Modeling of long-term cable lines load in real operating conditions

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In the article some basic aspects of numerical modeling of cable lines were discussed. Some often found cases, where the cable lines are placed in cable conduits and cable culverts, were analyzed. The analysis results were compared to the classical, circuit-models based approach of such issues. Basic sources of classical models errors, resulting from difficulty to precisely determine the real environmental quantities were calculated and discussed. Utility of numerical, field models was shown and influence of basic simplifications on calculating results was determined.

1. Introduction

Accurate selection of cable types and dimensions seems to be a very important problem that directly determinates the stability and reliability of cable lines systems. The designing processes typically involves solving of basic circuits models. The selection of cable types, in view of long-term loads and current overload, is very often limited to analysis of basic quantities of heat generation rates in reference conditions. The influence of environmental conditions of cables and the cable line configuration are satisfied by using of an arbitrary additional coefficients [5]. In many cases, the approach given above (generally compatible with obligated standards) enables rational determination of dimensions and types of energetic cables. However, a huge number of cable lines configurations and environmental conditions cause, that calculating results do not enable for fully optimal selection of cables. In such cases, necessity of high accuracy simulation results of numerical modeling techniques utility.

The article deals with an analysis of chosen aspects of long-term high-voltage cable lines load, arranged in cable conduits. The basic aim of the study was presentation of different calculating procedures, from commonly used circuit - based models of cable lines. Basic model for most presented calculations was the cable conduit of imposed dimensions and the high voltage cable of type XRUHKXS-FIMT 1x1000RMC/120, placed inside the conduit [6]. Some difficulties of analytical description of such problem requires the usage of numerical modeling, with assumption of exact reflection the real geometry and physical model. The influence of commonly used simplifications on calculations results quantity was shown. Among many parameters that determinate the physical model [1, 4], a special attention was put on the heat transfer phenomenon and the skin effect in conducting materials [3]. Some additional analysis were made to determinate the influence of cable conduits length on temperature distribution within the cables.

2. Modeling of cable lines

The geometry of analyzed system consists the model of high-voltage cable of type XRUHKXS-FIMT 1x1000RMC/120 placed inside the pipe current culvert pipe SRS 160, fulfilled with the air (Figure 1) [6].

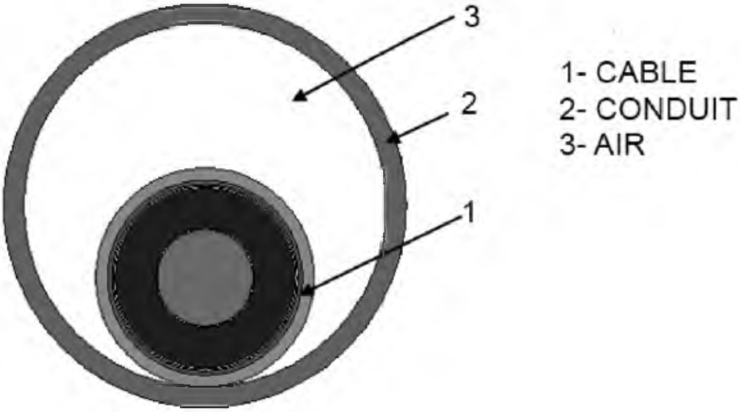

Fig. 1. Basic model of cable placed inside the culvert

Basic geometry of the model (Figure 1) and the boundary conditions were different, according to the objective of partial analysis. Among of used numerical models, both 2D and 3D calculations were done. All models were created in two independent FEM systems. Some authors calculating procedures were used. The whole task was divided into three separate problems.

All models were designed in two independent calculating systems. The solving procedures were supplemented with authors algorithms. Some basic, partial aims, leading to complex solving problems can be defined as:

- determination the influence of used heat source on calculation results;
- determination the influence of used simplifications of physical model on calculations accuracy;
- determination the influence of cable conduit length on maximal long-term thermal load of the cable line.

2.1. Analysis the possibility of constant current density model utility

The electro – thermal calculations, in all cases, require the coupled electromagnetics and thermal analysis utility. The type of coupling (weak or hard) and assumed simplifications are not be significantly important due to basic target of analysis in some cases. Heat conduction phenomenon in cable lines systems, can be described as (1) [1]:

$$\frac{\partial t}{\partial \tau} + (\mathbf{w} \cdot \nabla)\mathrm{t} = \frac{p_V}{c\rho} + \frac{1}{c\rho}[\nabla(\lambda \nabla \mathrm{t})] \tag{1}$$

The equation (1), in respect to long-term thermal loads of cable lines, can be simplified, *inter alia* by the possibility of neglecting the transient analysis. In general, however, calculations of the heat generation effects corresponding to the current conduction require utility of the equation of type (2) in cylindrical coordinate system. The solution of such problem is generally described by the Bessel functions of zero- and first order [4]:

$$\frac{d^2 H_\varphi}{dr^2} + \frac{1}{r}\frac{dH_\varphi}{dr} = \alpha^2 H_\varphi \tag{2}$$

where: $\alpha = [(1+j)/\delta]$ is the coefficient dependent on frequency and material parameters [2, 3, 7]. The boundary conditions in such problem can be formed as $H_{r=r_0} = \frac{I}{2\pi r_0}$ and $H_{r=0} = 0$.

The basic target of preliminary analysis, presented below, was determination of the quantity influence on the constant current in main conductor in respect to the accurate model (2). Such simplifications always correspond to eddy currents and the proximity phenomenon neglected in the model. In Figure 2, the temperature fields in the cross-section of cable line model were shown. Two cases were analyzed: for constant heat generation rate and for constant current value in main conductor.

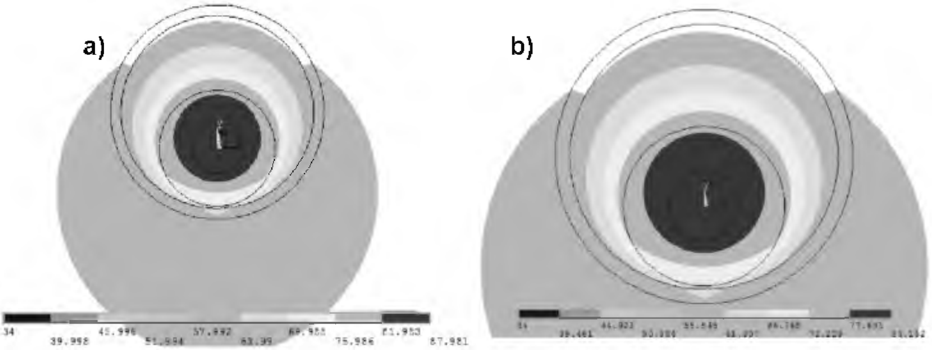

Fig. 2. Temperature distribution in cable line for different types of temperature load: a) constant heat generation load; b) current load

Basing on the calculations results, the differences of temperature distribution for the case of simplification of constant power distribution were calculated. The temperature fields were equal in both analyzed cases. However, temperature values differed by 5 Kelvins. Such differences are unacceptable because of the basic requirement of accuracy analysis. Analysis of the shape of temperature field within the main conductors enables declaration of non-impact of the eddy currents for temperature distribution in cables. Despite of equal total power values in both cases (36.11 W/m for full model and 35.25 W/m for simplified model), the maximal temperatures differed by 10%. The numerical model errors and discretization errors were omitted because of optimal model construction. Analysis of temperature field in main conductors (Figure 3) allows for assessement of the sources of differences between two analyzed cases.

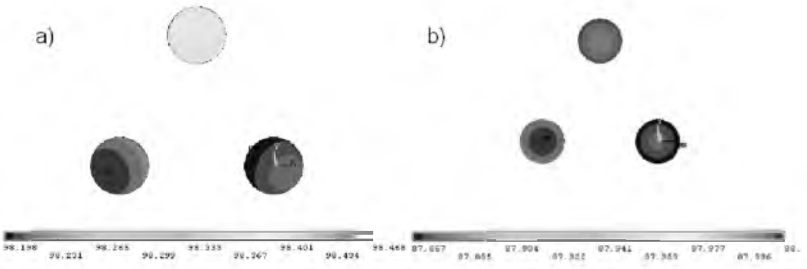

Fig. 3. Comparison of temperature fields within the main conductors for full (a) and simplified (b) models

For full model, the temperature distribution was similar to the Joule heat distribution. The phenomenon was observed despite of a high value of coppers thermal diffusivity, causing a strong homogeneity of temperatures within the conductors. The differences of temperature distribution in two models were observed especially for a high temperature values. In case of low load of cables, such effect was not visible. However, possibility of precise determination of heat generation in cable systems, under conditions of skin effect and the proximity effect and carry out calculations for maximal cable operating temperatures, clearly indicates the necessity of using the full coupling electromagnetic and thermal models.

2.2. Analysis of natural convection

Analysis of heat transfer phenomenon in fluids, in low temperature range requires, in most cases, taking into consideration the thermal convection. There is a huge number of equations for analysis of such phenomenon. In arrangement characterized for cable systems, the heat transfer occurs between surfaces located in proximity. In general, determination of convection heat transfer requires the solution of complex system of differential equations of amount of substance balance, the momentum balance and the energy balance, with appropriate conditions of uniqueness of the solution [1]. The momentum balance of unitary volume of fluid, named the Navier - Stokes equation (3 for exemplary x direction) is equal for constant coefficient of viscosity. The equation determines the time change of momentum of fluid (of mass ρ) induced by the gravity ($\rho \cdot g_x$), pressure gradient ($-(\partial p/\partial x)$) and the viscous force:

$$\rho \frac{dw_x}{d\tau} = \rho g_x - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 w_x}{\partial x^2} + \frac{\partial^2 w_y}{\partial y^2} + \frac{\partial^2 w_z}{\partial z^2} \right) + \frac{1}{3} \mu \frac{\partial}{\partial x} \left(\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} + \frac{\partial w_z}{\partial z} \right) \tag{3}$$

The energy balance equation for single-component fluids (4), despite a number of simplifying assumptions, enables for simultaneous determination of kinetic energy and the heat transfer:

$$\rho \frac{du}{d\tau} = \lambda \nabla^2 t - \rho \frac{pd\upsilon}{d\tau} + \mu \Theta_V + q_V \tag{4}$$

where: u - internal energy; λ - thermal conductivity; τ - time; ρ - density; υ- the dynamic coefficient of viscosity; q_V- heat generation rate; θ - Rayleigh dissipative function.

For the perfect gases, the Fourier - Kirchhoff equation for temperature distribution, takes the simple form (5):

$$\rho c_p \frac{dt}{d\tau} = \lambda \nabla^2 t + \frac{dp}{d\tau} + \mu \Theta_V + q_V \tag{5}$$

where: p- pressure; c_p- specific heat.

Despite simplifications of presented model, resulting *inter alia* from disregard of turbulences and variability of physical parameters of the fluids [2], direct solution of systems of presented equations require the utility of advanced techniques. The presented approach does not always guarantee a high precision of calculations.

In the analyzed problem of conduits, heat transfer occurs between surfaces located relatively close. Instead of full analysis of thermal convection, utility of simplified equations without taking into consideration the fluid velocity effects is very common. Utility of such rules enables composition of the set of dimensionless similarities (dependent on physical quantities determine the phenomenon) and criterial equations (dependent on the similarities). Such approach enables analyses of convection phenomenon in simply way, basing on test results of considerable generality. In geometrical closed systems (the example of closed system is a conduit fulfilled by fluid) [2, 3] there is possibility to use the basic equations of heat conduction instead of complicated balance equations [1]. Approximate analysis of heat transfer phenomenon in closed systems can be used to determinate the heat resistance of the fluid gap of a width δ and thermal conductivity λ (6) [1]:

$$W = \frac{1}{\alpha_{ot1} \cdot F} + \frac{\delta}{\lambda \cdot F} + \frac{1}{\alpha_{dt2} \cdot F} \tag{6}$$

where: α_{ot1} - heat transfer coefficient in warmer surface; α_{dt2} - heat transfer coefficient in colder surface; F- size of the gap cross-section.

During determination of the heat resistance of gas gaps, the equation (6) is not usually used, due to the difficulty to appoint α_{ot1} and α_{dt2} coefficients. In practice, the formula (7) is very popular:

$$W = \frac{\delta}{\lambda_e \cdot F} \tag{7}$$

The symbol λ_e is so-called the equivalent thermal conductivity. Actual value of this conductivity can be determined by using equation (8):

$$\lambda_e = \frac{\alpha_{ot1} \cdot \alpha_{dt2} \cdot \lambda \cdot \delta}{\lambda \cdot \alpha_{dt2} + \alpha_{ot1} \cdot \delta \cdot \alpha_{dt2} + \lambda \cdot \alpha_{ot1}} \tag{8}$$

In practice, determination of heat transfer coefficients α_{ot1} and α_{dt2} are very complicated. The value of λ_e can be calculated by using of criteria equation (9) [3]:

$$\frac{\lambda_e}{\lambda} = f(Ra) \tag{9}$$

The Rayleigh number is defined by equation (10):

$$Ra = \frac{g \cdot \delta^3 \cdot \beta \cdot (t1 - t2)}{a \cdot \nu} \tag{10}$$

where: g- acceleration due to gravity; δ- speciffic dimmension; $\beta = \frac{1}{273 + t_{ob}}$ - thermal expansion of the air; a- thermal diffusivity; ν - kinematic viscosity.

The quantity can be determinated basing on equations presented in Table 1.

Table 1. Criteria equations for determination of equivalent thermal conductivities

Author	**Equation**
Neumanna	$\lambda_e = \left[1 + \left(\frac{c1 \cdot Gr \cdot Pr^n}{Gr \cdot Pr + c2}\right)\right] \cdot \lambda(t_{ob})$
Jakoba	$\lambda_e = 0{,}075(Gr \cdot Pr)^{0.3} \cdot \lambda(t_{ob})$
Michiejew	$\lambda_e = C \cdot (Gr \cdot Pr)^n \cdot \lambda(t_{ob})$
Kraussold	$\lambda_e = 0{,}4(Gr \cdot Pr)^{0.2} \cdot \lambda(t_{ob})$

Heat transfer within the gaps, between external surfaces of cable conduits is calculated by using the same types of equations like for the thermal conduction. The value of thermal conductivity can not be directly used for fluids. In such cases the equivalent conductivity (9) is necessary. During the calculations the influence of physical model of convection heat transfer (full coupled model and the criteria equations) in the cable conduits on results quality was examined. The conduits fulfilled with air [2, 3] were analyzed. The 2D numerical model was designed (Figure 4).

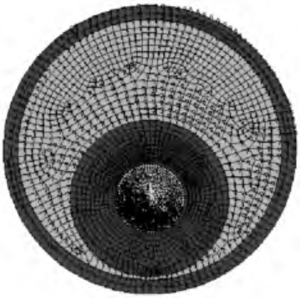

Fig. 4. View of the basic components of the model for determination of convection heat transfer calculating method on results quality

The model consists of the main conductor, one layer of the insulation of thermal conductivity of 1 W/(mK) [7] and steel conduit cover [3]. There was the gas air gap, between external surface of cable insulation and inner surface of conduit cover.

Two calculations variants were performed for different boundary conditions:

I) for constant temperature of main conductor (90°C) and constant temperature of conduits case (35°C);

II) for constant heat power in main conductor (the value corresponding to 1200 A) and constant temperature of conduits case (35°C).

The calculations were aimed at determination of influence of simplifications of convection heat transfer by using of equivalent thermal conductivities and full analysis (coupled flow and thermal fields) on results quality. In figure 5 the temperature distributions within the model were shown. The results of simplified (Fig. 5.a) and full (Fig. 5.b) model were done for the first variant for constant temperatures (I).

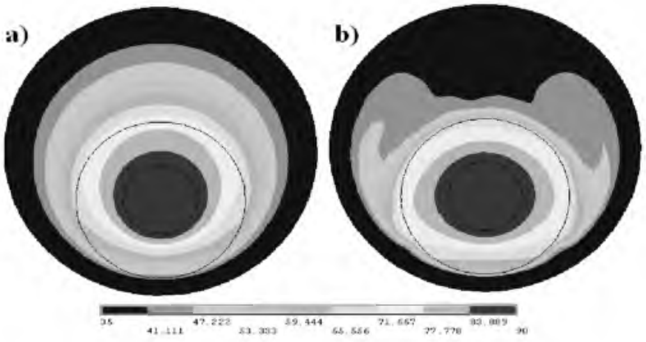

Fig. 5. Temperature fields within the conduits models: a) for simplified convection model; b) for full convection model

Presented results show a quite different temperature distribution within the cross section of the model for analyzed cases. Full model (Fig. 5.b) shows a slightly worse intensity of heat transfer from the simplifying model.

Observed trend seems to be consistent with expectations. Relative small fluid velocity inside the conduits (maximal values was about 0,12 m/s (Figure 6)) provides a conclusion of underdeveloped convection in analyzed cases.

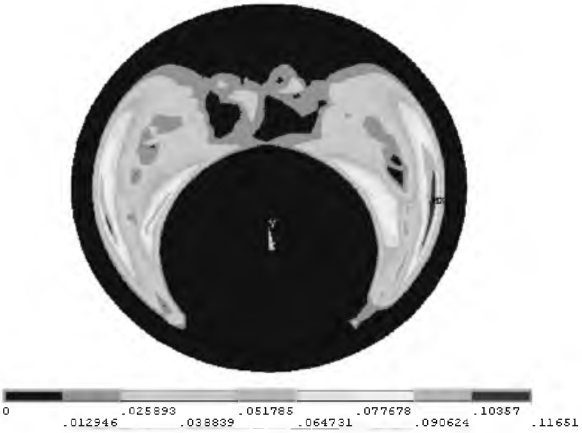

Fig. 6. Fluid velocity in exemplary cable conduit

To show the influence of used thermal convection heat transfer model on temperature values inside the system of cable conduits, some further analysis were done. The loads and boundary conditions were defined above as (II). Temperature distribution in steady state for two models were shown in Figure 7.

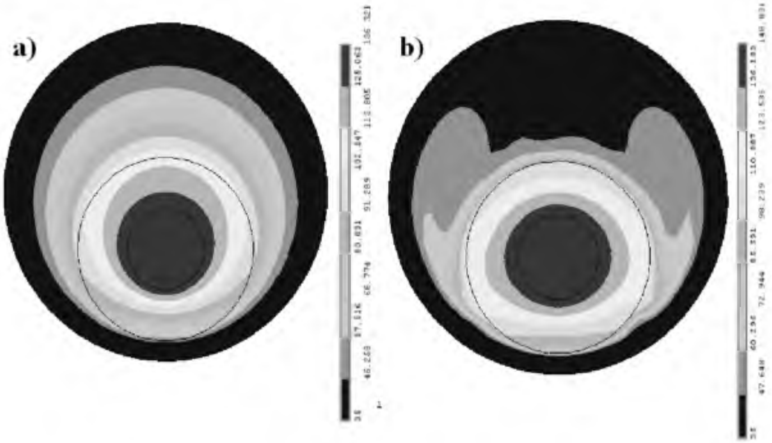

Fig. 7. Temperature fields for simplified (a) and full (b) model of convection heat transfer for the case of constant heat power

Maximal differences between calculation results for both cases do not exceed the values at 12 K. In addition to reached temperatures, maximal relative error was about 8%. However, reached results seems to be positive. Absence of turbulence convection inside the conduits (Figure 6) enables claim of possibility to use the simplified model with equivalent thermal conductivity instead of full model. A very interesting phenomenon seems to be a fact that maximal errors were at 8%. But the average error values were significantly lower. In Figure 8, temperature distributions in vertical axis of the model (in the air region) were shown for both models.

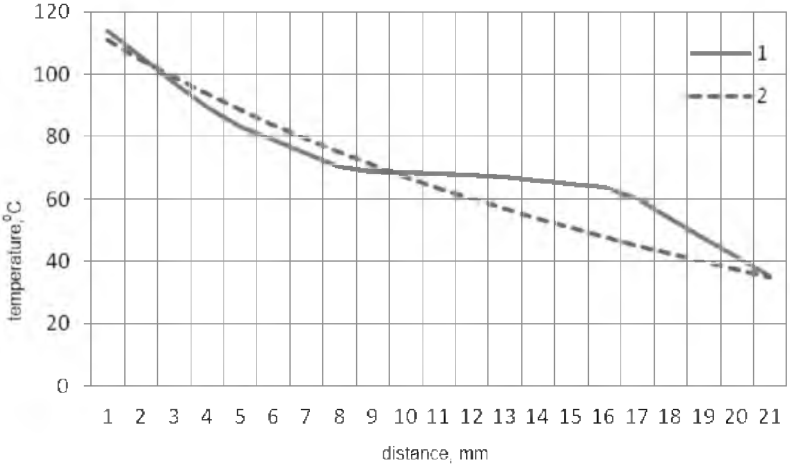

Fig. 8. Temperature distribution in vertical axis of the air region. 1- for the full CFD model; 2- for the simplified model (criterial analysis)

The result shows that the differences between analysed models were relatively small. Especially in areas important from the cable systems designing point of view, temperatures were almost the same. Different nature of temperature distributions inside the air gap is not significant and results from location of transition resistance between the solid state and gas for the full model. However, temperatures in external surfaces of the air gap were almost identical. The fact enables usage of alternative resistances–method to precisely calculate cable conduits [4].

2.3. Optimal mesh density

In most FEM systems, there is possibility to use automatic mesh generators. Users are informed of some fatal errors, like elements degenerations or inability to mesh the model. However, errors resulting from non-optimal mesh, are not indicated. Because of the necessity to guarantee the high accuracy of numerical simulation, some calculating experiments were done to determine optimal mesh density in the system of high-voltage cables. The system of cables in trefoil formation placed in ground was used. Due to the lack of analytical solution of heat generation in such systems, it was not possible to determine errors in relation to an exact solution. The accuracy control consisted of a bit by bit increasing of mesh density and comparing simulation results to determine the convergent solution. The starting point was the model, meshed by using of the automatic mesh tool. In Figure 9, exemplary meshes of different densities were shown. First mesh was generated automatically. In second case, finite elements mesh was concentrated in areas, where changes of elementary physical values were most intense.

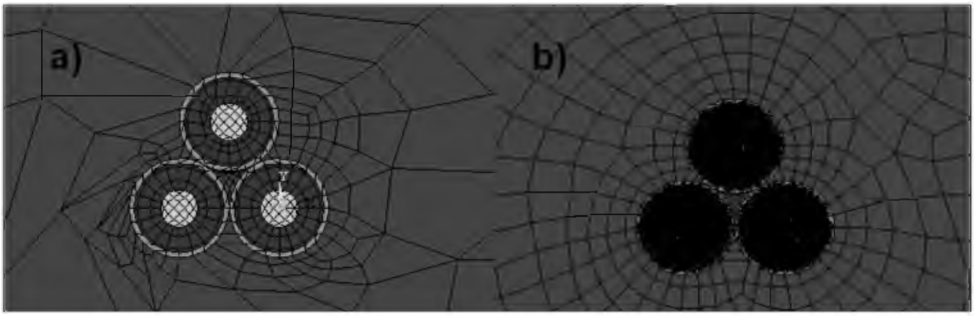

Fig. 9. View of finite element meshes of different densities

In Figure 10, temperature distribution within the cable system models has been shown. Results were obtained by using of models shown in Figure 9. Mesh density, like on Figure 9.b was optimal for analyzed cable system.

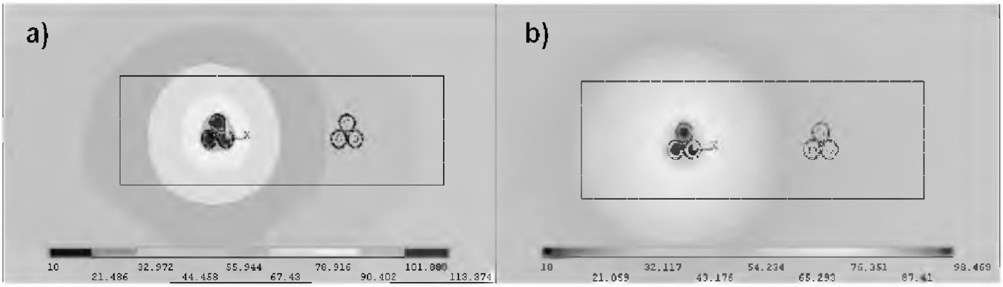

Fig. 10. Temperature distibution for different mesh density

The results for meshes of different number of elements (1000 ÷ 50000) were compared and the convergence was determined. Maximal temperature value as the function of number of elements has been shown in Figure 11. The temperature value for minimal number of elements has been reached by using of automatic mesher.

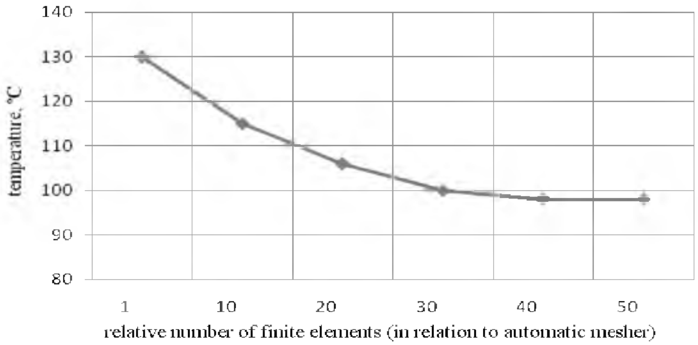

Fig. 11. Maximal temperatures in the model for diffenet nuber of finite elements

Basing on the simulation results, optimal number of finite elements in analysed case was about 40000. In addition to the basic mesh density (from automatic generator), number of elements was about 40 times greater in the cables. The rule schould be applied to every cables arranged in trefoil formation.

2.4. Influence of condict length on long-term cable load

The conduicts length seems to be a very important parameter that substantially affects the cable line loads. Basic aim of the calculations was determination of conduict influence on maximal long-term cable line load [5]. Maximal current values of cable lines were designated for the cases where 90°C cables temperature was achieved in steady state. Some 3D models of cable line in conduicts of different legths (3, 10 and 50 meters) were analyzed. In all cases the conduits fulfilled with air were simulated. The high voltage cable model of premmisible current value 1300 A was used. Due to the planar symentry of models, there was ability to create geometries of a half length of real cable conduits. Thermal boundary conditions correspond to the applicable standards [1, 5]. The temperature value of the ground surface was at 30°C and temperature at the depth of 4 meters was at 15°C. For all cases long-term loads of the cable line were determined. The model has been shown in Figure 12.

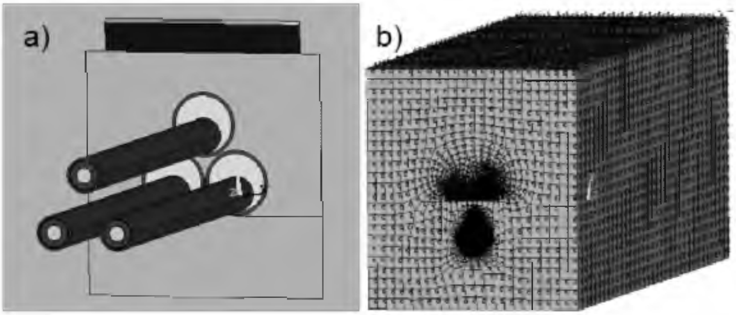

Fig. 12. End of the culvert view (a) and the mesh of 3D model (b)

The simulations results has been shown in Figure 13, where three current-temperature characteristics for different conduits lengths were presented.

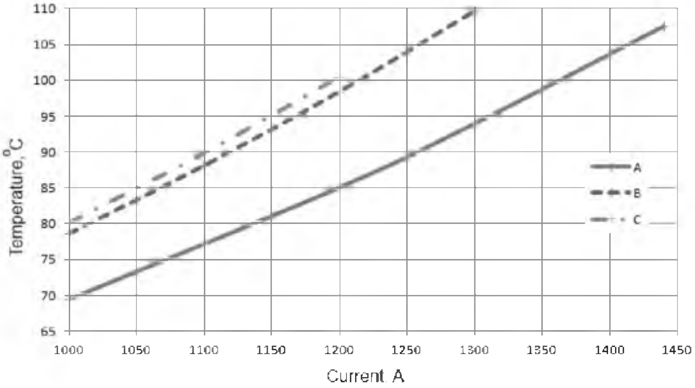

Fig. 13. Maximal model temperatures vs. current curves. A- conduit length 3m; B- conduit length 10m; C- conduit length 50m. A- conduit length 3m; B- conduit length 10m; C- conduit length 50m

As it was shown, there is a significant influence of conduit length on cable permissible load. For 3 meters cable conduits, maximum current value was less than in catalog of 50 amperes. For 10 and 50 meters conduits, difference in relation to the data directory, was at 200 A. For culverts fulfilled with air, the reduce of current carrying capacity is about 17% from basic arrangement of cables placed in ground. For relatively long culverts, the temperatures of the models were not significantly different. Temperature distribution in main conductors as the function of distance from the culvert end was shown in Figure 14 for three analyzed length.

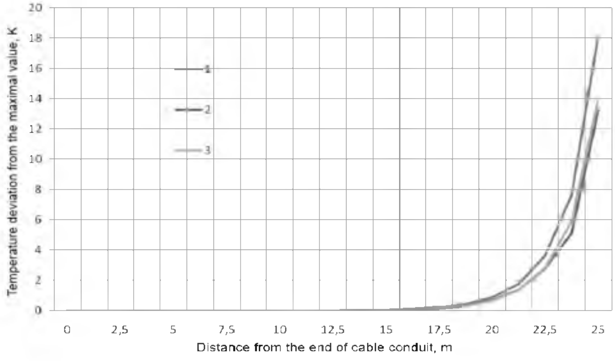

Fig. 14. Main conductors temperature deviations from maximal values for different cable conduits length. 1- conduit length 3m; 2- conduit length 10m; 3- conduit length 50m

The results show that for cable conduits of length greater than 8 meters, temperatures of main conductors are practically the same. There is no need to use a full 3D models in such cases.

3. Summary

In the article some results of analysis on cable systems modeling rules were described. The basic errors resulting from commonly accepted simplifications were analyzed. The influence of such errors on quality and accuracy of simulations were shown.

It was demonstrated that acceptance of simplifications as omission of skin effects is unacceptable for high voltage cables of conductors cross section larger than 630 mm^2. The precise analysis of long time thermal load in such systems requires to useful coupled electromagnetic and thermal models.

In the article some aspects of using of inexact thermal models were discussed. It was shown that in cases of cable conduits or cable trays systems, where cables are surrounding by fluids, there is possibility to use the simplified convection heat transfer model. In most cases it is possible to use the equivalent thermal conductivity theory and simulation the convection phenomenon in the same way as in case of thermal conduction. Despite from different temperature distributions in the fluid areas, total differences of the heat fluxes in both cases has not reach the value of 5%.

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