Multiphysics Finite Element Analysis of Underground Power Cable Ampacity

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Abstract— A method for calculating the ampacity of underground electric power cable line is discussed. The proposed method differs from the previous works by using coupled electromagnetic and thermal FEA analysis. Electromagnetic analysis is used to calculate the resistive AC losses in conductor, shield, and metallic sheath, taking into account skin and proximity effects. The equations of 2D AC magnetic field are coupled together with circuit equations in order to account different grounding modes. The resistive losses calculated by electromagnetic part of the model are summed up with the dielectric losses and transferred to the thermal part of the model as a heat sources.

The proposed method can be used in cases where the standard IEC 2087 calculation gives unreliable results due to unusual cable line formation, inhomogeneous soil, presence of metallic or concrete supports and other difficulties.

***Keywords*—**Cable ampacity, buried cable, finite element analysis, multiphysics, shield grounding

I. INTRODUCTION

The rated current of the underground electric power cable line is limited by the maximal allowable temperature of cable conductor, given by the standard or the cable manufacturer. The temperature raise in turn depends on resistive and dielectric losses in cable as well as on thermal conductivity of cables materials and the ability of surrounding media to conduct and dissipate the heat flux.

To calculate the ampacity of the cable line one must first assess the AC resistive losses in conductive cable elements: conductor, screen and armor.

The classical method of ampacity calculation is given by the IEC 60287 standard. Its theoretical background is a Neher-McGrath model [2], which was generalized later by many authors, in particular G.J. Anders [3]. The Neher-McGrath model relies on the thermal equivalent circuit technique. The parameters of the equivalent circuit are calculated by using a simplified 1D-model of the thermal field. Electromagnetic part of a calculation intended to assess the resistive and dielectric losses in the cable, is also based on a simplified model of the skin effect and proximity effects.

When the cables are located close to each other, it is necessary to take into account their thermal and electromagnetic interference. Electromagnetic interference is the proximity effect and the skin effect, and the fact that, depending on the chosen grounding mode, the screens and sheaths appear electrically connected into a closed loop. The thermal interference is that neighboring cables warm up to each other and the surrounding soil. Accounting of the mutual heating is especially complicated when cables are laid out in the open air or in restricted airspace - in a pipe or a rectangular conduit. In such case, the multiphysics model should be supplemented with fluid dynamics analysis.

Today FEA software [12] allows combining into a single model the AC electromagnetic analysis, grounding electric circuit, and the thermal analysis. Because the material properties, such as electric resistivity, depends on the temperature, one have to repeat electromagnetic and thermal analyses iteratively until the solution converges. Complexity of the model, however, is quite acceptable for engineering practice.

The advantages of FEA model is particularly evident when power cable line has rather complex structure of the , i.e. includes soil layers with different properties, strong electromagnetic interference between cables, metallic supporting structure, crossing pipelines e.t.c.

In this paper, we consider only steady-state cable ampacity calculation. Nevertheless, the FEA based approach, allows the ampacity calculation in transient conditions: the long-term transient, where the a priory known load curve allows a short-term uprating due to the inertia of thermal processes, and short-term transient, such as the raise of cable temperature due to short circuits of different kinds.

The history of FEA analysis for cable ampacity calculation begins presumably with [4], where the transient heat transfer FEA analysis was used three-phase buried cable line. Later

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many authors have contributed to application of the FEA technique for accurate predicting the ampacity of a cable line. Those include: clarification of the model geometry – the shape and the size of modelling area, optimal mesh density [5], short-term and long-term transient simulations [6], [7], taking into account the effect of the temperature on the cable losses, combining the heat transfer analysis with fluid dynamics [8], [9], estimation of resistive AC losses using the electromagnetic FEA model [10]. The accumulated engineering experience of the FEA simulation of the temperature field of cable lines was summarized in the IEC technical report [11].

The contribution of this paper is the combining of AC magnetic FEA simulation, Kirchhoff's equations of the grounding circuit , and steady state heat transfer FEA analysis into a single model of the power cable line.

II. ELECTROMAGNETIC MODEL

A. Equations of AC Magnetic Field

The governing equations of quasi-stationary magnetic field in frequency domain are written with respect to the phasor of the vector magnetic potential **A**, which has in the 2D-domain only one nonzero component $A = A_z$ [11]:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=-j_{extern}+j\omega\sigma\cdot A\,, \qquad (1)$$

where μ – is the absolute permeability (H/m), σ – electric resitivity (S/m), ω – cyclic frequency (rad/s), j_{extern} – the external current density (A/m^2).

The need of taking into account of the grounding circuit (with one end, with two ends or with transposition) requires combining the field equation (1) with the Kirchhoff's equation of the connected circuit. The equation of a circuit branch containing a solid conductor in magnetic field looks like this:

$$I=\frac{U}{R}=-\sigma\int_{\Omega} i\omega A\cdot ds\,, \qquad (2)$$

where U – is the conductor voltage drop (V), R – the DC resistance (Ohm), The integration is made over the conductor's cross-sectional area Ω.

Solving the equations (1) and (2) one obtains the distribution of the current density in all conductive parts of the model: conductor, shield, metallic sheath, and some metallic supporting structure.

B. Model Geometry

With two dimensional electromagnetic FEA simulation the model geometry contains the cross-sections of all cables, buried into the soil on the given depth. The left and right side borders of the modelling area located far enough to assign on it the no-field border condition.

Our experiments show that for a model containing one cable line increasing the model width over 15 m does not effect on the solution accuracy. The model allows taking into account the electric conductivity of soil as well as supporting metallic parts or pipes nearby.

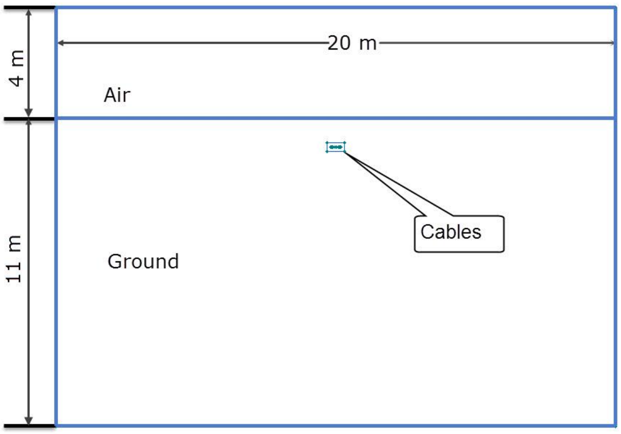


Fig. 1 The model geometry

The discretized cross section of the cable is shown on the figure 2.

In the real world, the conductive parts of the cable are made from separate wires or strips. Constructing the FEA model one can include the detailed geometry of wires or replace them by a solid metal cylinder. In many cases, the conductor wire structure plays an important role and cannot be neglected, for example with modelling of a pulse mode, high frequency losses and others. In our case – the steady state simulation by the fundamental frequency – the exact representation of the conductor's structure does not increase the accuracy, but requires much more resources. Moreover, the exact modelling of the wires is not an easy task because of some uncertainty of the shape of deformed wires and the contact resistivity between them.

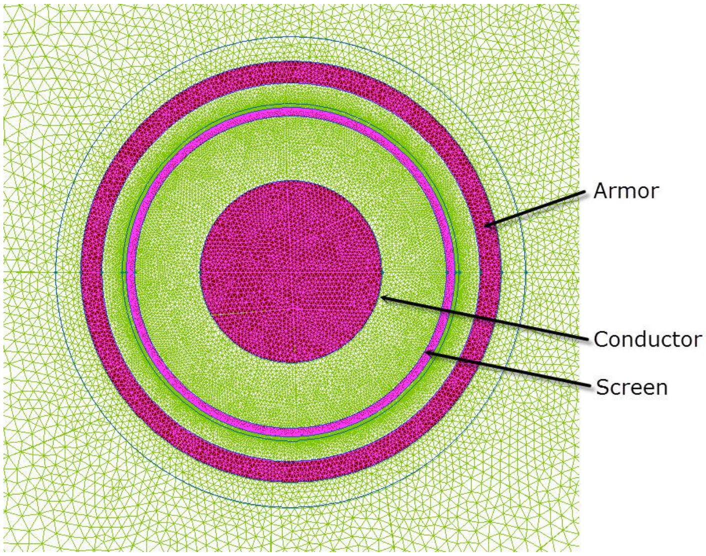


Fig. 2 The cable cross section with the FEM mesh

A separate question is how to choose properly the cross section and the conductivity of the solid cylinder representing the stranded conductor. In our experience, the best results can be obtained by choosing the inner and outer diameters of the conductor the same as in reality. Acting in this way we set the total cross sectional area a bit more than the sum of cross section area of all wires. To compensate that we propose proportionally decrease the electric conductivity and the thermal conductivity of the simplified conductors.

C. Single Point and Both Ends Grounding

The shield of a cable section can be grounded with one side or with two sides. With two-side grounding the closed loop is formed for circulating current. This current is induced by the alternating magnetic field created by the cable conductor current. The one-side grounding does not provide the loop for induced currents. On the other hand on the unbounded end of the cable shield the induced voltage is observed, that should be limited for sake of safety. We have to note that even with one-side grounding of the cable having both a screen and metallic sheath, these two are always electrically connected with both sides of the cable. This forms a closed loop for circulated current even with one-side grounding.

Presence or absence of a closed loop significantly affects on the amount of losses in the shield and sheath. To consider those one have to couple field equations (1) with the circuit equations (2).

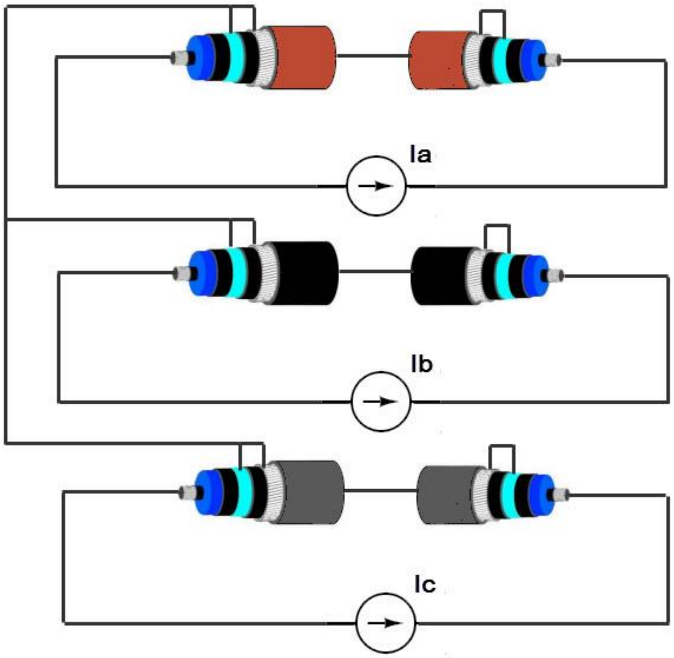


Fig. 3 Grounding the cable with one side

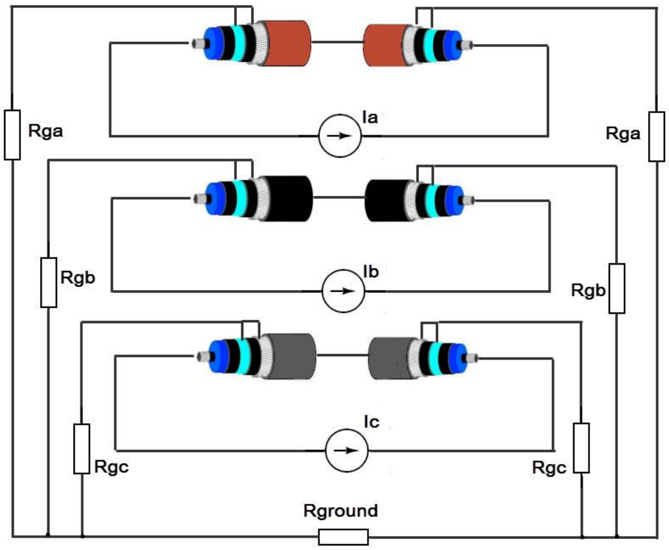


Fig. 4 Grounding the cable with two sides

The values of resistance in the grounding scheme are known with some degree of uncertainty. Therefore, we evaluated the sensitivity of the FEA solution to the values of the resistances R_{gX} and R_{ground}. The study shows that the variation of resistance R_g in the range from 1 to 10 Ohms has virtually no effect on the integral value of losses. The earth resistance R_{ground} has almost no effect for our model until the three phase cable loading is symmetric and zero sequence current is almost zero.

D. Dielectric Losses

According to IEC 60287-1-1 the dielectric losses per unit length of the cable can be calculated by the known value of the dielectric loss factor tgδ:

$$W_d = \omega C U^2 \cdot tg\delta \ , \tag{3}$$

where $\omega = 2\pi f$, C is the capacitance per unit length (F/m), U_o – is the voltage to earth (V).

The capacitance of a cylindrical capacitor is calculated by:

$$C = \frac{2\pi\varepsilon\varepsilon_0}{\ln\left(\frac{D_i}{d_c}\right)} \tag{4}$$

As long as we remain in the class of cables and conductors with cylindrical conductors and screen screens the refinement of formulas (3) and (4) by means of FEA is not required. The FEA model of dielectric losses may be needed for more complex geometry configurations such as cable joint and termination.

III. HEAT TRANFER MODEL

The thermal state of the loaded power cable line is defined by the partial differential equation of thermal conductivity. With steady state analysis it is reduced to:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) = -q \ , \tag{5}$$

where *T* is the temperature (*K*), *t* – time (*c*), λ – the thermal conductivity (*W/(m·K)*), *q* – the heat source density (*W/m*^{3}).

The thermal conductivity equation (5) is solved numerically on the same computational domain as the magnetic field equation (1) (see fig. 1) with the difference that the air above the ground surface is excluded from the domain. On the side boundaries of the domain we define the boundary condition of thermal insulation, on the bottom border – an isothermal boundary condition with the value of 4 deg. C, which is almost constant throughout the year. On the earth surface the convective boundary condition is set with the ambient temperature $T_0=25\ deg\ C$ and the convection coefficient α. The suitable value of the convection coefficient we choose by the dimensionless empirical equation:

$$Nu = 0.54\cdot\left(\Pr\cdot Gr\right)^{0.25}, \qquad (6),$$

where Nu is the Nusselt number, Pr is the Prandtl number, and Gr is the Grashof number.

From (6) obtain the convection heat transfer coefficient α:

$$\alpha = Nu\cdot\frac{\lambda}{L_{ref}}, \qquad (7)$$

where L_{ref} is a characteristic length of the model.

Using the equation (6) takes into account the average wind speed if such data are available.

IV. Simulation Results

The modern approach to field simulation in electrical equipment often is multidisciplinary [13] in order to catch the mutual interference of processes from different domains of physics.

The steady-state simulation loop begins with magnetic field simulation (1.) for obtaining the spatial distribution of the restive losses. The calculated resistive losses are summed up with the dielectric losses (2.) and transferred to the heat transfer analysis (3.). The thermal simulation gives us the temperature field, which is used for adjusting the conductivity of copper and aluminum (4.). Then the loop (1. – 4.) is repeated until the solution converges (normally 3-4 loops is sufficient).

The simulated cases include the cable formation in line (fig. 5 and 6) and the touching triangle formation (fig. 7, 8).

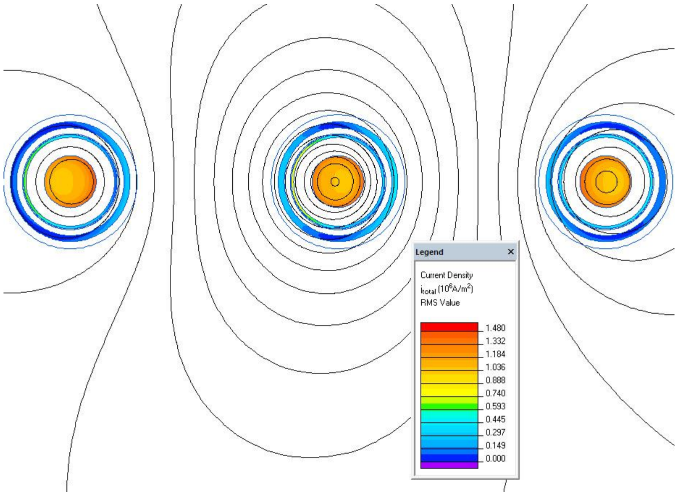


Fig. 5 Magnetic field and current density with line cable formation

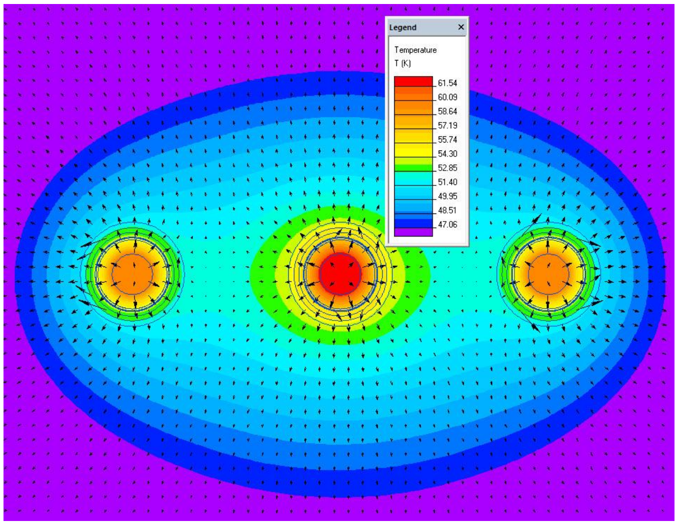


Fig. 6 Temperature field and heat flux vectors with line formation

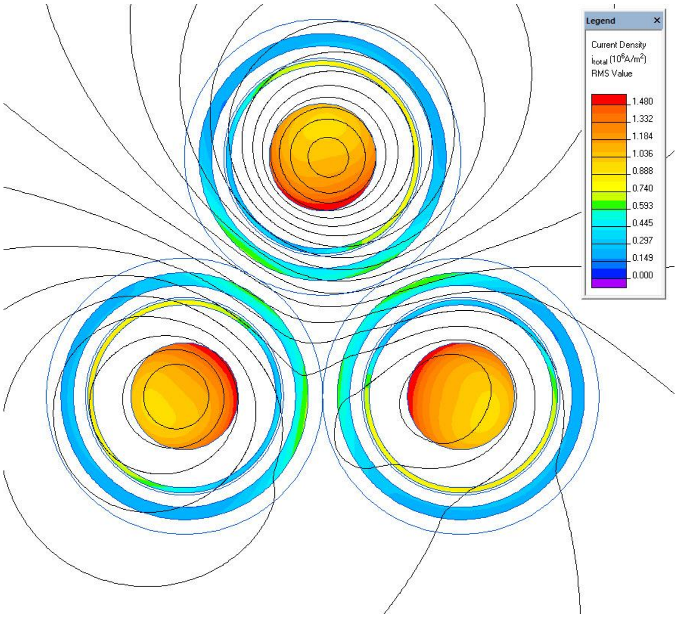


Fig. 7 Magnetic field and current density with triangle formation

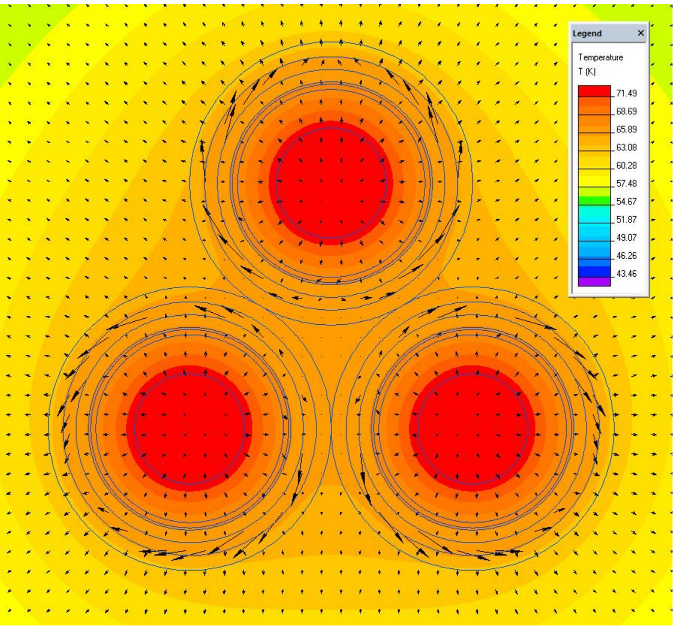
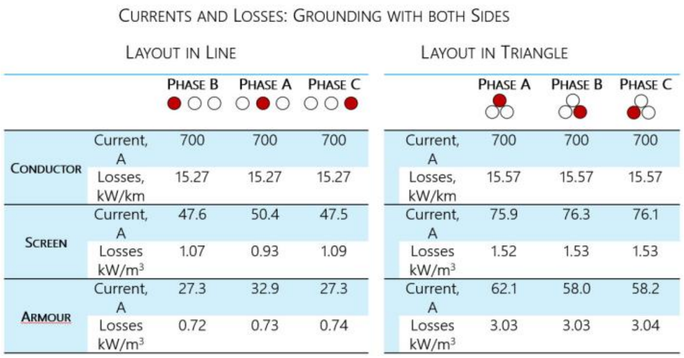


Fig. 8 Temperature field and heat flux with triangle formation

The resistive losses in cable conductors, screens and sheaths with two different formations are summarized in the table 1:

Table 1: Resistive losses in cable elements



CURRENTS AND LOSSES: GROUNDING WITH BOTH SIDES

	LAYOUT IN LINE				LAYOUT IN TRIANGLE			
		PHASE B ●○○	PHASE A ○●○	PHASE C ○○●		PHASE A	PHASE B	PHASE C
CONDUCTOR	Current, A	700	700	700	Current, A	700	700	700
	Losses, kW/km	15.27	15.27	15.27	Losses, kW/km	15.57	15.57	15.57
SCREEN	Current, A	47.6	50.4	47.5	Current, A	75.9	76.3	76.1
	Losses kW/m³	1.07	0.93	1.09	Losses kW/m³	1.52	1.53	1.53
ARMOUR	Current, A	27.3	32.9	27.3	Current, A	62.1	58.0	58.2
	Losses kW/m³	0.72	0.73	0.74	Losses kW/m³	3.03	3.03	3.04

V. CONCLUSION

Proposed further development of prediction the ampacity of underground cable line using multiphysics FEA simulation. The main contribution is the detailed consideration of cable grounding, taking into account more than one electromagnetic screen (namely the copper shield and the aluminum sheath). The proposed approach combines in a single model the AC magnetic FEA simulation, the grounding circuit, and the heat transfer FEA. The first two parts coupled by the strong link, i.e. they produced a single matrix after discretization. The magnetic and thermal parts of the model a coupled together by a two-directional loose (consecutive) link.

The FEA based calculation gives almost the same result as the standard IEC 60287 calculation when the construction of the cable line is ordinary. The dedicate software gives the answer almost as quickly as the IEC based software.

Benefits of the multiphysics FEA appears in situations more complex than those described in the standard, such as heterogeneous soil with thermal backfill, using of steel or concrete supporting construction. An important case is a line with two or more circuits.

Benefits of the FEA simulation also expected with very rapid transient conditions, such a direct lightning stroke [14].

Moreover, the FEA simulation of magnetic field gives exhaustive information about inductive interference of two or more circuits, both cable and overhead ones. In addition, the magnetic and electric field profiles on the earth surface can be used to fulfill the rules of electromagnetic ecology and designing magnetic shielding when needed.

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