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Coupled Electrical and Thermal Analysis of Power Cables Using Finite Element Method

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1. Introduction

Power cables are widely used in power transmission and distribution networks. Although overhead lines are often preferred for power transmission lines, power cables are preferred for ensuring safety of life, aesthetic appearance and secure operation in intense settlement areas. The simple structure of power cables turn to quite complex structure by increased heat, environmental and mechanical strains when voltage and transmitted power levels are increased. In addition, operation of existing systems at the highest capacity is of great importance. This requires identification of exact current carrying capacity of power cables.

Analytical and numerical approaches are available for defining current carrying capacity of power cables. Analytical approaches are based on IEC 60287 standard and there can only be applied in homogeneous ambient conditions and on simple geometries. For example, formation of surrounding environment of a cable with several materials having different thermal properties, heat sources in the vicinity of the cable, non constant temperature limit values make the analytical solution difficult. In this case, only numerical approaches can be used. Based on the general structure of power cables, especially the most preferred numerical approach among the other numerical approaches is the finite element method (Hwang et al., 2003), (Kocar et al., 2004), (IEC TR 62095).

There is a strong link between current carrying capacity and temperature distributions of power cables. Losses produced by voltage applied to a cable and current flowing through its conductor, generate heat in that cable. The current carrying capacity of a cable depends on effective distribution of produced heat from the cable to the surrounding environment. Insulating materials in cables and surrounding environment make this distribution difficult due to existence of high thermal resistances.

The current carrying capacity of power cables is defined as the maximum current value that the cable conductor can carry continuously without exceeding the limit temperature values of the cable components, in particular not exceeding that of insulating material. Therefore, the temperature values of the cable components during continuous operation should be determined. Numerical methods are used for calculation of temperature distribution in a cable and in its surrounding environment, based on generated heat inside the cable. For this purpose, the conductor temperature is calculated for a given conductor current. Then, new calculations are carried out by adjusting the current value.

Calculations in thermal analysis are made usually by using only boundary temperature conditions, geometry, and material information. Because of difficulty in identification and implementation of the problem, analyses taking into account the effects of electrical parameters on temperature or the effects of temperature on electrical parameters are performed very rare (Kovac et al., 2006). In this section, loss and heating mechanisms were evaluated together and current carrying capacity was defined based on this relationship. In numerical methods and especially in singular analyses by using the finite element method, heat sources of cables are entered to the analysis as fixed values. After defining the region and boundary conditions, temperature distribution is calculated. However, these losses are not constant in reality. Evaluation of loss and heating factors simultaneously allows the modeling of power cables closer to the reality.

In this section, use of electric-thermal combined model to determine temperature distribution and consequently current carrying capacity of cables and the solution with the finite element method is given. Later, environmental factors affecting the temperature distribution has been included in the model and the effect of these factors to current carrying capacity of the cables has been studied.

2. Modelling of power cables

Modelling means reducing the concerning parameters' number in a problem. Reducing the number of parameters enable to describe physical phenomena mathematically and this helps to find a solution. Complexity of a problem is reduced by simplifying it. The problem is solved by assuming that some of the parameters are unchangeable in a specific time. On the other hand, when dealing with the problems involving more than one branch of physics, the interaction among those have to be known in order to achieve the right solution. In the future, single-physics analysis for fast and accurate solving of simple problems and multi-physics applications for understanding and solving complex problems will continue to be used together (Dehning et al., 2006), (Zimmerman, 2006).

In this section, theoretical fundamentals to calculate temperature distribution in and around a power cable are given. The goal is to obtain the heat distribution by considering voltage applied to the power cable, current passing through the power cable, and electrical parameters of that power cable. Therefore, theoretical knowledge of electrical-thermal combined model, that is, common solution of electrical and thermal effects is given and current carrying capacity of the power cable is determined from the obtained heat distribution.

2.1 Electrical-thermal combined model for power cables

Power cables are produced in wide variety of types and named with various properties such as voltage level, type of conductor and dielectric materials, number of cores. Basic components of the power cables are conductor, insulator, shield, and protective layers (armour). Conductive material of a cable is usually copper. Ohmic losses occur due to current passing through the conductor material. Insulating materials are exposed to an electric field depending on applied voltage level. Therefore, there will be dielectric losses in that section of the cable. Eddy currents can develop on grounded shield of the cables. If the protective layer is made of magnetic materials, hysteresis and eddy current losses are seen in this section.

Main source of warming on the power cable is the electrical power loss ($R \cdot I^2$) generated by flowing current (I) through its conductor having resistance (R). The electrical power (loss) during time (t) spends electrical energy ($R \cdot I^2 \cdot t$), and this electric energy loss turns into heat energy. This heat spreads to the environment from the cable conductor. In this case, differential heat transfer equation is given in (1) (Lienhard, 2003).

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

Where;

θ : temperature as the independent variable (^{o}K),

k : thermal conductivity of the environment surrounding heat source (W/Km),

ρ : density of the medium as a substance (kg/m^3),

c : thermal capacity of the medium that transmits heat (J/kg^{o}K),

W : volumetric heat source intensity (W/m^3).

Since there is a close relation between heat energy and electrical energy (power loss), heat source intensity (W) due to electrical current can be expressed similar to electrical power.

$$P = J \cdot E \, \mathrm{dxdydz} \qquad (2)$$

Where J is current density, E is electrical field intensity; dx.dy.dz is the volume of material in the unit. As current density is $J = \sigma \cdot E$ and electrical field intensity is $E = J/\sigma$, ohmic losses in cable can be written as;

$$P = \frac{1}{\sigma} J^2 \, \mathrm{dxdydz} \qquad (3)$$

Where σ is electrical conductivity of the cable conductor and it is temperature dependent. In this study, this feature has been used to make thermal analysis by establishing a link between electrical conductivity and heat transfer. In equation (4), relation between electrical conductivity and temperature of the cable conductor is given as;

$$\sigma = \frac{1}{\rho_0 \cdot (1 + \alpha(\theta - \theta_0))} \qquad (4)$$

In the above equation ρ_0 is the specific resistivity at reference temperature value θ_0 ($\Omega \cdot$m); α is temperature coefficient of specific resistivity that describes the variation of specific resistivity with temperature.

Electrical loss produced on the conducting materials of the power cables depends on current density and conductivity of the materials. Ohmic losses on each conductor of a cable increases temperature of the power cable. Electrical conductivity of the cable conductor decreases with increasing temperature. During this phenomenon, ohmic losses increases and conductor gets more heat. This situation has been considered as electrical-thermal combined model (Karahan et al., 2009).

In the next section, examples of the use of electric-thermal model are presented. In this section, 10 kV, XLPE insulated medium voltage power cable and 0.6 / 1 kV, four-core PVC insulated low voltage power cable are modeled by considering only the ohmic losses. However, a model with dielectric losses is given at (Karahan et al., 2009).

2.2 Life estimation for power cables

Power cables are exposed to electrical, thermal, and mechanical stresses simultaneously depending on applied voltage and current passing through. In addition, chemical changes occur in the structure of dielectric material. In order to define the dielectric material life of power cables accelerated aging tests, which depends on voltage, frequency, and temperature are applied. Partial discharges and electrical treeing significantly reduce the life of a cable. Deterioration of dielectric material formed by partial discharges particularly depends on voltage and frequency. Increasing the temperature of the dielectric material leads to faster deterioration and reduced cable lifetime. Since power cables operate at high temperatures, it is very important to consider the effects of thermal stresses on aging of the cables (Malik et al., 1998).

Thermal degradation of organic and inorganic materials used as insulation in electrical service occurs due to the increase in temperature above the nominal value. Life span can be obtained using the Arrhenius equation (Pacheco et al., 2000).

$$\frac{dp}{dt} = A \cdot e^{\frac{-E_a}{k_B \theta}}$$

(5)

Where;

dp/dt   : Change in life expectancy over time
A   : Material constant
k_B : Boltzmann constant [eV/K]
θ   : Absolute temperature [°K]
E_a : Excitation (activation) energy [eV]

Depending on the temperature, equation (6) can be used to estimate the approximate life of the cable (Pacheco et al., 2000).

$$p = p_i \cdot e^{\left(\frac{-E_a}{k_B}\right) \cdot \frac{\Delta\theta}{\theta_i \cdot (\theta_i + \Delta\theta)}}$$

(6)

In this equation, p is life [days] at $\Delta\theta$ temperature increment; p_i is life [days] at θ_i temperature; $\Delta\theta$ is the amount of temperature increment [°K]; and θ_i is operating temperature of the cable [°K].

In this study, temperature distributions of the power cables were obtained under electrical, thermal and environmental stresses (humidity), and life span of the power cables was evaluated by using the above equations and obtained temperature variations.

3. Applications

3.1 5.8/10 kV XLPE cable model

In this study, the first electrical-thermal combined analysis were made for 5.8/10 kV, XLPE insulated, single core underground cable. All parameters of this cable were taken from (Anders, 1997).

The cable has a conductor of 300 mm² cross-sectional area and braided copper conductor with a diameter of 20.5 mm. In Table 1, thicknesses of the layers of the model cable are given in order.

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

Table 1. Layer thicknesses of the power cable.
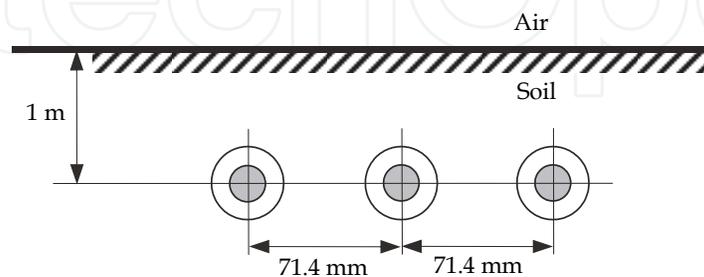
Fig. 1. Laying conditions of the cables.

Figure 1 shows the laying conditions taken into account for the cable. Here, it has been accepted that three exactly same cables having the above given properties are laid side by side at a depth of 1 m underground and they are parallel to the surface of the soil. The distance between the cables is left up to a cable diameter. Thermal resistivity of soil surrounding cables was taken as the reference value of 1 K·m/W. The temperature at far away boundaries is considered as 15°C.

3.1.1 Numerical analysis

For thermal analysis of the power cable, finite element method was used as a numerical method. The first step of the solution by this method is to define the problem with geometry, material and boundary conditions in a closed area. Accordingly the problem has been described in a rectangle solution region having a width of 10 m and length of 5 m, where three cables with the specifications given above are located. Description and consequently solution of the problem are made in two-dimensional Cartesian coordinates. In this case the third coordinate of the Cartesian coordinate system is the direction perpendicular to the solution plane. Accordingly, in the solution region, the axes of the cables defined as the two-dimensional cross-section will be parallel to the third coordinate axis. In the solution, the third coordinate, and therefore the cables are assumed to be infinite length cables.

Thermal conductivity (k) and thermal capacity (c) values of both cable components and soil that were taken into account in analysis are given in Table 2. The table also shows the ρ density values considered for the materials. These parameters are the parameters used in the heat transfer equation (1). Heat sources are defined according to the equation (3).

After geometrical and physical descriptions of the problem, the boundary conditions are defined. The temperature on bottom and side boundaries of the region is assumed as fixed (15°C), and the upper boundary is accepted as the convection boundary. Heat transfer coefficient *h* is computed from the following empirical equation (Thue, 1999).

Material	Thermal Conductivity k (W/K.m)	Thermal Capacity c (J/kg.K)	Density ρ (kg/m³)
Copper conductor	400	385	8700
XLPE insulation	1/3.5	385	1380
Copper wire screen	400	385	8700
PVC outer sheath	0.1	385	1760
Soil	1	890	1600

Table 2. Thermal properties of materials in the model.

$$h = 7.371 + 6.43 \cdot u^{0.75} \tag{7}$$

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

Second basic step of the finite element method is to discrete finite elements for solution region. Precision of computation increases with increasing number of finite elements. Therefore, mesh of solution region is divided 8519 triangle finite elements. This process is applied automatically and adaptively by used program.

Changing of cable losses with increasing cable temperature requires studying loss and warm-up mechanisms together. Ampacity of the power cable is determined depending on the temperature of the cable. The generated electrical-thermal combined model shows a non-linear behavior due to temperature-dependent electrical conductivity of the material.

Fig. 2 shows distribution of equi-temperature curve (line) obtained from performed analysis using the finite element method. According to the obtained distribution, the most heated cable is the one in the middle, as a result of the heat effect of cables on each side. The current value that makes the cable's insulation temperature 90°C is calculated as 626.214 A. This current value is calculated by multiplying the current density corresponding to the temperature of 90°C with the cross-sectional area of the conductor. This current value is the current carrying capacity of the cable, and it is close to result of the analytical solution of the same problem (Anders, 1997), which is 629 A.
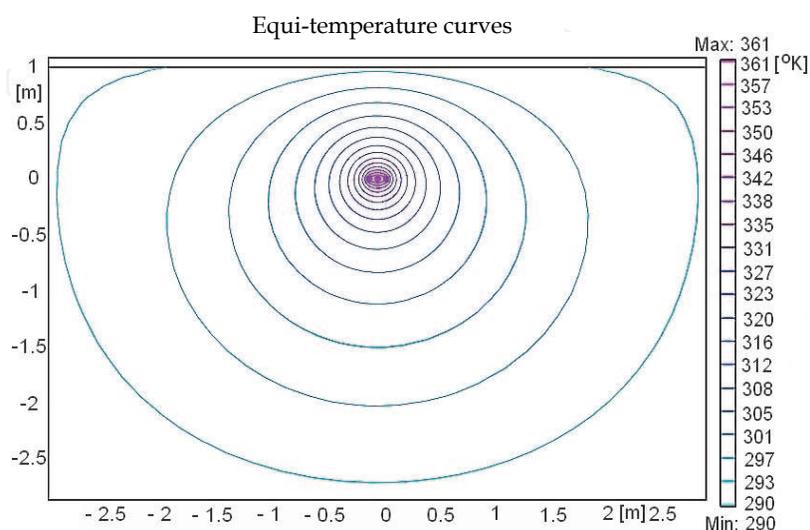

Fig. 2. Distribution of equi-temperature curves.

In Fig. 3, variation of temperature distribution depending on burial depth of the cable in the soil is shown. As shown in Fig. 3, the temperature of the cable with the convection effect shows a rapid decline towards the soil surface. This is not the case in the soil. It can be said that burial depth of the cables has a significant impact on cooling of the cables.

3.1.2 Effect of thermal conductivity of the soil on temperature distribution

Thermal conductivity or thermal resistance of the soil is seasons and climate-changing parameter. When the cable is laid in the soil with moisture more than normal, it is easier to disperse the heat generated by the cable. If the heat produced remains the same, according to the principle of conservation of energy, increase in dispersed heat will result in decrease in the heat amount kept by cable, therefore cable temperature drops and cable can carry more current. Thermal conductivity of the soil can drop up to 0.4 W/K·m value in areas where light rainfall occurs and high soil temperature and drying event in soil are possible. In this case, it will be difficult to disperse the heat generated by the cable; the cable current carrying capacity will drop. The variation of the soil thermal resistivity (conductivity) depending on soil and weather conditions is given in Table 3 (Tedas, 2005).
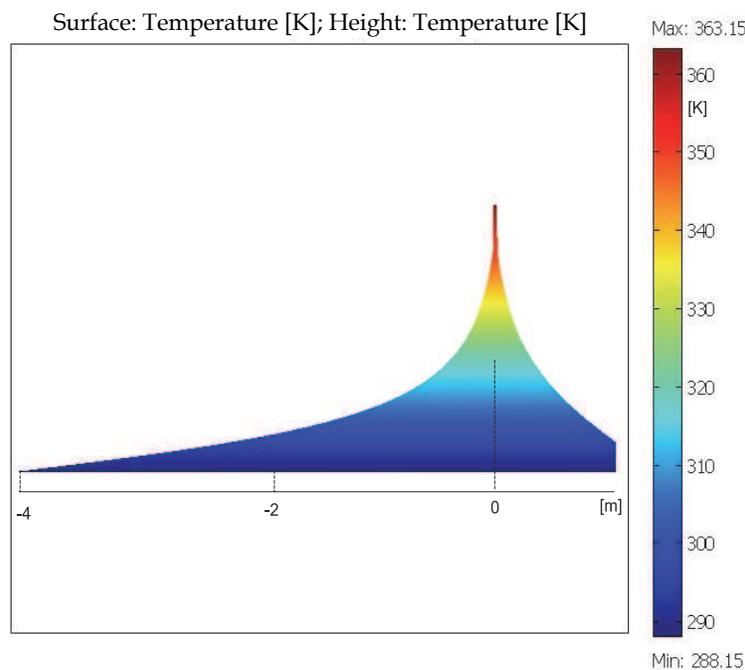
Fig. 3. Variation of temperature distribution with buried depth of the cable in soil.

Thermal Resistivity (K.m/W)	Thermal Conductivity (W/K.m)	Soil Conditions	Weather Conditions
0.7	1.4	Very moist	Continuous moist
1	1	Moist	Regular rain
2	0.5	Dry	Sparse rain
3	0.3	Very dry	too little rain or drought

Table 3. Variation of the soil thermal resistivity and conductivity with soil and weather conditions.

As can be seen from Table 3, at the continuous rainfall areas, soil moisture, and the value of thermal conductivity consequently increases.

While all the other circuit parameters and cable load are fixed, effect of the thermal conductivity of the surrounding environment on the cable temperature was studied. Therefore, by changing the soil thermal conductivity, which is normally encountered in the range of between 0.4 and 1.4 W/K·m, the effect on temperature and current carrying capacity of the cable is issued and results are given in Fig. 4. As shown in Fig. 4, the temperature of the cable increases remarkably with decreasing thermal conductivity of the soil or surrounding environment of the cable. This situation requires a reduction in the cable load.
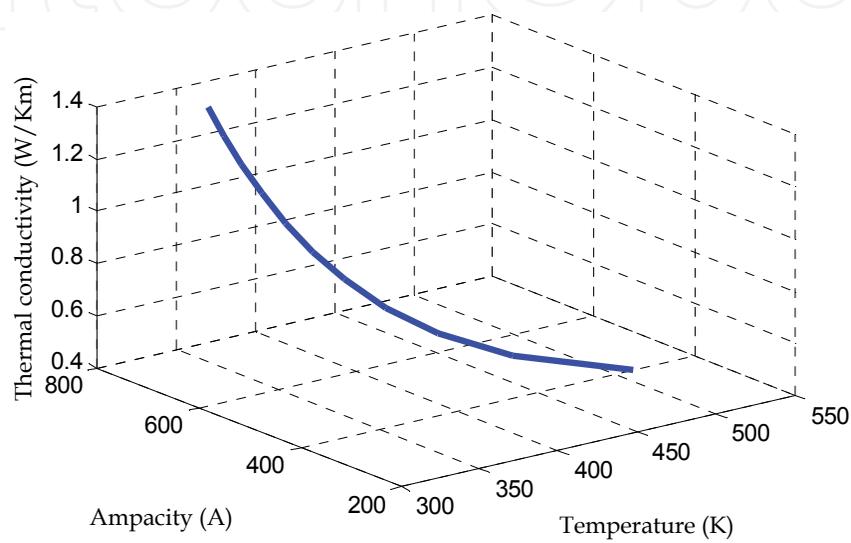
Fig. 4. Effect of variation in thermal conductivity of the soil on temperature and current carrying capacity (ampacity) of the cable.

When the cable load is 626.214 A and thermal conductivity of the soil is 1 W/Km, the temperature of the middle cable that would most heat up was found to be 90°C. For the thermal conductivity of 0.4 W/Km, this temperature increases up to 238°C (511.15°K). In this case, load of the cables should be reduced by 36%, and the current should to be reduced to 399.4 A. In the case of thermal conductivity of 1.4 W/K·m, the temperature of the cable decreases to 70.7°C (343.85°K). This value means that the cable can be loaded %15 more (720.23 A) compared to the case which the thermal conductivity of soil is 1 W/K·m.

3.1.3 Effect of drying of the soil on temperature distribution and current carrying capacity

In the numerical calculations, the value of thermal conductivity of the soil is usually assumed to be constant (Nguyen et al., 2010) (Jiankang et al., 2010). However, if the soil surrounding cable heats up, thermal conductivity varies. This leads to form a dry region around the cable. In this section, effect of the dry region around the cable on temperature distribution and current carrying capacity of the cable was studied.

In the previous section, in the case of the soil thermal conductivity is 1.4 W/K·m, current carrying capacity of the cable was found to be 720.23 A. In that calculation, the thermal conductivity of the soil was assumed that the value did not change depending on temperature value. In the experimental studies, critical temperature for drying of wet soil was determined as about 60°C (Gouda et al., 2011). Analyses were repeated by taking into

account the effect of drying of the soil and laying conditions. When the temperature for the surrounding soil exceeds 60°C, which is the critical temperature, this part of the soil was accepted as the dry soil and its thermal conductivity was included in the calculation with the value of 0.6 W/K·m.

The temperature distribution obtained from the numerical calculation using 720.23 A cable current, 1.4 W/K·m initial thermal conductivity of soil, as well as taking into account the effect of drying in soil is given in Fig. 5. As shown in Fig. 5, considering the effect of soil drying, temperature increased to 118.6°C (391.749°K). The cable heats up 28.6°C more compared to the case where the thermal conductivity of the soil was taken as a constant value of 1.4. The boundary of the dried soil, which means the temperature is higher than critical value of 60°C (333.15°K), is also shown in the figure. Then, how much cable current should be reduced was calculated depending on the effect of drying in the soil, and this value was calculated as 672.9 A.
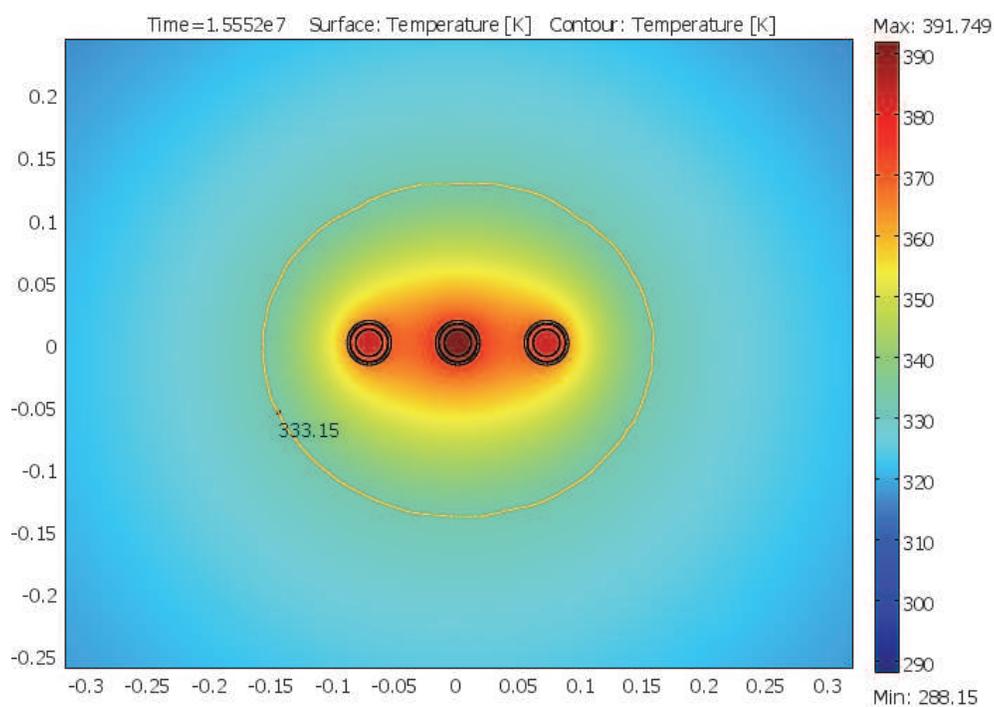
Fig. 5. Effect of drying in the soil on temperature distribution.

The new temperature distribution depending on this current value is given in Fig. 6. As a result of drying effect in soil, the current carrying capacity of the cable was reduced by about 7 %.

3.1.4 Effect of cable position on temperature distribution

In the calculations, the distance between the cables has been accepted that it is up to a cable diameter. If the distances among the three cables laid side by side are reduced, the cable in the middle is expected to heat up more because of two adjacent cables at both sides, as shown in Fig. 7(a). In this case, current carrying capacity of the middle cable will be reduced. Table 4 indicates the change in temperature of the middle cable depending on the distance between cables and corresponding current carrying capacity, obtained from the numerical solution.
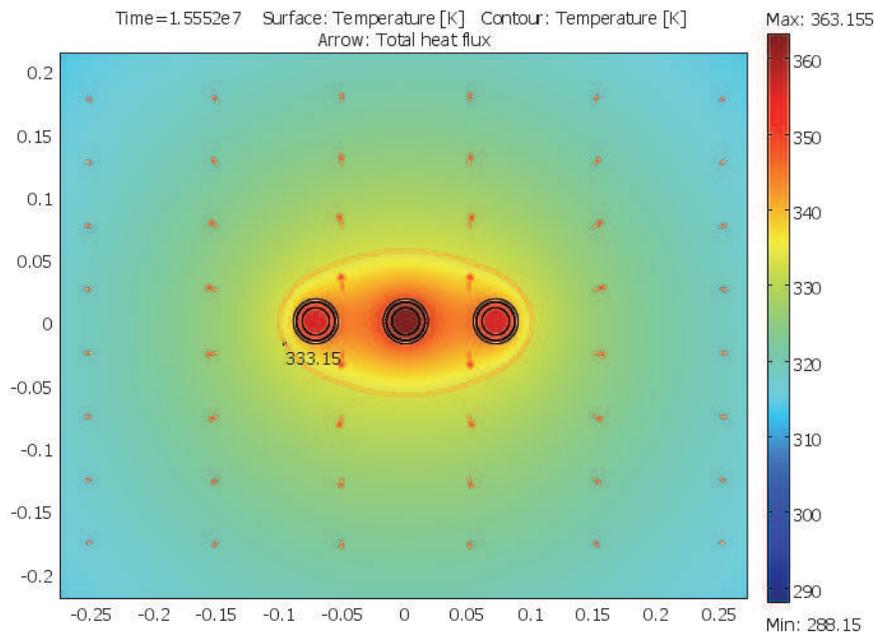
Fig. 6. Effect of the soil drying on temperature distribution.
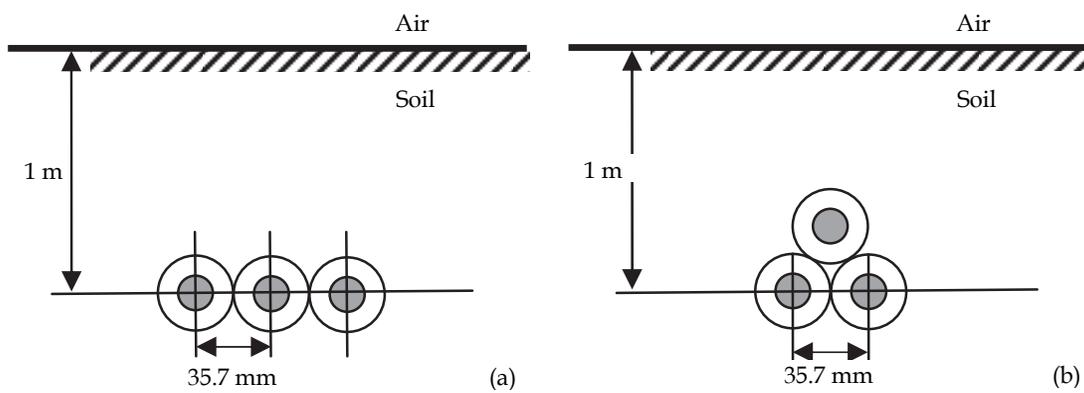
Fig. 7. Laying conditions of the cables.

As shown in Table 4, if there is no distance between the cables, temperature of the cable in the middle increases 10°C. This situation requires about 6% reduction in the cable load. The case where the distance between the cables is a diameter of a cable is the most appropriate case for the current carrying capacity of the cable.

Distance between the cables (mm)	Cable temperature (°C)	Current carrying capacity (A)
0	100.03	591.51
10	96.14	604.16
20	93.35	613.85
30	91.12	622.00
36	90.00	626.21

Table 4. Variation of temperature and current carrying capacity of the cable in middle with changing distance between the cables.

Triangle shaped another type of set-up, in which the cables contact to each other, is shown in Fig. 7(b). Each cable heats up more by the effect of two adjacent cables in this placement. The temperature distribution of a section with a height of 0.20 m and width of 0.16 m, which was obtained from the numerical analysis by using the same material and environmental properties given in section 3.1.1, is shown in Fig 8. As a result of this analysis, cables at the bottom heated up more when compared with the cable at the top but, the difference has been found to be fairly low. The current value that increases the temperature value of the bottom cables to 90 °C was found to be 590.63 A. This value is the current carrying capacity for the cables laid in the triangle shaped set-up.
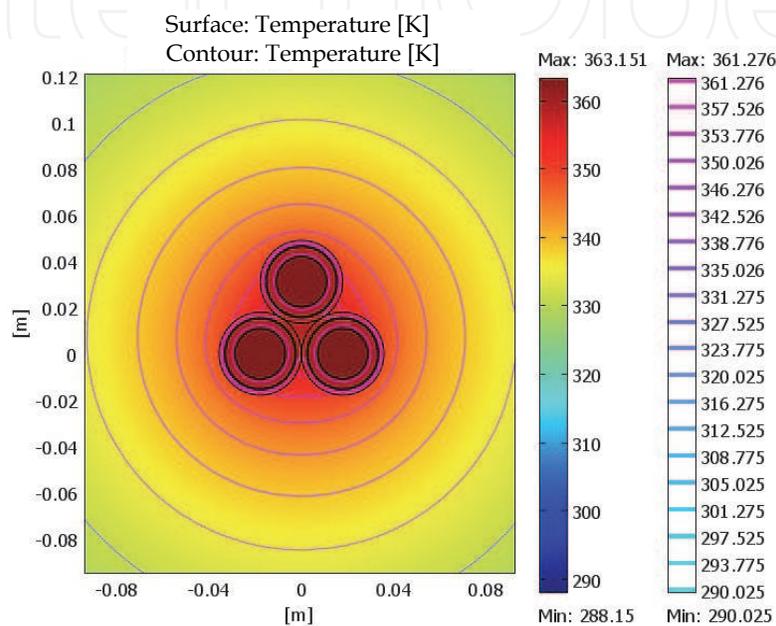
Fig. 8. Temperature distribution for the triangle-shaped set-up.

3.1.5 Single-cable status

In the studies conducted so far, the temperature distribution and current carrying capacity of 10 kV XLPE insulated cables having the triangle shaped and flat shaped set-up with a cable diameter distance have been determined. Other cables lay around or heat sources in the vicinity of the cable reduce the current carrying capacity remarkably. In case of using a single cable, the possible thermal effect of other cables will be eliminated and cable will carry more current. In this section, as shown in Fig. 9, the current carrying capacity of a
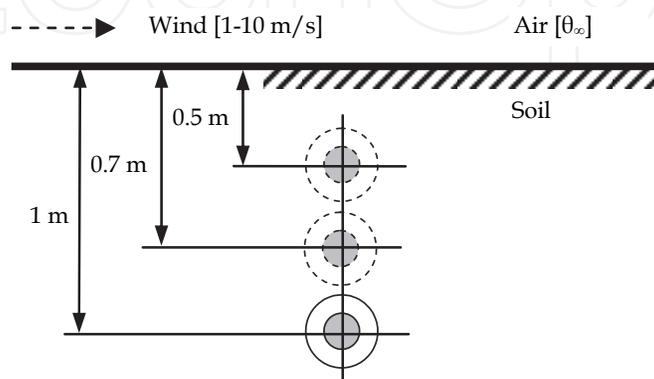

Fig. 9. A power cable buried in different depths.

single cable was calculated for different burial depths and then the impact of wind on the current carrying capacity of the cable has been examined.

In the created model, it is assumed that one 10 kV, XLPE insulated power cable is buried in soil and burial depth is 1 m. Physical descriptions and boundary conditions are the same as the values specified in section 3.1.1. The temperature distribution obtained by numerical analysis is shown in Fig. 10.
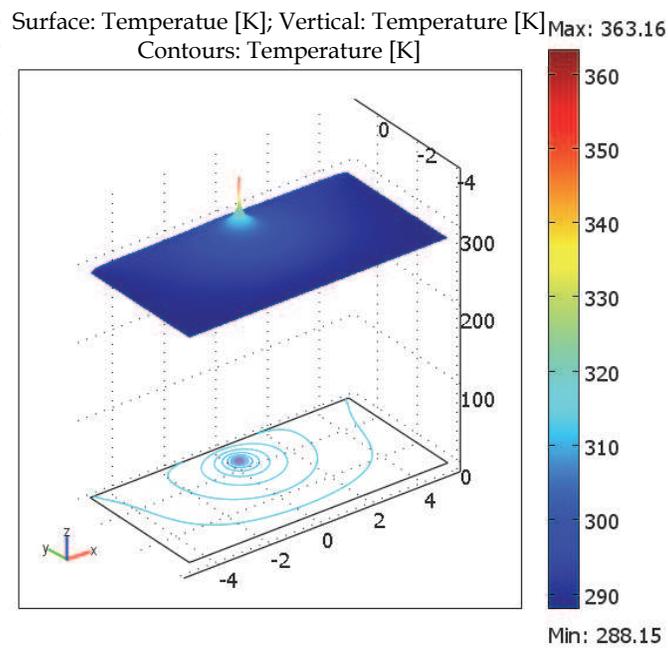

Fig. 10. Three-dimensional temperature distribution in the cable.

According to this distribution, current value which makes the temperature of the cable insulation is 90oC is calculated as 890.97 A. This value is the current carrying capacity for the configuration of stand-alone buried cables and it is 264 A more than that of the side by side configuration and 300 A more than that of triangle shaped set-up. The laying of the cable as closer to the ground surface changes the temperature distribution in and around the cable. For example, at 0.5, 0.7, and 1 m deep-buried case for the cable, the temperatures of the cable insulation depending on the current passing through the cable are shown in Fig. 11.

From the Fig. 11, it is shown that the current carrying capacity increases with the laying of the cable closer to the ground surface. When the cable was laid at a depth of 0.7 m, the current value that makes insulation temperature 90oC was found to be 906.45 A. Current value for a depth of 0.5 m is 922.63 A. Current carrying capacity of the buried cable to a depth of 0.5 m is about 32 A more than current carrying capacity of the buried cable to a depth of 1 m.

So far, it was assumed in the calculations that the wind speed was zero and the convection is the result of the temperature difference. In this section, the effect of change in wind speed on temperature distribution of buried cables has been investigated. Insulator temperatures have been calculated for the different wind speeds changing in the range of 1-10 m/s at each of burial depth by considering the current values that make the insulator temperature 90oC as constant value. As shown in Fig. 12, the increasing wind speed contributes to the cooling of the cables. In this case, the cable temperature will drop and small increase will be seen in the current carrying capacity.
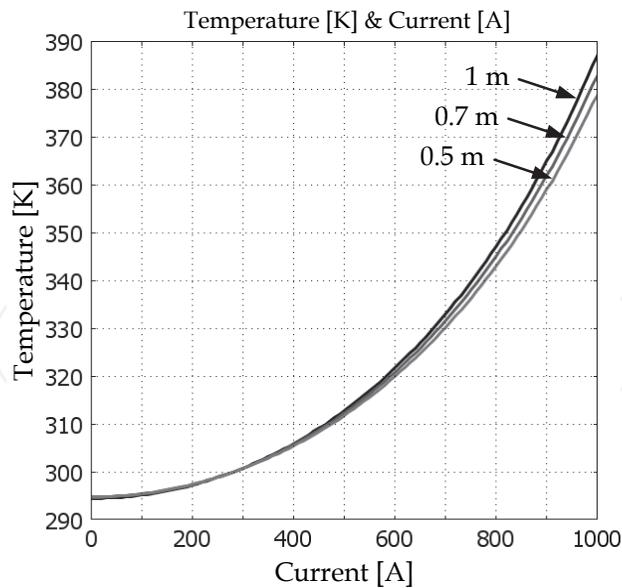
Fig. 11. Variation of temperature as a function of current in different buried depth.

The average wind speed for Istanbul is 3.2 m/s. (Internet, 2007). By taking into account this value, the temperature of the cable buried at 1 m depth will decrease about 0.8°C, while the temperature of the cable buried at 0.5 m depth will decrease about 2°C. This decrease for the cable buried at a depth of 0.5 m means the cable can be loaded 11 A more.

3.1.6 Relationship between cable temperature and cable life

In this section, the life of three exactly same cables laid side by side at a depth of 1 m has been calculated by using the temperature values determined in section 3.1.2 and 3.1.3. Decrease in the value of thermal conductivity of the soil and distance between the cables results in significant increase in temperature of the cables and consequently significant decrease in their current carrying capacities. This condition also reduces the life of the cable.
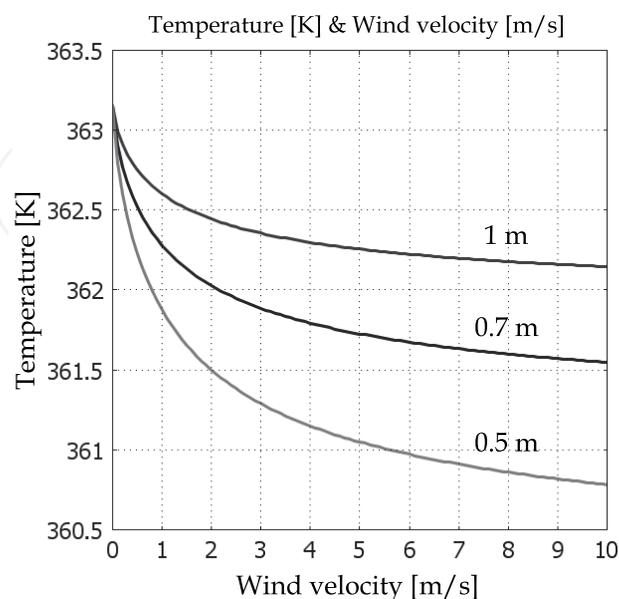

Fig. 12. Variation of temperature of the cable insulation with wind velocity.

In order to see the borders of this effect, cable life has been calculated for both cases by using the equation (6) and the results are indicated in Fig. 13 and Fig. 14. Activation energy of 1.1 eV for XPLE material, Boltzmann constant of $8.617 \cdot 10^{-5}$ eV/K was taken for the calculations and it is assumed that the life of XPLE insulated power cable at 90°C is 30 years. The relationship between the cable distances and life of cables for three different soil thermal conductivities has been shown in Fig. 13. As it is seen from the figure, cable life decreases
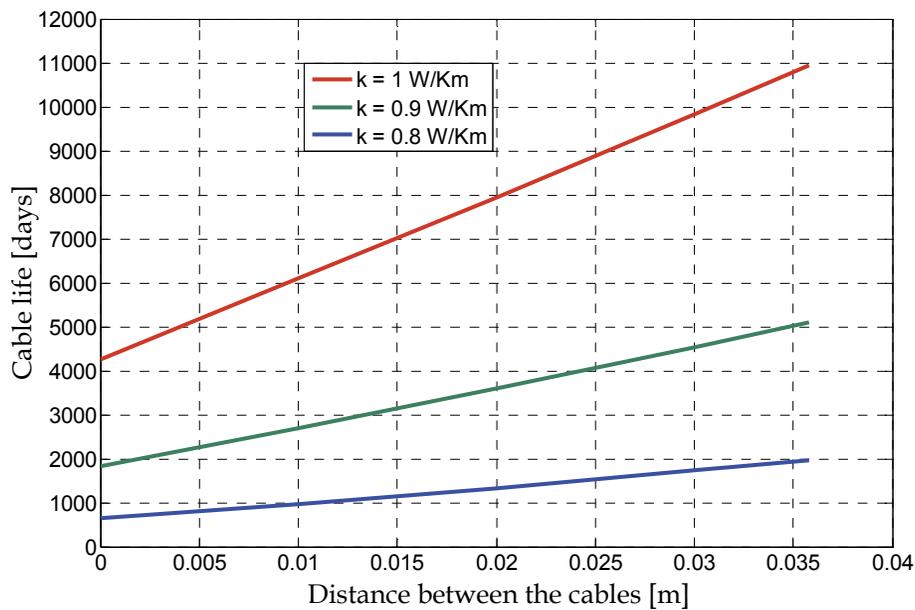
Fig. 13. Variation of the cable life as a function of distance between the cables in different thermal conductivities of the soil.
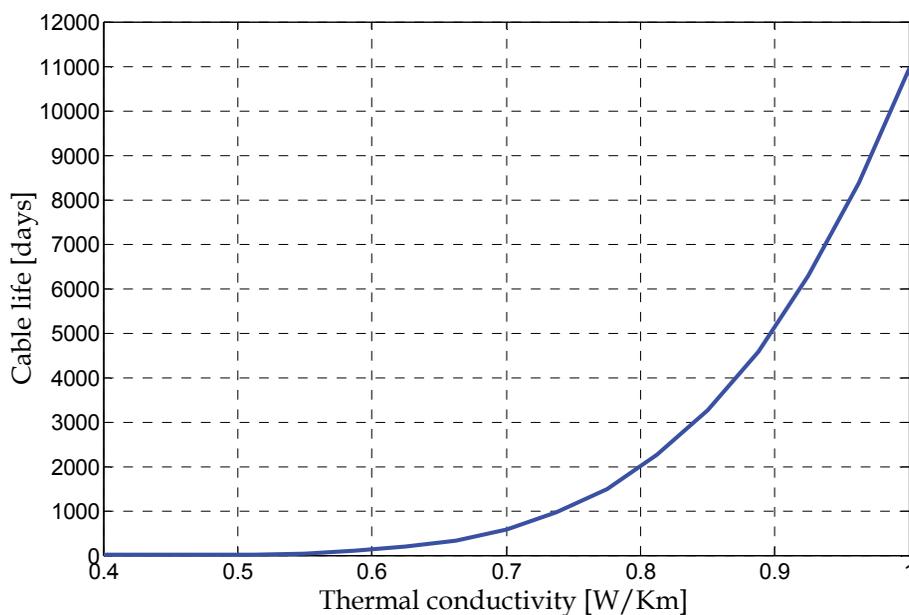
Fig. 14. Variation of the cable life as a function of thermal conductivity of the soil.

linearly depending on decrease in distance between the cables. In this analysis, the currents in the cables were assumed to be constant values and the cable temperatures (changing with

the cable distances) obtained from the numerical solution, were used for the calculation of cable's life. A decrease of 0.5 cm at cable distances leads to loss of 1000 days in the cable life when the thermal conductivity is 1 W/Km, as it is seen from the figure.

The life of cables laid side by side with a one diameter distance has been calculated in another analysis, depending on the change in the thermal conductivity of soil and given in Fig. 14. As a result of this analysis, in which the current values were assumed to be constant, it was seen that cable life increases logarithmically depending on the increase in the thermal conductivity of the soil. As it is seen from the figure, 10% decrease in the thermal conductivity of the soil results in 50% reduction in the cable life unless load conditions are adjusted.

3.2 0.6/1 kV PVC cable model
3.2.1 Experimental studies

This section covers the experimental studies performed in order to examine the relationship between current and temperature in power cables. For this purpose, current and also conductor and sheath temperatures were recorded for a current carrying low voltage power cable in an experiment at laboratory conditions and the obtained experimental data was used in numerical modeling of that cable.

The first cable used in the experiment is a low voltage power cable having the properties of 0.6/1/1.2 (U0/Un/Um) kV, 3 x 35/16 mm², $3^{1/2}$ core (3 phase, 1 neutral), PVC insulated, armored with galvanized flat steel wire, cross-hold steel band, PVC inner and outer sheaths. The catalog information of this PVC insulated cable having 29.1 mm outer diameter specifies that DC resistance at 20°C is 0.524 Ω/km and the maximum operating temperature is 70°C (Turkish Prysmian Cable and Systems Inc.).

In order to examine the relationship between current and temperature in case of the power cable in water and air, a polyester test container was used. During measurements, the cable was placed in the middle and at a 15 cm distance from the bottom of the container. In the first stage, current-temperature relation of the power cable placed in air was studied. The experimental set-up prepared for this purpose is shown in Fig. 15.

Fig. 15. Experimental set-up for 0.6/1 kV cable.

The required current for the power cable has been supplied from alternating current output ends of a 10 kW welding machine. Its the highest output current is 300 A. Current flowing through the cable is monitored by two ammeters which are iron-core, 1.5 classes, and 150 A. Output current is adjusted by use of a variac on the welding machine.

A digital thermometer having the properties of double input, ability to measure temperatures between -200 and 1370 ºC, and ± (%0.1 rdg + 0,7ºC) precision was used during the measurements. Two K-type thermocouples can be used with the thermometer and this enables to monitor the temperatures of different points simultaneously. These thermocouples were used to measure the conductor and sheath temperatures of the cable.

Conductor and sheath temperatures were measured on cable components at a 50 cm distance from the current source's both ends in accordance with the defined temperature measurement conditions in the Turkish Standard (TS EN 50393, 2006).

During the experiment phase conductors of the cable were connected to each other in serial order and alternative current was applied. Throughout the experiments, cable conductor and sheath temperatures at the point where the current source is connected to the cable and also ambient temperature were recorded with an interval of 10 min. Fig. 16 indicates the variations of current applied to the cable; the cable and ambient temperatures with time.
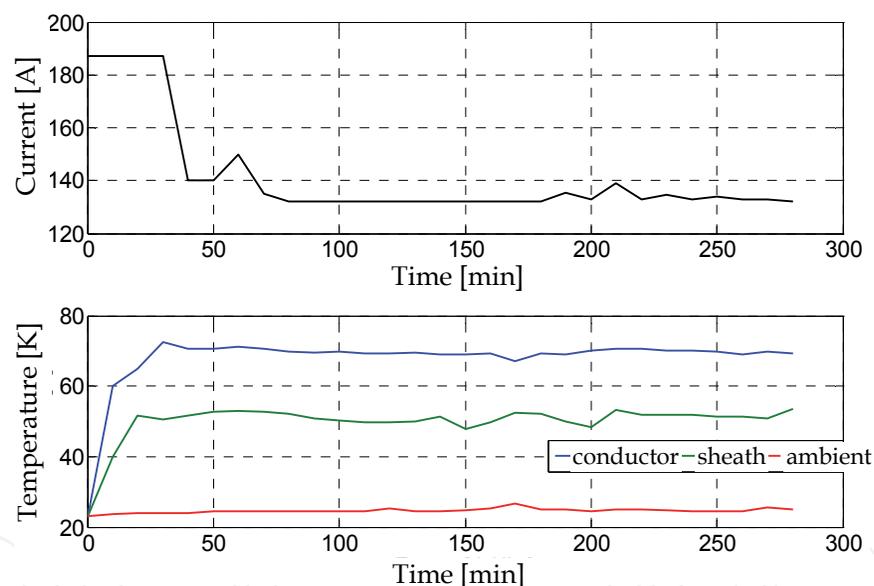

Fig. 16. Variations of current applied to the cable; the cable components and ambient temperatures with time

Conductor and sheath temperatures in the figure are the average of the values obtained from the both measurement points. In order to find the current carrying capacity of the cable it was starded with a high current value and then current was adjusted so that the conductor temperature can be kept constant at 70ºC. After almost 3 hours later the current and cable temperatures were stabilized. In that case, the cable was continued to be energized for another 2 hours. The highest current value that cable can carry in steady state operation was found to be 132 A, as it was in agreement with the defined value in the catalog of that cable.

As a second stage, first of all it was waited almost 3 hours for cooling of the cable warmed up during the measurements and then it was started to study the current-temperature relation of the cable that is under water. At this stage, test container was completely filled with water and 2.5 m of 4 m cable was immersed in water placing it at a distance of 35 cm from the water surface.

As it was performed earlier in the case where the power cable was in air, the current value that makes the conductor temperature 70°C was tried to be found and the cable was run at that current value for a certain time. The conductor and sheath temperatures were measured from the sections which are out of water, as it was explained above; at a 50 cm distance from the current source's both ends. Water temperature was also monitored to see the effect of current passing through to cable on the surrounding environment. Fig. 17 indicates the variations of current applied to the cable; the cable components, the ambient, and the water temperatures with time.
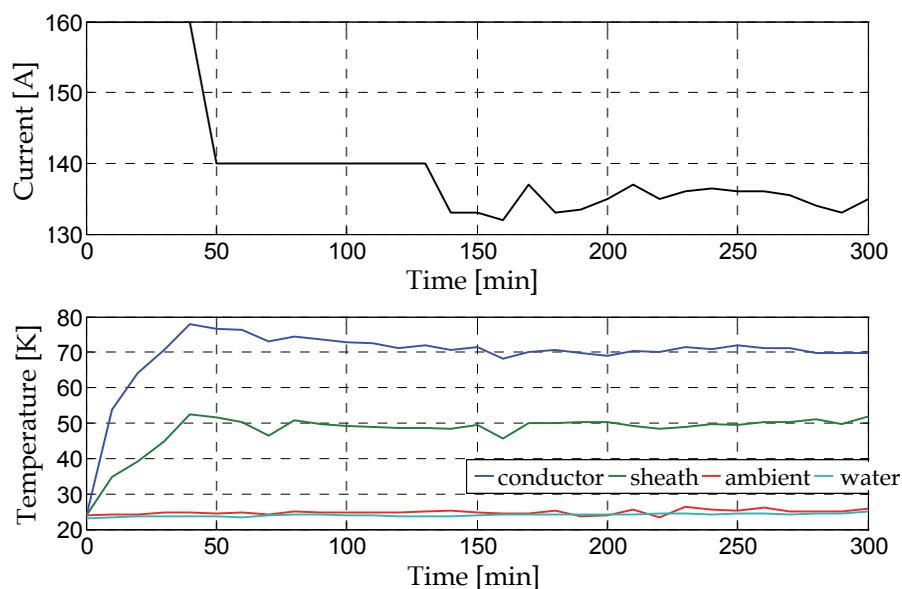
Fig. 17. Variations of current applied to the cable; the cable components, the ambient, and the water temperatures with time

As shown in Fig. 17, the conductor and the sheath temperatures have reached steady state values at the end of nearly two-hour work period. The average current value for the stable operation state is approximately 135 A. The current value that was obtained in the case where substantial portion of cable was immersed in water is a few amps higher than that of air environment.

3.2.2 Numerical solution

Cross section of 0.6 / 1 kV power cable is shown in Fig. 18. In the figure, O shows the center of the cable, O_1 and O_2 indicate the centers of the phase and neutral conductor, respectively. The radiuses of the other cable components are given in Table 5.

Numerical solution of the problem has two-stages. The numerical model of the power cable was created firstly for the air configuration, secondly for the water configuration and the steady-state temperature distributions were determined.
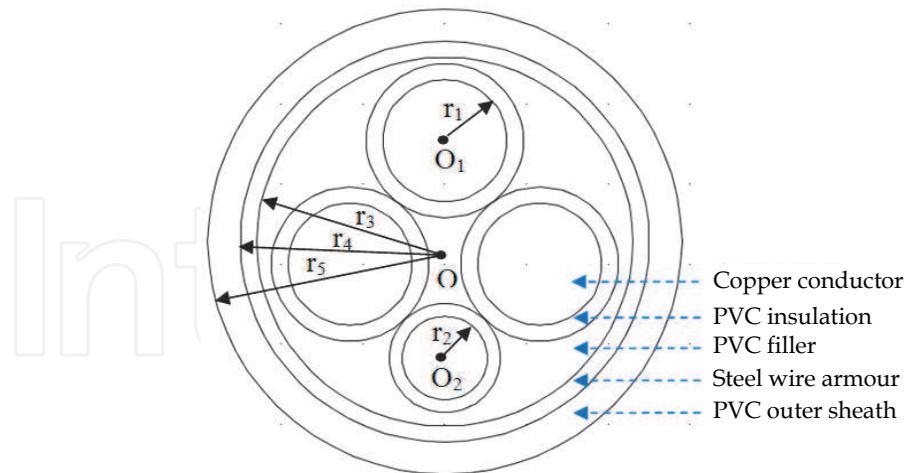
Fig. 18. View of 0.6/1 kV, 3 x 35/16 mm², PVC insulated power cable.

Cable Components	Radius (mm)
Phase conductors (r1)	3.8
Neutral conductor (r2)	2.6
Filling material (r3)	11.5
Armour (r4)	12.5
Outer sheath (r5)	14.5

Table 5. Radiuses of the cable components.

The first step of finding the temperature distrubiton of a power cable in air is to create the geometry of the problem. The problem was defined at 2 x 2 m solution region, where the cable with the given properties above was located. After creating the geometry of the problem, thermal parameters of the cable components and the surrounding environment are defined as given in Table 6.

Cable Material	Density ρ (kg/m³)	Thermal Capacity c (J/kg·K)	Thermal Conductivity k (W/K·m)
Conductor (copper)	8700	385	400
Insulator (PVC)	1760	385	0.1
Armour (steel)	7850	475	44.5
Air	1.205	1005	k_air(θ)

Table 6. Thermal parameters of the cable components.

Thermal conductivity of air varies with temperature. As shown in Fig. 19, the thermal conductivity of air increases depending on the increasing temperature of the air (Remsburg, 2001).

This case, which depends on increased temperature of power cables, provides better distribution of heat to the surrounding environment. By including the values given in Table 7 in the cable model, intermediate values corresponding to change in the air temperature have been found.
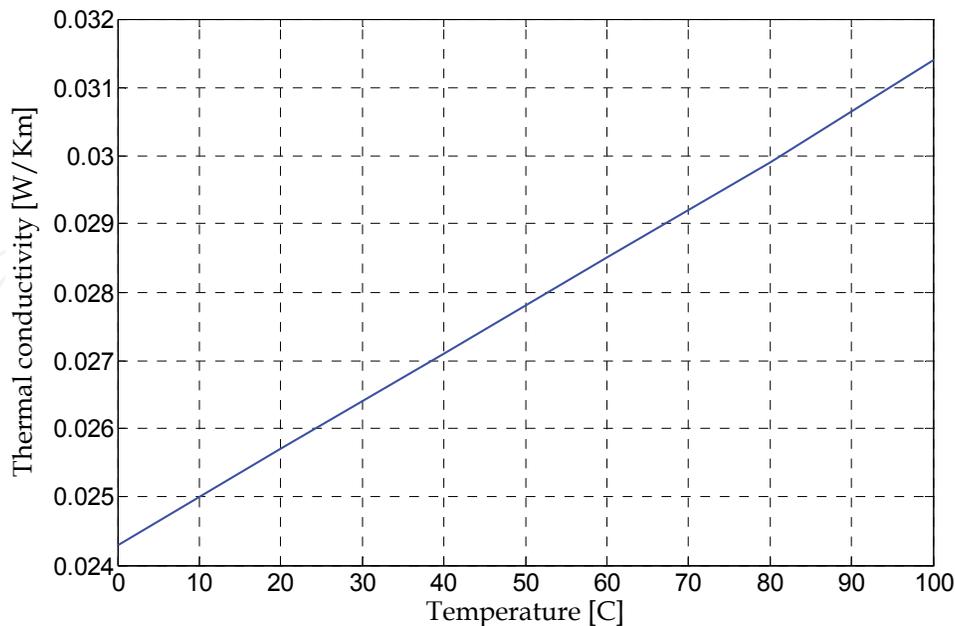
Fig. 19. Variation of thermal conductivity of air with temperature.

Temperature (°C)	Thermal Conductivity (W/mK)
0	0.0243
20	0.0257
40	0.0271
60	0.0285
80	0.0299
100	0.0314

Table 7. Variation in thermal conductivity of air with temperature.

The most important heat source for the existing cable is the ohmic losses formed by current flowing through the cable conductors. The equation of $P = J^2 / \sigma$ is used to calculate these losses. Ohmic losses in the conductor are described as "(132/(pi * 0.0038²))² /condCu" (W/m³)(132/(pi * 0.0038²))² / condCu" (W/m³). In this equation, condCu expression is the value of the electrical conductivity of the material, and it is a temperature-dependent parameter as shown in equation (4).

At the last step of the numerical analysis, the boundary conditions are indicated. Since the cable is located in a closed environment, free convection is available on the surface of the cable. Equation (7) is used to calculate heat transfer coefficient, and the wind speed is assumed as zero. The temperature of the outer boundary of the solution region is defined as constant temperature. This value is an average ambient temperature measured during the experiment (297.78°K) and it was added to the model.

After all these definitions, the region is divided into elements and the numerical solution is performed. The entire region is divided into 7212 elements. As a result of numerical analysis performed by using finite element method, the temperature distribution in and around the cable, and equi-temperature lines are shown in Fig. 20 and Fig. 21, respectively.
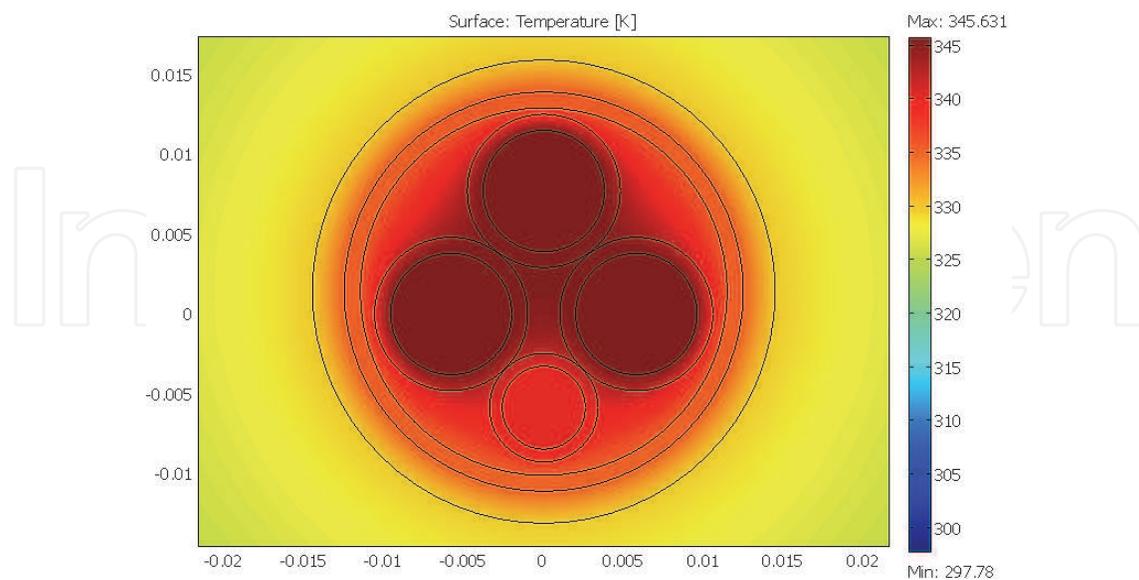
Fig. 20. Temperature distribution.
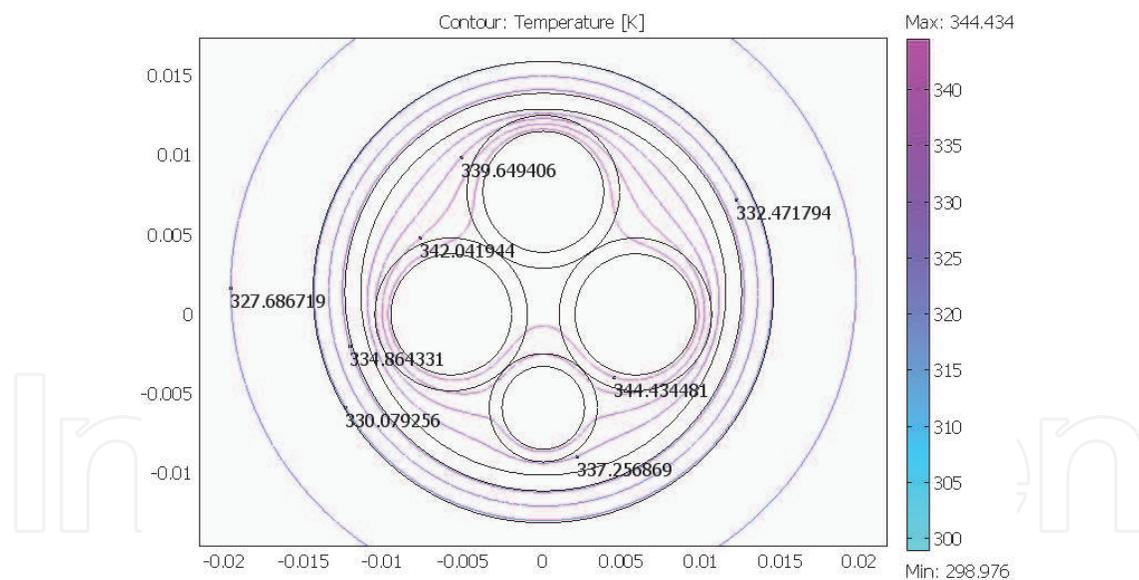
Fig. 21. Equi-temperature lines.

Temperature distribution during the balanced loading of the cable can be seen from the figures. In this case, there will be no current on the neutral conductor and the heat produced by currents passing through to three phase conductors will disperse to the surrounding environment. As seen in Fig. 20, the highest conductor temperature that can be reached was found to be 345.631°K (72.4°C). Steady state value of the average conductor temperature obtained from the experimental measurement is 70.1°C. Outer sheath temperature was

found as 329ºK (55.8ºC) by numerical analysis. The average sheath temperature obtained from the experimental measurements is approximately 52ºC. The results obtained from the numerical analysis are very close to the experimental results.

At the second stage of the numerical model, the condition where the same cable is in the water has been taken into consideration. The model established in this case is the same with the model described above except the properties of the surrounding environment. However, in the numerical model the whole cable is assumed to be in the water. Thermal properties of the water are given in Table 8.

Material of the Cable	Density ρ (kg/m³)	Thermal Capacity c (J/kg·K)	Thermal Conductivity k (W/K·m)
Water	997.1	4181	k_water(θ)

Table 8. Thermal properties of the water.

As seen in Fig. 22, the thermal conductivity of the water depends on the temperature (Remsburg, 2001). This dependence has been included in the model as described for the power cable in air. In addition, temperature of the water is considered to be 24.1ºC by calculating the average of measured values. After these definitions, the solution region is divided by finite elements, and then the numerical solution is carried out. As a result of performing the numerical analysis, the current-temperature curve for the power cable in the water environment is given in Fig. 23. As shown in the Fig. 23, the conductor temperature increases depending on the current passing through the cable. The ampacity of the cable was found to be 162.9 A considering the thermal strength of PVC material of 70ºC.
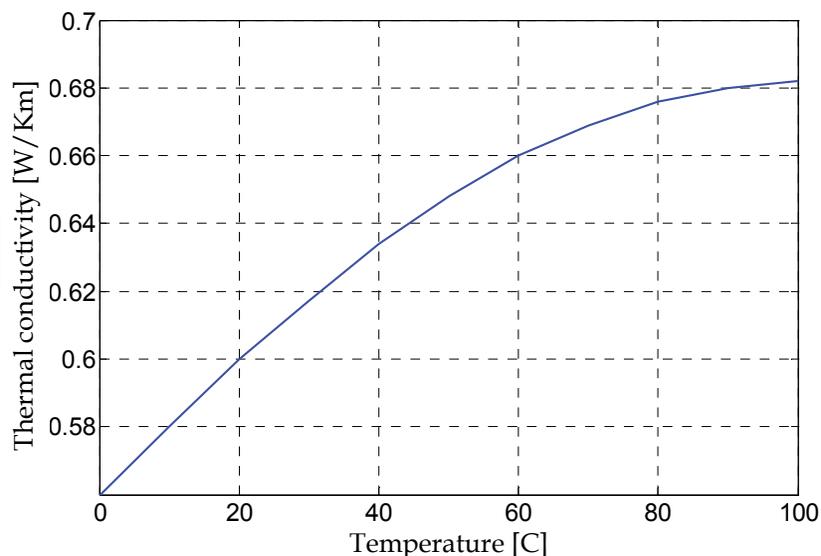

Fig. 22. Variation of thermal conductivity of the water with temperature.

This value is the value of the current carrying capacity where all of the cable is immersed in the water taking into account the water and environment temperature values in the laboratory conditions. In the experimental study, the current value to reach the value of the cable conductor temperature of 70°C is found as 135 A. In the experiment, 60% of the cable section is immersed in the water.
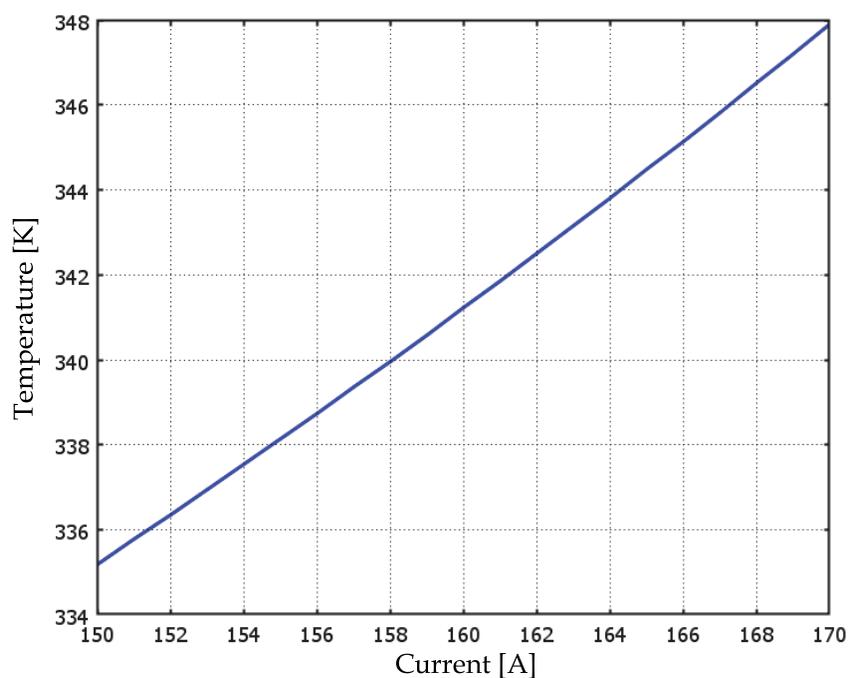

Fig. 23. Relation between current and temperature for the power cable immersed in water.

Therefore, the experimental study for the cable immersed in water can not be expected to give the actual behavior of the power cables. Beside this, the current value enabling the conductor to reach 70°C in the experimental study in water environment is higher than that of air environment. This indicates that power cables immersed in water has better cooling environment because of higher thermal conductivity of the water when compared with the air. Numerical analysis also confirms this result.

By using the numerical analysis common solution of electrical and thermal factors has been realized. Since electrical conductivity of the conductive material is temperature dependent, this increases the conductor temperature by 7ºC as a result of numerical analysis. Similarly, thermal conductivity of surrounding environment is defined as a temperature dependent parameter in the numerical model. In the numerical analysis for the power cable immersed in water, 0.6ºC decrease in the conductor temperature was seen when it was compared with the case, in which the thermal conductivity of water was taken as constant at 20ºC. This is because of the fact that increases in cable temperature results in increase in thermal conductivity of the water and then heat disperses more effectively from the cable to surrounding environment.

4. Conclusion

The thermal analyze of power cable systems is very important especially in terms of determining the current carrying capacity of those cables. Cable temperature depends on many factors, such as current passing through the cable, cable structure and materials used in the manufacture of the cable, laying styles of other cables around that cable, thermal properties of the environment, and moisture of the surrounding soil.

In this study, in which the temperature distribution is studied by taking into account the electrical losses depending on current density and electric field in heat conduction equation, not only the usual temperature conditions but also electrical conditions are considered for the solution.

In 10 kV XLPE insulated cable taken into consideration as an example, the dielectric losses have been neglected due to being very low when compared to the current depended losses. Changes in the current carrying capacity of the cable were investigated by using the temperature distributions determined with the finite element method. Results indicate that current increases the temperature and increased temperature decreases the current carrying capacity of the cable. In this case, it was realized that because of the decreased current due to increased temperature, the temperature decreased, and thus leading to increase in the current again and at the end the stable values in terms of the temperature and current were achieved.

The current carrying capacity of a cable is closely linked with the thermal conductivity of the surrounding environment, such as soil which is the case for the mentioned cable example. Because this resistance has a role to transmit the heat generated in the cable to the environment. In the XLPE insulated cable model, in the range of thermal conductivity of soil encountered in practice, when the thermal conductivity is changed, as expected, the current carrying capacity is increased with the increased thermal conductivity; on the other hand the current carrying capacity is reduced with the decreased thermal conductivity. In the meantime, increase in thermal conductivity reduces the heat kept in the cable, therefore reduces the temperature of the cable.

Usually, there can be other laid cables next to or in the vicinity of the cables. The heat generated by a cable usually has a negative effect on heat exchange of the adjacent cables. As seen in XLPE insulated cable model, when three pieces of cables are laid side by side, the cable in the middle heats up more because of both not being able to transmit its heat easily and getting heat from the side cables. This also lowers the current carrying capacity of the

center conductor. To reduce this effect it is necessary to increase the distance between cables. In the study that was conducted to see the effect of change in distance on the temperature distribution, it was seen a decrease in the cable temperature and an increase in the current carrying capacity when the distance was increased, as expected. At the end of our review, at least one cable diameter distance between the cables can be said to be appropriate in terms of the temperature and current conditions.

This study also reviewed the effect of cable burial depth on temperature distribution when a single XLPE insulated cable was considered. It was observed that the cables laid near to earth surface had increased current carrying capacity. This case is due to convection on earth. Reduction in the burial depth of cables provides better heat dissipation that is, better cooling for the cable. Again, in the case of a single cable example, analysis that was performed to study the effect of wind speed on the cable temperature indicated that the increase in wind speed slightly lowered the temperature of the cable. Considering the average wind speed for Istanbul for a power cable buried at a depth of 0.5 m, temperature value is 2°C less compared to cable buried at a depth of 1 m. The outcome of this case obtained from the numerical solution is that the cable can be loaded 11 A more. Based on this, in regions with strong wind, it can be seen that in order to operate the cable at the highest current carrying capacity, the wind speed is a parameter that can not be neglected.

Life of cables is closely linked with the operation conditions. Particularly temperature is one of the dominant factors affecting the life of a cable. For the three XLPE insulated cable model, change in cable life was examined with the temperature values found numerically using the expressions trying to establish a relationship between the temperature and cable life in our study. An increase in temperature shortens the life of the cable. Low temperatures increase both the life and the current carrying capacity of the cable.

Finally, experimental studies have been conducted to examine the relationship between the current and temperature in power cables. For this purpose, the conductor and sheath temperatures of 0.6/1 kV PVC insulated power cable in air and also in water have been studied. In the numerical model of the cable, the current value and environmental temperature obtained from the experiments were used as an input data and by adding temperature dependent electrical and thermal properties of both cable and surrounding environment to the model, the temperature distribution was determined for both the cable components and the surrounding environment. Temperature values obtained from the experimental measurements are in agreement with the results of the numerical solution.

As a result, running power cables in appropriate environmental and layout settings, and operating them in suitable working conditions, increase the cable life and its efficiency and make positive contribution to safety and economy of the connected power systems. This depends on, as in this study, effort put forward for modeling of cables closer to operating conditions, and further examining and evaluating.

5. Acknowledgment

6. References

Hwang, C. C., Jiang, Y. H., (2003). "Extensions to the finite element method for thermal analysis of underground cable systems", *Elsevier Electric Power Systems Research*, Vol. 64, pp. 159-164.

Kocar, I., Ertas, A., (2004). "Thermal analysis for determination of current carrying capacity of PE and XLPE insulated power cables using finite element method", IEEE MELECON 2004, May 12-15, 2004, Dubrovnik, Croatia, pp. 905-908.

IEC TR 62095 (2003). Electric Cables – Calculations for current ratings – Finite element method, IEC Standard, Geneva, Switzerland.

Kovac, N., Sarajcev, I., Poljak, D., (2006). "Nonlinear-Coupled Electric-Thermal Modeling of Underground Cable Systems", *IEEE Transactions on Power Delivery*, Vol. 21, No. 1, pp. 4-14.

Lienhard, J. H. (2003). *A Heat Transfer Text Book,* 3rd Ed., Phlogiston Press, Cambridge, Massachusetts.

Dehning, C., Wolf, K. (2006). *Why do Multi-Physics Analysis?*, Nafems Ltd, London, UK.

Zimmerman, W. B. J. (2006). *Multiphysics Modelling with Finite Element Methods*, World Scientific, Singapore.

Malik, N. H., Al-Arainy, A. A., Qureshi, M. I. (1998). *Electrical Insulation in Power Systems,* Marcel Dekker Inc., New York.

Pacheco, C. R., Oliveira, J. C., Vilaca, A. L. A. (2000). "Power quality impact on thermal behaviour and life expectancy of insulated cables", *IEEE Ninth International Conference on Harmonics and Quality of Power, Proceedings,* Orlando, FL, Vol. 3, pp. 893-898.

Anders, G. J. (1997). *Rating of Electric Power Cables – Ampacity Calculations for Transmission, Distribution and Industrial Applications*, IEEE Press, New York.

Thue W. A. (2003). *Electrical Power Cable Engineering*, 2nd Ed., Marcel Dekker, New York.

Tedas (Turkish Electrical Power Distribution Inc.), (2005). Assembly (application) principles and guidelines for power cables in the electrical power distribution networks.

Internet, 04/23/2007. istanbul.meteor.gov.tr/marmaraiklimi.htm

Turkish Prysmian Cable and Systems Inc., Conductors and Power Cables, Company Catalog.

TS EN 50393, Turkish Standard, (2007). *Cables - Test methods and requirements for accessories for use on distribution cables of rated voltage 0.6/1.0 (1.2) kV*.

Remsburg, R., (2001). *Thermal Design of Electronic Equipment*, CRC Press LLC, New York.

Gouda, O. E., El Dein, A. Z., Amer, G. M. (2011). "Effect of the formation of the dry zone around underground power cables on their ratings", *IEEE Transaction on Power Delivery*, Vol. 26, No. 2, pp. 972-978.

Nguyen, N., Phan Tu Vu, and Tlusty, J., (2010). "New approach of thermal field and ampacity of underground cables using adaptive hp- FEM", 2010 IEEE PES Transmission and Distribution Conference and Exposition, New Orleans, pp. 1-5.

Jiankang, Z., Qingquan, L., Youbing, F., Xianbo, D. and Songhua, L. (2010). "Optimization of ampacity for the unequally loaded power cables in duct banks", 2010 Asia-Pacific Power and Energy Engineering Conference (APPEEC), Chengdu, pp. 1-4.

Karahan, M., Varol, H. S., Kalenderli, Ö., (2009). Thermal analysis of power cables using finite element method and current-carrying capacity evaluation, *IJEE* (*Int. J. Engng Ed.*), Vol. 25, No. 6, pp. 1158-1165.
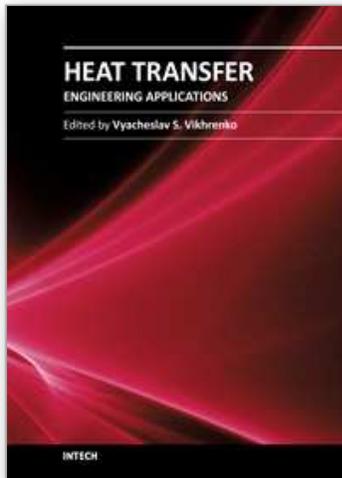
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