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Thermal State Effects on Potential Augmentation of the Ampacity of a Medium Voltage Underground Cable in Power Distribution: A Case Study

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ABSTRACT

This research aims at a deeper understanding of the steady-state thermal behavior of underground cables using Computational Heat Transfer (CHT) techniques modeling based Ansys Fluent software. The results concern the thermal study of 33 kV single and multiple copper conductors with a nominal conductor cross-section of 615 mm^2 buried in the ground for a single cable, two cables and for three cables in horizontal position. The most unfavorable summer conditions, the burial depth as well as the physical properties of the soil as a function of the moisture content, are studied. The operating current of the conductors is taken 940 A. The results show that the temperature of the cables decreases with the burial depth, a compromise temperature/cost of installation corresponds to 80 cm of burial depth. Further, the maximum temperature of a single cable buried in the ground is considerably lower than that allowed (363 K) for a good use, namely 313 K in summer conditions, so there is a considerable margin to increase its ampacity, also the temperature decrease with increase of water content of the soil surrounding the cable of approximately 2 to 5 degrees. The results obtained are in good agreement with those of the literature.

1. Introduction

The use of underground power transmission and distribution has been steadily increasing in recent years due to the increased demand for electric power and the extensive expansion of populations into large cities, which the case of Algeria. This seems to be the best solution to reduce the environmental impact and diminish the electromagnetic pollution in highly populated zones [1]. However, it is extremely difficult to build new underground cable networks in urban areas because of the high cost, the difficulties posed by the various existing underground networks and the environmental demands of the population.

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Therefore, it has become very important to try to increase the exploitation of the existing infrastructure of the power grids to overcome these challenges without additional investment to the extent possible. The problem of optimizing the electrical cables and their exploitation for good performance has become of great importance, especially with nowadays conditions, which require a high quality of service and the rationalization of the expenses. A good arrangement of the cable configuration, thus the working parameters under different loads, climatic conditions and soil properties, can lead to improved cable performance. In 1957, Neher and McGrath presented an appropriate method for calculating the permissible current of underground cable systems [2]. As such, Benato *et al.,* [3] presented a detailed study on different possibilities to increase the rated current of insulated cables. Proper thermal computation of a buried electrical cable system is essential to determine its permissible current. Commonly this calculation is based on IEC 60287-1-1 and IEC 60287-2-1. IEC 60287-1-1 [4] calculates the permissible current under a steady state, when at IEC 60287-2-1 [5], it estimates the thermal resistance between the cable system and the external environment. In this vision, computational heat transfer techniques can be used to predict numerically the thermal state of electrical buried cables in the ground under different configurations and working parameters. The numerical resolution of these problems for a precise estimate of the thermal state of the main components of the electricity distribution network will be the main and new contribution to academic and industrial knowledge in the field of very high voltage underground electric cables. Than can be used to assist specialists in performing the good cable configuration with the right parameters. The use of underground cables in Algeria has grown significantly over past two decades as a result of urban expansion and increased infrastructure activities. However, the weather conditions in Algeria are very severe especially in summer where the ambient temperature sometimes exceeds 50°C and the water content of the soil is very low. It adds to that the strong consumption of electrical energy by the population in this very hot period of the year. Under such conditions, current carrying capacity of the cable is highly influenced. The accuracy of methods for estimating the thermal state of underground conductors is crucial, especially in cases where the network is operating under high load conditions. The calculation of cable ampacity requires the evaluation of several parameters that can influence the operating characteristics of the underground cable. The ampacity depends not only on the structure and materials of the cable, but also on its installation method as well as the external environmental conditions such as the condition and properties of the backfill soil, configuration of the soil layers and its water content, the climatic conditions , and the depth of burial [6-9]. Chatzipanagiotou *et al.,* 2017 [10] investigated experimentally the effect of soil moisture content and buried depth on the ampacity of underground power cables. A downscaled laboratory model for an underground cable has been investigated experimentally with respect to these parameters. The experimental results of their study indicate that the presence of soil humidity influences the cable temperature. They found from the measurements that the thermal resistance of the ground decreases with the humidity. Al-Saud *et al.,* [11] presented an optimization model for underground power cable thermal circuit based on a generated gradient approach. The authors had demonstrated the use of nonlinear optimization in conjunction with finite element thermal field analysis. Sensitivity analysis of the cable temperatures on fluctuations in the cable circuit parameters was also included. The proposed finite element thermal analysis was implemented to evaluate cable temperature and its sensitivity concerning the optimized thermal parameters. Sellers *et al.,* in [12] provide the brief overview of investigations of ampacity of underground cables starting with the first very simplified models for calculating the current carrying capacity of underground cables that were created more than 100 years ago. Their goals were to examine objectively several improvements to the Neher-McGrath model, to incorporate recent heat transfer correlations, and to remove several assumptions considered in [2].

The suggested changes resulted in a more complex ampacity model, which lead to an increase in ampacity in some cases and a decrease in others. De Lieto Volaro *et al.,* [13] employed control-volume formulation of the finite difference method to determine the thermal resistance existing between an underground electrical power cable and the ground surface. Based on the numerical simulation, the authors had proposed a semi-empirical correlating equation for the design of buried electrical power cables and compared the results with IEC 60287 standard. Andrea Vallati and Marcin Pilarczyk [14] presented a modified Jaya algorithm for optimizing the material costs and electric-thermal performance of an underground power cable system. A high voltage (HV) underground cable line with three 400 kV AC cables arranged in flat formation in an exemplary case study is considered. They found that the use of efficient thermal backfill materials allows the maximum cable conductor temperature to be lowered.

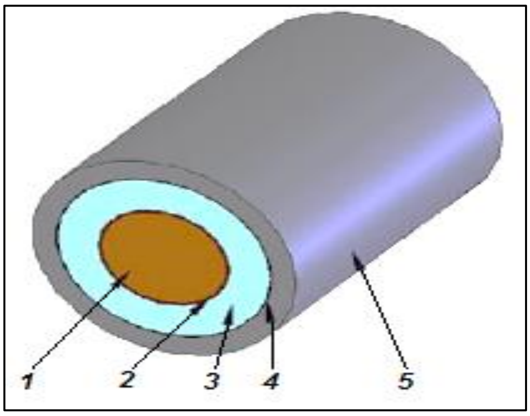
The effect of solar radiation on the thermal steady state of underground electric cables is not covered by IEC 60287 [4], IEC technical report TR 62095 [5] or 2017 edition of NFPA 70 [15]. This is why the effect of solar radiation is neglected by most researchers who deal with heating and charging problems with underground electric cables [16,17]. Among the researchers who considered this effect, there are those whose conclusions were consistent with the relevant IEC standards [18], those who found that solar radiation only affects the cables laid at low depths [19], as well as those who concluded that the effect of the sun can not be ignored in the case when the daily load peak coincides with the period of maximum solar activity [20,21]. Existing commercial CFD software can be employed for the analysis of heat transfer in the conductors and surrounding domains. There are some publications on the application of CFD packages for underground cables; although a number of cases with similar geometries were investigated using the CFD software. For example, Ansys Fluent CFD, software based on the finite volume method, was presented by Makhkamova in [22] in order to investigate the thermal state for overhead line conductors or underground.

In this work, a new model based on the Computational Heat Transfer (CHT) technique of the electric cable taken in its real working environment is proposed. The main objective of the work is to predict numerically the thermal state of electrical cables buried in the ground under different configurations and working under a current of 940 amperes, taking into account the physical properties of the soil for a range of content values in moisture. Firstly, we need to have the correct laying configuration of the cables following which the operating temperature of the cable is the lowest, secondly, to do the same thing when the cables are housed in HDPE ducts for possible extensions of the cable network and reasons for maintenance especially. We are looking for the temperature and the limit current of the cables in order to better exploit the existing electricity network without any additional modifications with the support of the different factors of the problem, especially since most of these installations are oversized. The design engineer usually overdimensions the section of the conductor with respect to the correspondent air cable lines, to decrease the electrical resistivity [23].

2. Problem modeling

2.1. Geometry

The physical design of the conductor is presented in Figure 1. The real geometry of the conductor is complex and contains the following components: the copper conductor core made of strands; the conductor screen (polyethylene); insulation (cross-linked polyethylene); the insulation screen (polyethylene); the copper screen; the binder tape (polyethylene) and oversheath (medium density polyethylene). For purpose of creating, the computational mesh the real geometry of the conductor was simplified (to reduce computational time) and presented as a combination of four co-axial cylinders. The outer diameter of the copper conductor and the oversheath is 28.3 and 60.4 mm, respectively.



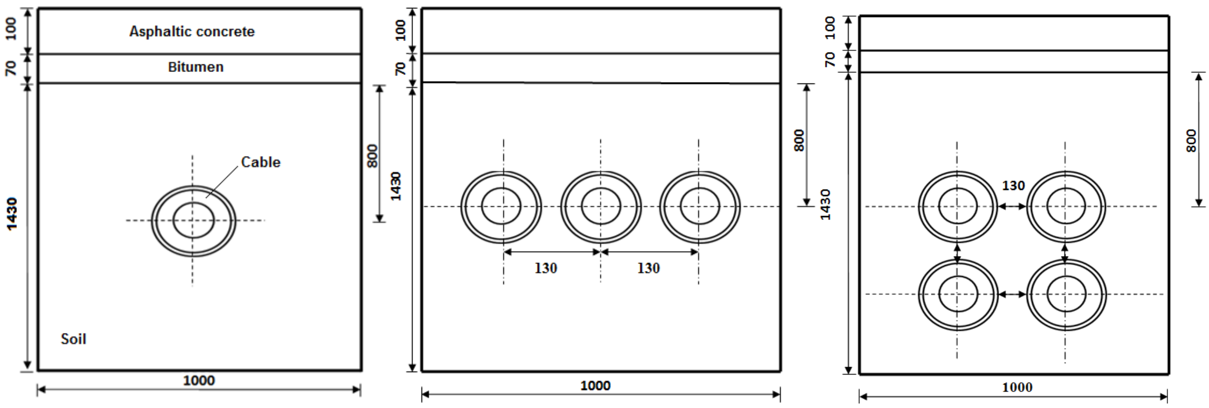
1. Copper conductor; 2. Conductor screen; 3. Insulation; 4. Copper screen; 5. Oversheath

Fig. 1. Geometry model of the cable

The dimensions of the simplified model are as follows: the diameter of copper cable with nominal area of conductor of 630 mm² is 28.3 mm; the thickness of insulation is 8 mm; the thickness of the copper wire screen is 1 mm and the thickness of oversheath is 2.7 mm.

2.2. Computational Domain

Figure 2 presents the computational domain used for the numerical modelling of the thermal state of a single copper cable buried in the soil. In this domain, the cable is placed at the centre of the soil the domain. These dimensions (in mm) of the domain are large enough to produce size independent solution [22].



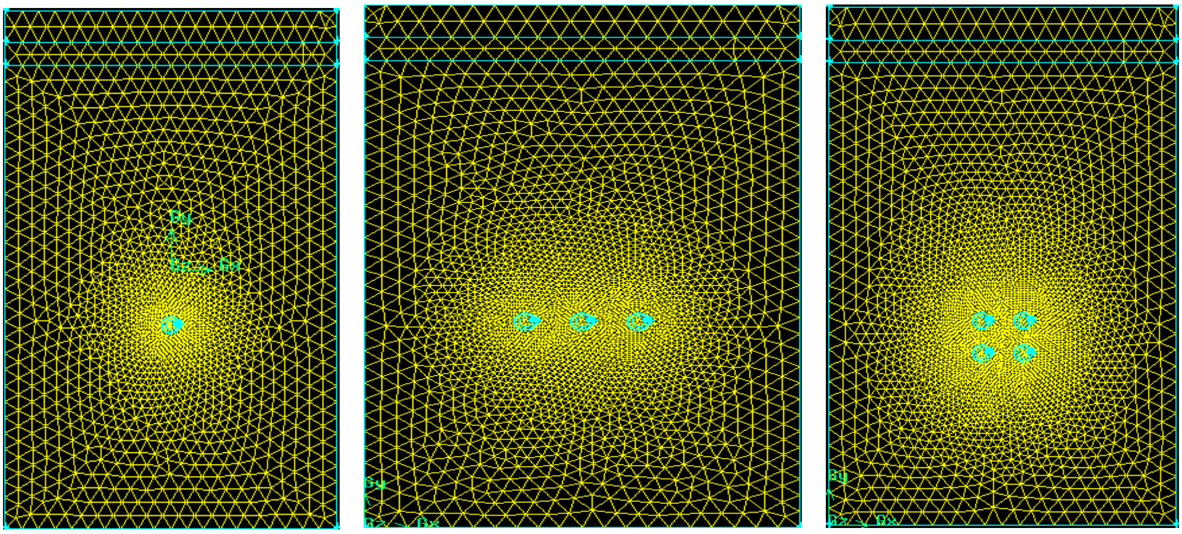
a) b) c)

Fig. 2. Computational domain for numerical study a) of single copper cable buried in soil, b) three buried cable, c) four buried cable

As previously, mesh refinement tests were conducted in order to ensure that the solutions are not mesh dependent.

2.3. Grid of Computational Domain

The choice of mesh is an essential point in the accuracy, we used the Tgrid-Map element that is triangular element and well suited for round shapes like cable case, (Figure 3).



a) b) c)

Fig. 3. Grid of computational domain a) Single cable buried in soil, b) three buried cable, c) four buried cable

3. Data and Assumptions for Calculations

The thermo-physical properties of the cable (XPLE BS7078) [23] constituting our model are summarized in Table 1.

Table 1
Thermo-physical properties for components of the cable [23]

Components of the cable	Density kg/m^3	Heat capacity J/kg K	Thermal conductivity W/m.K
Copper conductor	8978	381	387.6
Conductor screen (PVC)	1300	1330	0.182
Insulation	950	2300 @ 293K 3750 @ 353K	0.333
Copper screen	8900	385	370.4
Oversheath	1600	1500	0.25

The cable backfills considered in the study are as follows: native soil, Bitumen and Asphaltic concrete. Constant thermal conductivities of the backfills in the dry state are assumed. Performance typically involves laying the cable in a sand bed, rather than in the soil of the same excavated area, to improve heat dissipation and allow for a more standard installation process.

In our case, we used the same type of excavated soil for economic and simplification reasons. Soil is considered as a homogeneous medium and not as a porous substance. In summer conditions, the soil was assumed to dry soil. The thermo-physical properties of the backfills are gathered in Table 2.

Table 2
Thermo-physical properties for different types of physical domain [23]

Type of soil	Density, kg/m^3	Heat capacity, J/kg K	Thermal conductivity, W/m.K
Asphaltic concrete	2350	870	2.10
Bitumen	2350	870	1.90
Dry soil	1400	800	0.408

According to Electrical Standards P17 [24] for the summer conditions the soil and ambient temperatures are of 293 and 298 K, respectively [25]. The summer conditions are characterized by a low moisture content. The thermal rating for the 630 mm^2 cable in the flat formation in summer conditions is 940 A, which corresponds to a heat source, *q*, of 14200,7 W/m^3 [26], calculated as Joule losses by the following relation.

$$q = \frac{I^2 R}{A} \tag{1}$$

where *R* is the AC resistance of the copper conductor (Ω/m); *A* is the cross sectional area of the conductor (mm^2) and *I* is current in the cable (A). According to the BS 6622-1991 [26] the AC resistance of the copper is *R* = 0.0405 Ω/km at 363 K.

Accordingly, in all further simulations of the thermal state of underground cables the temperature at the top and at the bottom of the computational domain was set to be uniform and constant at the 298 K and 293 K level respectively in summer conditions. Additionally, a zero heat flux boundary condition was set on the left and right sides of the computational domain.

4. Results of Numerical Simulations

4.1. Grid Independency Test

The calculation time and the accuracy of the result are directly related to the quality of the mesh. In this study, we tested three meshes of increasing quality (1038, 3083, 241396 nodes). From the results obtained in the validation phase of the proposed numerical model (Figure 4). We opted for the mesh of 3083 nodes. This mesh ensures a good compromise between the quality of the mesh and the computation time and the precision of the sought solution. The cable temperature is determined from the two-dimensional steady state heat conduction equation discretized using the CFD Ansys Fluent code.

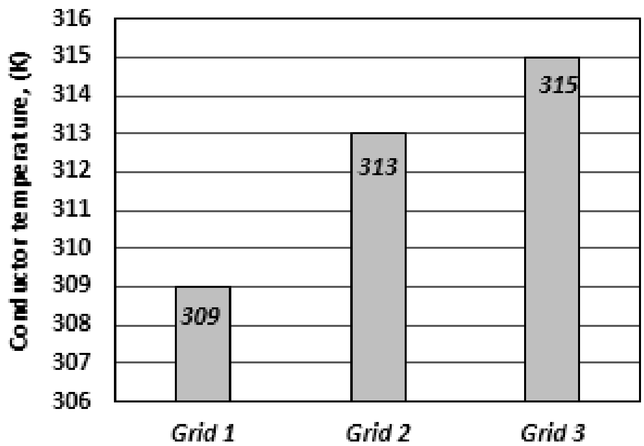


Fig. 4 Conductor temperature versus mesh

4.2. Effect of the Burial Depth

In aim to find the right depth of burial cable, several tests simulations were conducted. The results are presented in Figure 5. From the results, it can be seen that the conductor temperature decreases with depth. The choices of the height of the backfill are an optimization issue between the backfill cost and the current rating increase. Our choice was based on the 80 cm burial depth for which, it provides a satisfying compromise.

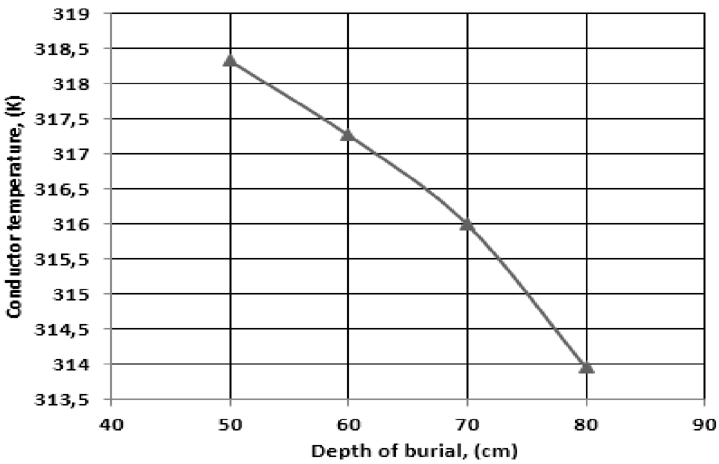


Fig. 5. Conductor temperature based on depth of burial

4.3. Effect of Current on the Temperature of the Cable

Figure 6 presents the variation of temperature as a function of the current resulting from the simulation tests. It can be seen that the temperature of the cable increases proportionally with the operating current. This result is in the same trend as that obtained by Moya *et al.,* [27].

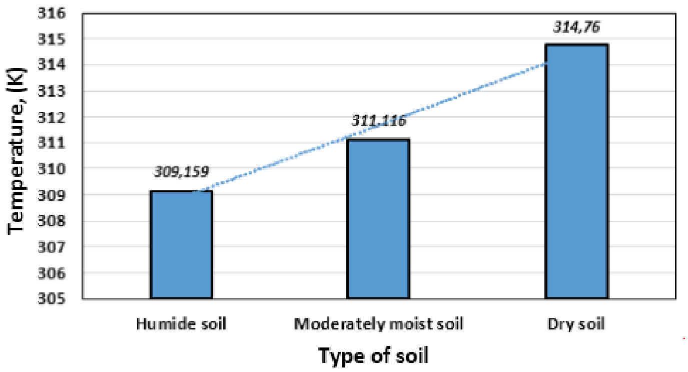


Fig. 6. Effect of current on cable temperature

4.4. Conductor Temperature Variation as a Function of Current

Figure 7 presents the variation of temperature as a function of the current resulting from the simulation tests. It can be seen that the temperature of the cable increases proportionally with the operating current. This result is in the same trend as that obtained by Moya *et al.,* [28].

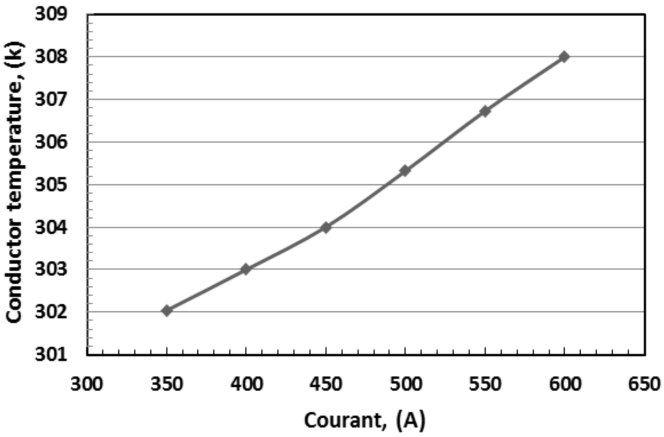


Fig. 7. Conductor temperature variation as a function of operating current

4.5. Temperature Distribution in a Single Buried Cable System

Figure 8 shows the temperature distribution at the cable as well as its vicinity for a working current of 940 A under summer conditions. As expected, the temperature distribution is symmetrical with reference to a vertical plane passing through the axis of the cable. In summer conditions, there is a low temperature gradient in the soil layers above the cable; this gradient is greater in the soil layer below the cable. This says that the temperature propagates from the cable to the roadway.

For summer conditions and a 940 A working current, the conductor's temperature rise is 313 K. This temperature is below the recommended limits [29]. Figure 9 shows the average temperature profile in the horizontal plane passing through the axis of the cable. There is a peak temperature at the cable level (place of the heat source) which is very normal, the temperature decreases as soon as we move away from the cable symmetrically. On the other hand, the temperature in the level of the pavement does not register a net change, this being said to the damping effect of soil on the propagation of the temperature.

4.6. Distribution of Temperature in a System of Three Buried Cables

Figure 10 shows the distribution of temperature around a system of three buried cables in dry soil carrying 940 A in summer conditions. It is observed that the temperature of the central cable reaches 342.19 K (Figure 11), this temperature is higher than that recorded for the case of a single cable under the same functioning conditions. This increase is due to the accumulation of heat caused by the two cables located on either side of the central cable. Despite this rise in temperature, the cables remain operating in the recommended standards. This result is in the same trend as that obtained by Irina Makhkamova [22]. As a result, it is recommended to further space cables from each other to prevent heat build-up at the center cable. As such and without recourse to a new calculation, it is sufficient for this configuration to insert the cables twice as before that is to say 260 mm.

Figure 11 shows the average temperature profile in the horizontal plane passing through the axis of the three cables.

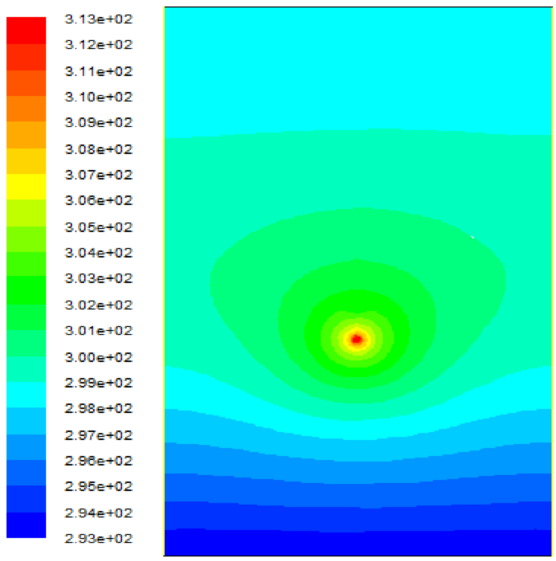


Fig. 8. Contours of temperature in a system of a single buried cable

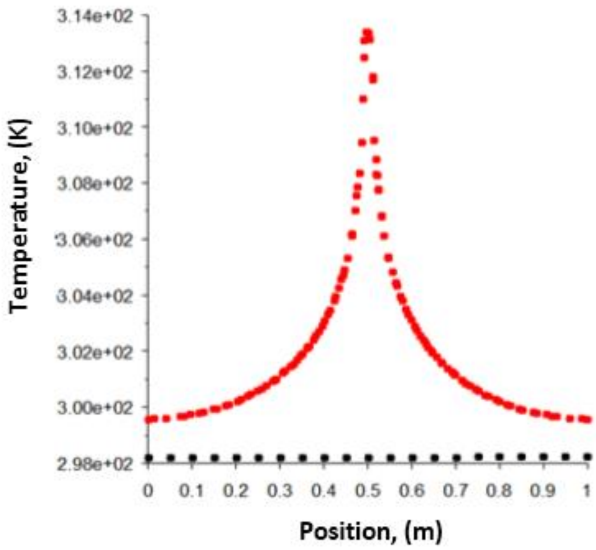


Fig. 9. Average temperature profile at the cable and the roadway

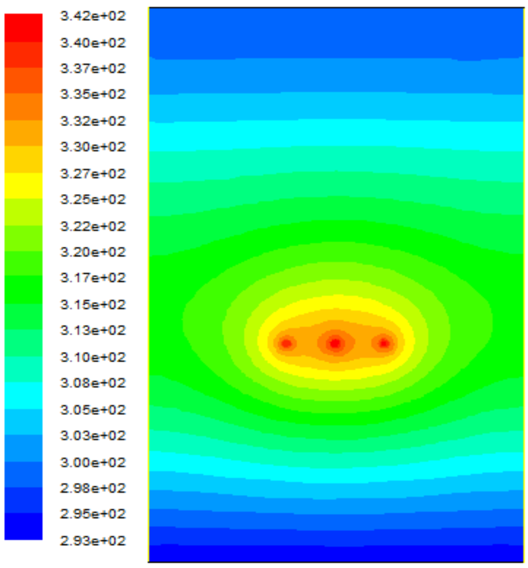


Fig. 10. Contours of temperature in a system of three buried cable

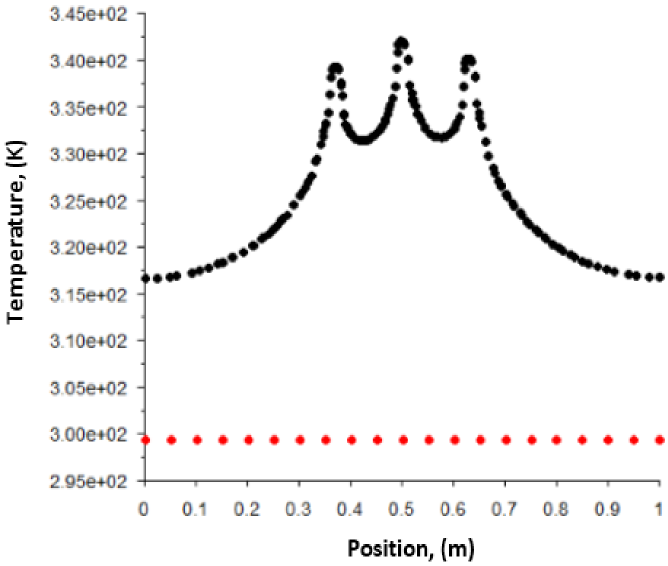


Fig. 11. Average temperature profile at the three cable and the roadway

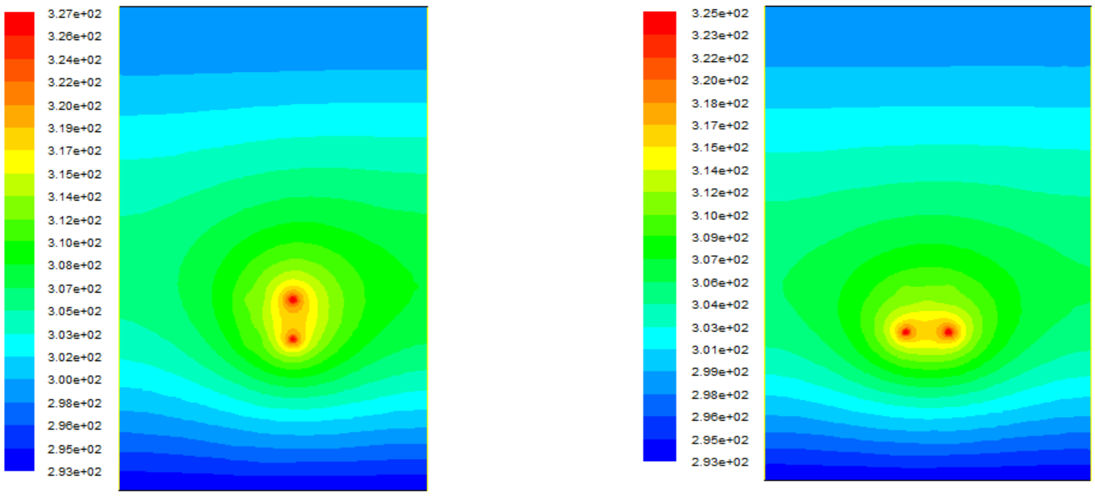
There are three temperature peaks above the cables (heat source), the peak of the middle cable is higher than the others, and this is due to the extra heat gain caused by the neighboring cables. The temperature decreases as soon as one moves away from the cable symmetrically. On the other hand, the pavement temperature (≈ 300 K) shows a net increase compared to that recorded for a single cable.

4.7. Distribution of Temperature in a System of Four Buried Cables

In this system consisting of four cables, two cables are active; the other two are emergency cables. This type of system is used in long and high power lines. Two alternative cable placements may occur; two piled cables or two cables in line position. Figure 12 (a) represents the distribution of the temperature in a system of two superimposed cables in operation carrying 940 A under severe climatic conditions. It is observed that the distribution of the temperature is non symmetric this is due to the barrier (resistance) represented by the two other spare cables. The maximum temperature recorded at the operational cable levels is 325 K. This temperature complies well with the recommended restrictions. It can be lowered further by increasing the inter-cable space to avoid the accumulation heat.

For the same system with four buried cables, Figure 12 (b) presents the case of two operational cables in line position. In this configuration, the temperature distribution is symmetrical with respect to a vertical axis passing through the middle of the cables. It should be noted that this configuration has a lower cable temperature (325 K) than that of piled cable configuration (327 K). In conclusion, the configuration of two cables in line is thermally recommended than that of two superimposed cables, especially since its implementation is easier and consequently economical than the first one.

Figure 13 shows the average temperature profile in the horizontal plane passing through the axis of the two cables. There are two temperature peaks above the cables (heat source), these two peaks are interspersed by a temperature gradient decreasing symmetrically between the two peaks. This is due to the gap separating the two cables. On the other hand, the pavement temperature (299 K) shows a slight decrease compared to the one recorded for the three cables, which is very physically acceptable.



a) b)

Fig. 12. Temperature contours in a system of four buried cables (a) two piled cables, (b) two cables in line

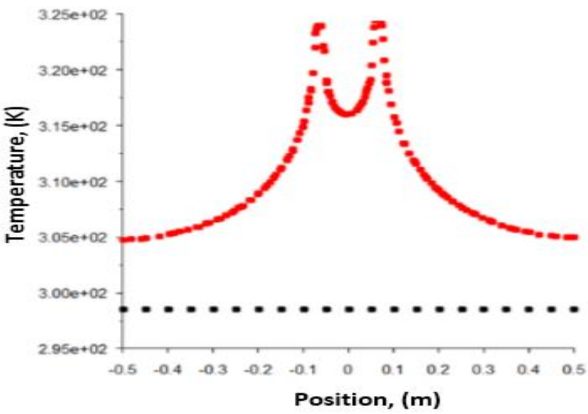


Fig. 13. Average temperature profile at the cables and the roadway

4.8. Effect of Solar Radiation

View the intensity of solar radiation in summer in our country. Examination of its possible effect on our model of electric cable buried in the ground is considered essential. Figure 14 shows the distribution of the temperature in the cable and its vicinity, for a working current of 940 A with summer condition with solar radiation support. As expected, the temperature distribution is symmetrical with reference to a vertical plane passing through the axis of the cable.

The results show that the temperature of the cable is 315 K and that of the roadway is 303 K. We conclude that the radiation effect on the cable is unimportant, although it significantly affects the ground surface. This conclusion is in good agreement with that obtained by Dardan *et al.,* [30]. Figure 15 shows the average temperature profile in the horizontal plane passing through the axis of the cable.

There is a peak temperature at the cable (heat source) which is very normal. The temperature decreases as soon as you move away from the cable symmetrically. On the other hand, the temperature in the pavement level shows a net change compared to the case without radiation.

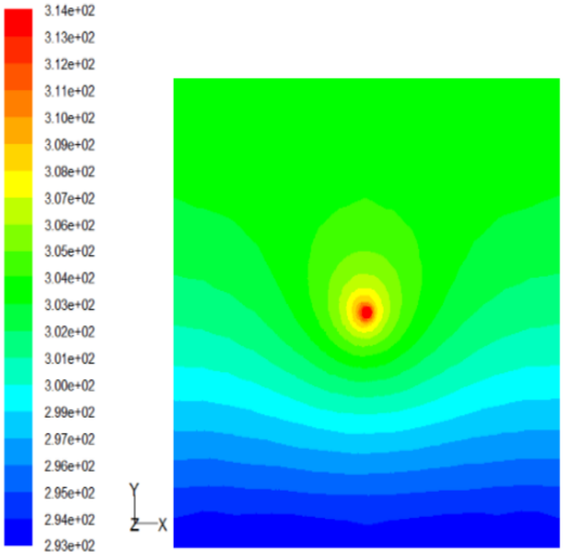


Fig. 14. Temperature contours of a cable under solar radiation

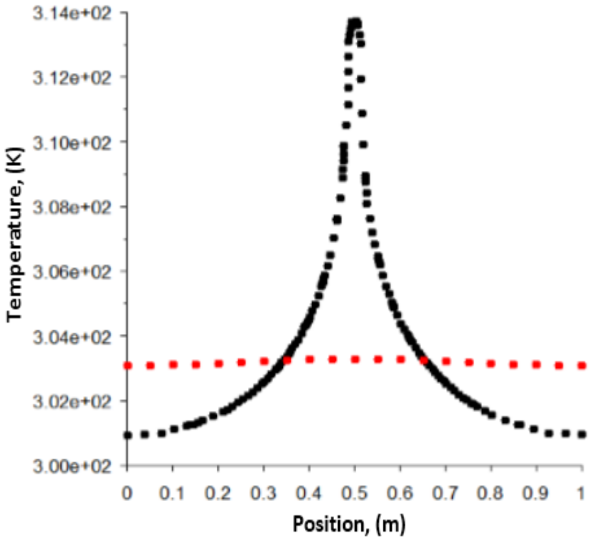


Fig. 15. Temperature profile of one buried cable and the roadway under solar radiation

5. Conclusions

The numerical results obtained in this work on the thermal exchanges around underground cables system in the most unfavorable working conditions make it possible to draw the following conclusions:

a) The temperature of the conductor decreases with the cable depth, based on several numerical tests; it has been found that the best depth of burial is 80 cm.
b) For a single buried cable operating under 940 A current in summer conditions, the maximum predicted conductor temperature is well below the recommended restrictions, so there is considerable potential for increasing its ability to carry more amperage.
c) The thermal state of three underground cables laid horizontally under summer conditions is very close to the safety limit, so there is no possibility of increasing the ampacity of

these cables unless the distance between the cables is increased interlocking between the cables.

d) The maximum conductor temperature is approximately 327 and 325 K in summer conditions for two cables buried in vertical and horizontal forms respectively. Thermally, this means that the best landfill position is the horizontal form.
e) The temperature of the cable working in full electric charge (940 A) placed in a cavity buried in the ground reaches 366 K. This exceeds the recommended restrictions. In this case, it is proposed to reduce the amperage up to 900 A so that the cable can operate within the safety limits.
f) The temperature of cables buried in the ground is inversely proportional to the soil moisture. So adding water to a porous material drastically decreases its thermal resistance.
g) The temperature of the cable increases proportionally with the increase of the operating current.
h) The results also showed that the radiation effect on cable temperature is negligible, although it significantly affects the ground surface.

The analysis of the results of the CHT simulations shows that this numerical technique offers a good accuracy in the prediction of thermal transfer around a system of permanent high voltage underground cables and can be used in the analysis and the management of transports and distribution of electrical energy. Finally, the application of CHT techniques allows the calculation and analysis of heat transfer in underground electrical cable systems.

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