STUDIES ON ELECTROMAGNETIC INDUCTION HEATING OF ELECTRIC CONDUCTOR INSULATION

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In this paper a numerical model analyzing the heating of a copper electrical conductor with vinyl polychloride (PVC) insulation is presented. There are taken into account two cases, namely the induction- and the conduction-heating. The results of the numerical simulations can be used to study the properties of electric cables and the presented method is suitable for research in the field of insulation testing. The simulation results of the induction heating are correlated to the ones obtained from the numerical model of heating produced by the load or fault electrical current that passes through the respective conductor leading to its degradation.

Keywords: electric conductor, induction heating, numerical simulation, PVC insulation

1. Introduction

Maintaining the reliability of electrical wires and cables depends largely on the characteristics of the insulating materials. Virtually, the life of an electric cable depends on the durability of the electrical insulating materials used in its construction. The heat released during operation, due to the Joule effect, in the electric current cable is an important factor in degrading its insulation. Behavior over time, in different modes of operation, is an important requirement in the design and manufacture of electric cables.

The phenomenon of electromagnetic induction discovered by M. Faraday in 1831 is the basis of inductive heating. Modern industrial applications of inductive technology include mainly melting and heat treatment of metals as well as thermal processing by indirect method of non-conducting materials in different manufacturing processes [1, 2].

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Heating by electromagnetic induction is the process of heating (without contact) of a metal part placed in a variable magnetic field. Usually, the magnetic inductor flux is produced by a coil that surrounds the heated element and at its terminal connections an alternating voltage is applied.

The action of the variable magnetic flux that crosses the metal piece leads to the appearance of electromotive voltages and implicitly of the eddy currents that by Joule effect produce the heating of the metal part [3].

Fig. 1 presents the physical phenomenon of eddy currents occurrence.

The main advantages of induction heating are [4-6]:

- maximum accuracy - the heating is made directionally, only the "target" part is heated without affecting the environment, there is no direct contact between the inductor and the heating part;
- high efficiency - the heating process is carried out with high power density in a short time, the start-stop is instantaneous;
- the technological process is automated and monitored - there is the possibility to control the heating speed, the depth of penetration in the heating part and the heating temperature;
- ecological working environment - there is no pollution due to the energy source, there are no toxic gas emissions;
- low maintenance costs of equipment, long operation life of the components and high stability in operation.

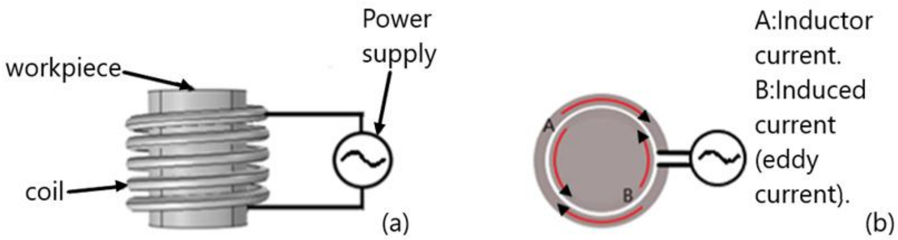
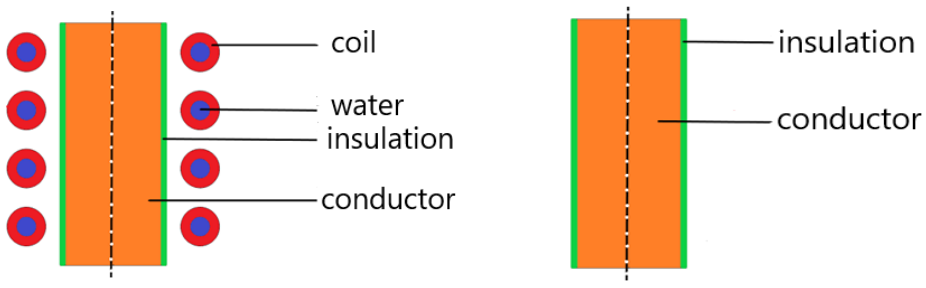


Fig. 1. Typical induction heating setup: (a) general view; (b) top view.

2. System description

In Fig. 2a the cross section of the induction heating system is presented. The system coil has four turns, having cylindrical section pipe-shaped through which the cooling agent (water) passes. The electrical conductor is covered with an insulation layer. In Fig. 2b, the cross section of the charged conductor is presented, having axial symmetry, surrounded only by the insulation layer.



a – the induction heating assembly b – the conductor in charge system

Fig. 2. Schematic representation of the two analyzed cases.

3. Mathematical model of the induction heating

In Fig. 3 it is shown the modelled two-dimensional (2D) axisymmetric domain D that is considered isotropic, unmovable, and homogenous, having the component sub-domains D1, D2, D3, D4.

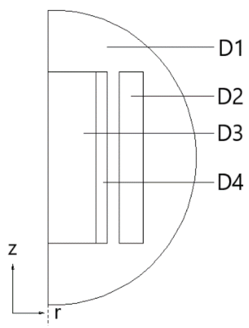


Fig. 3. The studied 2D axisymmetric domain D with D1 - air, D2 - inductor, D3 - heated part, D4 – insulation.

The numerical problem is solved using the magnetic vector potential method. The advantage of this method is that all the conditions, which must be fulfilled, are contained in one equation. If by solving this equation we can find the magnetic vector potential $\overline{A}$ than, by derivation, we can find the magnetic flux density $\overline{B}$, and the magnetic field strength $\overline{H}$. Knowing the value of $\overline{A}$ we can compute the density of the eddy currents induced in the working part and the induced electromagnetic power, which is the initial value for the thermal field problem [5].

The base relationships for the electromagnetic problem computation are the Maxwell equations:

$$\nabla \cdot \overline{B} = 0 \tag{1}$$

$$\nabla \cdot \overline{D} = \rho_c \tag{2}$$

$$\nabla \times \overline{E} = -\frac{\partial \overline{B}}{\partial t} \tag{3}$$

$$\nabla \times \overline{H} = \overline{J} + \frac{\partial \overline{D}}{\partial t} \tag{4}$$

where $\overline{H}$ is the magnetic field strength, $\overline{E}$ the electric field strength, σ the electric conductivity (S/m), $\overline{B}$ the magnetic field flux density, ρ_c the electric charge volume density (C/m^3) and $\overline{J}$ the electric current density [1, 7 – 13].

The constitutive equations for a linear isotropic environment are:

$$\overline{J} = \sigma \cdot \overline{E} \tag{5}$$

$$\overline{B} = \mu_0 \mu_r \cdot \overline{H} \tag{6}$$

$$\overline{D} = \varepsilon_0 \varepsilon_r \cdot \overline{E} \tag{7}$$

in which μ_0 is the absolute magnetic permeability of the vacuum (H/m), μ_r the relative magnetic permeability, ε_0 the absolute permittivity of the vacuum (F/m), ε_r the relative dielectric permittivity [14].

The magnetic vector potential can be defined as:

$$\overline{B} = \nabla \times \overline{A} \tag{8}$$

that determines equation (4) to be written:

$$\frac{1}{\mu_0 \mu_r} \nabla^2 \overline{A} + \overline{J}_s - j\omega \cdot \sigma \cdot \overline{A} = 0 \tag{9}$$

in which $\overline{J}_s$ is the source current density (of the inductor) (A/m^2) and ω the angular frequency (rad/s). The material quantities μ and σ are temperature dependent [8].

For the studied domains, the equation (9) becomes:

$$\frac{1}{\mu_0 \mu_r} \nabla^2 \overline{A} = 0 \qquad \text{for D1} \tag{10}$$

$$\frac{1}{\mu_0 \mu_r} \nabla^2 \overline{A} + \overline{J}_S - j\omega\sigma \cdot \overline{A} = 0 \qquad \text{for D2} \tag{11}$$

$$\frac{1}{\mu_0\mu_r}\nabla^2\overline{A} - j\omega\sigma\cdot\overline{A} = 0 \qquad \text{for D3} \quad (12)$$

The electromagnetic power induced in D3 and the eddy current density are calculated based on the magnetic vector potential $\overline{A}$:

$$\overline{J}_t = \sigma j\omega\cdot\overline{A} \quad (13)$$

$$Q = \frac{J_t^2}{\sigma} = \sigma(j\omega\cdot A)^2 \quad (14)$$

where J_t is the eddy current density (A/m^2) and Q is the induced electromagnetic power (W/m^3).

The losses due to polarization phenomenon P_d (W/m^3) are computed as it follows:

$$P_d = \omega\varepsilon_0\varepsilon_r^{\parallel}E^2 \qquad \text{for D4} \quad (15)$$

where P_d represents losses due to polarization phenomenon (W/m^3).

For the electrical permittivity it is considered the complex formulation:

$$\varepsilon_r = \varepsilon_r^{|} - j\varepsilon_r^{\parallel} \quad (16)$$

The real part of the relative electrical permittivity $\varepsilon_r^{|}$ has the same physical significance as the quantity ε_r in time-invariable electric fields. The imaginary part $\varepsilon_r^{\parallel}$ (loss factor) characterizes the dielectric losses by the polarization phenomenon.

The temperature in the working part is computed with the thermal transfer classical equation:

$$\lambda\cdot(\nabla^2 T) + Q + P_d = \rho c_p\frac{\partial T}{\partial t} \quad (17)$$

in which T is the temperature (degK), ρ the mass density (kg/m^3), c_p the specific heat (J/(kgK)), λ the thermal conductivity (W/(mK)), Q_{conv} the convection transferred heat (W/m^2), Q_{rad} the radiation transferred heat (W/m^2) and t the time variable (s). The quantities λ, ρ, c_p are temperature dependent parameters [9, 15 – 19].

The convection heat transfer equation is:

$$Q_{conv} = \alpha(T - T_0) \quad (18)$$

and the radiation heat transfer equation is:

$$Q_{rad} = \beta\cdot\sigma\ (T^4 - T_0^4) \quad (19)$$

in which α is the convection coefficient (W/(m^{2}K)); β the emission radiation coefficient, T_0 the ambient temperature (degK), and σ is the Stefan-Boltzman constant $(5.67\times10^{-8}\,\mathrm{W/m^2K^4})$ [8, 10].

4. Simulations

Since the electrical resistivity, magnetic permeability, thermal conductivity, and the specific heat, towards the environment, are strongly dependent on the temperature, the correct evaluation of the quantities related to the process of induction heating requires to consider the coupling between the electromagnetic and thermal field problems. Also, in the studied example from this paper, the coupling between the two electromagnetic and thermal fields is achieved by the fact that the electromagnetic power induced in the studied cable constitutes a function of force in the heat transfer equation [4, 12, 15].

Table 1 presents the characteristics of the materials in domain D used for the calculation of the electromagnetic and the thermal field.

Table 1

Physical characteristics and properties of the materials in the studied domain D [10, 20]

	Copper	PVC	Air
Electrical conductivity σ (S/m) at 293 degK	5.8×10^7	-	-
Real part of the complex relative dielectric permittivity at 293 degK	1	3	1
Imaginary part of the complex relative dielectric permittivity at 293 degK. The frequency of the electric field is 17 kHz	-	0.085	-
Relative magnetic permeability	1	1	1
Mass density ρ (kg/m^3)	8700	1300	1.3
Thermal conductivity λ (W/(mK)) at 293 degK	400	0.15	0.025
Specific heat C_p (J/(kgK)) at 293 degK	385	900	0.001

Tables 2 and 3 show the physical characteristics of the inductor and the conductor in the studied domain D [10].

Table 2

Induction coil dimensions and properties

Inner diameter (mm)	28
Outer diameter (mm)	44
Height (mm)	50
Number of turns	4
Cooling system	water

Table 3

Conductor dimensions and properties

Conductor Material	Copper
Insulation material	PVC
Length (mm)	50
Conductor diameter (mm)	20
Thickness of insulation (mm)	1

Tables 4 and 5 present the initial and boundary conditions for electromagnetic field and electric field problems for both analyzed situations.

Table 4

Boundary condition and initial values for the electromagnetic problem

Boundary condition/Initial values	Description
Outer boundary	$A = 0$
Asymmetry axis	$\partial A/\partial n = 0$
Inductor current (A)	93
Inductor current frequency (Hz)	17000

Table 5

Initial and boundary conditions for the problem of the conductor in charge

Voltage value imposed at the ends of the conductor (V)	0.00419
Voltage frequency (Hz)	50

Table 6 presents the initial and boundary conditions for heat transfer in both cases [10].

Table 6

Initial and boundary condition for heat transfer in the two analyzed situations

Initial temperature T_0 (degK)	293.15
Temperature of inductor cooling agent T (degK)	296
Convection coefficient α (W/m^{2}K)	5
Copper radiation coefficient β	0.3
PVC radiation coefficient β	0.9

The inductor is equipped with a cooling system based on water with the required equilibrium temperature of 296 degK. The simulation time in both cases is set at t = 2500 s. Fig. 4 presents the discretization mesh chosen for the electromagnetic induction problem and Fig. 5 represents the distribution of the magnetic vector potential in the studied domain at the time t = 900 s.

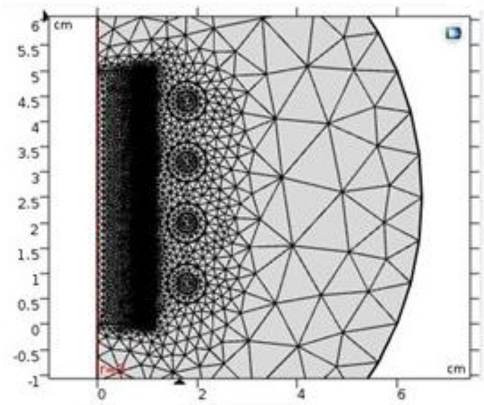


Fig. 4. Applied mesh in the electrical conductor and inductor zones.

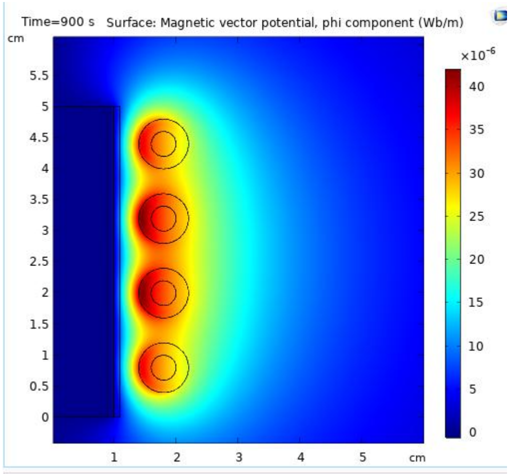


Fig. 5. Surface plot of the magnetic vector potential, phi component (Wb/m) at t = 900 s.

Fig. 6a presents the distribution of the electric field in the studied domain at the time t =2500 s. Fig. 6b presents the temperature field in the electromagnetic induction problem.

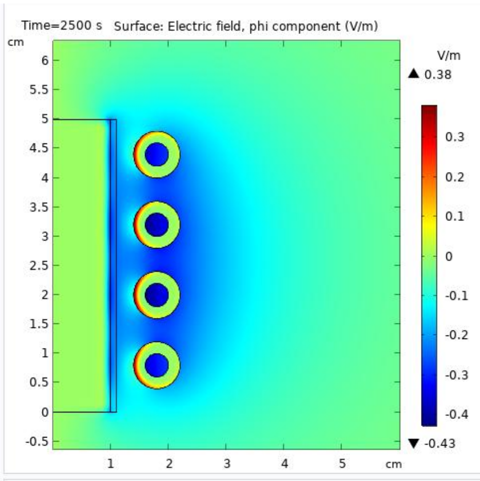


Fig. 6a. Surface plot of the electric field, phi component (V/m) at t = 2500 s.

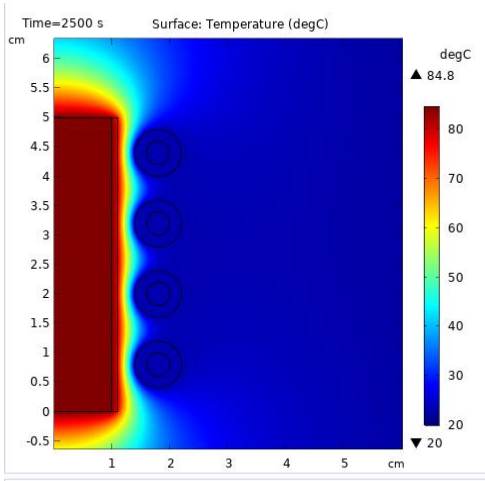


Fig. 6b. Temperature distribution in conductor – inductor layers at t = 2500 s.

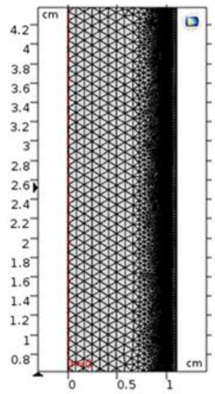


Fig. 7 Applied mesh in the conductor in charge domain.

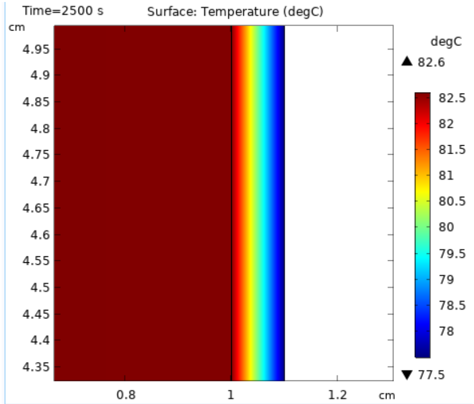


Fig. 8. Temperature distribution in the conductor in charge, t = 2500 s.

In the case of electric field problem, the used mesh is shown in Fig. 7 and the current in the conductor in charge is 1553 A. Fig. 8 presents the temperature field for the electric conduction problem at time t = 2500 s.

5. Results

A comparison between the temperature variation, through the imposed time interval, obtained in the edge ABCD of the insulation layer is shown in Fig. 9. It can be observed that the induction heating has an almost identical profile as the one obtained for conductive case.

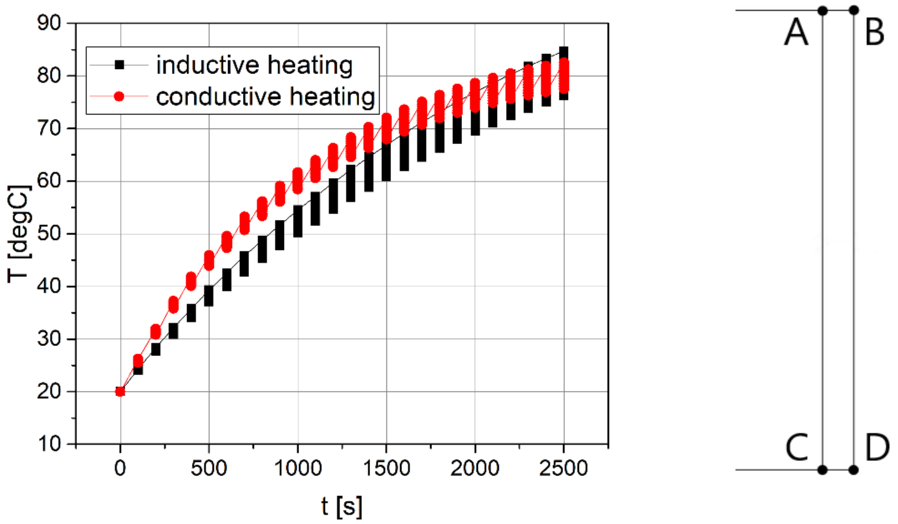


Fig. 9. Temperature variation in the edge ABCD in the two analyzed situations.

In Fig. 10 a comparison between the temperature values calculated in the two heating cases is presented. The analysis is performed in the middle of the conductor through a 1 mm line placed over the entire width of the insulation layer.

Fig. 11 shows the comparison of the temperature gradient in the two analyzed situations.

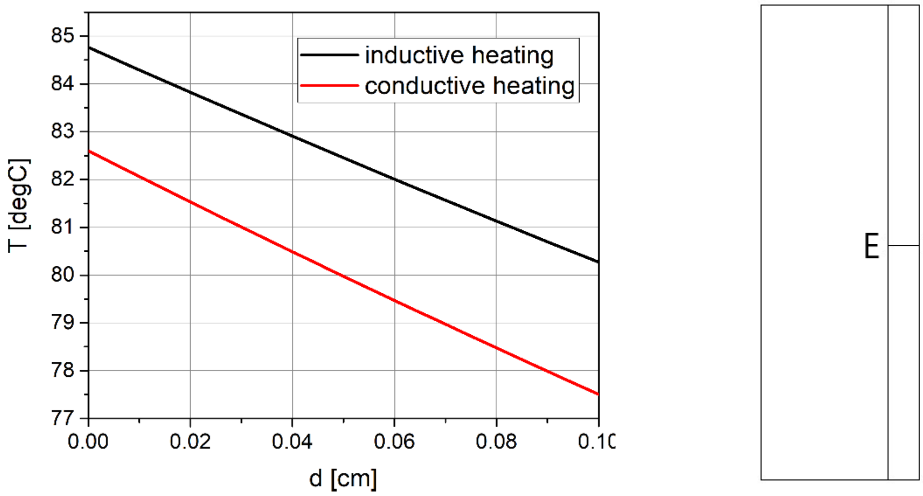


Fig. 10. Temperature variation between points E and F in the two analyzed situations.

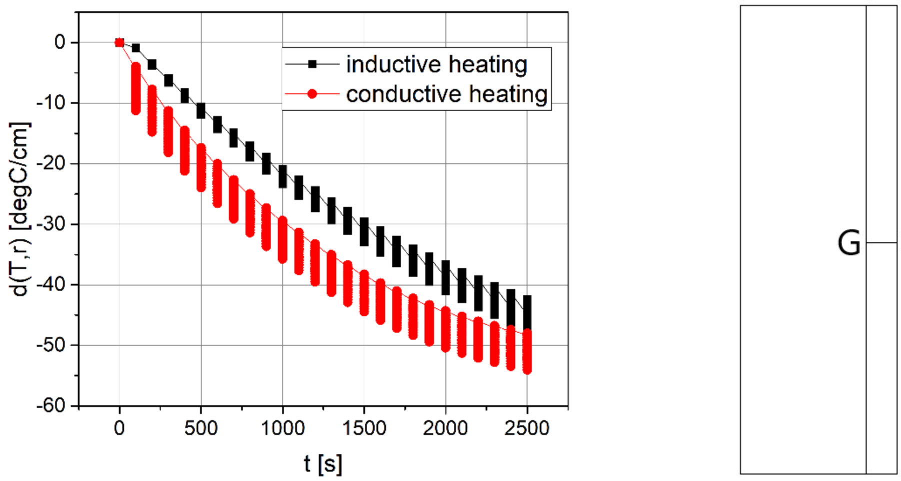


Fig. 11. Temperature gradient variation between points G and H in the two analyzed situations.

6. Conclusions

In this paper we have studied the behavior of the electric conductor insulation, heated through two methods: circulation of the conduction electric current and the electromagnetic induction.

Based on the obtained results, it can be observed that the thermal effect of the two methods is equivalent.

The proposed method of electromagnetic induction heating can be successfully applied to test the thermal degradation of electrical wiring insulation, which can replace the conductive heating procedure.

The obtained results can be useful in the case of electrical cable insulation testing if the thermal degradation of the insulation is done through induction heating.

Advantages of the proposed method:

- Low energy consumption due to directed heating.
- Good electrical efficiency.
- Possibility of speed control and heating temperature.
- The possibility of automating the technological process.
- Reduced environmental pollution.
- Short process time.
- The tested sample has small geometrical dimensions.

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