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Measurement and analysis of conductor surface temperature in dependence of current variation

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ABSTRACT

The reliability and service life of power cables is closely related to the cable ampacity and temperature rise in the power cable. In a conductor carries AC current, complex processes may appear, which directly affect the temperature of the conductor surface. So, to keep a conductor in a good state, it is necessary to maintain the conductor temperature in a acceptable value. In this paper, a procedure for measuring the temperature of conductor surface and the corresponding numerical processing of measurement results has been presented. The measurement of the temperature probe characteristics and the temperature measurement on the surface of the conductor, both required the use of certain numerical methods, such as interpolation and fitting of the measured values in time diagrams. The procedure was applied to three copper conductors with different cross section area and one aluminum conductor and the final results are presented graphically, in the form of time diagrams.

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1. INTRODUCTION

In addition to the development of intelligent networks, sustainable operation of high-voltage cables, as an important career in electricity transmission, contributes to guaranteeing the quality of energy resources and improving the safety and security of transmission lines [1]. The temperature of the alternating voltage conductors is one of the important parameter that directly determine their endurance [2]. Without a detailed study of the current working environment for high voltage cables, raising the conductor temperature above the allowable value will accelerate the aging of the cable insulation, increase the leakage current and ultimately lead to insulation failure [3]. Therefore, the temperature monitoring of cable conductors can estimate the carrying capacity of cables in real time and guarantee their safe and efficient operation [4]. However, in the case of time-varying currents, there is a surface effect in the conductor and an uneven distribution of current across the cross section of the conductor, so the problem is further complicated [5]. The specific resistance of the conductor changes with the change of temperature, which also affects the current distribution. The whole phenomenon is not linear, so a very complex mathematical apparatus is needed to determine the temperature distribution on the surface of the conductor, caused by the complex shape of the Joule effect [6].

During recent years, the development of online monitoring technology for the surface temperature of high voltage cables has become a standard for knowing the conductor temperature in high voltage cables [7]. There are two methods for monitoring the temperature of the transmission cable, which are contactless and contact temperature measurements. The infrared measurement technology method takes faster response time and requires simple equipment structure, but at the same time it is affected by infrared electromagnetic waves and environmental factors, which leads to poor measurement accuracy [8].

In the case of contact temperature sensors, thermocouple sensors are used to perform multipoint measurements. Compared to infrared thermometry, the measurement is flexible and allows temperature to be measured in several locations, but it is more difficult to maintain a safe electrical distance between sensors and equipment with higher voltage levels. Therefore, neither of the above two methods is considered the most suitable option for long-distance continuous monitoring of the temperature of cable conductors in complex laying environments [9]. These methods are used to find out the surface temperature of the conductors of high-voltage cables, but direct measurement of the conductor temperature is difficult to be achieved.

Currently, the main methods for calculating conductor temperature used in power cables include equivalent thermal circuit models [10], artificial intelligence algorithms [11], in addition to finite element analysis [12]. Also the standard (IEC 60287) is the standard used for the equivalent thermal circuit method, which gives a complete analysis method and an integrated formula for calculating the load capacity [13], but it does not take into account the effect of instantaneous changes in the external environment and other factors affecting the correction factor and therefore it cannot solve physical problems in an effective way, such as convection and radiation in addition to the coupling of heat transfer [14]. This leads to calculation errors that cause the final results to deviate from the actual values in complex and multi-loop environments therefore, it is not suitable for monitoring the surface temperature of conductors in real time [15].

Also, artificial intelligence algorithms have been applied for the purpose of predicting the temperature range of conductors by using support vector machines (SVM) [16], the trans-conductor temperature model was developed and the particle swarm optimization (PSO) algorithm was introduced in order to improve the parameters of the network model. The surface temperature of the conductor used in the measured cable and the load current were also used as basic model inputs to obtain the dynamic temperature of the conductor [17], but if this method is used, a large amount of sample data is required for the proposed model to calculate the conductor temperature [18]. In this paper, the numerical processing of the temperature measured values on conductor surface have been conducted by using MATLAB software package on a three samples of copper conductors with different cross-sectional areas, and on one sample of aluminum conductor.

2. METHOD

In the case of an AC current flowing through a conductor, uneven distribution of current across the cross section of the conductor will occur [19]. When the conductor has a cylindrical shape, it is most convenient to solve the problem in a cylindrical coordinate system, so that the axis of the conductor is placed in the direction z of the coordinate of the adopted system [20]. So, the vector of electric field and the current density vector have only z component, and the magnetic induction vector has only φ component [21]. These quantities depend only on time (t) and distances from the conductor axis (r) and do not depend on the coordinates φ and z as shown in [22]:

$$\overrightarrow{E_u} = \overrightarrow{\iota_z}.E_Z \tag{1}$$

$$\vec{J} = \overrightarrow{\iota_z}.J_Z \tag{2}$$

$$\vec{H} = \overrightarrow{\iota_\theta}.H_\theta \tag{3}$$

where: $\overrightarrow{E_u}$ is the vector of electric field strength in the conductor, $\vec{J}$ is the vector of current density and $\vec{H}$ is the vector of magnetic field strength. In the case when the current changes over time according to the simple periodic law, a complex notation can be used to solve the problem. In this case, Maxwell's first two equations in complex scalar form are used as shown in [23]:

$$-\frac{d\underline{E}}{\underline{dr}} = -J\mu\omega\underline{H} \tag{4}$$

$$\frac{d}{rdr}\left(r\underline{H}\right) = J \tag{5}$$

where μ is the permeability of the medium and ω is the angular frequency of the field source. When the value of H in (3) is substituting in (4), a partial differential equation for the spatial distribution of the complex intensity of the current density vector can be obtained as shown in [24]:

$$\frac{d}{rdr}\left[r\frac{d\underline{J}}{dr}\right] = J\mu\omega\underline{\sigma J} \tag{6}$$

where σ is the specific conductivity of the conducting material. The *Bessel differential equation* of zero order can be obtained as shown in:

$$\frac{d^2\underline{J}}{d\underline{u}^2}+\frac{d\underline{J}}{\underline{u}d\underline{u}}+\underline{J}=0 \tag{7}$$

$$\underline{U}=\sqrt{-j}\,\cdot S \tag{8}$$

$$S=\acute{K}\cdot r \tag{9}$$

$$\acute{K}=\sqrt{\omega\mu\sigma} \tag{10}$$

now, the distribution of the intensity of the current density vector over the conductor cross section $\underline{J}(0)$ can be expressed through the Bessel function as shown in:

$$\underline{J}(s)=\underline{J}(0)[Jber(s)+jbei(s)] \tag{11}$$

where *ber(s)* and *ber(s)* are the real and imaginary part of the *Bessel function* which represent the specific resistance of the conductor changes, more or less, with a certain temperature (ϑ) for smaller and larger temperature changes as shown in [24]:

$$\rho_\vartheta=\rho_0(1+\alpha\vartheta) \tag{12}$$

$$\rho_\vartheta=\rho_0(1+\alpha+\beta\vartheta^2+\gamma\vartheta^3) \tag{13}$$

where α, β and γ are the temperature coefficients of the conductor material, ρ_0 is the specific resistance of the material at 0 C. Expressions for changes in specific resistance due to changes in temperature in AC current can be written as shown in [24]:

$$\rho_\vartheta=\rho_0\big(1+\alpha_{20}(\vartheta-20)\big)(1+y_s+y_p\big) \tag{14}$$

$$\rho_\vartheta=K_1K_2\rho_{20}[1+\alpha_{20}(\vartheta-20)] \tag{15}$$

where k_1 , y_s are influence coefficients of the surface effect on the specific resistance of the material, and k_2 is the losses influence in ferromagnetic material. So, the volume density of Joule losses at each point of the conductor (dv) will be:

$$\frac{dP_J}{dv}=\vec{J}\cdot\vec{E}=J\cdot E=\rho\cdot J^2=\sigma\cdot E^2 \tag{16}$$

Joule losses P_J can be determined by integrating expression (16) over the total volume of the observed conductor as shown in:

$$P_J=\iiint\frac{dP_J}{dv}\cdot dv=\iiint J\cdot E.dv=\iiint\rho\cdot J^2\cdot dv=\iiint\sigma\cdot E^2\cdot dv \tag{17}$$

the energy converted from to heat during the time interval t, will be:

$$W_J=\int_0^t\iiint\frac{dP_J}{dv}\cdot dv\cdot dt=\int_0^t\iiint\rho\cdot J^2\cdot dv\cdot dt=\int_0^t\iiint\sigma\cdot E^2\cdot dv\cdot dt \tag{18}$$

the distribution of temperature over the entire volume of the conductor is [24]:

$$\Psi C_P=\frac{\partial T}{\partial t}-\nabla\cdot(K\nabla T)=\acute{q}_v \tag{19}$$

where q_v is the volumetric energy density of the heat source, Ψ is the specific mass of the conductor, k is the thermal conductivity of the conductor, Cp is the specific heat capacity.

Calculating the temperature distribution on the conductor surface is a very complex procedure because the Joule losses depends on the specific resistance of the material, as a result, the surface effect over a constant *k*, also will be depends on the conductor specific resistance. So, the current distribution over the conductor cross section will be depends on the temperature. From these results, we can conclude that the whole process of conductor heating is nonlinear and consists of numerous mutual influences [25]. There are some ready-made computer packages, such as COMSOL or some other procedures, can be used to solve such complex problems, but due to the complexity of this problem, it was decided within this work, for a start, to perform a temperature measurement only on the surface of the conductor, which is incomparably simpler than measurements at all points of the conductor. To measure the temperature on the conductor surface, a cylinder-shaped temperature probe with a diameter of 8 mm and a height of 14 mm has been used.

The resistance of the probe was measured in connection with four terminals; two voltage and two current. The resistance of the temperature probe depending on the temperature is given in Table 1 and graphically in Figure 1. FLUKE 9103 dry-well calibrator was used for calibration and maintain a constant temperature inside the probe, which changes the temperature in the probe in a range from -25 °C to 140 °C. FLUKE 8846a precision multimeter was used to measure the probe resistance. Figure 1 shown that the probe has a negative temperature coefficient.

Table 1. Measured probe resistance

Nominal temperature	20 40 60 80 100	120 140 160
Measured probe resistance [kΩ]	12.2 5.1 3.5 2.3 1.2	0.75 0.35 0.2
Measured temperature [°C]	21.3 40.5 60.1 81.3 95	101.9 118.2 132

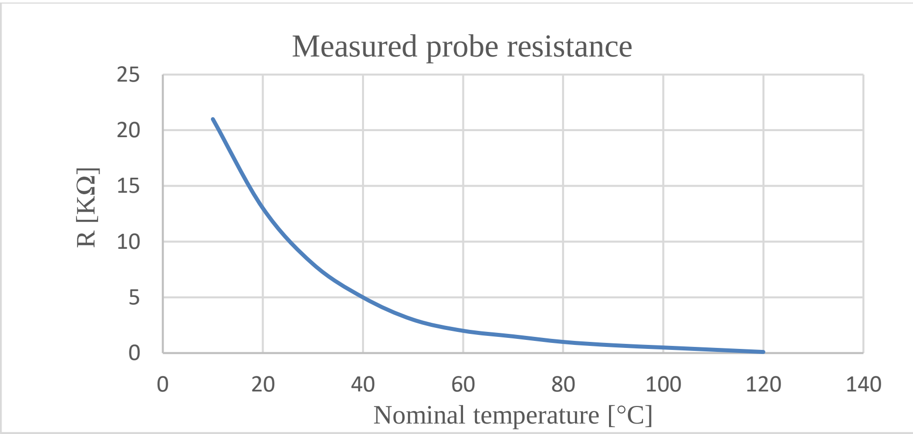

Figure 1. Dependence of probe resistance on temperature

2.1. Practical measurement of the conductor surface

For conducting a measurement of the conductor surface in electrical engineering laboratory, three copper conductors with cross-sectional area of: $\Phi = 6$ mm^2, $\Phi = 8$ mm^2 and $\Phi = 12$ mm^2, were selected, as well as one aluminum conductor with cross-sectional area of $\Phi = 8$ mm^2. Surface temperatures of each conductor were measured for 12 different rms values, every 15 seconds, for a total time interval of 30 minutes. When measuring the temperature at lower currents, there was no significant heating of the conductor, so the measurements could be performed continuously. However, at higher currents, the conductor became more and more heated, so before measuring at the next current, the measured conductor had to be cooled by a fan, until the conductor temperature reached the same initial value, unique for all measurements.

By numerical interpolation using the diagrams in Figures 1 and 2, the values of the temperature on the surface of the conductor with cross-sectional area ($\Phi = 8$ mm^2) for three different currents are determined as shown in Figure 3. The interpolation was done using the MATLAB program, using the "interp1" function. The obtained values of individual measurement are shown in Figure 2. Due to the imperfection of the measurement procedure, the obtained curves are not smooth as expected. Table 2 illustrates the measuring devices used in the practical measurement.

Table 2. Measuring devices

No.	Measuring devices Purpose
1.	Maxwell MC-25 603A For measuring the effective value of the current.
2.	Power generator for providing simple periodic current up to 180 A.
3.	FLUKE 8846 Multimeter to measure the resistance of the probe.

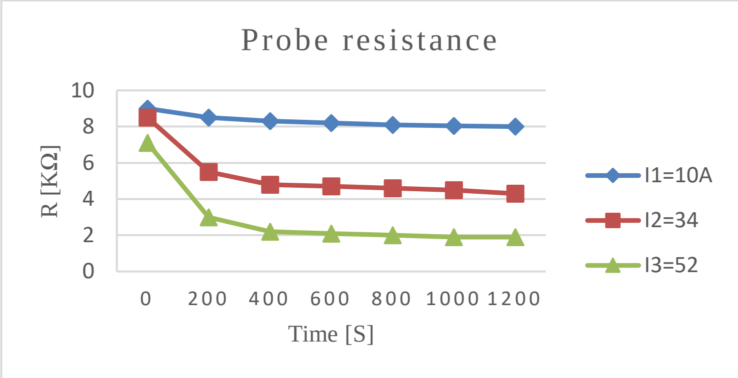

Figure 2. Graph representation of the probe resistance

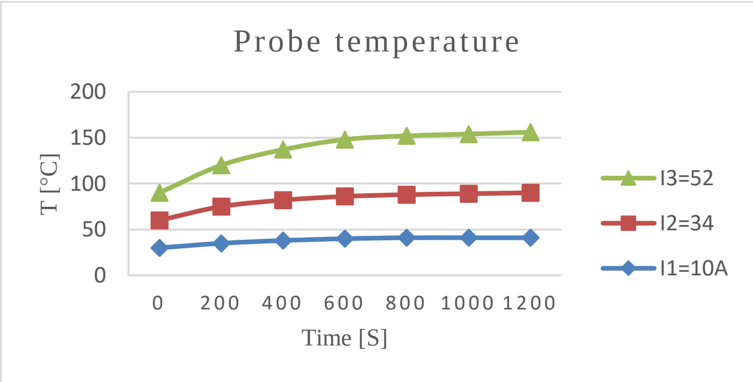

Figure 3. Graph representation of the probe temperature

3. RESULTS AND DISCUSSION

Figure 4 illustrates the temperature measurements on the surface of the copper conductor with smallest cross section, (Φ = 6 mm^2), while Figure 5 shows the temperature measurement on the conductor surface of the cross-sectional area (Φ = 8 mm^2). In Figures 4 and 5 deviations of the curves at higher currents are observed, which is a consequence of the variation of currents due to heating of the conductors and the impossibility of compensating for these changes by increasing the supply voltage of the conductors. Namely, the current in the conductor is regulated manually, using a potentiometer on the device for generating current, and this manual setting could not always monitor changes in temperature and thus changes in current.

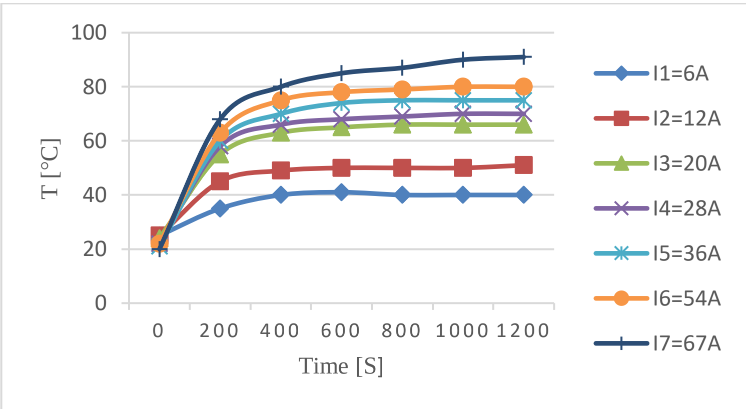

Figure 4. Graph representation of the surface temperature of the conductor Φ = 6 mm^2

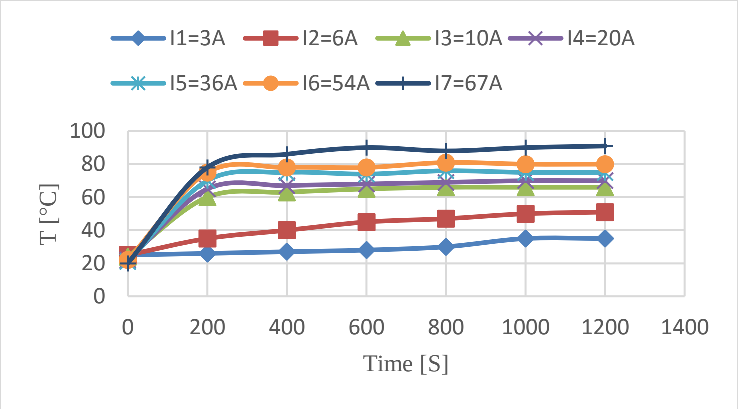

Figure 5. Graph representation of the surface temperature of the conductor Φ = 8 mm^2

Figure 6 shows the measurement of the temperature on the surface of copper conductor of the largest cross-sectional area (Φ 12 mm^2). In this case, all curves are completely smooth and grow monotonously almost all the time, which is a consequence of better maintaining a constant current and a significant increase in the temperature of the conductor. The time diagram of the temperature for the aluminum conductor is shown in Figure 7. As shown in Figure 7, the decrease in current strength, caused by the increase in specific resistance of the conductor due to the increase in temperature, is mostly successfully compensated by a timely increase in the supply voltage of the conductor, using a potentiometer on the generator.

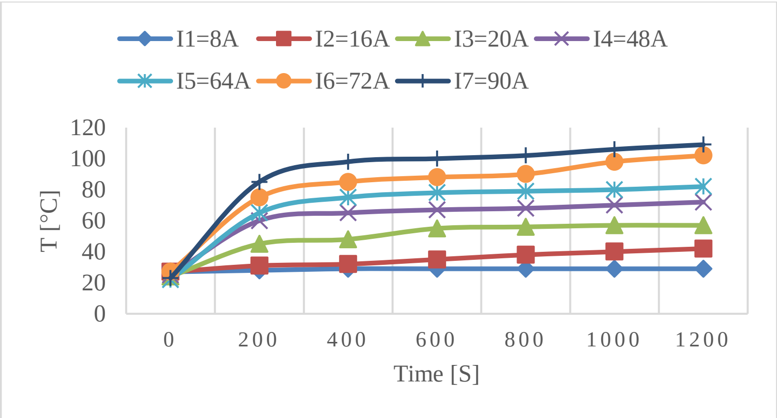

Figure 6. Graph representation of the surface temperature of the conductor with Φ =12 mm^2

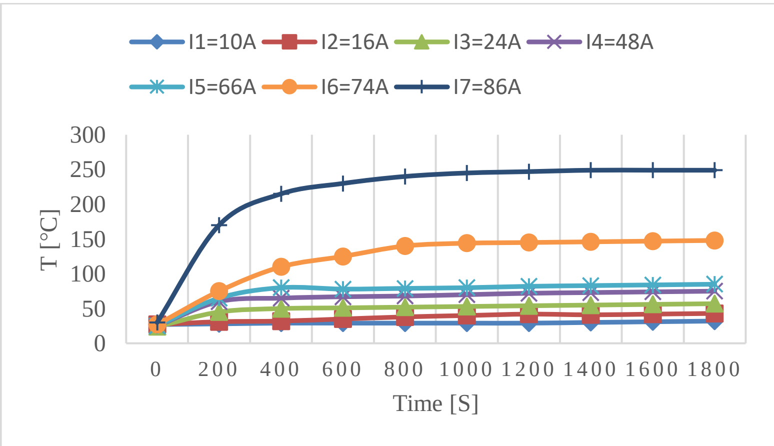

Figure 7. Graph representation of the temperature on the surface of the aluminum conductor

4. CONCLUSION

The aim of the research described in this paper is fully achieved by first determining all the necessary characteristics of the unknown temperature probe, and then using it, performed all the planned measurements. The measurement results had to be further processed using the procedures of numerical analysis, which was also successfully done. The obtained diagrams are very characteristic and can serve as typical forms of heating conductors with time-varying currents, including all the effects that accompany such currents. The results presented in this paper can also be used to verify the results obtained by calculations. In working on this issue, successfully solving all the problems that arose during the work, gained valuable experience in accurate temperature measurement.

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