TEMPERATURE MEASUREMENT AND CURRENT DETERMINATION OF HORIZONTALLY AND VERTICALLY PLACED LOW-VOLTAGE SINGLE CORE CABLE

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Abstract

This paper presents a procedure for measurement of surface temperature of a low-voltage single-core power cable with PVC insulation. Measurements were performed with the cable set into horizontal or vertical orientation, freely in the air. Three values of loading current of cable were used for measurements made in laboratory conditions. The current and the temperatures were measured during experiment. Measured cable temperatures were used for calculation of loading current of the cable and the result obtained was compared with the measured load current. The paper presents results obtained and appropriate discussion.

Keywords: power cable; heat transfer; convection, temperature measurement.

INTRODUCTION

Current-carrying capacity (or ampacity) of the cable depends on the cable construction and ambient conditions [1]. The current load of the cable that is installed in an air environment depends also on the type of material and the number of loaded conductors, insulation and sheath material, ambient temperature, number of cables installed in the group, the intensity of solar radiation, wind speed and other. The method for determining the current load and loss of the cable is defined by the standard IEC 60287 [1].

In the case of heat transfer, the power cable can be considered as long cylinder [2,3]. The heat that is generated in a conductor is transferred to the outer surface of cable sheath by conduction, and then from the cable surface to the environment by convection and radiation [2,3]. To calculate the value of cable current based on known cable surface temperatures, it is necessary to calculate the corresponding coefficient of convection. Some examples of the calculation and application of the convection coefficients are shown in [2] for horizontal and [3] for vertical orientation of the cable.

In this paper, temperature values for the horizontal and vertical orientation of the cable are obtained experimentally. Then, the cable current is calculated according to the correlation equations and compared with the measured current. A cable of simple construction was used in this paper, i.e. a single-core cable, with copper conductor and PVC insulation.

The following sections of the paper contain: the equations used in the calculations, description of the used measuring equipment and the measurement procedure and the results of the measurements with a discussion.

HEAT TRANSFER OF HORIZONTALLY AND VERTICALLY PLACED CABLE

Low-voltage single core cable with copper conductor and PVC insulation is used as the test sample in the performed experiments. It can be considered as a long cylinder. The amount of the heat that can be transferred by convection and radiation from the cable surface to the surrounding space, can be calculated using the expression [4]:

$$q'_{\text{tot}} = q'_{\text{conv}} + q'_{\text{rad}} = = h\pi D\left(T_{\text{s}} - T_{\text{a}}\right) + \varepsilon\pi D\sigma\left(T_{\text{s}}^4 - T_{\text{sur}}^4\right) \quad (1)$$

where h – convection coefficient; D – cable diameter; T_{s} – cable surface temperature; T_{a} – ambient air temperature; ε – cable surface emissivity; σ – Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m^{2}K^4); T_{sur} – ambient surface temperature.

The convection coefficient is determined based on the equation [4,5]:

$$h = \frac{k}{x}\text{Nu}_x \quad (2)$$

where k – air thermal conductivity under certain conditions, Nu_{x} – Nusselt's number, and x – specific dimension (i.e. diameter D or length L for horizontal or vertical cable, respectively).

The Nusselt number can be determined using correlation equations. For the horizontal cable orientation, a equation for horizontal cylinder can be applied [4]:

$$\text{Nu}_{\text{D}} = \left\{ 0.6 + \frac{0.387 \cdot \text{Ra}_{\text{D}}^{1/6}}{\left[1 + \left(\frac{0.559}{\text{Pr}}\right)^{9/16}\right]^{8/27}} \right\}^2 . \quad (3)$$

where Pr – Prandtl number. This equation is valid for Rayleigh number in the range of $\text{Ra}_{\text{D}} \leq 10^{12}$. In the case of a vertical cable (modeling with cylinder), a correlation equation for a vertical plate can be applied [5]:

$$\text{Nu}_{\text{L}} = \left\{ 0.825 + \frac{0.387 \cdot \text{Ra}_{\text{L}}^{1/6}}{\left[1 + \left(\frac{0.492}{\text{Pr}}\right)^{9/16}\right]^{8/27}} \right\}^2 \quad (4)$$

The equation (4) is valid for Rayleigh number in the range of $10^{-1} < \text{Ra}_{\text{L}} < 10^{12}$. Rayleigh number Ra_{x} in expression (3) and (4) can be calculated as follows [4]:

$$\text{Ra}_{\text{x}} = \frac{g\beta\left(T_s - T_a\right)x^3}{\nu\alpha}, \quad (5)$$

where g – acceleration of gravity; β – volumetric thermal expansion coefficient; ν – momentum diffusivity; α – thermal diffusivity; and x – specific dimension i.e. diameter D or length L for expressions (3) and (4), respectively. Air parameters are taken from the corresponding tables (appendix A from [6]).

The expression (4) can be used to calculate the Nusselt number for a vertical cylinder only if the following condition is met [5,6]:

$$\frac{D}{L} \geq \frac{35}{\text{Gr}_{\text{L}}^{1/4}} . \quad (6)$$

where Gr_{L} – Grashof number is calculated as the ratio of the Rayleigh and Prandtl numbers ($\text{Gr}_{\text{L}} = \text{Ra}_{\text{L}}/\text{Pr}$).

Given that the above condition is not feasible for thin cylinders, the convection coefficient h from (1) can be multiplied with the correction factor F [5]:

$$F = 1.3\left[\frac{\left(L/D\right)}{\text{Gr}_{\text{D}}}\right]^{1/4} + 1 . \quad (7)$$

When the steady state is achieved (constant cable surface temperature) total heat generated in a conductor transfers through cable insulation and sheath and is transferred to environment by convection and radiation. Since the PVC insulation and sheath are cylindrical, the total heat that is conducted through these two layers can be calculated by the following equation [6]:

$$q_{\text{tot}} = \frac{T_{\text{c}} - T_{\text{s}}}{\frac{1}{2\pi k_{ins}}\ln\frac{r_{\text{o}}}{r_{\text{i}}}}, \quad (8)$$

where T_{c} and T_{s} – are conductor and surface (sheath) temperatures, respectively; k_{ins} – thermal conductivity of insulation and sheath which is 1/6 W/mK for PVC; r_{i} and r_{o} – inner and outer radius of insulation with sheath, respectively.

Based on the measured cable surface temperature and the calculated value of total heat per unit length, the conductor surface temperature T_c can be determined by the equation (9):

$$T_c = T_s + q'_{tot}\left(\frac{1}{2\pi k_{ins}}\ln\frac{r_o}{r_i}\right), \quad (9)$$

after which the electrical resistance of a conductor $R(T_c)$ can be calculated as:

$$R(T_c) = R_{20}\left[1+\alpha(T_c - 20)\right], \quad (10)$$

where R_{20} – electrical resistance at 20 °C; α – the temperature coefficient (α_{Cu} = 0.00393 K^{-1}). Knowing the electrical resistance, the current through conductor can be calculated using the equation (11):

$$I_{calc.} = \sqrt{\frac{Q_{tot}}{R(T_c)}} = \sqrt{\frac{q'_{tot}\cdot L}{R(T_c)}}, \quad (11)$$

where Q_{tot} – total heat power; L – cable length.

Calculated value of current is compared with the measured value and a relative deviation has been expressed.

EQUIPMENT USED FOR MEASUREMENT

A single-core cable heating experiment was realized at the Faculty of Technical Sciences Cacak (Laboratory for electrical installations). The test sample is cable PP00 1×25 mm^2 with the length of 2.1 m. A total number of six measurements were performed: three measurements with different currents for each orientation of the cable (horizontal and vertical). The experimental setup is shown in Figure 1.

Cable has been set to short circuit operation through the step-down transformer (toroid) and autotransformer connected to the power network. The desired value of current through the cable is set using autotransformer. Cable current was measured using Benning CM3 type current clamp. For the horizontal orientation, the cable is placed on thin wooden supports to achieve a natural air flow around the cable (Fig. 1a). In the case of vertical orientation, one end of the cable was attached to the ceiling while other end hangs freely (Fig. 1b).

Type J thermocouples were used for measurement of surface temperature of the cable. Data acquisition equipment consists of: NI cDAQ-9174 with NI 9219 card and custom application created in LabVIEW software. A total of four thermocouples were installed: three for measuring of the cable surface temperature and one for measuring the ambient air temperature. Three thermocouples were attached to the cable surface with metal clamps, while the fourth thermocouple, that measures ambient temperature, was distanced from the cable.

(a) *(b)*

Fig. 1. *Laboratory setup for (a) horizontal and (b) vertical cable*

Before clamping the thermocouples to the cable surface, temperature deviation between thermocouples was checked and it did not exceed the value of 1 °C. Before the start of each measurement, the room conditions of free air flow around the cable were met: making sure that door and windows in the room were closed and the air conditioning was turned off.

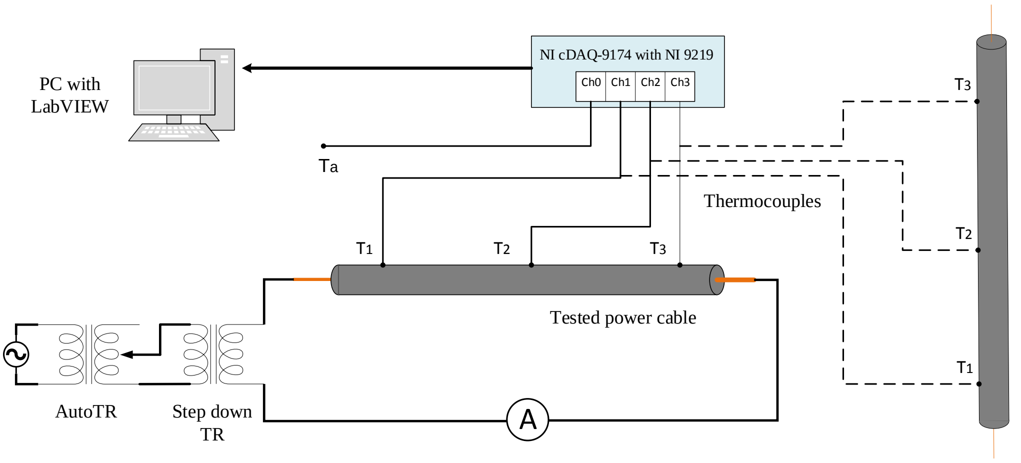

Fig. 2. *Scheme of a laboratory setup equipment with cable test sample in two orientation*

After switching on the power supply and setting the desired value of the current, the increase in temperature was causing a change in the electrical resistance of the conductor. A stable value of current was achieved by adjusting of autotransformer. The change in temperature and current was significant in the first part of the measurement, after which the effect of temperature change on resistance decreased, which is the result of the exponential stabilization of temperature. Also, changes in the supply voltage affect the value of the cable current due to the high turns ratio of step-down transformer.

MEASUREMENT AND CALCULATION RESULTS

In order to compare values of the current obtained by measurements and calculations, three measurements were performed for both cable orientations. These measurements were realized with three different current values: 130, 150 and 170 A. Each measurement lasted for an approximate period of 60 min. The displayed temperature T_s (Fig. 4 and Fig. 5) is the mean temperature of three measured points on cable surface, i.e. $T_s=(T_1+T_2+T_3)/3$.

Figure 3 shows the results of the surface cable and the environment (ambient air) temperature measurement in the case of a horizontally oriented cable. All three measurements were realized in approximately equal ambient temperatures, and in the steady state the ambient and cable surface temperatures were: 22.8 °C and 47.3 °C (for the current value of 130 A); 23.3 °C and 54.2 °C (150 A); 22.3 °C and 61 °C (170 A), respectively.

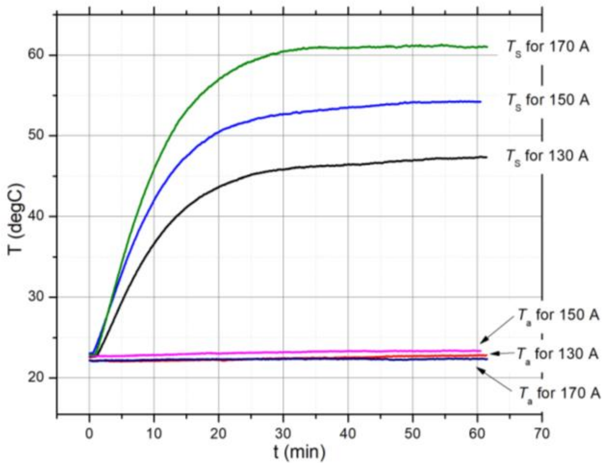

Fig. 3. *Cable surface and ambient air temperatures for horizontaly oriented cable*

Figure 4 shows the results of the surface cable and the environment temperature measurement in the case of a vertically placed cable. As with the horizontal cable orientation, the expected exponential increase of temperature was obtained.

Unlike the previous case (horizontal orientation), two measurements for vertical orientation were realized in equal ambient temperatures (for current values of 130 and 150 A). The third measurement (170 A) was performed at an ambient temperature of approximately 4 °C higher. Therefore the value of the temperature of the cable is higher at a current of 170 A. In the steady state the ambient and cable temperatures were: 20.7 °C and 44.3 °C (for the current value of 130 A); 20.7 °C and 51.3 °C (150 A); 25 °C and 63.1 °C (170 A).

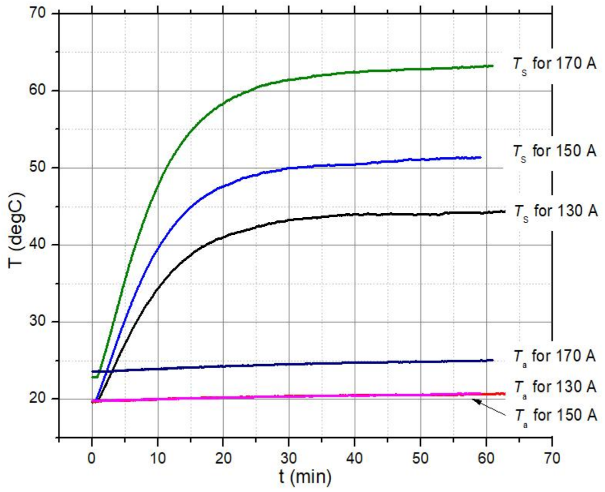

Fig. 4. *Cable surface and ambient air temperatures for vertically oriented cable*

Figure 5 shows the values of temperature differences between the cable surface and ambient air for all six measurements.

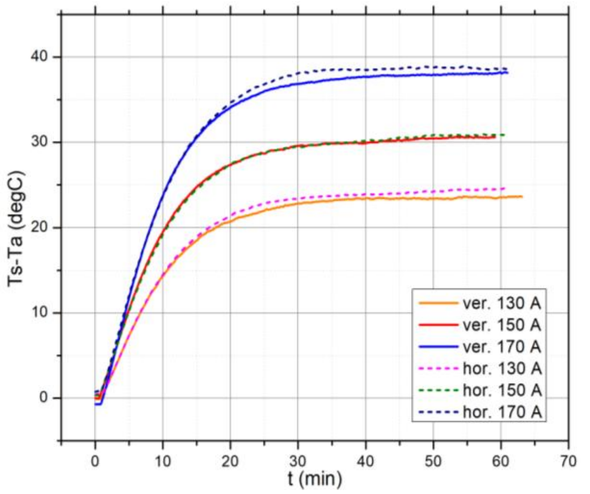

Fig. 5. *Temperature differences for all current values and orientations of the cable*

After the realized experiments of three values of currents for two orientations of the cable, stationary values of cable and ambient temperatures were obtained. These values were used to calculate the parameters of all three types of heat transfer and the value of the current through a conductor. The expressions (1)-(11) were used to calculate the value of current I_{calc} through a conductor. After that, the calculation of deviation from a measured value of current was calculated using the equation:

$$\delta I = \frac{I_{calc.} - I_{meas.}}{I_{meas.}} \cdot 100[\%]. \qquad (12)$$

where I_{meas} – measured current.

Data obtained by calculation for a horizontally and vertically oriented cable for all three values of current is shown in tables 1 and 2.

Tab. 1. *Data obtained by calculation for a horizontally oriented cable*

Calculated parameters	Measured current value [A]		
	130	150	170
h [W/m^{2}K]	7.804	8.222	8.631
q'_{tot} [W/m]	12.383	16.342	21.301
I [A]	125.5	141.9	160.5
δI [%]	**–3.5%**	**–5.4%**	**–5.6%**

Tab. 2. *Data obtained by calculation for a vertically oriented cable*

Calculated parameters	Measured current value [A]		
	130	150	170
h [W/m^{2}K]	6.24	6.594	6.916
q'_{tot} [W/m]	10.474	14.21	18.841
I [A]	116.3	133.3	149.7
δI [%]	**–10.5%**	**–11.1%**	**–11.9%**

It can be noted that the difference between the measured and calculated currents in a horizontally oriented cable ranges from –3.5 to –5.6%, which can be considered a satisfactory result. In addition, the calculated results for the vertical oriented cable have approximately twice the difference compared to the horizontal orientation of the cable, i.e. from –10.5 to –11.9%. A larger deviation, in this case, may have been occurred due to the error introduced by the correlation equation and the correction coefficient. Furthermore, it should be noted that the small amount of heat was dissipated at the cable ends (connections), which was neglected in this calculation.

CONCLUSION

The paper presents results of measurements of cable current and temperatures, as well as the method for calculation of cable current under certain conditions (cable orientations and surface and ambient temperatures) and the results obtained.The heat transfer equations for a horizontal and vertical cylinder are used in calculations to model the cable. The obtained results have an average percentage difference of about 5% and 11% for horizontal and vertical cable orientation, respectively.

Future research should focus on the study of reducing the deviation of a current value of a vertically oriented cable by researching other correlation equations. In addition, the value of heat dissipation at the connecting ends of the cable should be analyzed.

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