workers to run. Therefore cross bonding method is not capable to perform in any situation. Thus assessment of losses in the other types of grounding is investigated.

It should be mentioned that, eddy currents of sheaths occur in both multi conductor 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 in both ends grounding systems.

2.2.1 Analytical Method

According to IEC-60287, sheaths or screens losses factors, consist of losses due to eddy or circulating currents are defined as:

$$\lambda_1 = \lambda_1' + \lambda_1'' \quad (13)$$

where λ_1', λ_1'' are circulating loss and eddy loss factors, respectively. These factors are computed based on resistance and reactance computation of sheaths. Losses factors equations are presented in IEC-60287 for some special cables constructions and bonding systems. Eddy current and circulating current losses factors in symmetrical configurations are obtained as:

$$\lambda_1' = \frac{R_s}{R_{ac}} \cdot \frac{1}{1 + \left(\frac{R_s}{X_m}\right)^2} \quad (14)$$

$$\lambda_1'' = \frac{3\omega^2}{R_s . R_{ac}} \left(\frac{d_s}{2s}\right) . 10^{-14} \quad (15)$$

where R_s, X_m, d_s are sheath resistance, mutual reactance between sheath and conductor and mean diameter of sheath, respectively. It should be noted that usually eddy current losses are ignored in IEC calculations due to the low values.

2.2.2 Finite Element Method

FEM is another method for computation of sheath losses that is used for complicated systems and precise calculations. In this method, Sheaths are meshed to the small elements (e), and currents are calculated as was described for conductors. Thus sheath losses are calculated as:

$$P_s = \sum_e \iint_s \left(J_e(x,y) . J_e^*(x,y) \big/ \sigma \right) dxdy \quad (16)$$

3 Specifications of Studied Cables

In this paper two categories of underground power cables are studied. One type is single core medium voltage cables without any metallic layers and other type is medium voltage cables with metallic lead sheath according to IEC-60287. The material of insulation and outer covering are XLPE and PVC, respectively. All investigated cables have copper conductors with 630 mm^2 cross section and the thickness of lead sheath is 2 mm. Outer diameter of cables are 51 mm and 49.2 mm, for sheathed and unsheathed cables that are very close to each other and thus are comparable fairly. Cables are considered in both flat and triangular formations.

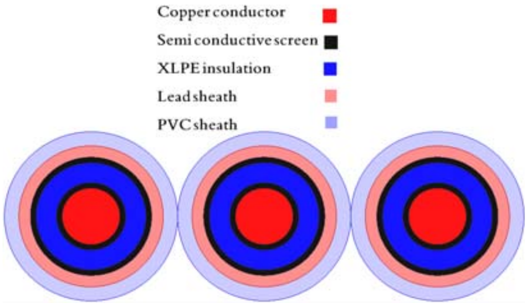

Fig. 1 Flat sheathed cables.

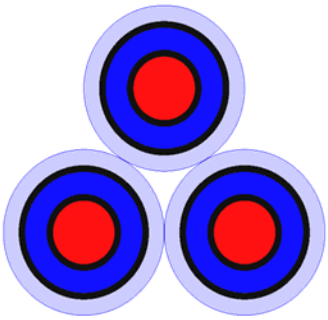

Fig. 2 Trefoil unsheathed cables.

4 Losses Computations by FEM and IEC

Also each construction and formation is assessed for adjacent cables and spaced cables with distances equal to cable outer diameter. Figs. 1 and 2 show the diagram of sheathed cables in flat formation and unsheathed cables in trefoil formation, respectively.

In this section conductor and sheath losses are computed by IEC formulations and FEM. Finite element simulation is performed by Ansoft Maxwell simulator in 2D-steady state domain, for precise consideration of proximity and skin effects in conductors and sheaths layers. Three phase system has balanced currents as:

$$I_a = 400\sqrt{2}\angle -2\pi/3, I_b = 400\sqrt{2}\angle 0, I_c = 400\sqrt{2}\angle 2\pi/3 \quad (17)$$

It should be mentioned that 400 (A) is not rated current of these cables and is selected only for losses computations of different situations. Fig. 3 shows the current density in flat unsheathed cables. Also Table 1 shows the losses results for unsheathed cables in flat and trefoil formations of adjacent cables, where P_i (i=a, b, c) denote to the power losses in three phases.

It is seen that IEC and FEM losses results are in a good agreement for trefoil and flat formations. However the difference between two methods is higher in flat formation than trefoil formation. IEC formulas assume symmetric positions for power cables. This assumption is reasonable for trefoil formations where gives better agreement with the FEM results in Table 1.

However this difference is very low, but more accurate results are presented by FEM that considers exact distances of conductors and thus proximity effects.

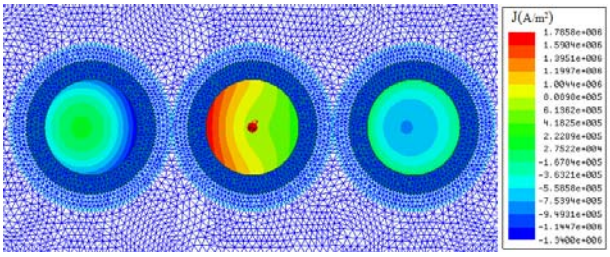

Fig. 3 Conductor current density in flat unsheathed cables.

Table 1 Adjacent unsheathed cables losses.

Loss(w/m)	Trefoil		Flat	
	FEM	IEC	FEM	IEC
P_a	5.268	5.266	5.014	5.266
P_b	5.268	5.266	5.731	5.266
P_c	5.268	5.266	5.071	5.266

Table 2 Adjacent sheathed cables losses.

Loss(w/m)	Trefoil		Flat	
	FEM	IEC	FEM	IEC
P_a	5.22	5.23	4.99	5.23
P_b	5.22	5.23	5.65	5.23
P_c	5.22	5.23	5.05	5.23
$P_{sa,e}$	0.0812	0.09	0.036	0.0511
$P_{sb,e}$	0.0811	0.09	0.154	0.17
$P_{sc,e}$	0.0812	0.09	0.046	0.05
$P_{sa,c}$	0.649	0.62	1.656	1.57
$P_{sb,c}$	0.65	0.62	0.628	0.544
$P_{sc,c}$	0.649	0.62	1.163	1.38

It is seen that losses in middle cable is higher than outer cables due to more proximity effect. Table 2 shows the conductor and lead sheath losses for trefoil and flat formations of sheathed cables in adjacent cables.

In this table $P_{si,e}$ and $P_{si,c}$ (i=a, b, c) denote the eddy current losses and circulating current losses of sheaths in each phase, respectively.

Also Figs. 4 and 5 show the conductor and sheath current densities in single point bonding sheathed cables. It is seen from Table 2 that FEM and IEC results are more similar in trefoil formation as described before. The difference of IEC and FEM is higher in flat formation. Especially in sheath losses computations, where IEC does not consider the proximity effects of sheaths. Also it is concluded from results of Table 2 that eddy currents losses have little effects on cable total losses. Also increasing the losses in single point bonding of sheaths are higher in flat formation due to the middle cable that is subjected to the more magnetic fields. Maximum total losses in sheathed cables are 0.76% and 1.8% higher than unsheathed cables in trefoil and flat formations, respectively. Increasing of sheath losses is higher in the cases of solid bonding sheaths, especially in flat formation. Increasing in maximum total losses are about 11% and 16% in solid bonding sheathed cables than unsheathed cables in trefoil and flat formations, respectively. In the cases of circulating currents, the minimum sheath loss is occurred in middle cable and maximum loss is in outer cable with phase lag conductor current.

In the next step of power losses analysis, the distances between cables are increased. Table 3 shows the losses of unsheathed cables with distances as much as cable outer diameter. However, spaced cables are not very usual in directly burial cables in trefoil formation, but it is used in prefabricated underground tunnels or ducts.

In the cases of spaced unsheathed cables, conductor losses in both formations are reduced due to the decreasing of proximity effect between conductors.

Spaced cables losses for sheathed cable are presented in Table 4. Resistive losses in both conductors and sheaths are very close to each other in FEM and IEC formulas. In spaced cables, proximity effect is lower than adjacent cables and conductors approximately act independent to each other.

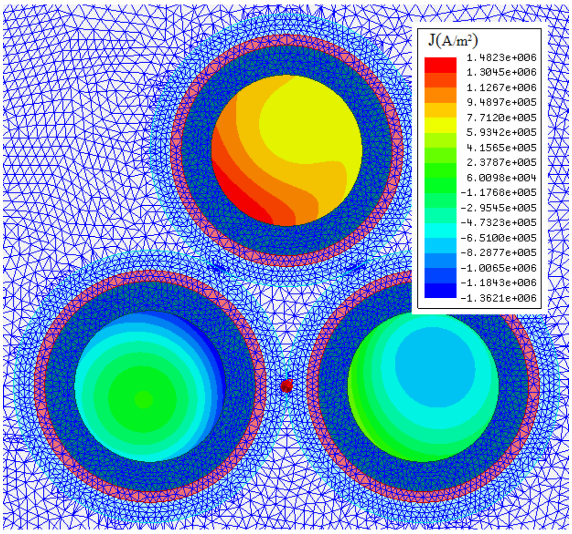

Fig. 4 Conductor current density in trefoil sheathed cables

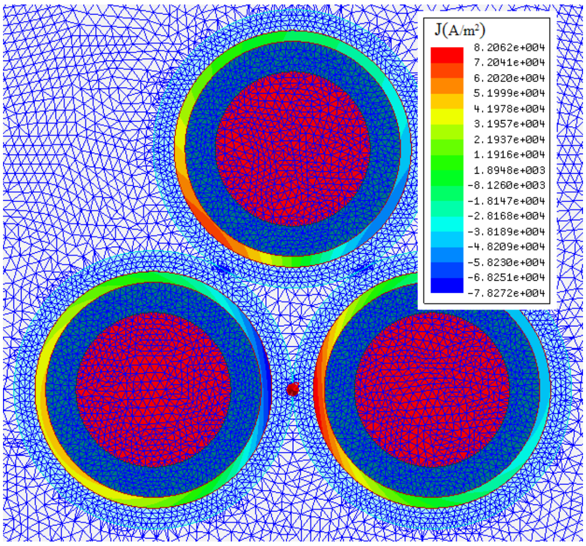

Fig. 5 Sheath current density in trefoil sheathed cables.

Table 3 Spaced unsheathed cables losses.

Loss(w/m)	Trefoil		Flat	
	FEM	IEC	FEM	IEC
P_a	4.9	4.9	4.8	4.9
P_b	4.9	4.9	5	4.9
P_c	4.9	4.9	4.8	4.9

Table 4 Spaced sheathed cables losses.

Loss(w/m)	Trefoil		Flat	
	FEM	IEC	FEM	IEC
P_a	4.91	4.9	4.8	4.9
P_b	4.91	4.9	5	4.9
P_c	4.91	4.9	4.8	4.9
$P_{sa,e}$	0.019	0.024	0.009	0.0122
$P_{sb,e}$	0.019	0.024	0.03	0.047
$P_{sc,e}$	0.019	0.024	0.01	0.0121
$P_{sa,c}$	1.91	1.92	3.53	3.418
$P_{sb,c}$	1.91	1.92	1.75	1.41
$P_{sc,c}$	1.91	1.92	2.66	3.03

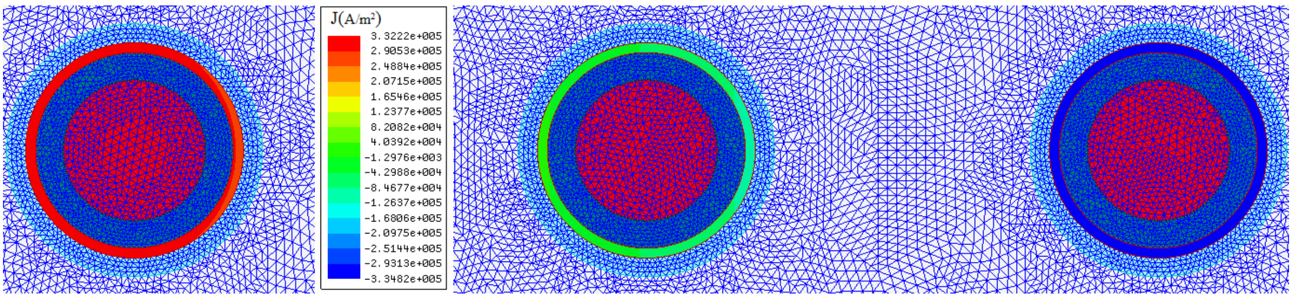

Fig. 6 Sheath current density in trefoil sheathed cable.

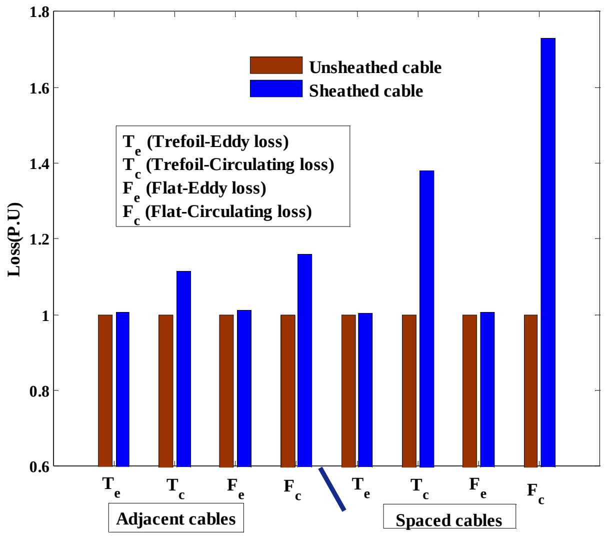

Fig. 7 Per unit total losses.

Thus even in flat formation two methods have similar results. In spaced cables, conductors losses in both flat and trefoil formations of sheathed cables are decreased. Also eddy current losses are reduced in sheath of each cable, as a result of lower influence of magnetic fields in phase conductors. On the other hand, sheath circulating losses have considerable increase and are even comparable to conductor losses. Also in some formations and distances, it can be more than conductor loss. In single point bonding of sheaths total resistive losses has 0.38% and 0.6% increment in sheathed cables than unsheathed cables. It is seen that increasing in loss is smaller than adjacent cables.

Fig. 6 shows sheath current density in solid bonding cable in flat formation. In solid bonding of sheaths circulating current losses are 38.9 % and 73.54 % higher than unsheathed cables in trefoil and flat formations, respectively. The increment is larger than adjacent cables.

For better comparison of increasing losses in sheathed and unsheathed cables the graphical view of losses in different cases are shown in Fig. 7. In this figure, maximum loss of unsheathed cables in each case is considered as base value in per unit conversion. T_e , F_e and T_c , F_c denote the eddy current and circulating current losses in trefoil and flat formations.

As it is seen in Fig. 7 total resistive loss is increased in sheathed cables. This increment is small in the case of single point bonding system compared to both ends bonding systems. Also cable losses are increased significantly in spaced cables in both ends bonding systems due to high circulating currents in lead sheaths.

5 Thermal Analysis

5.1 Finite Element Method

In this section, thermal analysis of different cases are performed by FEM to compare temperature increasing in different cases with respect to the calculated losses using FEM. Thermal equations are presented for some cable constructions and installations in IEC standard. But FEM can consider the accurate mutual heating effect of cables and give more precise results than IEC. The generated heat from cables losses can be transferred through conduction, convection and radiation. In the case of underground cables the main heat transmission method is by conduction. By considering the production of losses and dissipation of heat, in each instant, energy balanced equation is expressed as [2]:

$$W_1 + W_2 = W_o + \Delta W \tag{18}$$

where $W_1, W_2, \Delta W$ and W_o are the entering energy to the cable from other cables or solar radiation, the energy due to the internal losses of cable, stored energy in cable and the rate of energy dissipation from cables, respectively.

In underground cables, because of longer length than its diameter, and by considering homogeneous soil the heat dissipation equation can be expressed as:

$$\frac{\partial}{\partial x}\left(\frac{1}{\rho}\frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\rho}\frac{\partial \theta}{\partial y}\right) = -q \tag{19}$$

where q, θ and ρ are heat transfer rate, temperature and thermal resistivity, respectively. Also boundary conditions are stated as:

$$\begin{aligned} &T = T(x,y)\big|_\tau \quad , \quad \frac{1}{\rho}.\frac{\partial T}{\partial n}\bigg|_\tau + q = 0 \ , \\ &-\frac{1}{\rho}.\frac{\partial T}{\partial n}\bigg|_\tau = h\,(T - T_{inf})\big|_\tau \end{aligned} \tag{20}$$

where T_{inf}, τ and h are ambient temperature, region boundary and convection heat coefficient, respectively. Equation (19) can be applied for elements that constitute linear matrix equations. These equations also are dependent to the boundary condition. Two types of boundary conditions are selected in simulations. Isothermal boundary at ambient temperature is considered for upper side of cables that represents the ground surface. Other three boundaries are thermal insulation and the size of boundary is selected large enough to ensure the physical infinite boundary. Fig. 8 shows meshed configuration of sheathed adjacent flat cables in finite element simulation.

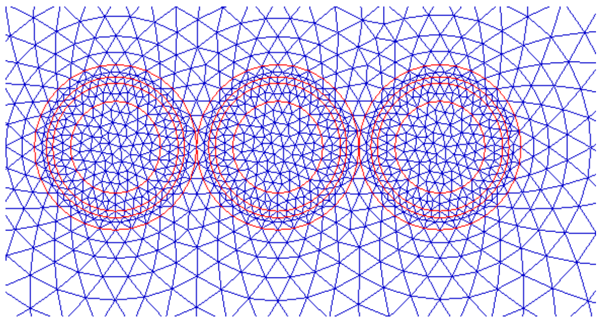

Fig. 8 Meshed configuration of adjacent flat sheathed cables.

5.2 Simulation results

Thermal simulations are performed by FEM with soil and surface ambient temperature equal to 20 ºC and 30 ºC, respectively. The cables burial depth is 0.8 m and thermal resistivity of soil is 1.5 (K.m/w). Dielectric losses in under studying cases are negligible and can be ignored in thermal simulations. Table 5 shows the maximum temperature of cables in different constructions of adjacent cables. Fig. 9 shows thermal simulation of single point bonding of trefoil sheathed cables.

Maximum conductor temperature in trefoil formation of unsheathed cable is slightly higher than single point bonding sheathed cable. While in the section 3 total calculated losses in sheathed cable are slightly higher than unsheathed cable. This is due to the presence of lead sheaths in the cables construction. In reality the thermal resistance of lead sheath is much smaller than insulation materials in cable. Therefore, composition of thermal resistances in sheathed cable is smaller than the only insulation resistance in unsheathed cable.

It may be expressed that the conductors losses have more effects on conductors temperature. Also the conductors losses in unsheathed cables are more than sheathed cables. For response to this challenge, another thermal analysis is performed on sheathed cable by considering the conductors losses equal to unsheathed cables and sheaths losses as single point bonding sheathed cables

Table 5 Temperature (θ°C) of adjacent cables.

	Unsheathed Cable	Sheathed Cable Single Point Bonding	Sheathed Cable Solid Bonding
Trefoil	47	46	48
Flat	47.1	46.2	50

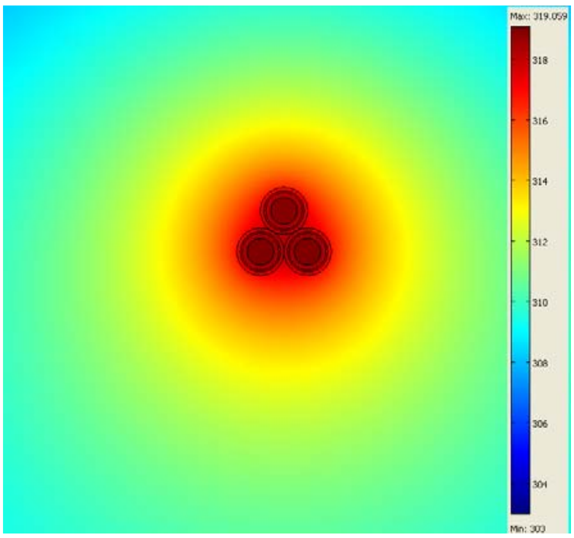

Fig. 9 Adjacent trefoil sheathed cables.

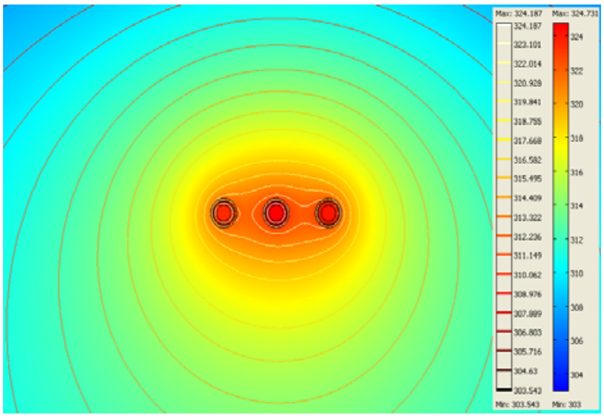

Fig. 10 Spaced flat sheathed cable.

Table 6 Temperature (θ°C) of spaced cables.

	Unsheathed Cable	Sheathed Cable Single Point Bonding	Sheathed Cable Solid Bonding
Trefoil	44	43.1	49
Flat	43.5	43	51.7

In this case maximum cable conductors temperature are 46.3 ºC and 46.4 ºC in trefoil and flat formations, respectively. In these simulations, temperatures are again lower than unsheathed cable. It should be noted that the difference between temperature of unsheathed cables and single point bonding sheathed cables are low and can be ignored; anyway temperature in sheathed cable is not higher as it is expected. There is similar analysis for flat formation of unsheathed and single point bonding sheathed cable.

In solid bonding sheaths the conductor temperature is higher than unsheathed cable due to the high circulating loss. The temperature increment is higher in flat formation than trefoil formation as the losses in flat is higher than trefoil formation. It should be noted that in all cases the conductor temperature does not reach to 90 ºC because the current is not the value of rated current of these types of cables. Thermal FEM results for spaced cables are presented in Table 6. FEM simulation for spaced solid bonding sheathed cables in flat formation is showed in Fig. 10.

Maximum temperature of trefoil formation in unsheathed cable is higher than single point bonding sheathed cable. Similar behavior exists for flat formation in unsheathed and single point bonding sheathed cables. Maximum temperatures in these cases are smaller than the similar cases of adjacent cables. This is due to two reasons. First is that distances between cables result in smaller conductors and sheaths losses and second, mutual heating effect between cables are decreased and thus each cable approximately has independent thermal field. But in the cases of solid bonding of sheaths temperatures are more than unsheathed cables. In spite of the increasing the distances between cables the temperature is higher than adjacent cables, due to the high sheaths circulating losses.

6 Conclusion

In this paper a new analysis is performed on unsheathed and lead sheathed underground power cables. Single point bonding and solid bonding grounding systems of sheaths are considered. Conductor and sheath losses are computed with IEC formulations and FEM. Thermal analysis are performed to investigation of lead sheath effects on maximum cable temperature. Summary of notifications based on simulations results are stated as bellow:

- IEC gets precise results for conductor losses of trefoil formation. It has accurate but not exact results for flat formation, where cables formation is asymmetric.
- Difference of IEC and FEM become larger in sheath losses of flat formation than trefoil formation. Especially in circulating current losses where IEC does not considered the proximity effects of sheaths.
- Calculated losses of sheaths using IEC and FEM, have more agreement with increasing of cables distances, due to the decreasing of proximity effects which is neglected in IEC.
- Cable temperature is decreased by increasing of cables distances in unsheathed and single point bonding sheathed cables. This is due to the decreasing of conductor and sheath losses, and also mutual heating effects of cables.
- In both ends bonding sheathed cables, temperature is increased by increasing of cables distances. Because circulating currents are larger in cables with higher distances.
- Losses are increased in single point bonding of sheathed cables than unsheathed cables. But owing to the lower thermal resistance of lead sheaths, temperatures are decreased. Moreover, in solid bonding sheaths, the circulating currents cause more losses and temperatures than unsheathed cables and single point bonding sheathed cables.

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