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Educational Setup for Power Cable Loading and Temperature Measurement

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Abstract: *This paper presents the equipment and procedure for temperature and current measurement on the low-voltage cables. Presented setup can be applied in teaching courses in the field of electrical installations, electrical heating or thermodynamics as a practical laboratory exercise. Two PVC insulated cables with different cross-sections were used as samples. A procedure for determining the heat transfer parameters of a cable modelled by a horizontal cylinder is also described. The values of the current obtained by the measurements were compared with the calculated values.*

Keywords: *power cable; heat transfer; temperature measurement; LabVIEW*

1. INTRODUCTION

As with most components in the electrical power systems, heating of power cables is mainly caused by internal losses, i.e. losses generated in conductors. The steady-state temperature of power cables is one of the most important parameters, which is 70 °C for PVC insulation, and 90 °C for cross-linked polyethylene. Current-carrying capacity (or ampacity) of the cable is determined by the characteristics of the cable: conductor material, number of loaded conductors and insulation material, as well as external conditions such as: installation type, ambient temperature (air or ground), number of cables laid in groups, thermal resistance of soil, intensity of solar radiation and wind speed. The current load of power cables and their losses are defined by the IEC 60287 and can be modelled with thermal-electric circuit [1, 2].

The cable in which heat is generated due to losses is cylindrical in shape and can be considered as long isothermal cylinder. Therefore, heat transfer equations for the cylinder can be applied and then current value can be calculated. Temperature and current measurement can be performed under controlled conditions in the laboratory. The values of current obtained by measurements can be compared with the values obtained by calculation.

The experimental setup presented in this paper was realized in the Laboratory for Electrical Installations at the Faculty of Technical Sciences in Čačak. This experiment can be applied as a practical exercise for students in subjects such as: Electrical installations, Electrical heating or Thermodynamics.

2. HEAT TRANSFER FROM HORIZONTAL CABLE

The single-core power cable, placed horizontally in the air, can be modelled with a thin horizontal cylinder. Also, cable insulation and sheath can be modelled with a hollow cylinder. Known temperatures of ambient and cable surfaces are used for determining the intensity of current through a conductor in the calculation procedure shown below.

Measurements are performed in the closed environment, simulating a case in which the only heat source is caused by losses in the cable conductor due to the current, i.e. excluding heat sources due to solar radiation.

Heat dissipation through the connecting ends of the conductors was neglected during the described calculation. The influence of the skin effect on the additional increase of the electrical resistance of the conductor, which can be calculated using the expressions given in [3] is also neglected.

The specific heat per unit length that is transferred from the surface of the cable to the environment (air) by convection and radiation can be determined by the following equation

$$\begin{aligned} q_{\text{tot}} &= q_{\text{conv}} + q_{\text{rad}} = \\ &= h\pi D\left(T_s - T_a\right) + \varepsilon\pi D\sigma\left(T_s^4 - T_{sur}^4\right), \end{aligned} \tag{1}$$

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 which is $5.67 \cdot 10^{-8}$ W/m^{2}K^4; T_{sur} – ambient surface temperature. The convection coefficient is determined based on the equation

$$h = \frac{k}{D} Nu, \tag{2}$$

where Nu – Nusselt's number; k –air thermal conductivity under certain conditions. The Nusselt number for the case of a horizontal cylinder can be determined based on a correlation formula [4]

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

That applies to $Ra \leq 10^{12}$, Ra – Rayleigh number calculated using a following equation

$$Ra = \frac{g\beta(T_s - T_a)D^3}{\upsilon\alpha}, \tag{4}$$

where g – acceleration of gravity; β – volumetric thermal expansion coefficient; ν – momentum diffusivity; α – thermal diffusivity; and Pr – Prandtl number. All parameters for air were taken from appendix in [4]. In the steady-state conditions, the specific heat flux that is transferred from the surface of the cable by convection and radiation is equal to heat generated in the conductor. The heat that is transferred by conduction to the surface of the cable through insulation and sheath is

$$q_{\mathrm{tot}} = \frac{T_{\mathrm{c}} - T_{\mathrm{s}}}{\frac{\rho_{\mathrm{th}}}{2\pi} \ln \frac{d_2}{d_1}}, \tag{5}$$

where T_{c} and T_{s} – are conductor and (sheath) surface temperatures, respectively; ρ_{th} – thermal resistance of insulation and sheath which is 6 Km/W for PVC; d_1 and d_2 – inner and outer radius of insulation with sheath, respectively.

If the temperature of the cable and the total specific heat flux values are known, the temperature on the surface of the conductor can be determined by the following equation:

$$T_{\mathrm{c}} = T_{\mathrm{s}} + q_{\mathrm{tot}} \left(\frac{\rho_{\mathrm{th}}}{2\pi} \ln \frac{d_2}{d_1} \right). \tag{6}$$

The electrical resistance of the conductor at temperature T_{c} is

$$R_{T_{\mathrm{c}}} = R_{20} \left[1 + \alpha (T_{\mathrm{c}} - 20) \right], \tag{7}$$

where R_{20} – electrical resistance at 20 °C; α – the temperature coefficient which is $\alpha_{\mathrm{Cu}} = 0.00393$ K^{-1} for copper. Based on the steady-state temperatures and specific heat flux, the current can be calculated using the equation

$$I = \sqrt{\frac{Q}{R_{T_{\mathrm{c}}}}} = \sqrt{\frac{q_{\mathrm{tot}} \cdot \ell}{R_{T_{\mathrm{c}}}}}, \tag{8}$$

where Q – total heat flux; ℓ - cable length.

3. USED EQUIPMENT AND MEASUREMENT PROCEDURE

Two samples of single-core low-voltage power cables type were used for the purposes of the experiment: PP00 1 × 25 mm^2 and PP00 1 × 35 mm^2. The length of both cables was 2.1 m. Figure 1 represents the used laboratory equipment, and Figure 2 represents the scheme of the experimental setup. The power cable that is being tested (1) was connected to the secondary of step-down transformer (2) with a transmission ratio of 350:4. The current of the cable directly depends on the primary voltage of the step-down transformer, so current value was adjusted using the autotransformer (3). The tested cables were placed on a thin vertical wooden support (4). This created the condition of natural air flow around the horizontally placed cable.

The current of the cable was measured using current clamps *Benning* CM 3 (5). The current was adjusted by reading the current value from the current clamps and regulating the voltage on autotransformer. Four J type thermocouples (6) and acquisition equipment (7): NI 9219 card with NI cDAQ-9174 chassis were used for temperature measurement. A total of four thermocouples were used: three for measuring the cable surface temperature and one for measuring the ambient temperature, i.e. ambient air. The cable surface temperature T_{s} was determined as the mean value of measured temperatures of all three thermocouples.

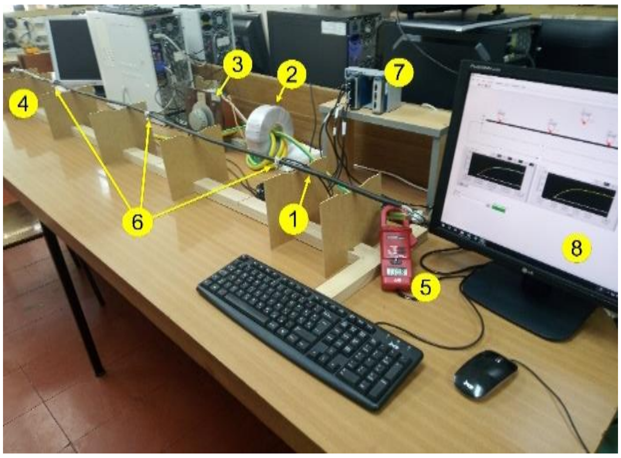

Figure 1. *Laboratory measuring equipment*

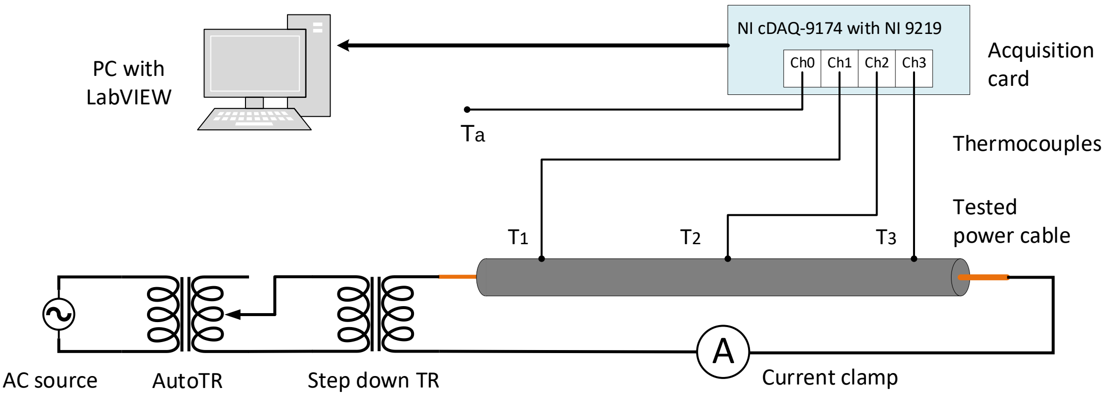

Figure 2. *Diagram of experimental setup*

The measured temperatures are downloaded and processed on a computer (8) i.e. created program in *LabVIEW* software. A user front panel shown in Fig. 3 was created in the *LabVIEW* software. This front panel shows the values of temperature on the surface of the cable at three measuring points, their mean value, and the ambient air temperature at one point. In addition to the temperature values, the program provides diagram of temperatures change over time. All measured temperature values can be recorded simultaneously in a *.xls* file.

Before the start of the measurement, the required natural air flow around the cable is achieved. Also, all windows and doors in the room were closed before and during the measurement and the air conditioner was turned off, which reduced the forced air flow in the room to a minimum. Before connecting autotransformer to the AC source (230 V, 50 Hz), the program was started and data recording was enabled. After that, the current of the cable is set to the desired value using an autotransformer. At the beginning of the measurement, a sudden increase in temperature is expressed, which leads to an increase in electrical resistance and a decrease in current, so a decrease in current is prevented by increasing the voltage.

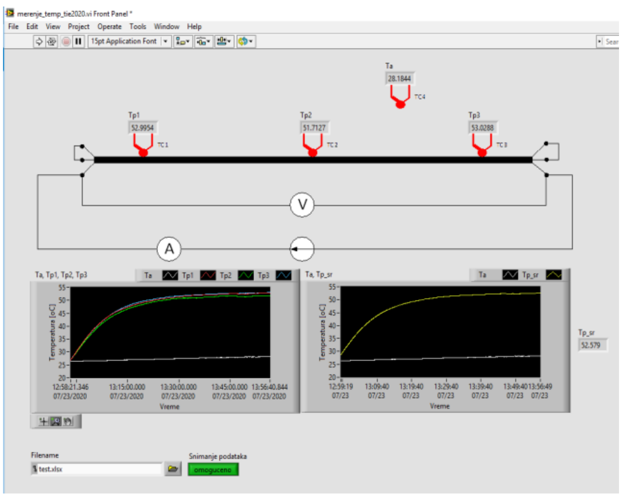

Figure 3. *Front panel in LabVIEW software*

Since it was necessary to maintain the value of the current load through a tested power cable, a continuous voltage adjustment using autotransformer was necessary. Measurement was ended when a steady state occurs.

4. MEASUREMENT RESULTS

The data processing and graphical display of the measured temperatures for two cables of different cross-sections were performed after the measurement. Figure 4 shows measured values of temperatures at the surface and ambient air for the PP00 1×35 mm^2 power cable. This cable was tested with two different load currents: 150 A and 180 A. In both cases, it is noticeable that the increase in cable temperature is exponential. Also, the increase in ambient temperature slightly contributes to the increase in cable temperature. The increase in ambient temperature was inevitable due to the existence of a heat source in the room. When the steady state occurred, the ambient and cable temperatures were 28 °C and 52 °C at a current value of 150 A, while temperatures were 28 °C and 62 °C at a current value of 180 A.

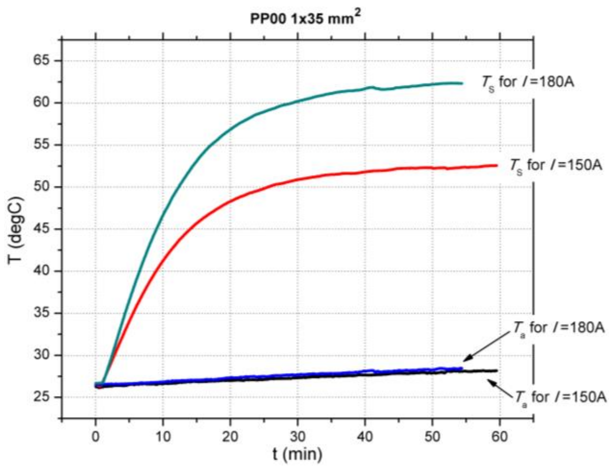

Figure 4. *The ambient and cable temperatures of 35 mm^2 power cable (150 A and 180 A)*

Figure 5 shows measured values of temperatures at the surface and ambient air for the PP00 1×25 mm^2 power cable. As in the previous case, this cable was also tested with two different load currents: 130 A and 150 A. These two measurements were made under different ambient conditions, so the temperature of the ambient is also different. At a current of 130 A in the steady state, the ambient and cable temperatures were 27 °C and 51 °C, respectively. At a current of 150 A, these temperatures were 29 °C and 60 °C, respectively.

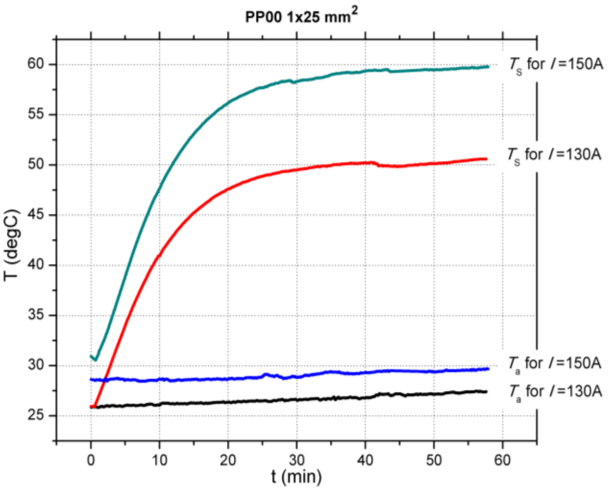

Figure 5. *The ambient and cable temperatures of 25 mm^2 power cable (130 A and 150 A)*

After the experiments, the values of the currents obtained by measurements and calculations were compared using equations (1)-(8):

(i) For the 35 mm^2 power cable with a current of 180 A: ambient and surface temperature are 29 °C and 62 °C, respectively which corresponds to the value of specific heat 18.61 W/m and current value of 179.8 A. The relative deviation in relation to the measured value of 180 A is **−0.11%**.

(ii) For the 35 mm^2 power cable with a current of 150 A: ambient and surface temperature are 28 °C and 52 °C, respectively which corresponds to the value of specific heat 12.74 W/m and current value of 149 A. The relative deviation in relation to the measured value of 150 A is **−0.67%**.

(iii) For the 25 mm^2 power cable with a current of 130 A: ambient and surface temperature are 27 °C and 51 °C, respectively which corresponds to the value of specific heat 12.26 W/m and current value of 124.1 A. The relative deviation in relation to the measured value of 130 A is **−4.54%**.

(iv) For the 25 mm^2 power cable with a current of 150 A: ambient and surface temperature are 29 °C and 60 °C, respectively which corresponds to the value of specific heat 16.71 W/m and current value of 142.2 A. The relative deviation in relation to the measured value of 150 A is **−5.32 %**.

Based on the results of temperature and current measurements and comparison with the calculated values, a satisfactory deviation in values was noticed, with a low percentage difference in current values. As pointed out in the second section, the part of the heat was dissipated through the conductor connections to the power cable. Neglecting that part of the heat affects the total value of the calculated specific heat *q* in reality has a higher value, and therefore the calculated current has a higher value.

5. CONCLUSION

The expected correlation between the cable temperature, the ambient temperature and the load current is proved through the examples presented in this paper. Also, the measured values were compared with the calculated values in heat transfer at the horizontal cable which gave small percentage difference.

Presented experimental setup for current load and temperature measurement of power cables can be helpful to students as a practical exercise in subjects such as: Electrical installations, Electrical heating or Thermodynamics (heat transfer). By implementing this setup in the mentioned subjects, student can confirm the results of calculations in all three methods of heat transfer and current load of cables. Also, by working on this setup, they can get familiar with the one of the methods for temperature measurement and the conditions for obtaining and controlling currents in laboratory conditions.

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REFERENCES

[1] *Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100% load factor) and calculation of losses –* General IEC 60287-1-1, 2006.

[2] Sedaghat, A., León, F. (2015). *Thermal analysis of power cables in free air: Evaluation and improvement of the iec standard ampacity calculations*. doi: 10.1109/TPWRD.2013.2296912

[3] Тасић, Д. (2001). *Основи електроенергетске кабловске технике*. Ниш: Електронски факултет.

[4] Moran, M. J., Shapiro, H. N., Munson, B. R. & DeWittet, D. P. (2003). *Introduction to thermal systems engineering: thermodynamics, fluid mechanics, and heat transfer*. John Wiley & Sons.