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Modelling the thermal effect of solar radiation on the ampacity of a low voltage underground cable

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ABSTRACT

Compared with other underground cables, low voltage cables are most intensely heated by the sun due to the low laying depth. Accordingly, the main purpose of this paper is to show how the heat of solar radiation affects the ampacity of a 0.4 kV multi-core cable through different cool pavements at laying depths between 0.4 and 1.0 m where this effect is significant. The objectives of this study are as follows: (i) to simulate experimentally the effect of thermal emissivity of the cool pavement surface on the cable in known laboratory conditions, (ii) to express the effect of solar absorptivity of the cool pavement surface on the cable based on an analogy between the thermal effect of the laboratory interior and the thermal effect of outdoor solar radiation, and (iii) to simulate numerically the thermal effect of solar radiation using a large-size FEM-based model for the most unfavourable summer conditions and the most common winter conditions. All the defined objectives have been successfully met and it has been shown that the ampacity of the cable installed at a depth of 0.7 m can be increased up to 45% in summer and up to 12.1% in winter compared to the corresponding base cases.

1. Introduction

Investigations of cool materials for pavements and roofs, in order to reduce the heating of public urban areas and thereby reduce electricity demand for air conditioning in the summer months, have been carried out at the end of the 20th century and the beginning of the 21st century [1,2]. In particular, all these were attempts to reduce the so-called 'urban heat island effect' (UHI effect). Analysing the results published on the topic of UHI effect, the authors came to the idea that cool pavements can also be used to increase the ampacity of underground power cables [3,4]. In this manner, according to [3], the ampacity of a 110 kV underground cable line adjacent to heating pipeline can be increased up to 25.4% for the most unfavourable summer conditions and up to 8% for the most common winter conditions. If there is no heating pipeline, then there is a possibility to increase the ampacity of this cable line up to 26.7% in summer under the same conditions [4]. Compared to 110 kV underground cables, which are usually installed at a depth of 1.5 m, low voltage cables (in accordance with relevant standards) are laid at a depth of 0.7 m where the thermal effect of solar radiation is significantly more pronounced.

The thermal effect of solar radiation on underground power cables is not covered by standards such as IEC 60287 [5], technical report IEC TR 62095 [6] or 2017 edition of NFPA 70 [7]. This is the basic reason why the effect of solar radiation is neglected by most researchers who deal with the heating and loading problems of underground power cables [8–10]. Among the researchers who considered this effect, there are those whose conclusions were consistent with the relevant IEC standards [11], those who found that solar radiation only affects the cables laid at low depths [12], as well as those who concluded that the effect of the sun can not be ignored in the case when the daily load peak coincides with the period of maximum solar activity [13,14]. In addition, the authors of this paper have previously found that the negative thermal effect of solar radiation on the ampacity of underground cable lines can be minimised using cool pavements [3,4]. Since all the results from Refs. [3,4,11–14] refer to power cables with rated voltages greater than 35 kV, it is interesting to see how the heat of solar radiation affects the ampacity of a 0.4 kV underground multi-core cable at different laying depths.

There are also a large number of research papers dealing with thermal analysis of underground power cables, such as [15–19]. However, along with these papers, many other publications which are not mentioned here do not take into account the effects of thermal

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emissivity and solar absorptivity of the pavement surface (pavement surface radiation properties) on the ampacity of underground power cables. In addition to the pavement surface radiation properties, the cable ampacity is also affected by thermal conductivity, thermal diffusivity and temperature of soils. It is possible to control these parameters using cool pavements, special cable beddings and systems for forced cooling or irrigation of cable beddings. So, there is a possibility to change the pavement surface radiation properties using cool pavements, the thermal conductivity and diffusivity of soils using special cable beddings, the soil temperature using systems for forced cooling, and all the parameters with the exception of the pavement surface radiation properties using systems for irrigation [3,4]. According to [20], special cable beddings, systems for forced cooling and systems for irrigation belong to conventional methods for controlling the thermal environment of underground power cables. Therefore, the application of cool pavements represents a completely new method.

For the purposes of this paper, a number of experiments were carried out to simulate the effect of the pavement surface emissivity on a physical model of an underground PP-00 4 × 16 mm^2 0.6/1 kV cable in a laboratory, where there was no solar radiation and where other ambient and boundary conditions were known. The low voltage multi-core cable and its internal heat sources were modelled by a copper pipe and a tubular heater, respectively. In order to analyse the effect of the surface radiation properties of different pavements on the thermal environment around the copper pipe, the pavement made of concrete blocks was coated with a white acrylic paint and a black one.

The transition from known laboratory conditions to appropriate outdoor conditions was carried out using an analogy between the thermal effect of the laboratory interior and the thermal effect of outdoor solar radiation, and by adjusting the outer surface temperature of the cable (using the volume power of heat sources in the energised conductors) to values corresponding to experimentally obtained temperatures of the copper pipe. With the transition to the actual ambient conditions in the thermal FEM-based modelling of the underground cable, the external dimensions of the small-size geometric model (domain) corresponding to experimental setup are also changed from 0.6 m × 0.49 m to 40 m × 21.5 m (which are about four times larger than those recommended in IEC TR 62095). Three different laying depths of the cable were considered, namely: 0.4 m (which approximately corresponds to experimental setup), 0.7 m (which is selected in accordance with the relevant technical report) and 1.0 m (which is chosen as the maximum possible depth at which a 0.4 kV cable can be installed). The thermal effect of solar radiation is included in the small- and large-size FEM models by means of a constant heat flux boundary condition.

The effect of solar radiation, i.e. cool pavements on the 0.4 kV underground multi-core cable is then analysed. It is also described how a cool pavement may be used as a mean to control the thermal environment surrounding the cable, as well as its ampacity. Also, it is assumed that the three-phase system is balanced, that the heat flux at a reference distance is 0 W/m^2, and that the cable trench is 0.5 m wide (which corresponds to experimental setup) and covered with a cool pavement. The following two cases are taken into consideration: (i) when the cable is installed in the bedding of standard size; and (ii) when the cable is installed in the trench completely filled with bedding material. According to the DIN VDE standards, the PP-00 4 × 16 mm^2 0.6/1 kV cable considered herein corresponds to the NYY type.

2. Experimental setup and materials

The experimental setup included heating the physical model of the 0.4 kV underground power cable with a regulated temperature of its outer surface, in the known thermal environment, without solar radiation. Fig. 1 shows a schematic diagram of the experimental setup for testing the thermal emissivity and solar absorptivity of different pavement surfaces. The thermal conductivities of all used materials are listed in Table 1, while the radiation properties of pavement surfaces, coatings and paints are summarised in Table 2. The parameters appearing in Tables 1 and 2 are used in experiments and FEM-based simulations, and have the following meanings: k is the thermal conductivity, α is the solar absorptivity and ε is the thermal emissivity.

The following experiments were performed: (i) with pavement made of concrete blocks, (ii) with concrete pavement coated with acrylic white paint, and (iii) with concrete pavement coated with acrylic black paint.

In these experiments, the J-type thermocouples were installed on the copper pipe at four different points (P1-P4), including the inner wall surface of the container (P5), the lower and upper surfaces of the pavement (P6 and P7) and the air (P8). The thermocouple P1 was directly connected to a microprocessor-based temperature regulator (NIGOS 1011P), while the thermocouples P2-P8 were connected through a data acquisition system (Agilent 34970A) to a laptop to collect the temperature data. The experiments were conducted using a 0.8 kW heater. The heater was mounted in the center of the copper pipe and connected to the power supply network by means of an auxiliary relay (SCHRACK multimode relay MT 326230). The temperatures at points P2-P4 were controlled by adjusting the temperature at point P1 with an error less than 1 °C for ambient temperatures 0–50 °C [3,4]. A specified control temperature at point P1 was fixed at 51, 56 and 61 °C. The temperature of the air was adjusted at 23 °C with an accuracy of ± 1.5 °C [3,4]. In order to study the steady-state temperature distribution, temperatures at 8 h from the start of each experiment were noted. The references [3,4] provide much more details on the experimental setup and procedure, as well as photographs of the experiments and more measurements performed with the same setup.

3. 2D FEM-based heat conduction model

Except for the verification of the experimental observations, the purpose of simulations in the present study is to include and quantify the thermal effect of solar radiation. Accordingly, a two-dimensional (2D) FEM-based model is designed based on the second order nonlinear partial differential equation for steady-state heat conduction [3,4]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+Q_v=0 \tag{1}$$

where k is in W/(m·K); T is the temperature in K; x, y are Cartesian spatial coordinates in m; and Q_v is the volume power of heat sources in W/m^3. Although the equation (1) is written as a linear equation, FEM-based modelling, simulations and analysis of temperature distribution over computational domains will be non-linear due to the radiation boundary condition.

If the effect of heating pipeline is excluded, if the three 110 kV single-core cables are replaced by one 0.4 kV four-core cable, and if the dimensions of the cable trench are consistently reduced, then the FEM-based models from Refs. [3,4] reduce exactly to the one used in this paper. This means that the heating pipeline is replaced by the native soil and the 1.2-m-wide trench is replaced by a 0.5-m-wide trench. Three different depths of the trench are considered: 0.5, 0.8 and 1.1 m.

The PP-00 4 × 16 mm^2 0.6/1 kV cable is modelled by an equivalent construction composed of the four round copper conductors and outer PVC sheath with outer diameters 0.0048 and 0.022 m, respectively. In addition, it is assumed that the core insulations, filling of unvulcanised rubber and outer sheath represent one object (i.e. block) having the same thermal conductivity as PVC. The transverse cross-section shown in Fig. 1 represents the small-size computational domain that will be used for the verification of the experimental observations. Fig. 2 illustrates the large-size computational domain for the case when the cable is laid in the bedding of a standard size 0.5 m × 0.4 m.

The software package COMSOL is used to solve a system of second

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