Analytical formulas for external thermal resistance for power cables buried in stratified soil

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ABSTRACT

Analytical formulas are derived for the external thermal resistance for power cables buried in stratified soil. The stratification consists of a horizontal layer of finite thickness sitting on top of soil beneath. The layer and soil beneath have different thermal conductivities. By comparing finite element analysis and published literature with the derived formulas, the methods are found to be in good agreement. For ease of implementation into existing framework, the formulas are presented as adaptations to IEC 60287-2-1 formulas for cables placed in uniform soil.

KEYWORDS

Current rating, power cables, external thermal resistance, steady-state heat conduction, stratified soil, IEC 60287-2-1

INTRODUCTION

Current rating calculations of power cables have been a problem of interest for cable specialists for a very long time, with major early contributions from Forbes, Kennelly, Mie and others [1][2]. Based on these foundations and subsequent developments, Neher & McGrath contributed with what formed the basis of the IEC 60287 standard [3][4].

In addition to the cable's material properties, the environment in which the cable is placed will influence its current rating. Several types of external environments are covered by IEC 60287-2-1, such as cables buried directly in uniform soil. In this case, the effect of the surrounding soil on the cable's current rating is expressed as an external thermal resistance. It is given by the Kennelly formula

$$T_4 = \frac{1}{2\pi}\rho_T \ln\left(u + \sqrt{u^2 - 1}\right) \qquad [1]$$

with $u = 2L/D_e$ and where ρ_T is the thermal resistivity of the soil, L is the depth of burial and D_e is the external diameter of the power cable [1][5]. Two other examples covered by IEC 60287-2-1 include a group of cables buried in uniform soil and cables placed in pipes.

Scenarios not covered by governing standards are typically analysed by Finite Element Analysis (FEA). However, the use of FEA requires dedicated software, user competence and can be quite time-consuming.

Experienced in current rating calculations both using standards and FEA, the authors have identified two situations that frequently appear in projects and require FEA analysis due to the lack of simple, governing analytical formulas. The two situations relate to cables buried in stratified soil where the soil stratifications have different thermal conductivity.

Specifically, this paper analyses the situation where cables are located either in a horizontal stratification layer or below it, with the two situations referred to as case A and B, respectively. The situations are depicted in Figure 1. In the remainder of the paper, the horizontal layer and the soil beneath will be referred to as region 1 and 2, respectively, with differing thermal conductivities k_1 and k_2.

Analytical formulas are derived for both of these scenarios. As IEC 60287-2-1 provides analytical formulas for the external thermal resistance of cables buried in uniform soil, this work proposes adaptation/correction terms to IEC 60287-2-1 for cases A and B, for ease of application and integration.

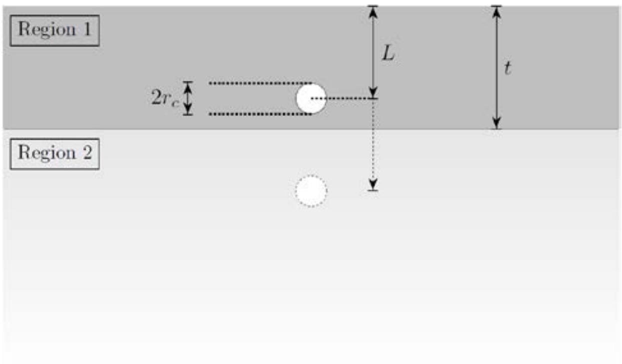

Figure 1: Cable with radius r_c buried at depth L in stratified soil with a horizontal layer of thickness t. The two cases analysed herein are i) cable buried in the horizontal layer (Case A), ii) cable buried below the horizontal layer (Case B).

PROBLEM STATEMENT

The problems investigated herein are governed mathematically by the steady-state heat equation for piece-wise uniform thermal conductivities

$$\nabla^2\theta(x,y) = -\frac{Q(x,y)}{k} \qquad [2]$$

where $\theta(x,y)$ is the temperature field to be determined, Q represents the heat sources that are present and k is the thermal conductivity of the soil.

In steady-state operation, the material properties of the power cable do not influence its surface temperature. Only the net heat generated within the cable and the thermal resistance represented by the surroundings determine the surface temperature. Therefore, the cable can be treated as a line heat source located along the centre axis of the cable, with the cross-sectional area occupied by the cable replaced by soil. It should be noted this involves a slight approximation. The Kennelly formula introduces a small