Int. J. Engng Ed. Vol. 25, No. 6, pp. 1158–1165, 2009
Printed in Great Britain.
0949-149X/91 $3.00+0.00
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Thermal Analysis of Power Cables Using Finite Element Method and Current-carrying Capacity Evaluation*

MURAT KARAHAN[1], H. SELCUK VAROL[2], ÖZCAN KALENDERLI[3]
[1]*Dumlupinar University, Simav Technical Education Faculty, Kutahya 43500, Turkey.*
E-mail: mkarahan@dpu.edu.tr
[2]*Marmara University, Technical Education Faculty, Istanbul 34722, Turkey.*
E-mail: hsvarol@marmara.edu.tr
[3]*Istanbul Technical University, Electrical-Electronics Faculty, Istanbul 34469, Turkey.*
E-mail: ozcan@elk.itu.edu.tr

For engineering education students, solution of an electric-thermal multiphysics problem by using COMSOL program which is based on finite element method has been presented. In considering the problem, the current-carrying capacity and heat distribution of power cables buried in soil were determined depending on the thermal conductivity of the surrounding soil and different buried depths, from the temperature distribution calculations using COMSOL (FEMLAB). The electrical losses due to the current flowing in the cable conductor and electric field which heats up the cable was taken into consideration in the heat conduction equation, to accommodate the electrical losses in calculating the current-carrying capacity. The results show that the current-carrying capacity of the cable with increasing conductivity is increased and wind velocity has a low influence on the current-carrying capacity. Also humidity content in insulating material has an important effect on increase in the temperature of power cables because of increasing insulation conductivity after a certain temperature.

Keywords: power cable; thermal analysis; FEM; multiphysics analysis; COMSOL

INTRODUCTION

MODELLING THE COMBINED EFFECTS of two or more interrelated physical phenomena is called multiphysics modelling. Multiphysics modelling and analysis allow engineers and designers to evaluate their designs operating under real-world conditions or to determine the combined effects of multiple physical phenomena on a design. Therefore, multiphysics modelling has become a standard research and design tool in academia and industry [1–3]. From this point of view, importance and applications of this subject are increasing in engineering education.

Previously, solving coupled-physics interactions required many manual file transfers, data exchanges and problem setups to perform each physics analysis. Today, multiphysics software packages based on finite element methods such as COMSOL Multiphysics (previously FEMLAB) automatically combine the effects of two or more interrelated physical phenomena. These tools automatically manage the exchange of data between the different kinds of physics and perform information transfers.

Typically, with multiphysics analysis, exchange of data between physics fields requires careful coordination, and the different mesh requirements for the various fields, loads and boundary conditions must be correlated. For all this to function correctly requires a complex feedback loop between the various fields so that the coupled analysis converges to an accurate solution.

The more common and mature analyses of coupled physics include fluid–structure, thermal–mechanical, and electric–thermal interactions. In an electric– thermal interaction, current flowing in a conductor generates resistive heating. For example, heat is generated whenever there are dynamics; and heat always affects other material properties such as electrical conductivity, chemical reaction rates and the viscosity of fluids, to name but a few.

An example of common multiphysics coupling is that between current conduction and thermal management in power cables. Such an example showing multiphysics application on electrical engineering and education has been presented here using COMSOL.

THE PROBLEM DEFINITION IN COMSOL

Nowadays power cables are widely used in electric power transmission and distribution. Power cables operate under high electrical, ther-

* Accepted 9 September 2009.

mal, mechanical and environmental stresses. Each of these stresses affects current-carrying capacity of the power cables.

There are many analytical and numerical methods for computation of current carrying capacity of power cables. Analytical methods are based on the International Electrotechnical Commission (IEC) 60287 standard and they are generally applied only on cables with simple geometry for homogeneous ambient conditions. At more complex structures and conditions, use of numerical methods is more appropriate. One of the most preferred numerical methods in engineering education and applications is finite element method (FEM) [4].

There is strong relation between the current-carrying capacity of power cables and heat distribution. Applied voltage to cable and currents flowing through the cable components result in electrical power loss and heat. This heat disperses from heat source to the near environment. Cable materials and surrounding ambience due to their high thermal resistances impede heat distribution.

Numerical methods can be used for computation of heat distribution in the cable and out of cable by using a defined heat source. Thermal analyses are made generally by using boundary temperatures, cable geometry and properties of material. It is difficult to compute heat distribution by taking into consideration influence of electrical behaviours on heat or effect of heat on electrical properties. Our computations of heat distribution and current carrying capacity of power cables have been carried out by taking into consideration the combination of electrical loss and heat events as a multiphysics problem. Electrical properties of the cable components vary with increase or decrease of temperature. In this case, cable loss varies. When loss and heat factors are simultaneously used, solution of the problem becomes more suitable to real conditions. This plus the finite element method of COMSOL are used for computations of heat distribution and current carrying capacity of power cables. Also, environmental factors are included in models of the problem to examine their effect.

MODELLING OF POWER CABLE

Electrical-thermal combined model of power cable

The main source of heat in cables is electrical power loss. This power loss, $R.I^2$ arises from the flowing current I through cable conductor and resistance, R of this conductor. Electrical power used during time t becomes electrical energy loss $R.I^2.t$ and generally converts into heat energy. This heat spreads around the heat source. In this case, heat transfer equation becomes [5];

$$\nabla \cdot (k\nabla\theta) + W = \rho c \frac{\partial \theta}{\partial t} \tag{1}$$

Where θ is temperature as independent parameter, k is thermal conductivity of ambient surrounding heat source, ρ is ambient density, c is thermal capacity of the ambient, and W volumetric heat source intensity. There is a close relation between heat energy and electrical energy (power loss) due to electrical current, as in the following equation.

$$P = J \cdot Edxdydz \tag{2}$$

Where $\boldsymbol{J}$ is current density, $\boldsymbol{E}$ is electrical field intensity; dx.dy.dz is unit volume of material. For current density $\boldsymbol{J} = \sigma{\cdot}\boldsymbol{E}$ and electrical field intensity $\boldsymbol{E} = \boldsymbol{J}/\sigma$, resistive loss in cable can be written;

$$P = \frac{1}{\sigma} J^2 dxdydz \tag{3}$$

Where σ is electrical conductivity of cable conductor and it is dependent to heat. In this paper, this relation between electrical conductivity and heat transfer has been used to make thermal analysis.

APPLICATIONS USING COMSOL

10 kV XLPE power cable model

As an application, computation of heat distribution of 5.8/10 kV, single core underground power cable which is widely used in electrical distribution systems is carried out by using finite element method with electrical-thermal analysis of multiphysics module of COMSOL (Figure 1). All parameters are taken from reference [6].

The conductor of the power cable is stranded copper with a cross-section of 300 mm^2 and diameter of 20.5 mm. Order and thicknesses of layers in the cable structure are given in Table 1. Side by side lying conditions of three power cables

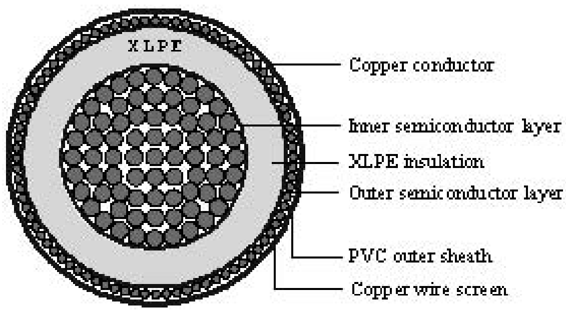


Fig. 1. Structure of power cable.

Table 1. Layers of the power cable

Layer	Thickness (mm)
Inner semiconductor	0.6
XLPE insulation	3.4
Outer semiconductor	0.6
Copper wire screen	0.7
PVC outer sheath	2.3

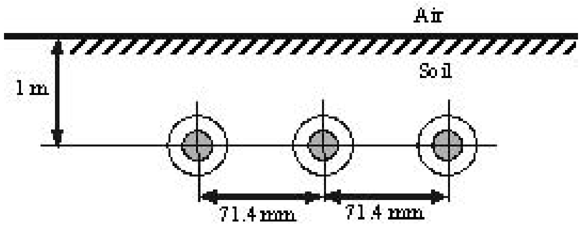


Fig. 2. Positions of cables buried in the soil.

Table 2. Thermal properties of materials used in the model

Material	Thermal Conductivity k (W/K.m)	Thermal Capacity c (J/kg.K)	Density ρ (kg/m^3)
Cu conductor	400	385	8700
XLPE insulation	1/3.5	385	1380
Cu wire screen	400	385	8700
PVC sheath	0.1	385	1760
Soil	1	890	1600

which have similar properties as above are shown in Figure 2. Distance among the cables is up to one cable diameter. Thermal resistivity of soil surrounding the cables has been accepted as 1 Km/W.

Thermal analysis of the model cable is carried out using the finite element method with combined static heat and electric. As first step of the method, geometry, materials and boundary conditions of the problem in the closed region are defined. The closed solution region of the three cables is taken as a rectangular region of 10 m width and 5 m height. Computation is performed in two dimensional rectangular coordinates. It can be assumed that a third coordinate or the cable axis is perpendicular to the solution region. In the computation, cable lengths have been assumed as infinite.

For values of thermal conductivity k, thermal capacity c and density ρ, those given in Table 2 are used. These parameters are parameters in heat transfer equation (1). Heat sources have been determined according to equation (3).

After geometrical and physical definitions, boundary conditions of the problem are determined. Top and bottom boundaries of the solution region have been accepted as a constant temperature of 15°C. Top boundary has been taken as the convective boundary. Heat transfer coefficient h is computed from following empirical equation [7].

$$h = 7.371 + 6.43 \cdot u^{0.75} \tag{4}$$

Where u is wind velocity in m/s at ground surface on buried cable. In the analysis, wind velocity is taken as zero and source of convection is assumed to be the temperature difference.

Second basic step of the finite element method is to establish discrete finite elements for the solution region. Precision of computation increases with increasing number of finite elements. Therefore, mesh of solution region is divided into 8519 triangle finite elements. This process is made automatically and adaptively by the COMSOL program. A section (1 m x 0.6 m) of the obtained mesh is shown in Figure 3.

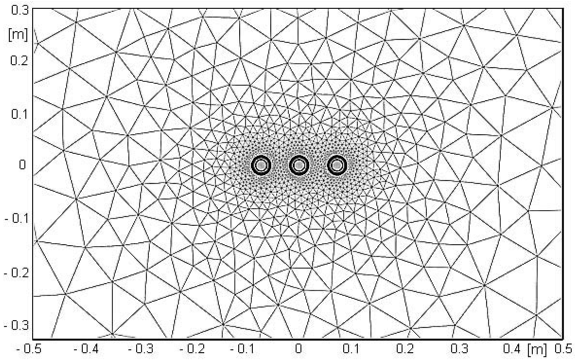


Fig. 3. Solution region divided by finite elements.

At end of combined electrical-heat analysis, distribution of equi-temperature curves as seen from Figure 4 is obtained by using post processing properties of COMSOL. According to this distribution, middle cable warms up more than the others. Current value when the temperature of cable insulation is 90°C is calculated as 626.21 A. This value has been found by multiplying calculated current density with conductor cross-section. This current-carrying capacity of the cable tallies very closely with the 629 A given in reference [6].

Thermal conductivity or resistivity of soil changes with atmospheric and climatic conditions. These cases affect current carrying capacity of power cables. If thermal conductivity of soil increases or thermal resistivity of soil decreases by environmental factors, current-carrying capacity of cables increases.

In our experiment, thermal conductivity of soil has been changed between 0.4 and 1.4 W/K.m and effect of this parameter on cable temperature and current carrying capacity has been investigated (Figure 5). As seen from Figure 5, if thermal conductivity of soil or ambient of cable decrease, cable temperature increases. In this situation, the cable load must decrease.

Neighbouring cables or other heat sources reduce current-carrying capacity of power cables. Current flowing from an isolated cable is higher than from unisolated cable. At this point, we compute current- carrying capacity of the power cable for three buried depths (Figure 6) and the effect of wind on current- carrying capacity is investigated. In the mentioned model, a power cable having 10 kV rated voltage, XLPE insulation and 1 m buried depth is considered. Physical definitions and boundary conditions have the same values used in the preceding model. Figure 7 shows a 3D heat distribution obtained from FEM analysis with COMSOL. According to this distribution, current value when temperature of the cable insulation is 90°C is calculated as 890.97 A. This value is the current-carrying capa-

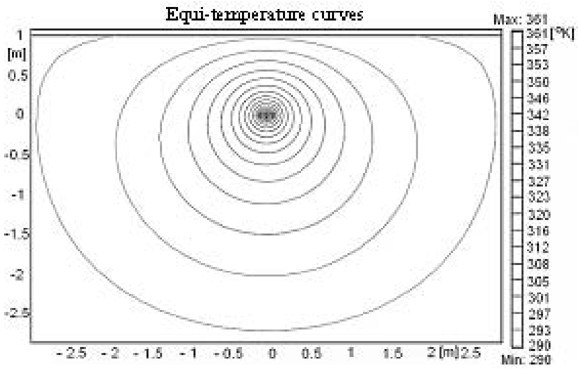


Fig. 4. Distribution of equi-temperature curves.

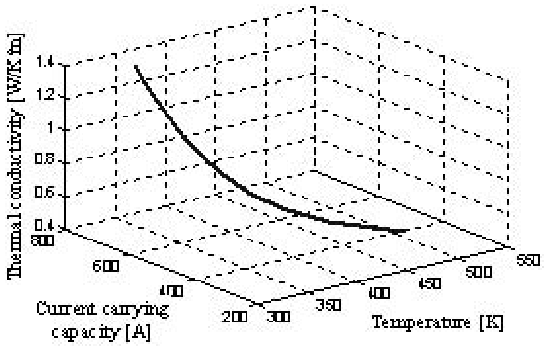


Fig. 5. Influence of soil thermal conductivity on current-carrying capacity and temperature of cable.

city of the single cable and is higher than the previous model with three cables.

Laying a power cable near ground surface changes heat distribution in the cable and at the outside. According to analyses performed at depths of 0.5, 0.7 and 1 m, variation of insulation temperature of the cable with current is as shown in Figure 8. As seen in Figure 8, current-carrying capacity increases when cable is layed near to the ground surface. For 0.7 m buried depth, and a cable insulation temperature of 90°C, current value is calculated to be 906.45 A. For 0.5 m buried depth, it is 922.63 A. Last current value is higher by 32 A than when the cable buried to 1 m.

The effect of wind velocity on heat distribution of underground power cables has also been investigated.

For 90°C insulation temperature, current value

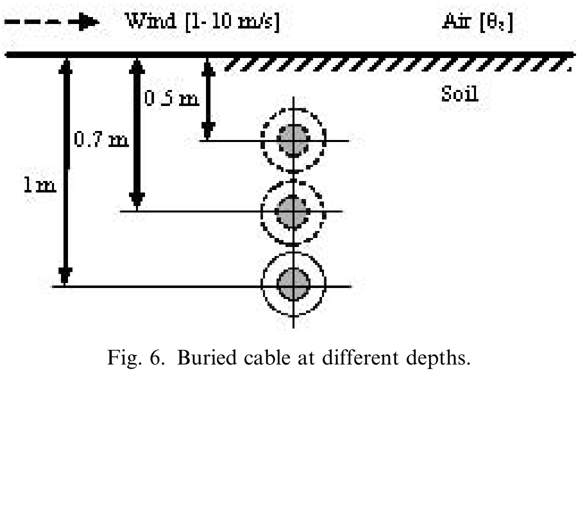


Fig. 6. Buried cable at different depths.

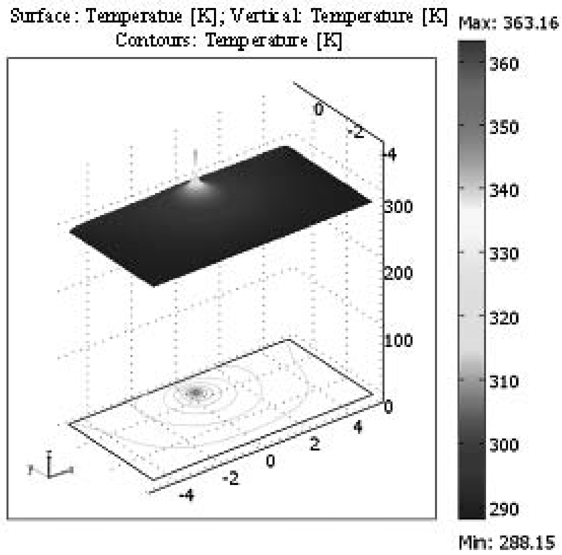


Fig. 7. 3D temperature distribution at the cable.

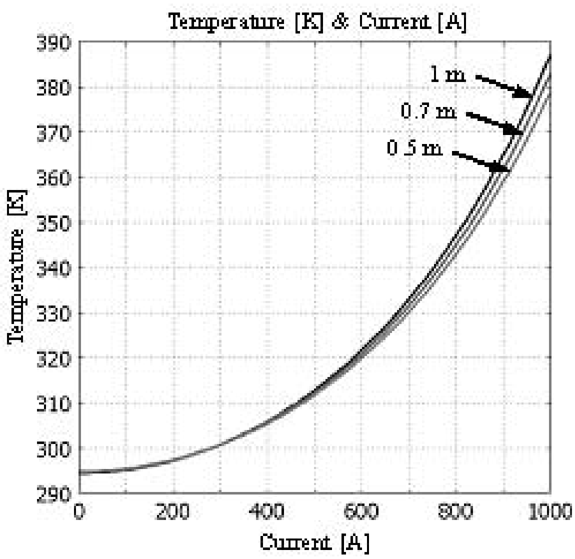


Fig. 8. Temperature variation with current as function of buried depth.

is taken as constant for each of three buried depths and wind velocity is changed between 1 and 10 m/s. As seen from Figure 9, increasing wind velocity contributes to cooling of the cable. In this case, cable temperature decreases and current-carrying capacity of the cable increases a little. Average wind velocity for Istanbul in Turkey is equal to 3.2 m/s [8]. For this wind velocity, cable insulation temperature decreased 0.8°C for 1 m buried depth of cable. For the same wind velocity, temperature decreased about 2°C for 0.5 m buried depth of cable. This means that in 0.5 m the cable carries 11 A more current than for 1 m buried depth.

10 kV PILC power cable model

A cable with paper insulation and lead sheath (PILC) is modelled with an electrical-heat model.

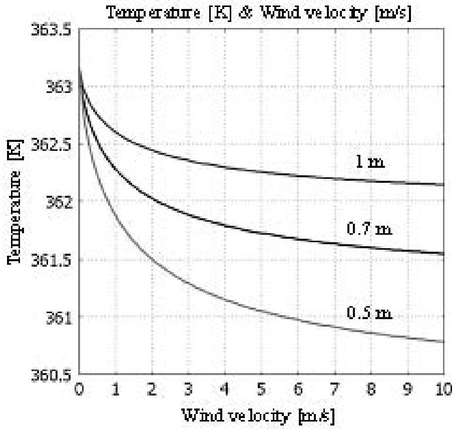


Fig. 9. Temperature variation of cable insulation with wind velocity.

Voltage of the model cable is 10 kV and the cable is accepted in the soil. Two heat sources for the cable are considered. These are heat by resistive loss due to load current, and by dielectric loss in the cable's insulating material.

Losses due to currents flowing from insulating material can be written as $\sigma \cdot E^2$ by using equation (2) and $J = \sigma \cdot E$ equation. Dielectric losses are considered with the following equation [9].

$$P_{diel} = (\sigma_{DC} + \omega \varepsilon_r^{''}(\omega)\varepsilon_0)E^2 \tag{5}$$

Where;

σ_{DC} : DC conductivity of insulating material [S/m]
ω : Angular frequency [rad/s]
ϵ_0 : Free space permittivity [$8.8542 \cdot 10^{-12}$ F/m]
ϵ_r'' : Relative permittivity against polarization loss

For an insulating material, dc conductivity loss and polarization loss cannot be recognized. Thus in literature, ac conductivity is often defined by the following equation.

$$\sigma_{AC} = \sigma_{DC} + \omega \varepsilon_0 \varepsilon_r^{''} \tag{6}$$

If right and left sides of this equation are divided by $\omega\epsilon_0$, equation (6) becomes;

$$\frac{\sigma_{AC}}{\omega\varepsilon_0} = \varepsilon_r^{''} + \frac{\sigma_{DC}}{\omega\varepsilon_0} \tag{7}$$

First term of equation (7) is apparent dielectric loss factor and it can be written as $\epsilon''_{r,App}$. In this case, ac conductivity loss of insulating material is written as follows [9]:

$$\sigma_{AC}E^2 = \omega\varepsilon_0\varepsilon_{r,App}^{''}E^2 \tag{8}$$

Electrical conductivity of insulating material as a function of temperature is given by Arrhenius formula in equation (9).

$$\sigma = \sigma_0 \cdot e^{\frac{-E_a}{k_B}\left(\frac{1}{\theta} - \frac{1}{\theta_0}\right)} \tag{9}$$

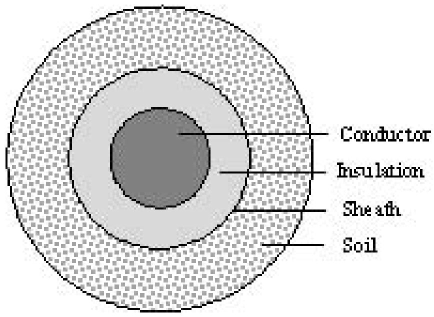


Fig. 10. 2D definition of the problem.

Where;

σ_0 : Conductivity at temperature θ_0 [S/m]
E_a : Activation energy [eV]
k_B : Boltzmann constant [eV/K]

As can be seen from equations (8) and (9), apparent relative dielectric factor is a function of temperature and this relation can be given by the Arrhenius equation. In addition to this, it has been found that dielectric permittivity changes humidity and the permittivity increases rapidly with increasing humidity [10]. In our model we investigated these relations and showed that dielectric loss is important for 10 kV cables.

Two-dimensional geometry of the cable with paper insulation and soil is shown in Figure 10. Here, only conductor, insulation, sheath of the cable and soil are considered. Radius of conductor and thickness of insulation of the cable are taken as 5 mm. A cylindrical solution region surrounding the cable having 0.2 m radius is defined. On the boundary of this region, temperature of soil is taken as a constant 10°C. To simulate electrical boundary conditions, voltage of 5.8 kV is applied between conductor and screen of the cable. Electrical parameters of the power cable are given in Table 3. In this table, θ_0 is initial temperature of media. Dielectric permittivity, e_{rd} of the cable insulation has been computed from the following equation (10).

$$\varepsilon_{rd} = \varepsilon_r' - j\varepsilon_r'' \tag{10}$$

ϵ_r' is relative permittivity of dielectric and its value for paper insulation is taken 4. ϵ_r'' is apparent dielectric loss factor; it is defined with equation (9) having Arrhenius relation [9].

$$\varepsilon_{r,App}^{''} = \varepsilon_{r,App,0}^{''} \cdot e^{\frac{-E_a}{k_B}\left(\frac{1}{\theta} - \frac{1}{\theta_0}\right)} \tag{11}$$

Table 3. Parameters of PILC cable model

Parameter	Conductor	Insulation	Soil
σ (S/m)	5.998e7	0	0
ϵ_r	1	ϵ_{rd}	1
k (W/mK)	400	0.2	1
ρ (kg/m^3)	8960	1000	1300
c (J/kgK)	385	1300	870
θ_0 (K)	283.15	283.15	283.15

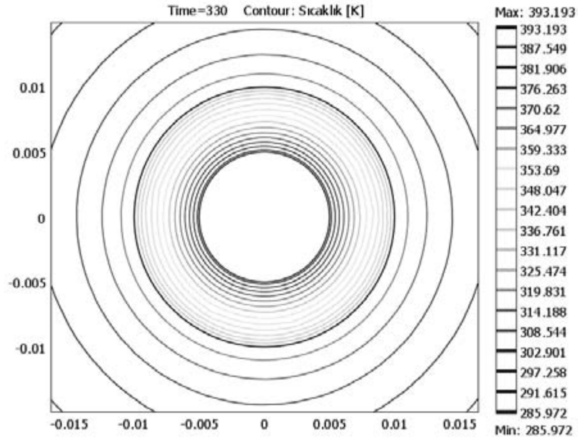


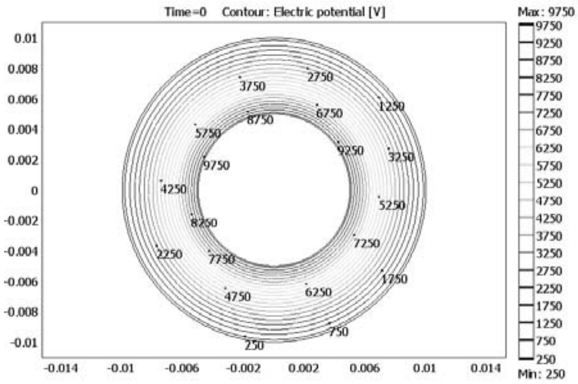
Fig. 11. Equi-temperature lines in PILC cable and soil.

Where

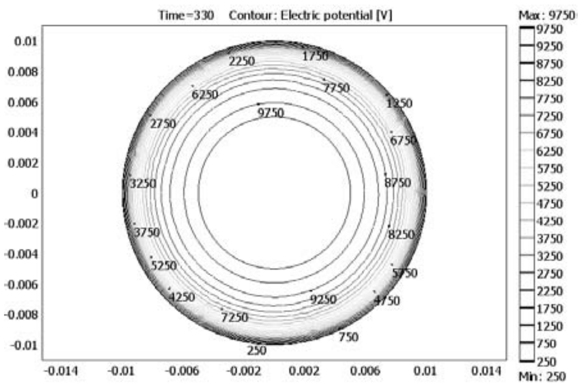
$\epsilon''_{r,App,0}$: Relative permittivity at temperature θ_0,
E_a : Activation energy [eV],
k_B : Boltzmann constant [eV/K].

In the performed numerical analysis for paper insulation activation, energy is taken as 0.7eV, and relative apparent permittivity is 0.72 at 10°C temperature and 5% relative humidity.

As the last step, heat sources in the cable are defined. Dielectric losses of the insulating material



(a)



(b)

Fig. 12. (a) Initial potential distribution (b) Potential distribution after 330 seconds.

change with ac electrical conductivity and applied electrical field. These losses are defined by $\sigma_{AA}E^2$ in equation (8). Conductivity loss of the cable conductor is added to model with J^2/σ.

Resulting heat distribution in the cable and soil are shown in Figure 11. Cable temperature at 330 seconds of time variable solution has been reached 120°C. If dielectric losses are not taken into account, cable temperature is computed at 111°C. This effect of dielectric losses on heating of the cable is due to increase in ac conductivity with increasing heat. Conductivity of insulating material increases due to increase in relative apparent dielectric loss as a function of increasing heat increases. It can be seen in Figure 12(a), that potential distribution has begun from conductor surface and finished at sheath, and in Figure 12(b) this distribution has begun from inside the insulation.

DISCUSSION AND CONCLUSION

Thermal analysis of power cables is important for the determination of current-carrying capacity. Cable temperature depends on current flowing through the cable, cable structure, material properties in the structure, laying form and thermal properties of environment of the cable.

We have computed heat distribution by considering electric losses in a thermal conduction equation. Also, electric loss depends on current density and electrical field. Thus, electro-thermal analysis is carried out instead of conventionally thermal analysis.

For one XLPE cable, the effect of buried depth on heat distribution has been investigated; it is observed that current-carrying capacity of cables increases when laid near the surface. This situation is due to convection on the ground surface. Again, for one cable, the effect of wind velocity on heat distribution has been investigated; increasing wind velocity decreases cable heat a little. Thus, current capacity in windy regions will become higher than elsewhere.

In the numerical analysis performed with COMSOL, it is seen that conductivity of insulating material depends on its humidity content; conductivity rises rapidly after a certain temperature. Increasing conductivity increases dielectric loss. This causes further heating of the cable.

Consequently, power cables must be operated in suitable conditions, when efficiency and cable life increases and systems having these cables become more reliable and economical. It is desirable, therefore, that cables are suitably modelled and analysed according to real operating conditions as in this paper.

In order to solve a field problem, a field calculation program is usually required. The mathematical method behind such a program is usually the finite element method (FEM). FEM has been the most widely used method in engineering. Therefore, FEM is usually one of the topics in undergraduate courses of engineering education. Several publications with introductory material for FEM in electromagnetic courses at undergraduate and graduate levels have been published [13–24]. COMSOL can be used to introduce students to the finite element method. The FEM program COMSOL Multiphysics (previously FEMLAB) is a standalone program. Students can see the overall structure of the method, i.e. the steps are shown explicitly, and then can keep more focused on steps of particular interest.

Generally speaking, graduate students in engineering education are familiar with the finite element method, but they lack engineering experience and multiphysics analysis. They do not know how to deal with multiphysics engineering problems using their knowledge, which is why we have presented here an example of a typical multiphysics problem and its solution with COMSOL Multiphysics program. Regarding FEM in electrotechnical multiphysics analysis, we have converted it to be compatible with the FEM program COMSOL Multiphysics. Special attention has been paid to electrical and thermal aspects in an analysis.

This paper presents materials covered in a course at graduate level. This material should enable the graduate student to use FEM analysis in graduate research as well as when needed later in the workplace. It is hoped that this work will encourage use of COMSOL Multiphysics in undergraduate courses.

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Murat Karahan received B.Sc., M.Sc. and Ph.D. degrees from the Marmara University (MU), Istanbul, Turkey, all in Electrical Education Department, in 1993, 1999 and 2007 respectively. He is an assistant professor in Electronics and Computer Education Department of Dumlupinar University, Simav Technical Education Faculty. His research interests have been focused on power systems and numerical methods.

H. Selcuk Varol received a Ph.D. degree from Surrey University, England, in Physical Electronics, in 1979. He is a professor in Technical Education Faculty of the Marmara University, Istanbul. His research interests have been focused on Physical Electronics.

Özcan Kalenderli received the B.Sc., M.Sc. and Ph.D. degrees from Istanbul Technical University (ITU), Istanbul, Turkey, all in electrical engineering, in 1978, 1980, and 1991, respectively. He is an associate professor with ITU Electrical Engineering Department. His research interests are in the areas of discharge phenomena, generation and measurement of high voltages, numerical analysis of electrostatic fields, protection against over-voltages and grounding.