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Evaluation of the loading capacity of a pair of three-phase high voltage cable systems using the finite-element method

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ABSTRACT

A finite-element model is developed for the analysis of the heating of a pair of three-phase 110 kV underground cable systems in normal and emergency conditions. The main contribution of the paper is the inclusion of the solar emission and radiation in the evaluation of the ampacity of cables and the analysis of their effects. In addition, alternative approaches in dealing with emergency cases are studied providing a reference for future applications in practice. The model developed is used for the study of a practical case being under construction in Belgrade city area.

1. Introduction

The evaluation of the loading capacity of underground HV cable systems installed in urban area is a complex task as it implies the consideration of many specific factors including cable trench profile, and the properties of bedding and of various backfill materials and covers. Thoroughly elaborated analytical approaches addressing the stationary cyclic load diagrams of cables have been provided in the past [1,2]. Analytical methods have been also developed for calculating the heating of cable bundles laid out in air in buildings [3] and buried in ground [4,5], both in steady-state and transient conditions. The boundaries of the drying out area around the cables have been approximately modeled by a cylindrical isothermal plane at the critical temperature for drying out of the soil, determined based upon a series of experiments [6]. The aforementioned approaches provide good answers in the most of cases in practice. However, the idealizations introduced related to various structural details and thermal characteristics of materials used in cable trenches reflect upon the results obtained. The method of finite-elements enables a more detailed modeling of cable trenches. In [7], this method has been used for the analysis of the temperature rise of cables in case of step function loads, by assuming a uniform environment. A more complex model that takes into account the real shape and structure of cables and trench has been elaborated in [8]. The present paper uses an enhanced version of the previously mentioned model, which now incorporates also the effects of the heat transfer by radiation and solar emission, to evaluate the loading capacity of a pair of three-phase cable systems sharing the same trench. These two phenomena partially compensate each other at specific ambient condition, which explains the good behavior of the model suggested in [8] when compared with experimental results [9]. However, the model presented in this paper accounts for all processes affecting the heating of cables and, therefore, can be applied in all ambient conditions appearing in practice. It is used for analyzing various loading conditions of the considered cable systems including overloads caused by outages.

2. Finite-element model

2.1. Linear approximation of radiation expression

The heat emitted by the radiation from a not black body per unit surface equals, with respect to the Stefan–Bolzmann law [10],

$$R = \sigma\varepsilon_0(\vartheta + 273)^4 \tag{1}$$

ϑ designates the body temperature, and σ and ε_0 are the radiation and emissivity constants. The relevant value for the radiation constant is $\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4). For the emissivity constant the value $\varepsilon_0 = 0.95$ is adopted, which is characteristic for a grey body as is the pavement above the trench. For a modest range of temperatures (ϑ_1, ϑ_2) Eq. (1) can be approximated by a linear function

$$R = \sigma\varepsilon_0 g_0 \vartheta \tag{2}$$

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with slope g_0 satisfying the relationship

$$g_0\sigma\varepsilon_0\int_{\vartheta 1}^{\vartheta 2}\vartheta d\vartheta = \sigma\varepsilon_0\int_{\vartheta 1}^{\vartheta 2}(\vartheta+273)^4 d\vartheta \quad (3)$$

that gives

$$g_0 = \frac{2((\vartheta_2+273)^5-(\vartheta_1+273)^5)}{5(\vartheta_2^2-\vartheta_1^2)} \quad (4)$$

If the heat dissipated in the air from the cable trench surface should be determined, then temperatures ϑ_1 and ϑ_2 are the extreme seasonal pavement temperatures. Parameter g_0 should be separately determined for each season for which the loading capacity analysis has to be performed.

A linear function can also approximate the ambient (air) radiation, acting as a thermal load for cables. The slope of this function is determined by Eq. (4) with ϑ_1 and ϑ_2 being extreme air temperatures in the period under consideration.

2.2. Solar emission

The solar emission is, in authors' country, E = 0.65 kW/m^2 in winter and E = 1.35 kW/m^2 in summer, during characteristic periods of day. The exposed bodies absorb a portion of this heat, proportionally to the body apsorptivity constant. For grey colored pavement surface this constant equals α_0 = 0.80.

2.3. Effect of draining out of soil

Based upon a wide set of experimental results, the following empirical expression is constructed for determining the temperature of the boundary isotherm separating the drying out and non-drying out areas [6]

$$\vartheta_B = \vartheta_S + 15 + (1-m)\frac{100}{3} \quad (5)$$

with ϑ_S and m being the soil temperature and cable load factor, respectively. In Eq. (5), the temperatures are in °C.

2.4. Transient temperature equation

The transient temperature equation for the cables' subspace partitioned into a network of finite elements with N nodes has the following general form

$$[C]\frac{d[\vartheta(t)]}{dt} + [K][\vartheta(t)] = [R(t)] \quad (6)$$

The mathematical model developed in [8] is enhanced by including the radiation and solar emission effects, for completeness. In Eq. (6), $[\vartheta(t)]$ is N dimensional column vector of temperatures of nodes, $[C]$ is N by N heat capacitance matrix, $[K]$ is N by N heat conductance, convection and radiation matrix, and $[R(t)]$ is N dimensional heat load vector stemming from internal heat generation and surface convection, ambient radiation, and solar emission. All these matrices and vectors are formed from the corresponding data for the finite elements covering the space domain under consideration. The parameter matrices in Eq. (6) are

$$[K] = [K_c] + [K_h] + [K_r] \quad (7)$$

$$[R(t)] = [R_Q(t)] + [R_h(t)] + [R_r(t)] + [R_s] \quad (8)$$

Indices c, h, r and s in Eqs. (7) and (8) denote conduction, convection, radiation and solar emission, respectively. Index Q refers to the element internal heat generation. The Joule losses in phase conductors and metallic sheaths including the change of associated resistances with temperature are taken into account as well as the dielectric losses in the insulating materials. Triangular finite elements are used in this analysis. The matrices figuring in Eqs. (6)–(8) are obtained by transferring the corresponding relationships for elements written for their nodes in local coordinates (Appendix A) to entire network numbering scheme. Eqs. (7) and (8) in their general form relate only to the boundary elements with edges lying on the pavement surface. For all other nodes, only $[K_c]$ and $[R_Q(t)]$ are not null matrices. For nodes remote from cables, temperatures are fixed at the presumed ambient temperature. It is clear that for equally loaded pair of cable systems the analysis of the temperature field could be performed for a half of the space under consideration separated from the other half by the plane of symmetry between the systems. Then, the boundary conditions for the edges of elements lying in this plane would be no heat transfer through the plane. However, as this paper investigates emergencies with significantly different current flows through the considered two cable systems, such a simplification of the approach was not possible.

By discretization for a minor step Δt Eq. (6) converts into a simple recurrent relationship for determining temperature variation in time [8,11]

$$[K_E][\vartheta(t_{n+1})] = [R_E(t_{n+1})] \quad (9)$$

where

$$[K_E] = \gamma[K] + \frac{[C]}{\Delta t} \quad (10)$$

$$[R_E(t_{n+1})] = \left[-(1-\gamma)[K] + \frac{1}{\Delta t}[C]\right]\cdot[\vartheta(t_n)] + (1-\gamma)[R(t_n)] + \gamma[R(t_{n+1})] \quad (11)$$

with γ being the integration stability factor. In this analysis $\gamma = 1/2$ and Δt = 5 min has been adopted as in [8], providing a good accuracy with the modest computer time consumption.

In Eq. (6), we assumed that the heat capacities of materials under consideration do not depend on the temperature. In the processes of heating of underground cables, the temperatures of materials rang from the ambient temperature to maximum 90 °C, which is a quite narrow interval. Therefore, such an assumption is generally taken as justified [2,5–7]. Otherwise, the variation of heat capacities with temperature could be easily modeled in the stepwise calculation process described in this paper.

2.5. Loading capacity evaluation

The practical task is to determine the maximum loading capacity of a pair of three-phase cable systems supplying the same consumption area by taking into account as detailed as possible the cable trench shape and impacts of various materials including non-draining mixture, backfill and covers. Possible emergencies of various durations are also considered. These situations can arise after the outage of one of the cable systems causing an extra load for the sound system. The maximum allowable conductor temperature during the emergencies must not exceed this maximum temperature for normal daily cycling loads, for security reasons.

The required input data for the calculation process are the per unit cyclic load diagram for cables in normal operation, and the duration, the magnitude and the shape of the superimposed emergency load.

The calculation procedure implies the following steps:

1. Adopt the magnitudes of the considered cyclic diagram that should serve as an initial guess at the final solution.
2. For a set of succeeding daily diagrams, using Eq. (12), calculate the temperatures of network nodes. Proceed with this calculation until the stationary temperature pattern is reached. If the draining out condition is met during the calculation flow, change