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Analysis of underground cable ampacity considering non-uniform soil temperature distributions

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ABSTRACT

An analytical model for the assessment of cable ampacity due to non-uniform underground temperature distribution is presented. The uneven underground temperature is usually caused by a non-uniform surface heating (e.g., a street or parking crossing, etc.), which is extended for certain length along the cable installation and in depth. The underground temperature distribution is obtained by solving the heat equation with the respective boundary conditions. The cable ampacity reduction is calculated as a function of the surface temperature distribution and the cable depth of burial. The model is validated and several numerical results are obtained for different installation conditions.

1. Introduction

The use of high-voltage underground cables for energy distribution is increasing every year due to their practical advantages, esthetics, and low environmental impact [1]. In order to improve cable reliability, it is important to determine the maximum allowed currents in a given installation. This parameter is helpful to avoid overloads that may lead eventually to insulation failure or reduced service life.

Cable ampacity calculation requires the assessment of several adverse factors that may affect underground cable operational characteristics, such as soil conditions, thermal conductivities of cable components, cable geometry, trench profile, trays, backfilling, bedding properties, burial depth, segments of conduit, radiation and convection, harmonics currents, etc. [2–11]. The combined action of all these factors may reduce cable ampacity up to 40% of its rated capacity [2].

The assessment of cable ampacity for a given installation is basically a problem of heat dissipation generated in the different cable components, i.e., conductor, insulation, metallic screen, and cover. The problem is complicated by the fact that any unfavorable thermal conditions decrease the heat dissipation rate and therefore cable ampacity must be reduced [2,5,6].

There are different approaches for cable ampacity analysis. In general, they can be classified in numerical and analytical models. Numerical models rely mainly in the finite element method (FEM) [3,5,6,8,9,12–14]. The impact on cable loading capacity of several factors like ground surface heat, cable trench profile, concrete and asphalt cover, mixtures for bedding, both in steady-state and transient conditions, have been analyzed using this approach in [3]. In [12], the impact of solar emission and radiation is incorporated into the FEM. In [14], a comparative study about FEM accuracy in cable ampacity calculation has been presented.

Several derating factors have been calculated for cables in conduits [5]. The derating factors are dependent on conduit length, soil resistivity, burial depth, and number of cables in the conduit. In [6], the influence of metallic trays and non-sinusoidal currents on low-voltage cables ampacity is analyzed, leading to derating factors influenced considerably by large cable cross-sections and harmonic loads. In [8], Hwang et al. carried out studies using FEM in order to obtain derating factors for cables in open-top and covered trays. The effect of backfilling on cable ampacity is analyzed in [9,13] and shows that this parameter has a significant effect on loading capacity.

On the other hand, there are also several studies based on analytical methods aimed to calculate cable ampacity. In [1], the effect of a large burial depth is analyzed, and in [2] and [11] some derating factors are proposed. These factors take into account the influence of burial depth and non-favorable thermal conditions, like those encountered in street crossing. Some other publica-

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tions deal with the development of simplified analytic models for calculating thermal conductivity [4], the impact of harmonic currents, and optimization of cable installation for increasing ampacity [7]. In addition, derating factors due to the formation of dry zones and the type of backfill around underground cables are proposed in [10]; the impact of plug-in electric vehicles and the transient heating of underground cables and their thermal degradation have been analyzed in [15].

From the above review, it is a clear trend to obtain derating factors dependant on diverse operating and installation conditions. In addition, it is evident that thermal conditions inside underground installation are rarely constant along the installation route. This may result in a non-uniform temperature distribution along the underground cable system and into the ground depth. Temperature distribution in the ground is especially important because most of the available right-of-ways are already occupied either by other power or communication circuits, and therefore burying cables at greater depths is more and more frequent [1].

Usually, the available models for calculating cable ampacity reduction consider an unfavorable region of heat dissipation, as an area with well-defined borders and constant temperature along the entire region [11], i.e., street crossing. Under such considerations, the ambient temperature can change steeply when the power cable crosses the border into an unfavorable thermal region. On the other hand, the temperature change into the ground depth of this region is usually neglected.

In this paper, an analytical model for calculating cable ampacity reduction (derating factors), due to unfavorable regions with a non-uniform underground temperature distribution, is presented. The proposed model takes into account the ambient temperature gradient along the underground cable and into the ground depth. The temperature distribution inside and outside the unfavorable region is obtained by solving analytically the heat equation. The boundary conditions for the heat equation are taken in Dirichlet form by assuming that the temperature distribution on the surface is known.

2. Underground temperature distribution

Let us consider a high-voltage cable crossing a section of unfavorable thermal conditions of length $2l$, with a surface temperature θ_1, Region 1 in Fig. 1. However, the cable is rated for Region 2, with a surface temperature θ_2. The cable is buried at a depth h, and when crossing Region 2, the cable might be placed in a pipe.

In order to find the temperature at any point in the cable, it is first required to find the underground temperature distribution which varies in two dimensions—along the cable and with depth. This approach is used for modeling with better accuracy the heat dissipation phenomenon in cable underground installations. So, the following stationary heat equation should be solved:

$$\nabla^2\theta = 0 \tag{1}$$

where, ∇^2 is the Laplace operator. Eq. (1) should be considered together with the respective boundary conditions. In this paper, the boundary conditions in Dirichlet form are taken, i.e., the temperature distribution on the soil surface is considered known.

Then, according to the chosen system of coordinated axis, the surface temperature can be represented by the formula:

$$\theta_S = \begin{cases} \theta_2 & x < -l \\ \theta_1 & -l \le x \le l \\ \theta_2 & l < x \end{cases} \tag{2}$$

The solution to Eq. (1) with the boundary conditions as in (2) has the form [17]:

$$\theta(\mathbf{r}) = -\int_S \frac{\partial G(\mathbf{r},\mathbf{r}')}{\partial \mathbf{n}'}\theta_S\left(\mathbf{r}'\right) d\mathbf{S}' \tag{3}$$

where, $\mathbf{r}$ is the radius-vector, $\mathbf{n}'$ is the unitary normal vector to the surface $\mathbf{S}$ at the point with the radius-vector $\mathbf{r}'$, $G(\mathbf{r},\mathbf{r}')$ is the Green's function for the Dirichlet problem of the Laplace equation (1) [17] which has the form:

$$G\left(\mathbf{r},\mathbf{r}'\right) = \frac{1}{4\pi\left|\mathbf{r}-\mathbf{r}'\right|} - \frac{1}{4\pi\left|\mathbf{r}-\mathbf{r}'^{*}\right|} \tag{4}$$

where, $\mathbf{r}'^{*}$ is the radius-vector $\mathbf{r}' = (x', y', z')$ reflected with respect to soil surface, i.e., $\mathbf{r}'^{*} = (x', -y', z')$. Substituting the Green's function (4) and the boundary condition (2) into solution (3) and calculating the respective integral over the entire soil surface, the underground temperature distribution can be expressed as a function of two coordinates:

$$\theta(x,y) = \theta_2 + \frac{\theta_1-\theta_2}{\pi}\left(\arctan\frac{x+l}{|y|} - \arctan\frac{x-l}{|y|}\right) \tag{5}$$

In Fig. 2, the calculated temperature distribution (5) is shown. The surface temperatures in the Regions 1 and 2 are taken as $\theta_1 = 30\,^{\circ}\mathrm{C}$ and $\theta_2 = 15\,^{\circ}\mathrm{C}$, the street width is 4 m. One can observe that in depth there are no strict borders between Regions 1 and 2,

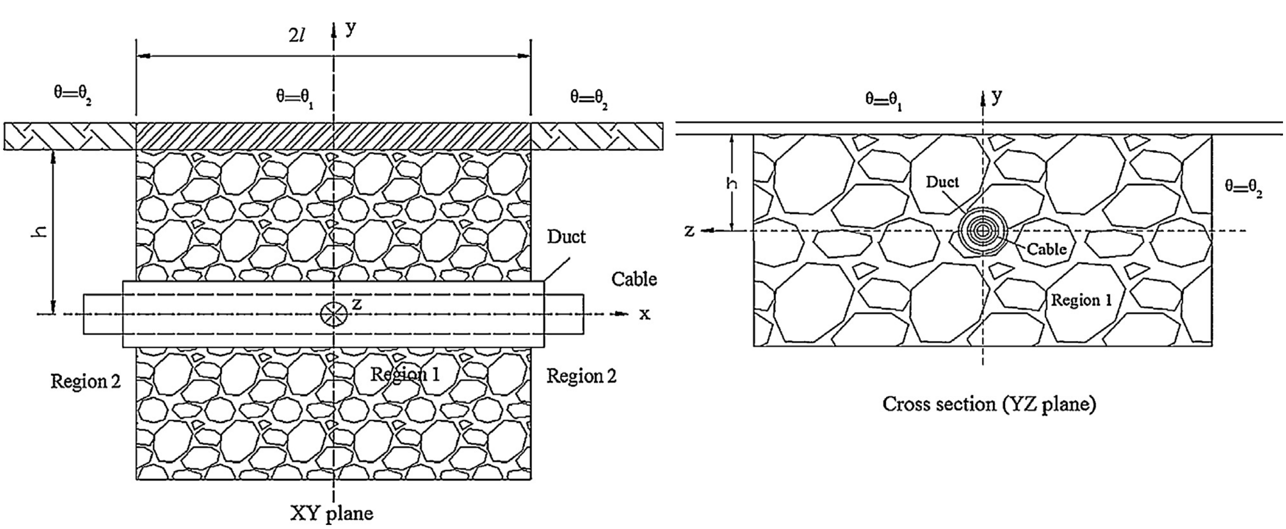

Fig. 1. Cable crossing an unfavorable thermal region, Region 1.