2018 IEEE International Conference on Environment and Electrical Engineering and
2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)

Electromagnetic and Thermal Analysis of High Voltage Three-Phase Underground Cables Using Finite Element Method

Stefania Conti
Emanuele Dilettoso
Santi Agatino Rizzo

Electromagnetic and Thermal Analysis of High Voltage Three-Phase Underground Cables Using Finite Element Method

Stefania Conti, *Member, IEEE*
Dip. di Ingegneria Civile e Architettura
University of Catania
stefania.conti@dieei.unict.it

Emanuele Dilettoso and Santi Agatino Rizzo
Dip. di Ingegneria Elettrica Elettronica e Informatica
University of Catania
emanuele.dilettoso@dieei.unict.it, santi.rizzo@dieei.unict.it

***Abstract*— In this paper a three core high-voltage underground cable used for urban power networks is analyzed by means of Finite Element Method. The electrical analysis is performed in order to investigate the electric stress within the cable, also in presence of defect in the insulation layer. The electro-thermal analysis permits the full description of the cable behavior not only in terms of electric and magnetic performances, but also regarding the effect of the Joule heating on the surrounding ambient.**

***Keywords*— High Voltage; Underground Three Phase Cables; Finite Element Method; Electromagnetic Field Analysis; Thermal Analysis**

I. INTRODUCTION

Nowadays the three phase underground cables have a substantial role in the power delivery distribution network and, consequently, it is essential a complete knowledge of the cable behavior in order to evaluate performance and to prevent ageing, degradation and fails. Moreover, installation of High Voltage (HV) cables in urban area is non-trivial. In order to fit well in urban area they often are hidden in underground tunnels, with preexistent installations, like gas pipes, water pipes, telecommunication cables [1]. Hence, it is necessary to evaluate the impact of electromagnetic fields and heating produced by power cables both on other installations and live organisms. Nevertheless, public urban MV and LV installations tend to have complex implementation especially in the so called Smart Grids, characterized by continuously increasing loading of distribution systems, also due to the presence of distributed generators injecting power into the networks [3].

Finite Elements Method (FEM) is an effective tool, characterized by good accuracy and reliability that permits the study of cables behavior under different aspects, such as the electromagnetic, thermal and mechanical, also by means of coupled analyses [3-5]. The computational cost, generally the major drawback of applying FEM, is, in this kind of application, quite irrelevant, being possible to perform the study of cables by using e simple 2D analysis.

In this paper FEM is used for electromagnetic and thermal study of three core HV cable. The paper is organized as follows. In section II the examined cable is described. In section III the details and results of electrical analysis are given. Section IV explains the coupled electromagnetic-thermal analysis performed and shows some remarkable results of simulation. The author's conclusions follow in section V.

II. THREE CORE HV UNDERGROUND CABLE SPECIFICATION

Underground cables are generally required to deliver 3-phase power. Although for the purpose either three-core cable or three single core cables may be used, the former solution presents certain advantages in terms of costs and power losses. The considered cable is inspired to the CityCable of NKTcables®, construction code 2X(FL)2YVF ST2Y [7] developed especially for high voltage (up to 132KV) installations in urban areas as well as in industrial compounds. It provides compact and strong three cores design, fast and cheap retrofitting of existing installation and no risk of environmental pollution. It consists of different layers as shown in Fig.1. The material used for the three circular phase conductors is stranded copper; the insulating material is the Cross Linked Polyethylene (XLPE). In order to smooth the field distortion, a semi-conductor layer is used both around the copper and the XLPE insulation. Each single core is surrounded by a coated aluminum foil and a polyethylene over-sheath: this combination, called aluminum polyethylene laminated (APL) sheath, ensures high short circuit capability and water-tightness combined with lowest, weight and smallest dimensions. The group of the three cables is sheathed by polyethylene.

Both wire armor and external pipe are made of steel. Finally, the external covering of the pipe is a polyethylene layer. Geometrical data of the cable are given in Table I. The laying depth of the cable is p=1.2m, i.e. the standard depth reported in technical data [7]. Voltages and currents of the phases are a balanced 3-phase set at frequency f=50Hz. Electrical, magnetic and thermal properties of the materials employed in this model are given in Table II.

The FEM analysis was performed in COMSOL Multiphisycs [8]. The FEM mesh used consists of 15930 triangular elements; the minimum element quality is 0.07321 and the average quality is 0.8103. The chosen mesh represents a good trade-off between computational costs and solution accuracy. Fig.2 plots the mesh in the cable area.

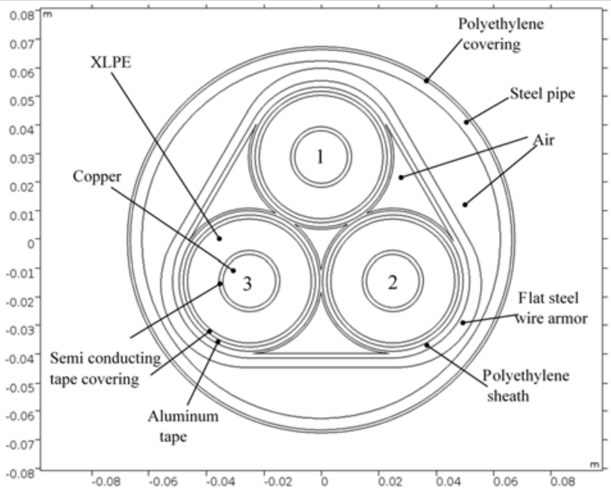


Fig. 1. Geometry of the cross section of the cable [m]

TABLE I. GEOMETRICAL DATA

Parameter	***Values[mm]***
Diameter of conductor	18.4
Thickness of inner semi-conductor	1.4
Thickness of XLPE insulation	11
Thichness of outher semi-conductor	1.4
Thickness of APL sheath	2
Thickness of Polyethylene sheat	1
Thickness of Steel wire armour	2
Thickness of Steel pipe	4
Thickness of Polyethylene covering	1
Overall diameter d_c	135

III. ELECTRICAL ANALYSIS

A 2D in-plane current conservation problem in the frequency domain is achieved in order to investigate the electric stress within the cable. Under the assumptions of quasi-static time-harmonic steady-state behavior, supposing that the electric field is curl-free, the problem can be conveniently analyzed in terms of electric potential, by solving the differential equation:

$$-\nabla\cdot\big((\sigma+j\omega\varepsilon)\nabla V\big)=0 \tag{1}$$

where V is the electric potential, σ is the electric conductivity, $\omega=2\pi f$ is the angular frequency and $\varepsilon=\varepsilon_r\varepsilon_0$ is the electric permittivity. The boundary value problem is completed by the following Dirichlet boundary conditions on the three phase conductors

$$V_1=V_0,\quad V_2=V_0 e^{-j\frac{2\pi}{3}},\quad V_3=V_0 e^{+j\frac{2\pi}{3}}, \tag{2}$$

combined with $V_g=0$ on ground.

Note that supposing the electric field $\vec{E}$ curl-free implies:

$$\nabla\times\vec{E}=-j\omega\vec{B}=0 \tag{3}$$

As ω isn't zero, and considering in this model the electric fields only in plane xy, the z-component B_z of the magnetic flux density $\vec{B}$ must be equal to zero. Subsequently the solution of (1), the electric field $\vec{E}$ can be obtained by:

$$\vec{E}=-\nabla V \tag{4}$$

The current density $\vec{J}$ is calculated using the following constitutive relations:

$$\vec{J}=\sigma\vec{E} \tag{5}$$

In the case investigated the RMS value of the line voltage is 132KV, then $V_0=132/\sqrt{3})$KV.

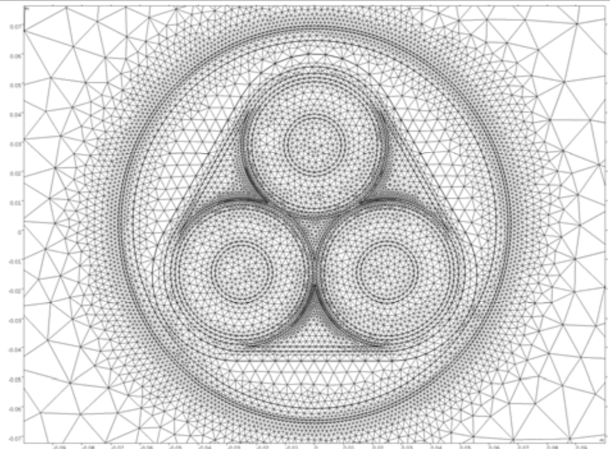


Fig. 2. FEM mesh in the cable area

TABLE II. MATERIALS PROPERTIES

Material	ε_r relative permittivity	μ_r relative permeability	σ electrical conductivity [S/m]	κ thermal conductivity [W/(m·K)]
Copper	1	1	5.99e7	400
Steel	1	4	4.7e6	50.2
Aluminum	1	1	3.77e7	237
Polyethylene	2.25	1	1.0e-18	0.46
Semiconductor	2.25	1	2	10
XLPE	2.5	1	1.0e-18	0.46
Soil (dry)	1	1	28	0.4

An Intel® Core™ i5-6200 CPU (2.3GHz) was used for the analysis; the linear solver found the solution in about 4s. The voltage distribution in the cable is shown in fig.3; as can be seen the voltage at the steel sheath is approximately zero. Fig.4 plots the electric field stress along the radius of a phase. The result agrees with the cable technical data, that report a maximum field strength at conductor screen and at core screen of 10.3 KV/mm and 4.9 KV/mm respectively [7].

It is well known that a stronger and inhomogeneous electrical field can be caused by voids, bubbles, or defects in the XLPE insulation [6]. Fig. 5 shows the results of inserting a void-defect in the XLPE layer of phase 2; the void defect causes a distortion and an increase of the electric field. Moreover, this effect becomes stronger as the distance d from the conductor decreases. Fig. 6 plots the electric field stress through the defect when d=5mm (a) and d=2mm (b): as might be seen, in the latter case the value of the electric field exceeds the maximum values expected in the technical data.

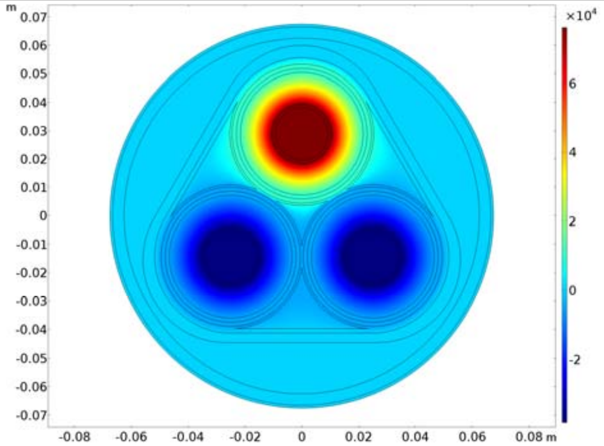


Fig. 3. Electric Potential plot [V/m] in the cable area

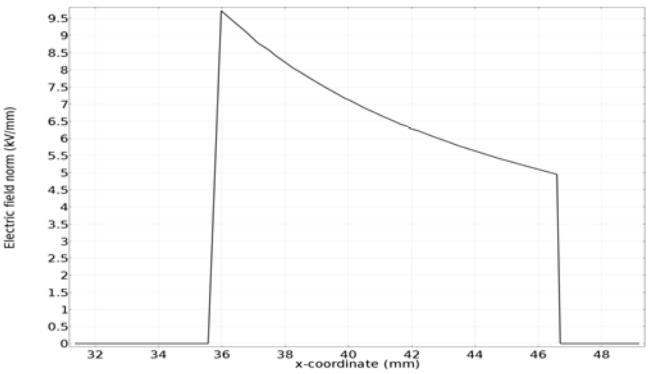


Fig. 4. Electric field stress [KV/mm] of the cable in radial direction

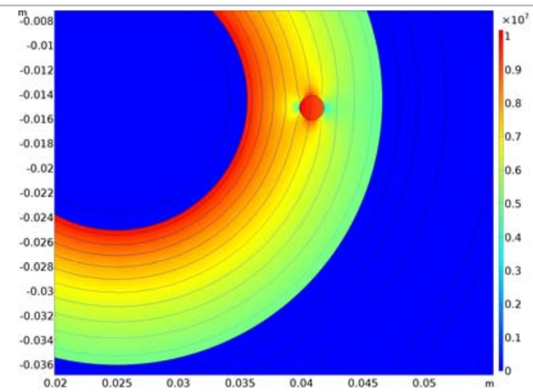
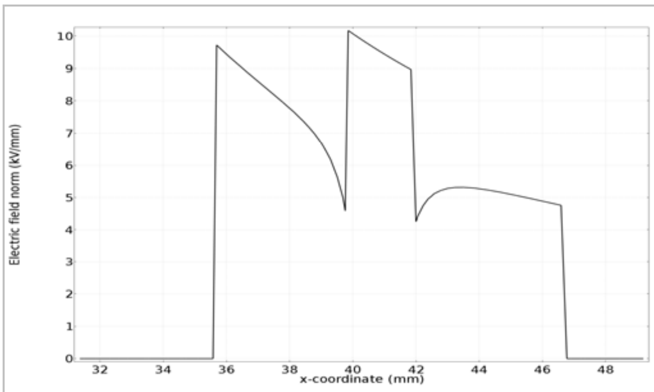
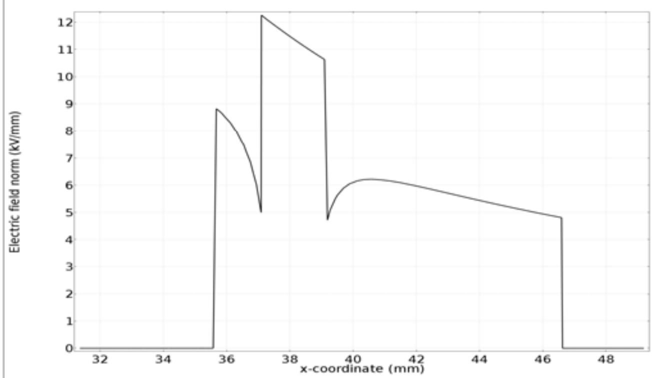


Fig. 5. Electric field [V/m] distribution in presence of a void-defect



(a)



(b)

Fig. 6. Electric field stress [KV/mm] in radial direction in presence of a void defect in the XLPE layer (a) d=5mm (b) d=2 mm

IV. Coupled electromagnetic thermal analysis

The aim of this analysis is the evaluation of per-unit-length parameters and the study of the behavior of the cable at operating temperature. At first the electromagnetic is solved, and the solution thus obtained is used to compute the heating power density inside the conductors, from which a steady-state thermal analysis is performed by considering the same mesh. The electrical conductivity of the conductor is assumed to be temperature-dependent and so, although the electromagnetic problem is linear, an iterative procedure needs to be used to solve the coupled problem [9].

The scope of magnetic analysis is the solution of Maxwell–Ampère's law in the frequency domain, using the z-component of the vector potential $\vec{A}$ as unknown. Indeed, being the magnetic flux density $\vec{B}$ a solenoidal vector field, it is possible to define $\vec{A}$ as:

$$\vec{B}=\nabla\times\vec{A} \tag{6}$$

The equation to solve in the FEM domain is the following curl-curl equation:

$$-\omega^2\varepsilon\vec{A}+j\omega\sigma\vec{A}+\nabla\times\left(\mu^{-1}\nabla\times\vec{A}\right)=\vec{J}_s \tag{7}$$

where $\mu=\mu_r\mu_0$ is the magnetic permeability and $\vec{J}_s$ is the applied source current density. The values of other fields can be derived from $\vec{A}$ by means of (6), Maxwell equations and constitutive relations. In particular, the conduction current $\vec{J}$ is calculated by:

$$\vec{J}=\sigma\vec{E}=-j\omega\sigma\vec{A} \tag{8}$$

The solution of (8) is used to compute the heating power density Q inside the conductors,

$$Q=\left|\vec{J}\right|^2\Big/2\sigma \tag{9}$$

from which a steady-state thermal analysis is performed by solving the Poisson differential equation:

$$-\nabla\cdot(\kappa\nabla T)=Q \tag{10}$$

where T is the temperature and κ is the thermal conductivity. It is faithful to assume that the thermal response time is much larger than the transient time of the electromagnetic fields.

The FEM domain for the electromagnetic analysis is a circular domain with a diameter equal to $5d_c$, and on its boundaries it is imposed the condition:

$$\hat{n}\times\vec{A}=0 \tag{11}$$

being n̂ the outward unit vector to the boundary.

The electrical conductivity varies with the temperature as:

$$\sigma(T)=\frac{\sigma_0}{1+\alpha(T-T_{ref})} \tag{12}$$

where σ_0 is the conductivity at temperature T_{ref} =20°C =293.15K and α is the electrical resistivity temperature coefficient. The values of σ_0 are those in Table II; α is equal to $0.00386K^{-1}$ for the copper and $0.00390K^{-1}$ for the aluminum, whereas the variation of the conductivity of steel with temperature is negligible. The coils are modelled as multi-conductors (stranded) coils, i.e. are not subject to skin effect and, in this case, the source current density $\vec{J}_s$ is equal to:

$$\vec{J}_s=\frac{I_s}{A_{coil}} \tag{13}$$

where I_s is the current coming from an outside source and A_{coil} is the cross sectional surface of the core. The 3-phase set of currents in the coils is:

$$I_1=I_0,\quad I_2=I_0e^{-j\frac{2\pi}{3}},\quad I_3=I_0e^{+j\frac{2\pi}{3}} \tag{14}$$

being I_0=406A the maximum value of current, as in data sheet.

The ambient temperature considered in the thermal analysis is T=15°C as indicated in technical data of the cable. The iterative non-linear solver found an accurate solution in five iterations and about 25s. The distribution of the norm of the magnetic flux density in the cable is shown in Fig. 7. Fig. 8 plots the temperature distribution in the cable. The maximum temperature of the cable is 77.35 °C, that is the operating temperature of real cables (about 70 to 90°C). Fig. 9 shows the temperature in the space around the cable: note that the when the cable carries the maximum current value the soil surface temperature raise up from 15°C to about 35°C.

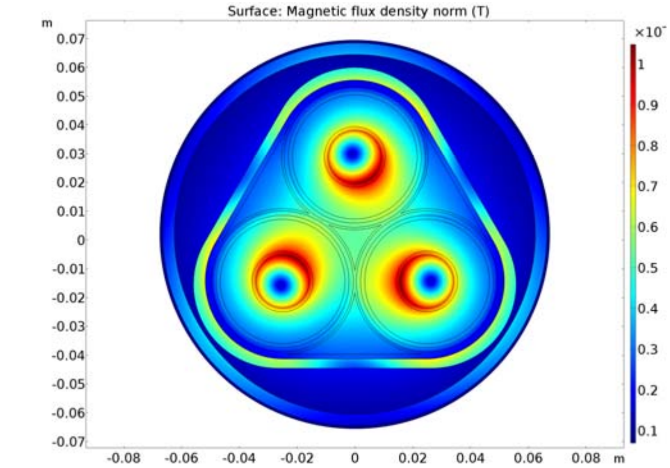


Fig. 7. Magnetic flux density [T] in the cable

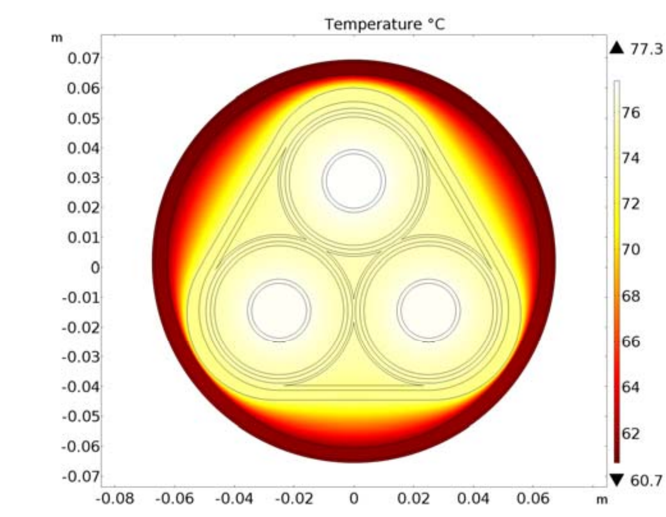


Fig. 8. Cable temperature [°C]

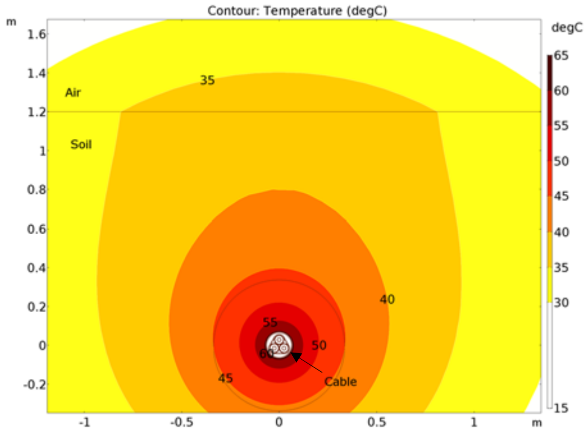


Fig. 9. Soil and air temperature [°C]

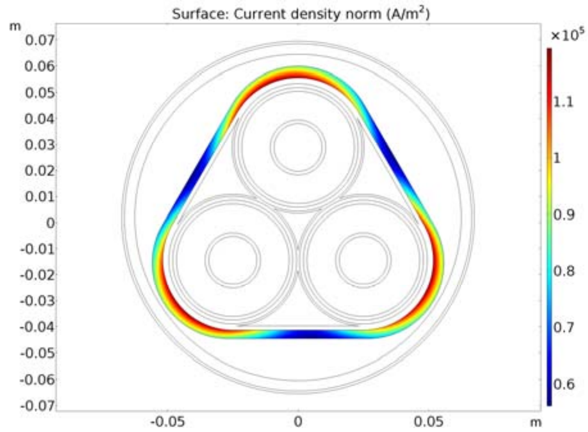


Fig. 11. Steel armor current density [A/m²]

The per-unit-length parameters at operating temperature were calculated and are reported, together with technical data, in Table III. There is a good matching between the declared data and the results of FEM simulation. Table IV shows the undesired power losses for sheath, armor and pipe. The corresponding current densities are shown in Fig. 10, Fig. 11 and Fig. 12 respectively.

TABLE III. CABLE PER-UNIT-LENGTH PARAMETERS

	Conductor AC resistance [Ω/km]	**Inductance [mH/km]**
FEM simulation	0.1001	0.35
Technical data (operating at 90°)	0.0975	0.38

TABLE IV. CABLE LOSSES

Power losses [kW/km]		
Aluminum sheath	**Steel armour**	**Steel pipe**
4.18	1.03	0.603

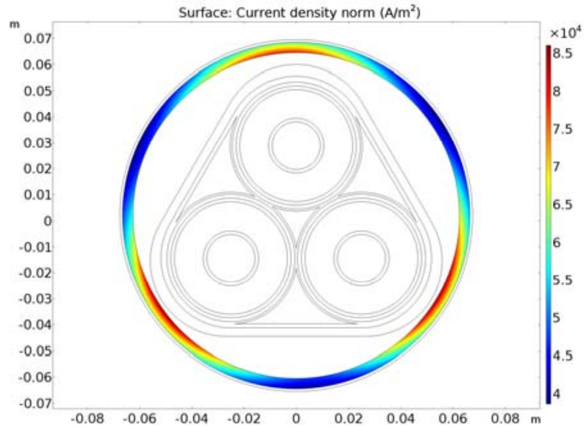


Fig. 12. Steel pipe current density [A/m²]

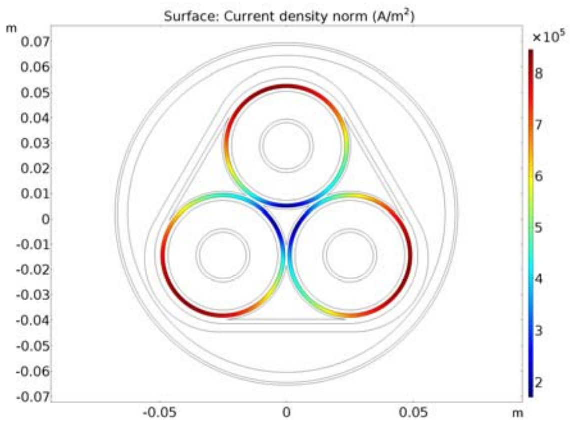


Fig. 10. Aluminum sheath current density [A/m²]

V. CONCLUSION

A three Core HV underground cable used for urban power network was analyzed by means of Finite Element Method. Electrical analysis showed correctness of technical data, it was demonstrated as the presence of defect in insulation layer could cause relevant peaks of the electric field strength, higher than the maximum values declared. Thanks to the electro-thermal analysis was performed the calculation of per-unit-length parameters at operative temperature; undesired power losses were also evaluated. It was pointed out that when the cable carries high currents, the temperature of the soil rises considerably.

REFERENCES

[1] M. A. Prsa, N. D. Mucalica, K. K. Kasas-Lazetic, "Determination of electromagnetic field in a three-phase system with three single-core power electric cables 110 KV", procedings of IEEE EUROCON 2009, May 2009.

[2] J. Cho, K. Sim, J. Bae, H. Kim, J. Kim, K. Seong, H. Jang, C. Lee and D. Koh, "Design and Experimental Results of a 3 Phase 30 m HTS Power Cable", Ieee Transactions On Applied Superconductivity, Vol. 16, No. 2, June 2006, pp. 1602-1605

[3] S. Conti, S. Raiti, G. Tina, U. Vagliasindi, "Distributed Generation in LV distribution networks: voltage and thermal constraints", in *Proc. of*

2003 IEEE PowerTech Conference, Vol.2, 23 June 2003, Bologna, pp. 413-418.

[4] C. Kocatepe, C.F. Kumru an T. Ozturk, “Analysis of eccentric axial high voltage underground cable”, 2011 7th International Conference on Electrical and Electronics Engineering (ELECO), Bursa, Turkey, December 2011

[5] M. Kumar, M. S. Bhaskar,S. Padmanaban, P. Siano, F. Blaabjerg and Z. Leonowicz, “Electric field analysis of extra high voltage (EHV) underground cables using finite element method.”, Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe). IEEE Press, 2017.

[6] M Alsharif , P. A. Wallace, D. M- Hepburn and C. Zhou, “FEM Modelling of Electric Field and Potential Distributions of MV XLPE Cables Containing Void Defect”, Proceedings of the 2012 COMSOL Conference in Milan, Milan (Italy), 2012.

[7] http://www.nkt.com/industries/power-transmission

[8] https://www.comsol.com/documentation

[9] G. Aiello, S. Alfonzetti, E. Dilettoso, N. Salerno, "Transient Thermal Analysis of an Eddy-Current Heated Conductor Applying FEM-DBCI", IEEE Transactions on Magnetics, vol. 49, n. 5, 2013, pp. 1861 - 1864