



Finite Element Method Based Design of a Computer Application Interface for Thermal Analysis of Underground Power Cable System

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Highlights

- A finite element method based application is designed for thermal analysis of power cables.
- Effects of material properties on thermal distribution of power cables.
- Influence of application designed on electrical engineering education is analyzed via survey.

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Abstract

The aim of thermal analysis of underground power cable studies is to optimize electrical and physical parameters of cable system and to transfer maximum power with minimum losses. For such problems, finite element method is mostly preferred, since they have complex geometry and requires multi-disciplinary (thermal and electrical) study. However, design, calculation and analysis of the problem is quite challenging since it requires advanced knowledge in related areas. Therefore, it becomes difficult particularly for engineers and students to study on thermal analysis of underground cables which has an important role in power system. In this context, it is aimed to design an application to perform thermal analysis of a typical medium voltage underground cable system. The application is designed using Comsol Multiphysics and allows users to perform two-dimensional, time-dependent thermal analyses. It also provides users to set several thermal, electrical and physical parameters as inputs and allows to compare thermal distribution results at desired points and regions. In the study, a series of thermal analyses are performed and results are presented for a sample loading scenario to indicate performance of the application. Besides, the application designed is used as a training material in a seminar in Yildiz Technical University, Electrical Engineering Department. Results showed that the application can be used as a useful tool for engineering education.

1. INTRODUCTION

Recently, number of studies on energy continuity, system stability, failure prediction, on-line monitoring and energy efficiency has increased considerably in order to prevent faults in distribution systems [1-3]. The main purpose of these studies establishing a continuous, reliable and monitorable system by minimizing losses in electrical and economic terms. In this regard, there is a significant increase in the number of power system efficiency, stability and predictive maintenance studies particularly on medium voltage (MV) equipment and the network [4-7]. Besides, distribution networks have a complex structure and unexpected failures in any equipment directly affect the end user. For these reasons, studies on critical MV equipment should be given priority in literature. One of the most worthy equipment especially for the distribution system operators is MV power cables. In case of overloading in peak demand periods, conductor temperature exceeds the maximum operating temperature which also leads to an increase in failure probability and rapid reduction in cable life [2, 8, 9]. In addition, getting out of dimensional standards such as laying depth, horizontal distance between cables, filler height etc. are other factors that cause the cable to overheat and reduce its life-time [9-17]. It is fact that the life-time of a cable operated above the rated operating temperature is less than expected. In this case, unexpected faults may occur on the cable, joints and terminations that cause serious economic losses and operational problems [18]. In order to prevent these faults, the cable conductor temperature should be measured, calculated and determined for each laying type and different loading scenarios. However, on-line temperature measurement is not

economically feasible due to the high cost of field measuring equipment and components. In addition, installation of a set-up for instant monitoring of conductor temperature requires extra investment costs. While these investments are feasible for higher energy transmission and long distances, it is not economical and operational for lower energy and short distances [19]. On the other hand, there are various types of cable system (CS) that need to be analyzed and examined because the dimensions and type of the CS differ according to the load current, rated voltage, number of circuits, physical and geographical structure of the region to be applied [20, 21].

For these reasons, analytical, thermal modeling and numerical solution methods are used in the literature in order to determine or predict the conductor temperature and thermal distribution [9, 22-24]. Among these methods, the most preferred one is the finite element method (FEM). The main advantages of the FEM are; being appropriate for designing complex geometries, parameter changes on the problem and their effects can be easily observed, fast and accurate solution can be listed with the help of computer [25, 26]. Therefore, FEM based software is widely preferred in the literature for the thermal analysis of CS. However, in order to solve such problems even with the help of software, advanced knowledge of electrical, thermal and numerical methods is required. Such multi-disciplinary problems are particularly challenging for engineers and engineering students working in the design and operation of MV systems and limit the ability to conduct detailed thermal investigation. In order to overcome these problems, some applications have been designed and analysis methods have been developed to conduct thermal analysis. In these studies, ampacity of the cable is generally calculated using the equations in the IEC-60287 standard and the tables in IEEE 835 [27]. In Ref. 28, authors contributed to the development of equations in IEC 60287 by using FEM and conducting experimental studies for cables located in free air [28]. In Ref. 29, an application interface has been designed in which the ampacity value of the cable can be calculated using the basic Neher-McGrath method. With this application, users can only calculate the ampacity value of the CS [29]. Besides, an electromagnetic-thermal coupled model is proposed for ampacity calculations for a 110 kV underground power CS in Ref. 30. In Ref. 30, an algorithm is proposed to calculate the optimum ampacity of cable considering economic aspects and uncertainty of affected parameters based on heuristic optimization method and probabilistic approach [30]. In Ref. 20, authors proposed a new electro-thermal optimization algorithm to determine ampacity of parallel power cables [20]. In Ref. 31, an efficient methodology for optimizing power cable thermal performance with respect to configuration parameters involving cable spacing, depth of burial and size of backfill. This methodology integrates features of the FEM coupled with the flexibility and effectiveness of the particle swarm optimization algorithm in order to handle various geometrical parameters in the complex surrounding operating environment [31]. As can be seen in the literature, complex calculations and advanced knowledge are required to calculate cable ampacity. However, it should be noted that these analyzes can be present in a more practical way for educational and application purposes. In addition, it has been mentioned in the references that environmental factors and CS geometry are quite important in ampacity calculations. Therefore, most parameters (starting conditions, wind speed, cable sizes, channel sizes, material properties, etc.) in the CS should be controllable to perform a consistent analysis.

In this study, an application interface has been designed by using COMSOL Multiphysics software for practicing thermal analysis of a three-phase MV underground CS. The problem is modeled in two dimensions and the effects of changes in current, conductor cross-section, horizontal distance between cables, etc. on the current carrying capacity and thermal distribution of the cable can be easily observed with the help of the application. Thermal analyses are performed for a sample loading scenario to indicate performance of the application and the results analyzed. In addition, a survey is conducted with a group of participants in order to determine the performance and functionality of the designed application. The results showed that it would be quite beneficial to use the application as educational material and also in practical applications. Thus, a useful study has been put forward for the applications and training of the companies, R&D engineers and engineering students working in the related field. In the second part of the study, the CS, heat transfer theory and method of calculation of losses are introduced. In the third section, details of the application designed is presented. In the fourth part, thermal analyzes are carried out for a sample loading scenario and the results obtained are discussed. In addition, survey results and their assessments are also presented in the fourth part. The advantages of the application, processing capacity and the possible future developments for application are explained in the conclusion section.

2. MATERIAL AND METHOD

In this study, an application interface is developed using Comsol Multiphysics to help users for performing temperature distribution analyses of a MV underground CS practically. In this section, technical properties of the CS examined and the loss equations used for thermal analysis are presented.

2.1. Definition of Cable System

There are three single core, copper conductor, XLPE insulated and 36 kV rated voltage MV underground cables in flat arrangement in the underground CS examined. Technical specifications of the cable is given in Table 1.

Table 1. Technical specifications of 1x240/25 mm² Cu, XLPE insulated cable

Parameters	Value
Cable	1x240/25 mm ² Cu
Rated voltage [kV]	20.3/35
Nominal cross-sectional area [mm ²]	240
Conductor form	Stranded round
Nominal Ampacity [A] [at 90°C]	559
Conductor radius [mm]	8.74
Inner semi conductor thickness [mm]	0.6
XLPE thickness [mm]	9
Outer semi conductor thickness [mm]	0.9
Copper sheath thickness [mm]	0.206
Polyethylene (PE) jacket thickness [mm]	1.382
Outer layer thickness, HDPE [mm]	2.672
Outer diameter [mm]	47

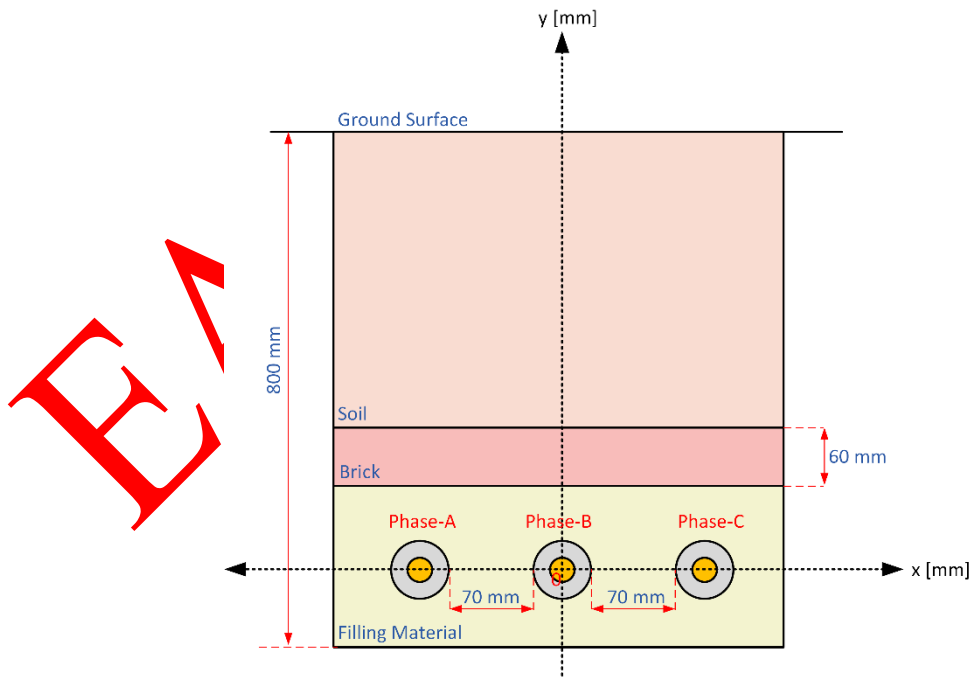


Figure 1. Dimensions of cable layout system

This type of cable arrangement and layout geometry are a typical laying model, which is widely preferred and used in MV voltage distribution systems. As shown in Figure 1, three single-core cables are placed in a CS with 80 cm depth and 40 cm width. These cables are laid horizontally in the CS, with a distance of 7

cm between them and in a filling material with a higher thermal conductivity than the soil [27]. In addition, there is a 60 mm thick brick on the top of the cables to ensure the mechanical protection of the cables and to alert workers to the presence of the cable line during any excavation. In many studies on thermal analysis of cables, protection bricks have not been taken into account. These bricks, which are also used in practice, are not used adjacent along the cable route but are laid at regular intervals. However in this study, the thermal conductivity value of the brick material is taken into consideration in order to see the low thermal conductivity value of the brick material and its effect on cable thermal distribution and ampacity.

2.2. Heat Transfer Analysis Technique

In the study, heat transfer analyses of MV CS are performed by finite element method. The problem is modeled in two dimensions and Comsol Multiphysics software, "Heat Transfer in Solids" interface is used for the analyses. This module create solution by using the heat conduction Equation (1) as follows [8],

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = q + \nabla(k\nabla T) . \quad (1)$$

where ρ is density in kg.m^3 , C_p is the specific heat capacity in $\text{J.kg}^{-1}.\text{K}^{-1}$, $\frac{\partial T}{\partial t}$ is the change in temperature over time, q is the rate at which heat is generated per unit volume of medium in W.m^{-3} , k is the thermal conductivity in $\text{W.m}^{-1}.\text{K}^{-1}$ and ∇T is the temperature gradient. Equation (1) is the general form of the heat diffusion equation and it states that at any point in the medium, sum of the rate of energy transfer by conduction into a unit volume and the volumetric rate of thermal energy generation should be equal to the rate of change of thermal energy stored within the volume [9]. When this temperature distribution is known, the conduction heat flux at any point in the material or on its surface may be computed.

This study aim to investigate maximum operation temperature of MV cables for standard conditions and also effects of the changes in cable layout system (geometry, distance between cables, different filling materials etc.), time dependent analyses are carried out. In addition, time-dependent analysis contributes to the reduction of the computing time for the simulation and the design of a basic and simpler interface for users.

So under steady-state conditions, there can be no change in the amount of energy storage ($\frac{\partial T}{\partial t} = 0$) and the heat equation for two dimensions can be simplified as in Equation (2) [9]

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + q = 0 . \quad (2)$$

In addition, the heat transfer on the soil surface is realized convective. According to this boundary condition, transfer of the heat reaching the surface (q_0) and the heat transfer coefficient (h) are calculated due to the wind speed as in Equations (3) and (4), respectively [32]

$$q_0 = h \cdot (T_{ext} - T) \quad (3)$$

$$h = 7.371 + 6.43 \cdot v^{3/4} . \quad (4)$$

Here, T_{ext} is the surface temperature in $^{\circ}\text{C}$, v is the wind speed in m/s and h is the heat transfer coefficient in $\text{W/m}^2.\text{K}$. In the following sections, calculation method of the losses in conductor and dielectric media is introduced.

2.3. Calculation of Losses in Cable

Power losses in the cable can be classified as current and voltage dependent losses. The load current through the cable conductor leads to losses in the conductor and thus to heating. This current also causes voltage induction, current flow and heating in the shield due to the opposite inductance. Another loss is the dielectric losses occurred in the XLPE medium due to the voltage.

In this study, conductor and dielectric losses are taken into consideration in the case of balanced loading of the phases. Sheath losses are not taken into consideration because the losses occurred in the cable sheath are considerably lower than the losses in the conductor and do not significantly affect the temperature distribution [33]. Furthermore, the calculation of sheath losses significantly increases the processing density and analysis time of the application. An example of a power cable drawing is given in Figure 2 in order to better understand the dimensional parameters given in the equations.

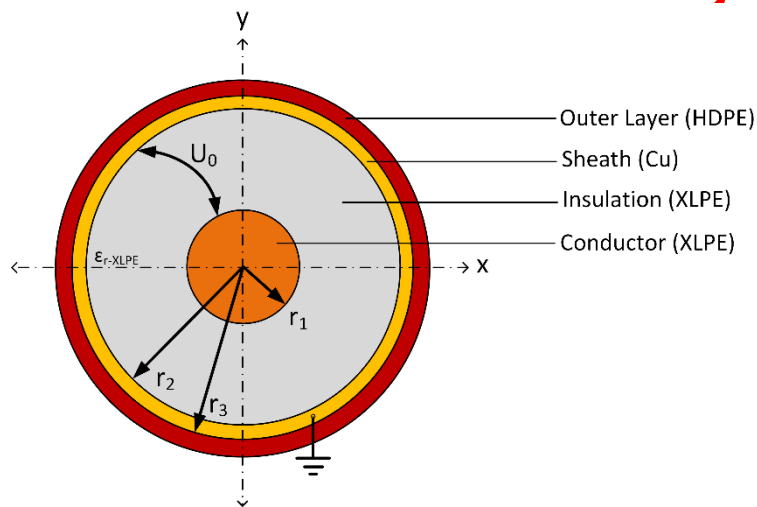


Figure 2. Dimensions and layers of a MV underground cable

2.3.1. Conductor losses

The losses in a conductive environment depend on the waveform and conductor resistance of the current passing through the cable conductor. Therefore, when calculating the AC resistance of a conductor, the coefficients of skin effect and proximity effect and material temperature should be taken into account. Equation (5) means that the DC resistance value at any temperature (T_2) is calculated from the DC resistance value at 20 °C. AC resistance value for the determined temperature is calculated by using skin and proximity effect coefficients in Equation (6) [34],

$$R_{DC} = \frac{\rho_{Cu} \cdot l}{S} \cdot [1 + \alpha_{20} \cdot (T_2 - 20)] \quad (5)$$

$$R_{AC} = R_{DC} \cdot [1 + y_s + y_p] \quad (6)$$

Here, l is cable length in meter, ρ_{Cu} is conductor conductivity at 20°C in $\Omega \cdot m$, S is conductor cross-sectional area in mm^2 , α_{20} is temperature coefficient at 20°C and T_2 is temperature of the resistance to be calculated. y_s and y_p are skin and proximity effect coefficients as calculated in [34]. In the simulation, heat losses in the conductor regions (P_C) are defined as volumetric losses (Q_C) in W/m^3 . Therefore, the copper loss in the cables' conductor is calculated as in Equation (7)

$$Q_C = \frac{P_C}{S_C \cdot l} = \frac{I_{AC}^2 \cdot R_{AC}}{\pi \cdot r_1^2 \cdot l} \quad (7)$$

Here, I_{AC} is the RMS value of alternating phase current in A, R_{AC} is the AC resistance of conductor in Ω , S_C is the cross-sectional area of conductor in m^2 , l is the cable length in m and r_l is the conductor radius in m.

2.3.2. Dielectric losses

Dielectric losses in the cables' insulation layer occurs as a result of high voltage applied to the conductor. This loss arise from various electrical events in dielectrics such as conduction, polarization and ionization. Sum of all these losses is introduced by dielectric losses (P_D) in literature and can be estimated for parallel equivalent circuit as in Equation (8)

$$Q_D = \frac{P_D}{S_D \cdot l} = \frac{\omega \cdot C_0 \cdot \epsilon_r \cdot U_0^2 \cdot \tan\delta}{\pi \cdot (r_2^2 - r_1^2) \cdot l} \quad (8)$$

In Equation (8), ω is angular frequency in rad/second, C_0 is the geometric capacitance of insulation in F, ϵ_r is the relative permittivity of dielectric material, U_0 is the applied voltage (phase to ground) in V, $\tan\delta$ is the dielectric dissipation factor measured at 50 Hz mains frequency, S_D is the cross-sectional area of dielectric layer in m^2 , l is the cable length in m, r_2 and r_1 are outer radius of insulation and radius of conductor in m, respectively. Although relative permittivity (ϵ_r) is considered as a fixed coefficient in most studies, it is a temperature dependent material property and varies with the changing temperature. Therefore, the value of relative permittivity at 90°C rated temperature need to be considered.

3. APPLICATION INTERFACE DESIGN

In this part of the study, details of an application interface designed with the help of COMSOL Application Builder. The aim of designing this application interface is to present simple and basic calculation tool for engineers working in the related area. It is a fact that solving problems on heat transfer especially using finite element method can be quite complex and detailed study and requires hard working. To overcome this issue, an application in COMSOL is developed for a simpler interface. The most important feature of the designed interface application is that the parameters which may affect the thermal distribution or maximum operating temperature of the system can be changed by the user in a practical way and the effects of this change can be observed again.

One of the important feature of the application interface is allowing the user to change dimensional size of the CS such as cable layout width / depth, location of cables, distance between cables, cable cross-section, brick thickness. Also, the interface allows user to modify the properties of the materials contained in the CS. For instance, when the cable conductor is aluminum instead of copper or a different thermal filler material is used, maximum allowed ampacity can be determined. Furthermore, with the designed interface, the user can set the initial conditions, surface wind speed/temperature, boundary conditions and see the effect of changes. Before the simulation, the user can check the dimensional changes made in the plot geometry window. After the analysis, the user can obtain the temperature distribution of the CS and temperature changes at the probes' coordinates can also be observed. The flow chart of the proposed temperature calculation method for the designed interface application is given in Figure 3.

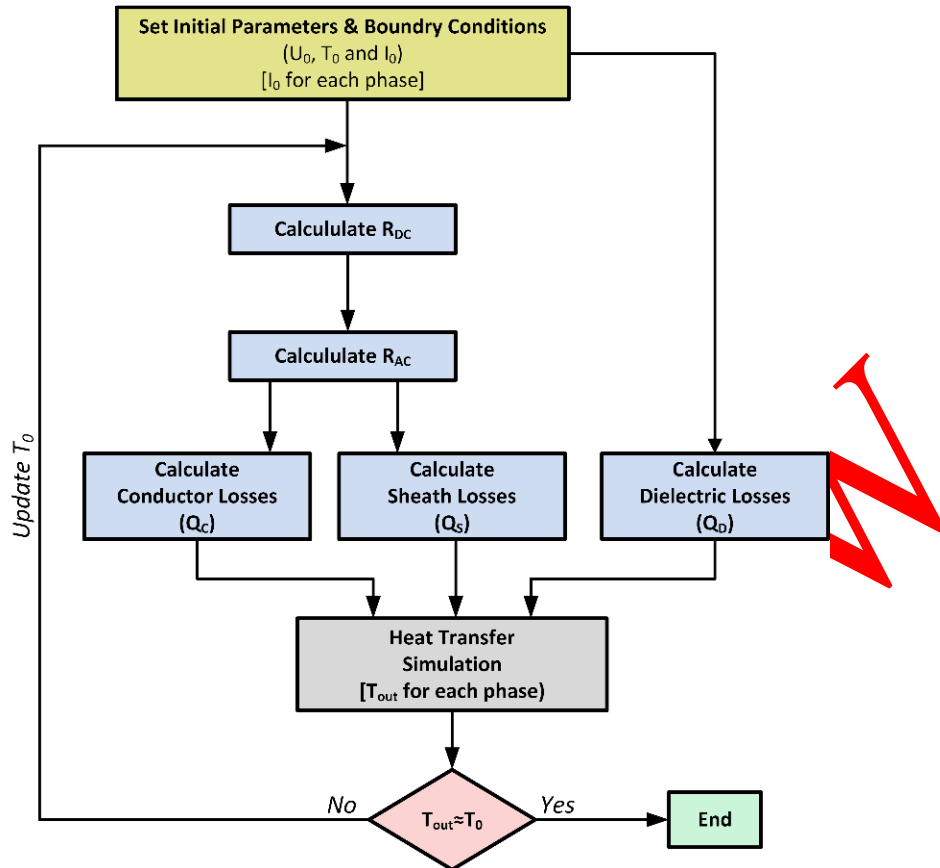


Figure 3. Flow chart of temperature calculation method for the designed interface application

The application first starts with the calculation of losses (Q_C) in conductor and dielectric (Q_D) medium for initial temperature (T_0). Then heat transfer simulation is performed to calculate the change in temperature. Here, T_{out} represent the temperature in cables' conductor. If the calculated temperature (T_{out}) is equal to initial temperature, it means that the system is thermally balanced for the specified initial currents (I_0). Otherwise, initial temperature T_0 is updated as T_{out} and R_{DC} , R_{AC} , and conductor losses are recalculated for the simulation. This cycle continues until the calculated temperature of the conductor and the temperature calculated in the previous step are equal ($T_{out}=T_0$). In other words, the temperature of conductor changes with time and the application aims to reach thermally steady state condition. Therefore, the maximum temperature of conductor and also the change in temperature with time can be determined for the specific current (I_0).

4. RESULTS AND DISCUSSION

In this section, details of the inputs and outputs of the designed application interface are introduced. Additionally, interface designed is tested with a sample loading scenario and the results are discussed.

4.1. Properties of Application Interface Designed

The main purpose of designing the application interface is to enable users to analyze in a practical way without dealing with complex software interface details such as equations, boundary conditions, geometry, parameter and variable definitions. Therefore, the section where input values are defined clearly stated as in Figure 4.

Cable Parameters		Material Properties		Conductor	XLPE	Metallic Sheath	Outer Sheath	Brick	Soil	Filling Material
Conductor Radius (r_con) :	8.74 mm	Relative Permittivity :	1	2.3	1	1	1	1	1	1
Inner-Outer Semicond. Thickness (a_sc) :	0.6 mm	Density [kg/m ³] :	8700	1380	8700	1760	2000	1330	1600	
Dielectric Layer Thickness (a_xlpe) :	9 mm	Heat Capacity [J/kg.K] :	385	4049	385	1900	841	1140	890	
Metallic Sheath Thickness (a_sh) :	0.206 mm	Thermal Conductivity [W/m.K] :	400	0.2857	400	0.1	0.81	1	2	
HDPE Thickness (a_hdpe) :	2.6 mm	Reference Resistivity [ohm.m] :	1.72e-8	1e13	1.72e-8	1e13	1e15	1e15	1e15	
Phase-A current (I_a) :	540 A	Resistivity Temp. Coeff. [1/K] :	3.9e-3	0	3.9e-3	0	0	0	0	
Phase-B current (I_b) :	540 A	Dissipation Factor :		0.004						
Phase-C current (I_c) :	540 A									
Rated Voltage (U) :	36000 V									
Frequency (f) :	50 Hz									

Cable Layout System Dimensions		Boundary / Initial Conditions		Simulation Parameters	
Center Cable Coordinate (x,y) :	0 0 mm	Initial Temperature (Phase-A Conductor) :	60 °C	Simulation Step Size (t_s) :	120 min
Cable Layout Width :	400 mm	Initial Temperature (Phase-B Conductor) :	60 °C	Simulation Duration (t_sim) :	1500 h
Cable Layout Depth :	1000 mm	Initial Temperature (Phase-C Conductor) :	60 °C	Temp. Probe-1 Coord. (x,y) :	0 0 mm
Brick Thickness :	60 mm	Initial Temperature (Sand filling) :	20 °C	Temp. Probe-2 Coord. (x,y) :	23.428 0 mm
Distance Between Cables :	70 mm	Initial Temperature (Soil) :	20 °C	Temp. Probe-3 Coord. (x,y) :	-156.86 0 mm
		Initial Temperature (Surface) :	20 °C	Cut Line Coord. - Start Point (x,y) :	-116.86 0 mm
		Wind Velocity :	2.5 m/s	Cut Line Coord. - End Point (x,y) :	116.86 0 mm

Figure 4. Input parameters section of the designed interface

The data that can be entered as input by the users are clustered under five main headings.

- I. Cable parameters
- II. Material properties
- III. Cable layout system dimensions
- IV. Boundary/Initial conditions
- V. Simulation parameters

In the first part, the inputs such as dimensions of all layers of the cable, current values of the phases, cable rated voltage can be defined by the users. With the help of the inputs under this section, the user can perform thermal analysis for different type of cables. Furthermore, since the current of each phase can be entered separately, it is possible to obtain thermal distribution in balanced and unbalanced load conditions. In the second part, the properties of the cable layers, protection brick, soil and filler material can be changed. With the help of these inputs, the user can perform thermal analysis in case the cable conductor is aluminum or if different filler material is used. Thus, it can be determined how the use of different materials affects the thermal distribution and the maximum current carrying capacity of the cable.

The input data in the third section belongs to the CS geometry and in this section, dimensions of problem geometry can be changed. Furthermore, the effect of distance between the cables on the thermal distribution can be examined. Boundary conditions and initial conditions such as initial temperature of the conductors, earth temperature etc. can be changed in section 4. This section will contribute to a significant reduction in the time required for analysis if users determine an initial temperature close to its final temperature value. The last section contains the simulation time, the simulation step, the coordinates of temperature measuring probes and the cut line. With these inputs, the user can obtain the temperature results at the desired points and regions. General layout of graphical outputs of the designed application interface are presented in Figure 5.

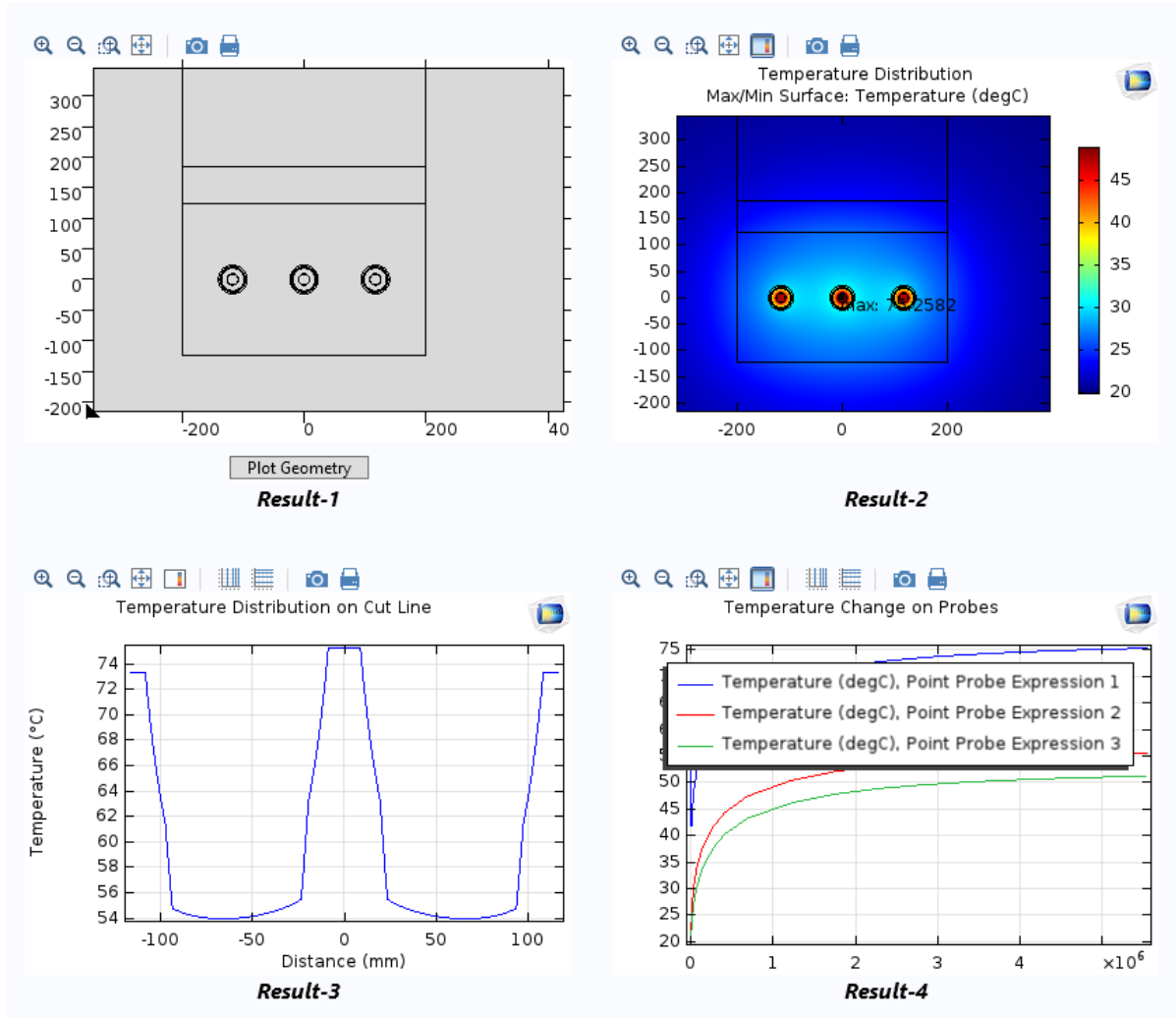


Figure 5. Graphic outputs of the designed application interface

In the first result figure (Result-1), the user can see the system geometry and especially in cases where dimensional changes are made, the last state of the problem geometry can be seen with the Plot Geometry button. This output is intended to prevent problems such as crossing of boundaries in case of incorrect data input. Result-2 shows the output as a result of the thermal distribution gradient in the cable laying system. With this output, the user can see the maximum and minimum temperature range and the point where the maximum temperature occurs. Result-3 shows the temperature distribution on a line. The coordinates of the starting and ending points of this line can be set under the simulation parameters section. Result-4 shows the time-dependent temperature variation of the three temperature probes whose coordinates are introduced in the simulation parameters section. With this output, the user can observe whether the system is thermally stable or how long it will reach a certain temperature value. Furthermore, if the system requires a long time and high processing capacity to reach steady-state, this output can be used to adjust the initial temperatures in the system, thereby shortening the simulation time.

4.2. Thermal Analysis Results of Sample Loading Scenario

In this section, with the help of the designed application interface, thermal analyzes are carried out for a typical underground CS. It is seen from Figure 5 that it is possible to perform thermal analysis for many variables. However, since the main purpose of the study is to reveal the application interface capabilities, only four sample parameters are investigated; CS depth (h), thermal conductivity of the filling material (k_{fm}), surface temperature ($T_{Surface}$) and the distance between cables (a). In order to observe the effect of change in the specified parameters on the maximum temperature of the cable, remaining parameters are kept constant. In the analysis, medium voltage cable, whose specifications is stated in Table 1, is located

horizontally in the CS as given in Figure 1. Each phase is balanced and loaded with 540 A. In addition, soil temperature and surface wind speed are determined as 20°C and 2.5 m/s, respectively. Maximum conductor temperature values obtained due to the distance between cables and the surface temperature are given in Table 2.

Table 2. Maximum conductor temperature values obtained due to the distance between cables and the surface temperature

Distance Between Cables (a [mm])	Surface Temperature (T _{Surface} [°C])		
	10	20	30
0	81.58°C	91.33°C	101.99°C
35	74.10°C	83.91°C	93.72°C
70	70.07°C	79.76°C	89.43°C

The analyzes are carried out for 70 cm, 35 cm and 0 cm where the cables were adjacent. 10°C, 20°C and 30°C values are taken into consideration for the surface temperature. As can be seen from Table 2, while the distance between the cables is 70 cm and the surface temperature is 20°C, maximum conductor temperature is obtained as 79.76°C. When the distance between the cables is halved (35cm) and surface temperature remains constant, maximum conductor temperature increased by 5.2% (4°C). This increase in the conductor temperature is expected as it becomes difficult to dissipate the occurring heat when the cables come close together. However, when the distance is reduced again by 35 cm and the cables are adjacent, maximum conductor temperature increases by 8.8% (7.42°C) to 91.33°C. It is seen that there is a nonlinear relationship between the distance between the cables and the maximum conductor temperature. In cases where the surface temperature is 10°C and 30°C, the increase rates that occur in the maximum conductor temperature are given in Figure 6. In Figure 6, when the surface temperature is 10°C and 30°C, the temperature change depending on the distance between the cables is nonlinear. If the distance between cables is reduced from 70 cm to 35, the temperature increase is 5.75% for 10°C and 4.79% for 30°C. In case the distance decreases from 35 cm to 0 cm, the temperature increase is 10.1% for 10°C and 8.82% for 30°C. Based on this, it can be said that the effect of decreasing the distance between the cables on the maximum conductor temperature is more effective at low surface temperatures. In addition, 10°C increase in surface temperature causes maximum conductor temperature to increase by 12-13%. Therefore, it has been determined that the distance between the cables and the ambient temperature have a significant effect on the loading capacity of the cable.

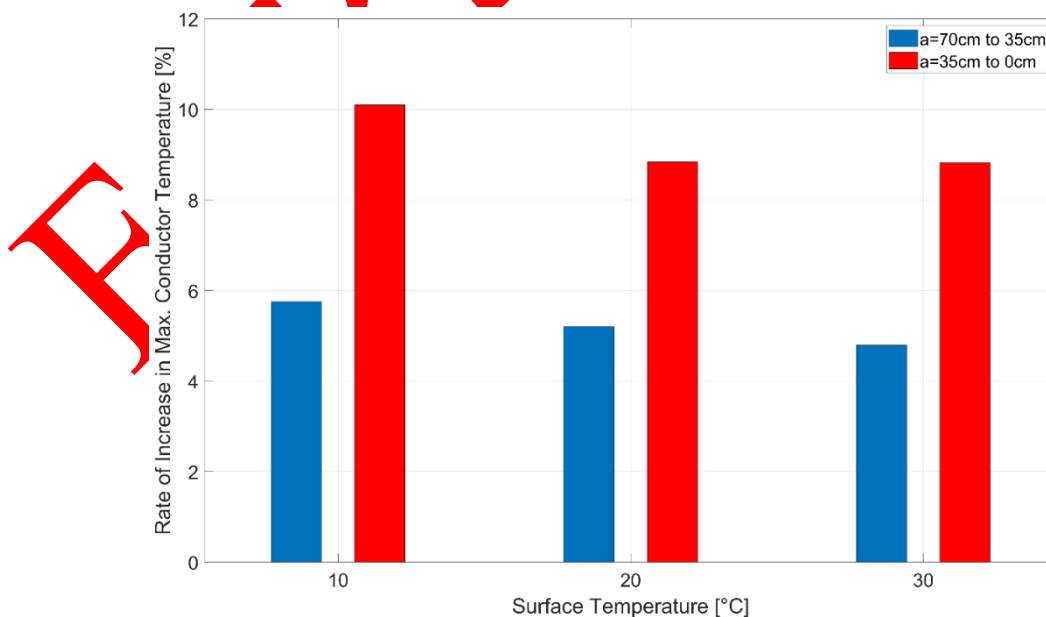


Figure 6. Rate of increase in max. conductor temperature due to surface temperature and distance between cables

In addition to the parameters of surface temperature and distance between cables, the effect of thermal conductivity of the filling material and the depth of the CS on the maximum conductor temperature is investigated. For the laying depth of cable, three levels are specified as 60, 80 and 100 cm. In cases where three different filling materials are used for each of these three depth values, maximum conductor temperature values were calculated. Thermal conductivity values of filling materials were chosen as 1.0, 1.5 and 2.0 W/m.K. The change in maximum conductor temperature due to the CS laying depth is given in Figure 7.

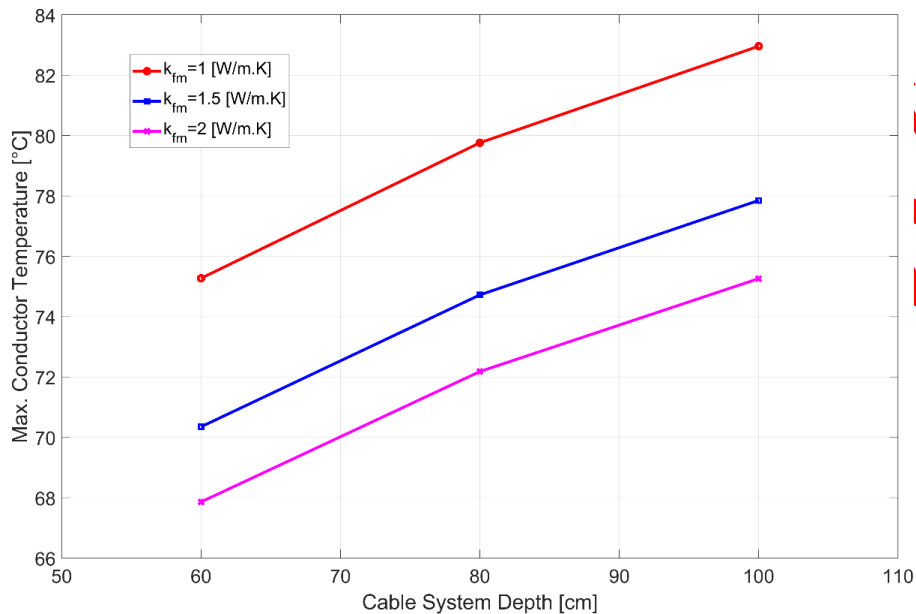


Figure 7. Relation between maximum conductor temperature and CS depth for different filling material

In Figure 7, maximum conductor temperature is obtained as 75.27°C when CS depth is 60 cm and the thermal conductivity of filling material is 1 W/m.K. Under the same conditions, when CS depth is 80 cm, maximum conductor temperature increased by 6% and reached to 79.76°C. Although the laying depth is increased at the same rate, the rate of increase in the maximum conductor temperature decreased to 4%. As the conductors are deeply laid, temperature of the conductor increases, as the heat in the conductor becomes difficult to dissipate. However, the slope of this increase also shows a decreasing behavior with increasing laying depth. This behavior is quite similar for all filling materials, as can be seen in Figure 7.

Increasing the thermal conductivity value of the filling material causes the maximum conductor temperature value to decrease. This is an expected behavior due to higher thermal conduction of filling material. However, there is no linear relationship between the increase of thermal conductivity value and the decrease in maximum conductor temperature. For instance, while laying depth is 80 cm and the thermal conductivity of the filling material is 1 W/m.K, maximum conductor temperature is obtained as 79.76°C. When the thermal conductivity value is increasing by 50% to 1.5 W/m.K, maximum conductor temperature decreased by 6.3% to 74.72°C. When the thermal conductivity value is increased by 100% (2.0 W/m.K), a decrease of 12.6% is expected in the maximum conductor temperature, however this ratio is calculated as 9.5%. As can be clearly seen from here, there is an inverse but nonlinear relation between the thermal conductivity of filling material and maximum conductor temperature.

As a result, it is seen that there is a nonlinear relation between all parameters examined and the maximum conductor temperature. For this reason, it is very important to analyze all applications that are considered beneficial to reduce the maximum conductor temperature before application and to determine to what extent it will benefit. In addition, it is possible to obtain more precise results and characteristic curves by increasing the number of parameters and analyzes examined with the designed interface. Thus, it is possible to determine the most suitable design in terms of electrical, thermal and economic terms for the designed CS.

4.3. Survey Study

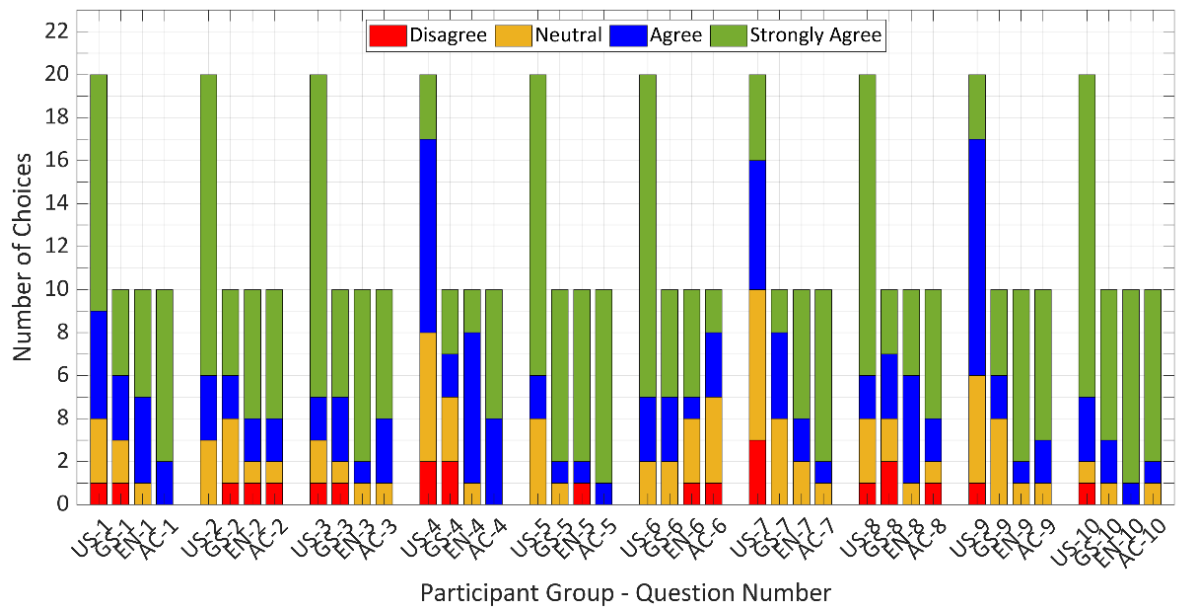
To evaluate the effectiveness of the application interface as training material and its suitability for field applications, it was utilized in a seminar at Yıldız Technical University, Department of Electrical Engineering. Feedback was obtained through a survey from seminar attendees, including students, engineers, and academicians. In order to determine the efficiency and functionality of the application prepared as educational material, electrical engineers working in the related sector and academicians are also invited to the seminar and their opinions are received about the application. Firstly, the participants are informed about the purpose, algorithm, features, benefits and usage of the application. Afterwards, the participants are asked to perform a sample thermal analysis using the application and evaluate the results. After the analysis study, a questionnaire of ten questions is directed to all participants and asked to answer. The purpose of this questionnaire is to determine the teaching effectiveness, performance and usability of the designed application. The survey is conducted with 20 undergraduate students, 10 graduate students, 10 engineers and 10 academicians, and the results are presented in Table 3.

Table 3. Survey questions and results

No	Questions	Strongly Disagree (1 pt)	Disagree (2 pts)	Neutral (3 pts)	Agree (4 pts)	Strongly Agree (5 pts)	Weighted Average (%)
1	Interface is easy to use	0	2	6	14	28	4.36
2	Design of interface is user-friendly	0	3	8	9	30	4.32
3	Visual design of interface is practical	0	2	5	9	34	4.50
4	Calculation speed of interface is adequate	0	4	10	22	14	3.92
5	Number of variables in the interface is satisfactory	0	1	5	5	39	4.64
6	Number of interface outputs/results is sufficient.	0	2	11	12	25	4.20
7	Interface helps to understand thermal analysis fundamentals	0	3	14	13	20	4.00
8	Interface is sufficient for thermal analysis of underground CSs	0	4	7	12	27	4.24
9	Effects of variable change on conductor temperature and ampacity is easy to consider with the help of interface	0	1	11	16	22	4.18
10	Interface is convenient for education and research purposes	0	1	3	7	39	4.68

In the questionnaire, the participants are given the opportunity to give answers consisting five levels and the score of each answer is stated in Table 3. In addition, the weighted averages of the answers given for each question are calculated and given in Table 3.

The first three questions in the questionnaire are related with the formal features of the designed application. At this point, quite positive answers are received from all users and a weighted average of over 4.3% is obtained for the first three questions. It is seen that the group that answers these three questions as “disagree” or “neutral” is mostly undergraduate and graduate students. It can be seen from here that the ease of use and functionality of the application is sufficient, but it needs to be partially developed for using as education material. The rates of the participant groups are given in Table 3 and the distribution of the individual responses of each participant group is given in Figure 8. Here, US stands for undergraduate students, GS for graduate students, EN for engineers and AC for academics. The numbers after the abbreviations represent the question number.



Participant Group - Question Number
Figure 8. Answer distributions of survey participants

In the fourth question, the weighted average is calculated as 3.92%. Here, the group that is dissatisfied with the simulation speed is mostly undergraduate and graduate students. It takes about a minute to perform a single simulation with the designed application. However, this duration is directly proportional to the hardware features of the computer used. It is a fact that simulation time will be shorter with the computers as workstation with higher RAM and processor speed. For this reason, it has been seen that the simulation speed satisfaction of engineers and academicians is at a sufficient level.

In the fifth question, where the adequacy of the number of variables is tested, it is seen that all participants are satisfied with a weighted average of 4.64%. This is because the application allows all material properties in the problem geometry and even the channel geometry properties to be changed. In addition, since the cable dimensions can be changed and each phase can be loaded individually, quite positive feedback has been received from engineers and academic participants.

The adequacy of the simulation outputs has been tested in the sixth question and it is seen that the results with 4.0% weighted average are very positive. In particular, undergraduate and graduate students stated that the number of outputs are sufficient. One of the most important outputs of thermal analysis is the maximum conductor temperature and this value can be specified at the desired three points with the help of application. In addition, the application offers the user the opportunity to see the thermal distribution on a specific line. In the questionnaire, only one engineer and one academician stated that the outcomes are insufficient with "disagree" vote. Therefore, the output number of the designed application can be improved in terms of application and academic use.

The fact that material parameters can be changed with the application helps to understand how effective these parameters are in thermal distribution. In this context, in the seventh question, undergraduate and graduate students found the design sufficient to understand the thermal analysis. However, in these two groups of students, three students answered "disagree" and eleven students answered "neutral" to the seventh question. The main reason for this result is that thermal analysis of cables is a multidisciplinary subject, it uses finite element numerical method for solution and requires a certain theoretical background. For this purpose, it will be useful to add fundamental expressions and equations about thermal analysis to the interface and to support them with a help menu. For this purpose, it will be useful to add basic expressions and equations related to thermal analysis to the application and to support them with a help menu.

The participants are asked whether the application designed in the eighth question is sufficient to perform thermal analysis of underground cables and a weighted average of 4.24% is obtained. It is understood that

the designed application is sufficient for thermal analysis of underground cables. However, it is seen that there are four "disagree" responses among undergraduate and graduate students and one among academicians. For this reason, same application structure can be used to design different types of CSs.

The ninth question helps to understand how effective the change of current, material parameters and geometry on thermal distribution. In this regard, particularly undergraduate and graduate students found the application design sufficient to understand thermal analysis since weighted average of this question is obtained as 4.18%. For this reason, it is thought that it will be more beneficial in terms of education to test all the variables in the application for sample scenarios and to present the results.

The last question has the highest weighted average rate of the survey with 4.68%. It is concluded that almost all of the surveyed group agree that the designed application can be used for educational and research purposes. Especially, positive feedback from academics and engineers supports the effectiveness and functionality of the designed application.

5. CONCLUSION

In this paper, an application interface is designed which can perform thermal analysis of underground CSs with the help of Comsol Multiphysics. In the study, 36 kV, three-phase, flat formation system is used as sample system and details of the application designed and its capabilities are presented. Additionally, a survey is directed to participants to consider the efficiency of the application as a training material. According to the survey results, all participants are quite agree with the formal and technical contents of the application. This study aimed that the engineers working in the related area and engineering students can perform thermal analysis in practical way. Furthermore, it allows easy determination of how variable changes within the CS affect the thermal distribution of the system. In this way, users will be able to determine and optimize the maximum load current of the system, the most efficient filler material, the most suitable cable and duct dimensions. With these analyzes, maximum loading limits of the CS will be determined and contribute to energy efficiency. In addition, it is possible to determine the optimum geometry and physical, thermal and electrical parameters before installation. All outputs obtained with the help of this study will contribute to the studies of companies working in the field of energy transmission and distribution and also education of engineering students.

CONFLICTS OF INTEREST

No conflict of interest was declared by the author.

REFERENCES

- [1] Fu, C., Si, W., and Liang, Y., "On-line Computation of the Underground Power Cable Core's Temperature and Ampacity based on FEM and Environment Detection", Condition Monitoring and Diagnosis, Perth, 1-5, (2018).
- [2] Lewin, P.L., Hao, L., Swaffield, D.J., and Swingler, S.G., "Condition Monitoring of Power Cables", IET Power Convention, UK, 1-7, (2007).
- [3] Zhao, W., Song, Y.H., and Min, Y., "Wavelet Analysis Based Scheme for Fault Detection and Classification in Underground Power Cable Systems", Electric Power Systems Research, 53(1): 23-30, (2000).
- [4] Xiong, L., Chen, Y., Jiao, Y., Wang, J., and Hu, X., "Study on the Effect of Cable Group Laying Mode on Temperature Field Distribution and Cable Ampacity", Energies, 12(17): 3397, (2019).
- [5] Mazzanti, G., and Member, S., "The Effects of Seasonal Factors on Life and Reliability of High Voltage AC Cables Subjected to Load Cycles", IEEE Transactions on Power Delivery, 35(4): 2080-2088, (2019).

- [6] Bustamante, S., Minguez, R., Arroyo, A., Manana, M., Laso, A., Castro, P., and Martinez, R., "Thermal Behaviour of Medium-Voltage Underground Cables Under High-Load Operating Conditions", *Applied Thermal Engineering*, 156: 444-452, (2019).
- [7] Wang, P.Y., Ma, H., Liu, G., Han, Z. Z., Guo, D.M., Xu, T., and Kang, L.Y., "Dynamic Thermal Analysis of High-Voltage Power Cable Insulation for Cable Dynamic Thermal Rating", *IEEE Access*, 7: 56095–56106, (2019).
- [8] Karahan M., Kalenderli O., "Coupled Electrical and Thermal Analysis of Power Cables Using Finite Element Method", *Heat Transfer - Engineering Applications*, InTech, (2011).
- [9] Shazly, J.H., Mostafa, M.A., Ibrahim, D.K., and Abo El Zahab, E.E., "Thermal Analysis of High-Voltage Cables with Several Types of Insulation for Different Configurations in the Presence of Harmonics", *IET Generation, Transmission & Distribution*, 11(14): 3439–3448, (2017).
- [10] Bicen, Y., and Aras, F., "Steady State Effects of Design Properties and Environmental Conditions on Underground Power Cable Ampacity", *10th International Conference on Electrical and Electronics Engineering*, Bursa, 81–84, (2018).
- [11] Parekh, D.K., and Modi, B., "Computer Application for Finding Underground Power Cable Ampacity", *2nd International Conference for Convergence in Technology*, Mumbai, 601–606, (2017).
- [12] Calcara, L., Pompili, M., and Cauzillo, B.A., "Ampacity of MV Underground Cables: The Influence of Soil Thermal Resistivity", *5th International Youth Conference on Energy*, Pisa, 1–5, (2015).
- [13] Radzi, A.S., Arifin, N.A.N, Anthony, T.M., Aida, Z., Azlina, N., Raj, A., Chakrabarty, C., and Syaza, N., "The Effect on Ampacity for Multiple Cable Crossing and Mitigation to Improve Its Ampacity", *IEEE International Conference on Power and Energy*, Melaka, 301–305, (2017).
- [14] Shen, Y., Niu, H., You, Y., Zhuang, X., and Xu, T., "Promoting Cable Ampacity by Filling Low Thermal Resistivity Medium in Ducts", *IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Hong Kong, 1–4, (2013).
- [15] Yang, L., Qiu, W., Huang, J., Hao, Y., Fu, M., Hou, S., and Li, L., "Comparison of Conductor-Temperature Calculations Based on Different Radial-Position-Temperature Detections for High-Voltage Power Cable", *Energies*, 11(1): 117, (2018).
- [16] Bates, C., Mamedal, K., and Cain, D., "How to Include Soil Thermal Instability in Underground Cable Ampacity Calculations", *IEEE Industry Applications Society Annual Meeting*, Portland, 1–8, (2016).
- [17] Gouda, O.E., El Dein, A.Z., and Amer, G.M., "The Effect of the Artificial Backfill Materials on the Ampacity of the Underground Cables", *7th International Multi-Conference on Systems, Signals and Devices*, Amman, 1–6, (2010).
- [18] Cichy, A., Sakowicz, B., and Kaminski, M., "Economic Optimization of an Underground Power Cable Installation", *IEEE Transactions on Power Delivery*, 33(3): 1124–1133, (2018).
- [19] Yang, Y., Darwish, M., Moghadam, M., Lucas-Clements, C., Obrien, G., and Quennell, D., "Power Cable Cost Benefit Analysis: A Critical Review", *53rd International Universities Power Engineering Conference*, Glasgow, 1-6, (2018).
- [20] Rasoulpoor, M., Mirzaie, M., and Mirimani, S.M., "Arrangement Optimization of Power Cables in

- Harmonic Currents to Achieve the Maximum Ampacity Using ICA”, *Electric Power Components and Systems*, 46(16–17): 1820–1833, (2018).
- [21] Sun, B., and Makram, E., “Configuration Optimization of Cables in Ductbank Based on Their Ampacity”, *Journal of Power and Energy Engineering*, 6(4): 1-15, (2018).
- [22] Dai, D., Hu, M., and Luo, L., “Calculation of Thermal Distribution and Ampacity for Underground Power Cable System by Using Electromagnetic-Thermal Coupled Model”, *IEEE Electrical Insulation Conference*, Philadelphia, 303–306, (2014).
- [23] Jian, W., Huan, J., Xiao, M., and Xu, B., “Ampacity Analysis of Buried Cables Based on Electromagnetic-Thermal Finite Element Method”, *2nd International Conference on Smart Grid and Smart Cities*, Kuala Lumpur, 73–79, (2018).
- [24] Quan, L., Fu, C., Si, W., Yang, J., and Wang, Q., “Numerical Study of Heat Transfer in Underground Power Cable System”, *Energy Procedia*, 158: 5317–5322, (2019).
- [25] Rasoulpoor, M., Mirzaie, M., and Mirimani, S.M., “Losses Distribution in Sheathed Power Cables Under Non-Sinusoidal Currents Using Numerical Method”, *Computer Applications in Engineering Education*, 24(5): 692-705, (2016).
- [26] Cardoso, J.R., Silva, V.C., Abe, N.M., and Rossi, L.N., “Approach to Teaching the Finite Element Method Applied to Electromagnetic Problems with Axial Symmetry to Electrical Engineering Students”, *Computer Applications in Engineering Education*, 7(3): 133–145, (1999).
- [27] International Electrotechnical Commission, “IEC 60287-1-1 Electric Cables – Calculation of the Current Rating”, (2023).
- [28] Sedaghat, A., and De Leon, F., “Thermal Analysis of Power Cables in Free Air: Evaluation and Improvement of the IEC Standard Ampacity Calculations”, *IEEE Transactions on Power Delivery*, 29(5): 2306–2314, (2014).
- [29] Parekh, D.K., and Velani, K., “Computer Aided Application to Calculate and Analysis of Underground Power Cable Ampacity”, *Innovations in Power and Advanced Computing Technologies*, Vellore, 1-6, (2017).
- [30] Shabani, H., and Vahidi, B., “A Probabilistic Approach for Optimal Power Cable Ampacity Computation by Considering Uncertainty of Parameters and Economic Constraints”, *International Journal of Electrical Power & Energy Systems*, 106: 432–443, (2019).
- [31] Al-Saud, M.S., “PSO of Power Cable Performance in Complex Surroundings”, *IET Generation, Transmission & Distribution*, 12(10): 2452-2461, (2018).
- [32] Hwang, C.C., and Jiang, Y.H., “Extensions to the Finite Element Method for Thermal Analysis of Underground Cable Systems”, *Electric Power Systems Research*, 64(2): 159–164, (2003).
- [33] Wadhwa, C.L., *Electrical Power Systems*, 4th ed, New Delhi: New Age Int’L Publishers, (2006).
- [34] Anders, G.J., and Institute of Electrical and Electronics Engineers, *Rating of Electric Power Cables in Unfavorable Thermal Environment*, Wiley-IEEE Press, (2005).