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Development of a Thermal Model of a High-Voltage Insulated Cable using the Finite Element Method to Improve the Grid Integration of Renewable Energies

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Abstract. The increase of renewable energies in the current landscape makes Dynamic Line Rating (DLR) of transmission and distribution lines very meaningful to drive the production of these renewable energies. In order to be able to operate the lines dynamically, even in emergency situations, it is necessary to know the behaviour of the cables in detail. In particular, this study focuses on the dynamic management of high-voltage insulated cables. The main objective of this work focuses on the development of a model based on the Finite Element Method (FEM) to obtain the temperature reached by the cable conductors under different operating conditions. The FEM model was developed and validated by monitoring the current and temperature of a high-voltage insulated transmission line in operation. As a result of this FEM model, it was possible to obtain the temperature reached by the conductors in different scenarios in which the current flowing through the cables was higher than 900A. In addition, FEM model scenarios were developed where the line was operated close to its maximum load to test its behaviour.

Key words. Cable monitoring, dynamic rating, finite element method, high-voltage insulated cable, transient thermal analysis.

1. Introduction

Due to the increasing production of energy from renewable sources and the continuous improvement of the electricity transmission grid, the design and improvement of the performance and operation of insulated cables has nowadays become a subject of scientific interest [1]. The safe operation of an insulated cable depends on the operating temperature of its conductor, so accurate thermal evaluation of the cable is essential to improve the Dynamic Line Rating (DLR) [2] [3]. For high-voltage insulated cables, the calculation of the maximum allowable current without exceeding the maximum temperature [4] and the emergency rated capacity at a given temperature [5] are common calculations for the management and operation of this type of cable.

Laying cables in underground tunnels is a common way to install cables in urban areas [6]. IEC calculation cannot solve many kinds of physical coupling problems, such as air convection, radiation and heat transfer in the tunnel, so it is necessary to use Finite Element Methods (FEM) to accurately check the thermal behaviour of cables [7]. Several studies explain the FEM models used in different cable conditions. A 3D transient analysis in a FEM model to obtain the temperature distribution in insulated cable joints is shown in [3]. In [6], [7], the influence of different layouts of cables laid in free air in tunnels under static conditions is studied using FEM. Another study [8] presents new advances in 3D geometry length reduction, which makes it possible to develop an electro-thermal FEM model of a submarine cable to estimate the current carrying capacity under specific conditions.

This study shows the creation and validation of a transient thermal FEM model based on monitored temperature and current measurements of an in-service high-voltage transmission line to estimate the temperature of the conductors under different operating conditions. The measurements used to build and calibrate the thermal model were taken using fibre-based passive sensors.

2. Theoretical model

IEC 60287-1-1 [4] and IEC 60853-2 [5] provide guidelines for calculating the maximum permissible current without exceeding the maximum conductor temperature and the emergency rating at a given temperature. Both calculations use the following equations to calculate the losses per unit volume in the conductors, insulation and metal screen. The conductor losses per unit volume, $\boldsymbol{Q_c}$ (W/m^3), are calculated as follows:

$$\boldsymbol{Q_c = \frac{I^2 R}{A_C}} \quad (1)$$

where $\boldsymbol{I}$ is the current flowing in one conductor (A), $\boldsymbol{A_C}$ is the cross-sectional area of the conductor (m^2) and $\boldsymbol{R}$ is the AC resistance per unit length of the conductor at a given operating temperature (Ω/m). $\boldsymbol{R}$ is calculated as:

$$\boldsymbol{R = R_0[1 + \alpha_{20}(\theta - 20)](1 + y_s + y_p)} \qquad (2)$$

where $\boldsymbol{R_0}$ is the DC resistance of the conductor at 20 °C (Ω/m), $\boldsymbol{\alpha_{20}}$ is the constant mass temperature coefficient at 20 °C per kelvin, $\boldsymbol{\theta}$ is the cable operating temperature (°C) and $\boldsymbol{y_s}$ and $\boldsymbol{y_p}$ are the skin and proximity effect factors, respectively, calculated using the expressions given in [4].

The dielectric losses per unit volume, $\boldsymbol{Q_d}$ (W/m^3), are estimated as:

$$\boldsymbol{Q_d = \frac{W_d}{A_{ins}}}; \qquad \boldsymbol{W_d = \omega C {U_0}^2 \tan\delta} \qquad (3)$$

where $\boldsymbol{W_d}$ is the dielectric loss per unit length for the insulation surrounding the conductor (W/m), $\boldsymbol{A_{ins}}$ is the insulation area (m^2), $\boldsymbol{\omega = 2\pi f}$, $\boldsymbol{C}$ is the capacitance per unit length (F/m), $\boldsymbol{U_0}$ is the voltage to earth (V), and $\boldsymbol{\tan\delta}$ is the loss factor of the insulation at power frequency and operating temperature [4].

The sheath losses per unit volume, $\boldsymbol{Q_s}$ (W/m^3), are:

$$\boldsymbol{Q_s = \frac{(\lambda_1) I^2 R}{A_{sh}}} \qquad (3)$$

where $\boldsymbol{\lambda_1}$ is the ratio of the losses in the metal screen to the total losses in all the conductors in the cable [4], and $\boldsymbol{A_{sh}}$ is the screen area (m^2).

3. Material and method

A. Experimental measurements

In this study, an in-service high-voltage insulated cable of Red Eléctrica de España (REE) was monitored. The commercial designation of the cable is RHE-RA+2OL 127/220kV 1x2000M+H315 whose maximum temperature is 90 °C. It is a single-core copper cable 127/220 kV 1x2000 mm^2 with cross-linked polyethylene (XLPE) insulation and a screen of copper wires with a cross-section of 315 mm^2. High density polyethylene (HDPE) is used for the outer sheath. The main characteristics of the cable are given in Table I.

Due to the long length of the line, approximately 8.6 km, the cross-bonding configuration is used to reduce the circulating currents through the metal screen of the cables. The line is divided into five major sections, each of which is divided into three minor sections. The screens are directly connected to earth at the ends and at every third joint, and at the two intermediate joints, the screens are transposed and isolated from earth by means of voltage limiters.

The line has different cable arrangements. At the ends, corresponding to the indoor substations, the cables are in the air, protected from solar radiation and in contact

Table I. - Cable characteristics

RHE-RA+2OL 127/220kV 1x2000M+H315	
Type of cable	Cu/XLPE/Cu/HDPE
Cross-sectional area (mm^2)	2000
Nominal conductor diameter (mm)	56.6
Nominal insulation thickness (mm)	21.1
Nominal diameter over insulation (mm)	103.3
Section of screen (mm²)	315
Nominal sheath thickness (mm)	4.5
External diameter (mm)	121.8
DC resistance at 20 °C (Ω/km)	0.009
Nominal capacity (µF/km])	0.251
Maximum conductor temperature at continuous load (°C)	90

with each other in a trefoil formation. In the galleries, where the joints are located, the cables are laid in the air in a flat formation. The type of installation of the line between junction chambers, and junction chambers and substations is cables in tubes embedded in concrete. In the latter type of installation, the cables are laid in a trefoil formation when leaving the substations and in a flat formation between the junction chambers.

The monitoring equipment was developed by Lumiker and its general operation is explained in [9], [10]. The system consists of static temperature sensors (STS), which measure the ambient and cable sheath temperature, and optical current transformers (OCT), which measure the current in the conductors and screens. The OCTs for conductors (OCT_OC) and for screens (OCT_CS) developed by Lumiker are shown in Fig. 1.

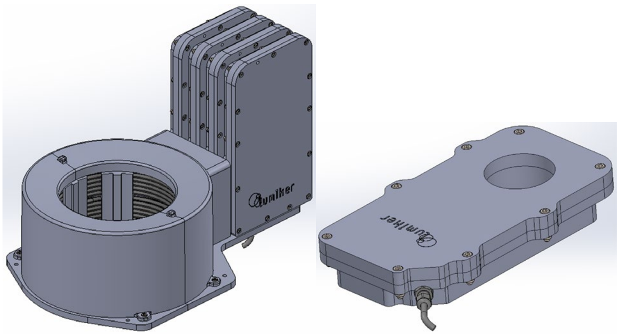

Fig. 1. OCTs of conductors (left) and screens (right) developed by Lumiker.

Fig. 2 shows the location of the temperature and current sensors installed in the two head-end substations and in three of the four junction chambers corresponding to the third junction of the major sections discussed above (the screens are directly connected to earth in these junction chambers). The temperature sensors are named STS_y_xxx and the cable and screen OCTs are named OCT_OC_y_xxx and OCT_CS_y_xxx respectively, where y is the phase being monitored (R, S, T) or the ambient temperature (Amb), and xxxx is the location of the probe (SE1, SE2, CE1, CE2, or CE3). In total, there are 16 temperature measurements, 15 on the outer sheaths of the three phases of the line in the two substations and the three monitored galleries, and 1 ambient temperature measurement in junction chamber 1. As far as current

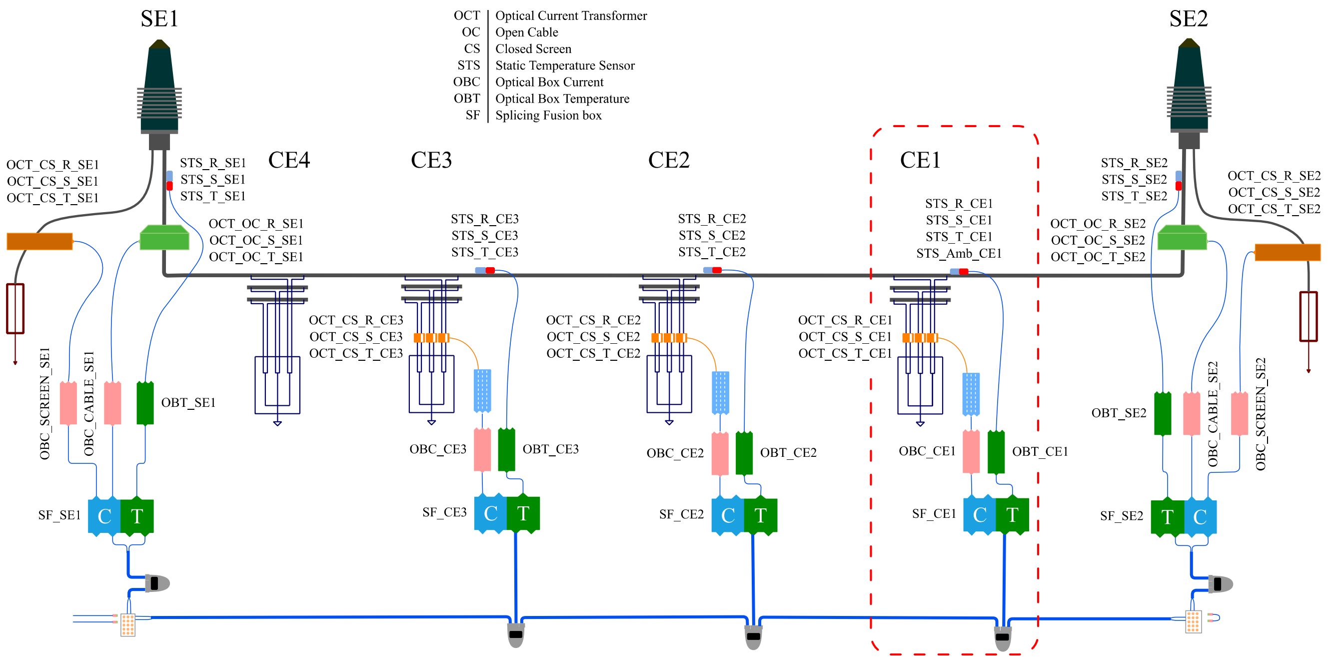

Fig. 2. Location of temperature (STS_y_xxx) and current (OCT_OC_y_xxx and OCT_CS_y_xxx) sensors.

measurements are concerned, there are 21 in total. There are 6 conductor current measurements, 1 measurement in each phase in the two substations, and 15 screen current measurements, 1 measurement in each of the phases in the two substations and the three monitored galleries described above. The refresh rate for temperature data is every minute, while the refresh rate for current data is every five minutes. The total number of data collected per day is:

- 23,040 Temperature data.
- 6,048 Current module data.
- 6,048 Current phase data.
- 429,408 Odd current harmonics data (up to order 143).

B. Numerical model (FEM)

The main objective of finite element methods in multiphysics cable simulation is to determine the conductor temperature for a given current and operating conditions. Ansys Mechanical [11] was selected as the software to create the FEM model.

As indicated in the previous section, there is only one probe monitoring the ambient temperature along the line and it is used as a boundary condition, the FEM model was created for one of the monitored zones, junction chamber 1 (denoted CE1 in Fig. 2). In the junction chambers, the cables are laid in the same plane in a vertical position without touching each other, as shown in Fig. 3.

As the cable construction is complex due to the copper wire screen, the cable geometry was simplified as shown in Fig. 4 to simplify the model simulations and reduce the computation time. In this simplified geometry, the cross-section of the screen and the thickness of the outer sheath were kept.


Fig. 3. Cable arrangement in junction chamber 1 (labelled CE1 and boxed in red in Fig. 2).

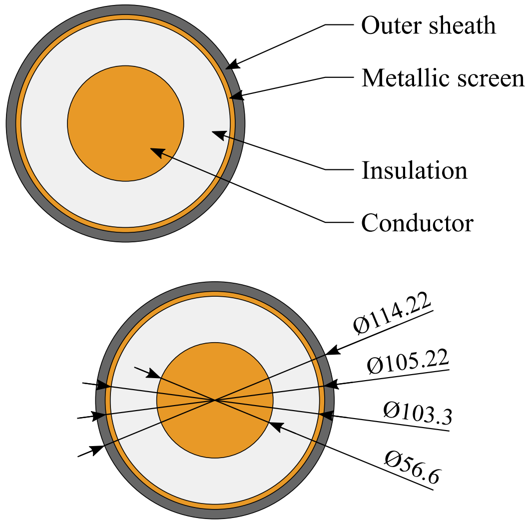

Fig. 4. Simplified cable geometry.

The simulations were carried out in a transient state, so it was necessary to perform iterations to adjust the losses with the temperature of the conductors and screens, as indicated in IEC TR 62095 [12], using equations (1)-(4).

The geometry created was a rectangular prism 6.3 m high, 6.3 m wide, and 0.1 m deep, as shown in Fig. 5. The upper

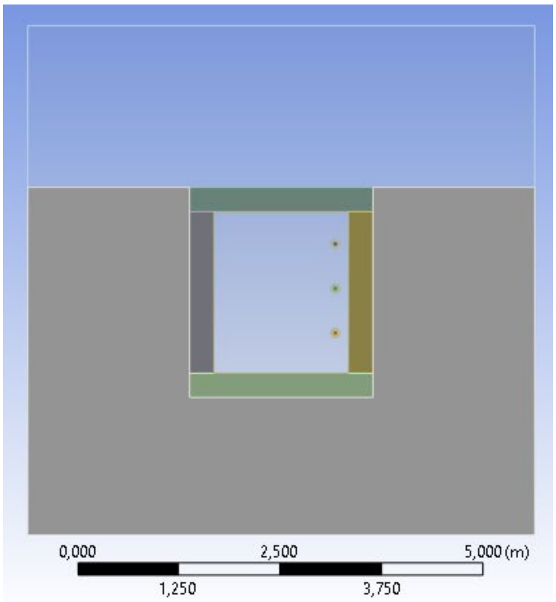

Fig. 5. Geometry created to simulate the cables in the junction chamber 1.

part, 2 m high, is modelled as air, which corresponds to the outside. Below the exterior line is the junction chamber, formed by four concrete walls. On the right wall, the cables are placed in the same plane in a vertical position at a distance of 55 cm between axes. The remainder of the model below the outer line and around the junction chamber corresponds to the ground.

The linear periodic boundary condition was applied to the entire geometry to simulate a model with translational symmetry, where the structure is assumed to repeat in a given direction to infinity. It was assumed that the left, right, and bottom surfaces of the medium were perfectly insulated because they were widely separated from the heat generation by the cable. Heat transfer by convection and radiation was considered for the cable surfaces. The ambient temperature used for these boundary conditions is the monitored ambient temperature in junction chamber 1. The boundary conditions applied to each of the cables are shown in Fig. 6. The values of the properties of the materials used in the simulations are given in Table II.

C. Numerical model validation

The results obtained from the FEM model were compared with those obtained from experimental measurements to validate the numerical model created. The first simulations of the FEM model were carried out in short-term transient regimes to check the heating and cooling of the cables as a function of the current flowing through them and to be able to adjust the boundary conditions.

To compare the monitored and simulated temperatures, probes were created on the outer sheaths of the cables in the FEM model. In addition, three probes were also created on the conductors to obtain the temperature they reached. As it is not possible to measure the actual temperature of the conductors, the FEM model was validated by comparing the measured and simulated temperatures of the outer sheaths.

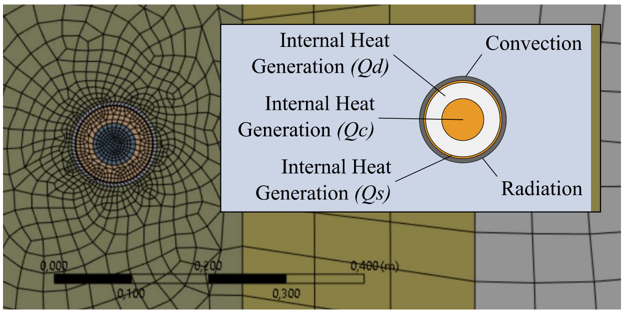

Fig. 6. Cable mesh and boundary conditions.

Table II. - Properties of materials used in simulations [11], [13]

Material	Thermal conductivity (W/m·K)	Specific heat (J/kg·K)	Density (kg/m³)
Copper	400	385	8933
XLPE	0.28	2300	950
HDPE	0.4811	1780	958.5
Concrete	1.1765	880	2320
Soil	1	1300	1900
Air	0.026	1007	1.1614

As an example of the validation of the FEM model results in transient regimes, Figures 7 and 8 show the temperature and current data monitored on the line for approximately 1 and 5 days, respectively, compared to the temperature values obtained in the FEM model.

From Fig. 7 it can be seen that the temperature of the outer sheath of the upper cable obtained in the simulation closely follows the temperature measured when the current flowing through it is high (heating period). In contrast, when the current decreases (cooling period), the simulated temperature is slightly lower than the real one,

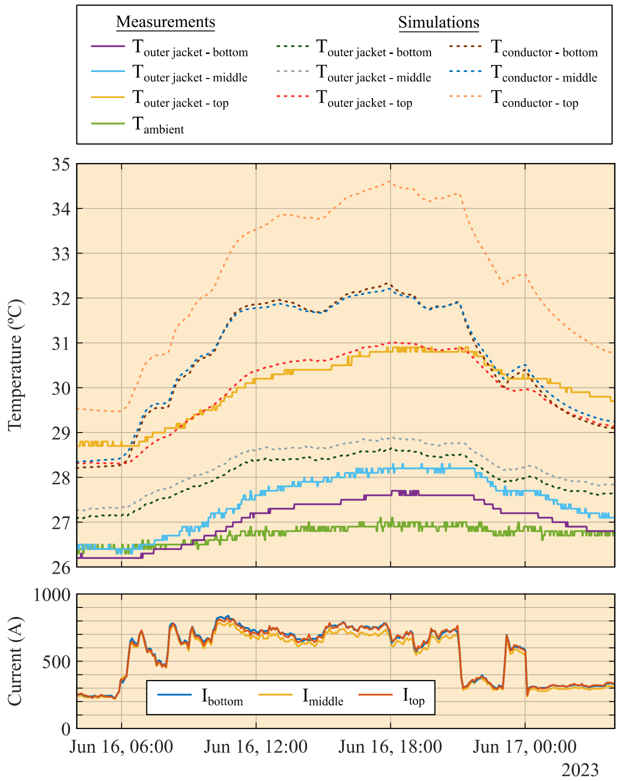

Fig. 7. Example of validation of FEM model results.

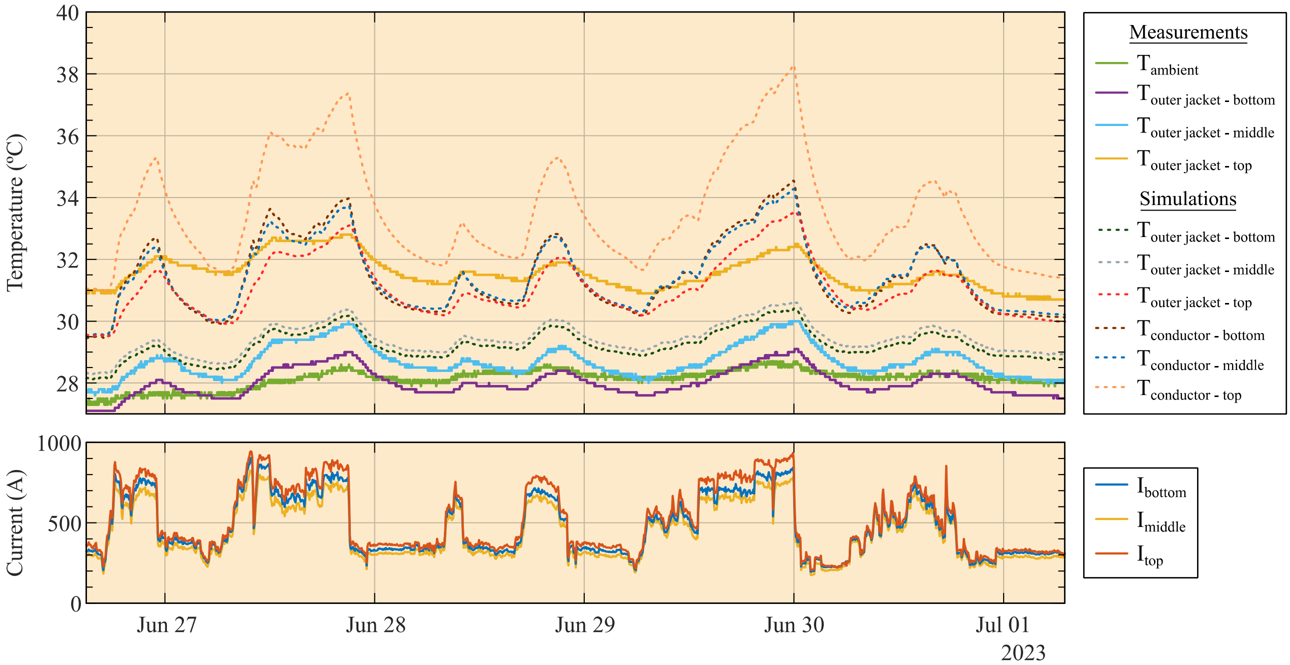

Fig. 8. Validation of FEM model results and monitoring data for 4.7 days of line operation with peak currents of 945 A.

around 0.7–0.4 °C. For the other two cables, the simulated temperatures are slightly higher than the real ones, with a difference of 0.5–1.2 °C, but the trend obtained is very similar in both cases. Fig. 8 shows the comparison of the monitored temperature data and the FEM model data in the situation where the current reached approximately 945 A in summer (end of June and beginning of July) when the average ambient temperature in junction chamber 1 was 28.1 °C. These results are similar to those shown in Fig. 7. Therefore, the proposed FEM model can be considered valid and can be used to study the temperature of conductors under different operating conditions.

4. Results and discussion

The main result of the validation of the FEM model was to obtain the temperature reached by the conductors under different conditions. As an example of the application of the developed FEM model, Fig. 9 shows the temperature distribution in the model geometry under the real operating conditions of the line shown in Fig. 8.

As mentioned above, the main objective of the development of the FEM model is to be able to obtain the temperature reached by the conductors, which cannot be achieved by monitoring the temperature of the outer sheaths alone. With the developed FEM model, it is possible to apply any load to the line and observe the temperature reached in the three conductors.

Fig. 10 shows the results of the FEM model when a load of 800 A is applied for 4 hours, 2500 A for 4 hours, and finally for 8 hours with a current of 300 A, with an ambient temperature of 25 °C and a soil temperature of 22 °C. It can be seen that the highest temperature is reached in the cable conductor at the top, as shown in Figures 7 and 8. Contrary to the previous comparisons (Figures 7 and 8), the temperature difference between the sheath and the conductor is very high for the three cables, exceeding

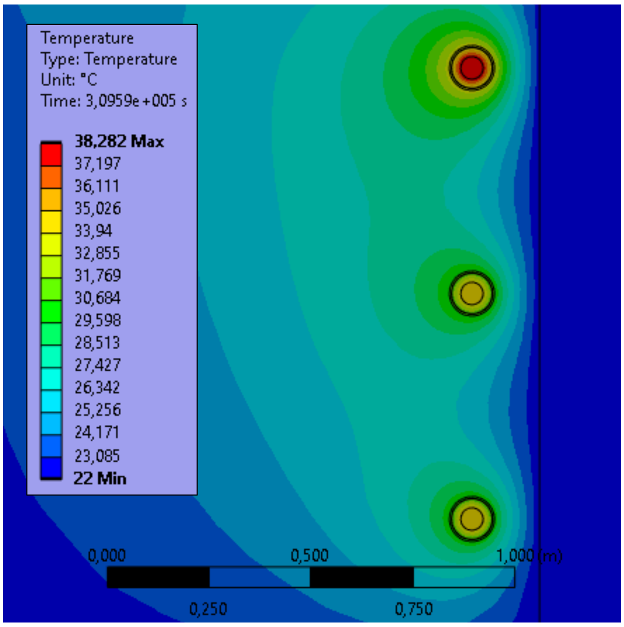

Fig. 9. Temperature reached in the conductors under actual line operating conditions.

30 °C at the end of the 2500 A application period. This temperature difference is normal due to the high current being passed through the conductors, as the heat goes to the outer layers of the cable, the heat is dissipated by convection and radiation effects on the outer sheath. Although this is normal, it will be necessary in the future to validate these results with monitored temperature and current data. However, this can be quite complicated, as insulated cables do not normally operate at high operating rates, so the currents flowing through the conductors will only be higher than 900–1000 A in very exceptional cases. In addition to verifying the results of the FEM model with the monitored temperature data in the case of higher load line operation, this model will be tested in winter conditions (lower ambient and ground temperatures), resulting in higher conductor ampacities.

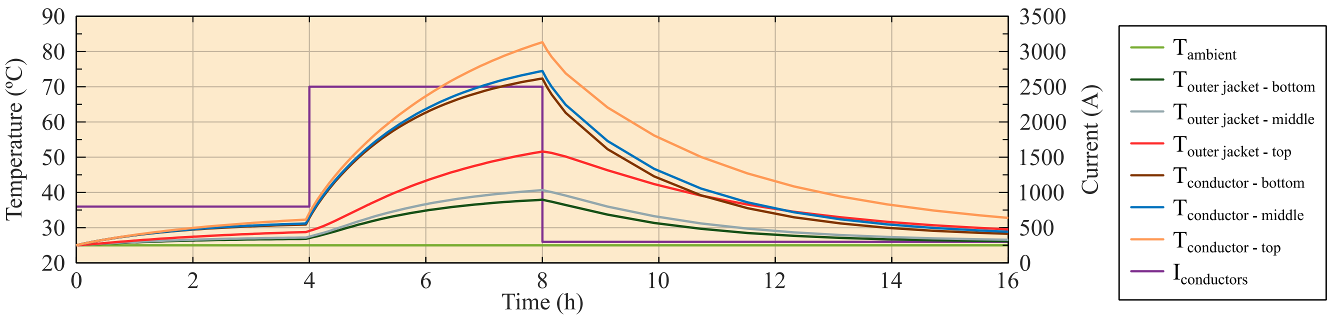

Fig. 10. FEM model results under high current load.

5. Conclusion

This study presents the development of an FEM-based model for the thermal analysis of high-voltage insulated cables. The developed FEM model was validated using data from current and temperature monitoring on a real high-voltage line (220 kV). It was based on a section of the line where, in addition to monitoring the current through the conductors and the temperature on the outer sheath, the ambient temperature was also monitored. This section corresponds to a junction chamber where the insulated cables are laid in the same plane in a vertical position.

One of the limitations of the study is the impossibility of validating the FEM model with high line loads, as it is very rare today for an insulated cable to be close to its rated value. This will be a point to investigate in the future with new line monitoring data or the possible development of new models of loaded lines, for example during cable ageing tests where high currents are circulated through them. Another limitation for the development of the remaining FEM models of the line was that the ambient temperature was not monitored, so for future installations temperature probes will be installed to measure the ambient temperature in all monitoring areas.

The main objective of the FEM model presented in this work is the dynamic management of the line, using the monitored data as a starting point and obtaining the behaviour of the cables. In this way, the FEM models can be used as a basis for decision-making in cable operation: analysis of emergency scenarios, temperature forecasts, etc. The development of new FEM models can be applied to any insulated cable line in the power grid.

Future work will focus on the effect of cable ageing on thermal behaviour and electrical performance, as well as incorporating complex material properties such as the thermal dependence of thermal conductivity.

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