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Numerical simulation of heat dissipation processes in underground power cable system situated in thermal backfill and buried in a multilayered soil

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ABSTRACT

This paper presents the thermal analysis of the underground transmission line, planned to be installed in one of the Polish power plants. The computations are performed by using the Finite Element Method (FEM) code, developed by the authors. The paper considers a system of three power cables arranged in flat (in-line) formation. The cable line is buried in the multilayered soil. The soil layers characteristic and thermal properties are determined from geological measurements. Different conditions of cable bedding are analyzed including power cables placement in the FTB or direct burial in a mother ground. The cable line burial depth, measured from the ground level, varies from 1 m to 2.5 m. Additionally, to include the effect of dry zones formation on the temperature distribution in cable line and surroundings, soil and FTB thermal conductivities are considered as a temperature-dependent. The proposed approach for determining the temperature-dependent thermal conductivity of soil layers is discussed in detail. The FEM simulation results are also compared with the results of the simulation that consider soil layers as homogeneous materials. Therefore, thermal conductivity is assumed to be constant for each layer. The results obtained by using the FEM code, developed by the authors, are compared with the results of ANSYS simulations, and a good agreement was found.

1. Introduction

The underground power cable transmission line operates at the maximum possible electric current. Cable ampacity is a maximum electrical current that may be safely transferred without exceeding temperature limitations. Cable ampacity may be also described as current carrying capacity. The current carrying capacity mostly depends on the conductor temperature. Thus, heat dissipation process from the cable conductor to the surrounding soil plays a crucial role in evaluating the performance of buried cable systems [1,2]. First Joule's law states that cable electric resistance and current load affects heat generation rate from the cable core. When the cable core temperature is too high, the cable conductor overheat may experience. Thus, cable insulation meltdown may occur what leads directly to the transmission line malfunction.

The traditional method (IEC and IEEE-Standards [3,4]) is often used in calculating the thermal resistance between the cable system and the external environment. The standard procedure assumes that the soil is a homogeneous medium with constant thermal conductivity. In fact, the soil is multilayered and consists of quartz, organic matter, and other materials which thermal properties differ from each other. In the general case soil shall be regarded as a porous medium. Heat conduction from the hot cable to surroundings depends on the thermal conductivity of each soil layer, which in turn depends on the porosity, liquid–vapor transport and temperature [5]. When the porosity is considerable, and the pores are saturated with water, the thermal conductivity of soil increases [6,7]. Furthermore, the soil layers thermal conductivity decreases with a rise in temperature [8]. When liquid water, which is existing in the soil pores, evaporates then the soil is drying out and loses its ability to conduct heat. Moreover, the trench shape, power cables arrangement type and configuration of the soil layers influence the temperature distribution in the ground, bedding layer and cable core.

Many studies have been performed recently to understand the heat transfer in the porous media. The conducted analysis include, among others: liquid–vapor heat and mass transfer [5,9]; flow and thermal non-equilibrium through a porous medium [10]; the local thermal non-equilibrium condition of porous media [11]; heat

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Nomenclature

A	cross-sectional area, m^2
a	soil thermal conductivity equation coefficient
C	capacitance for the cable core situated in a vacuum, F/m
d	diameter, m
E	total number of finite elements in FEM model
f	alternating current (AC) frequency, Hz
f^e	element load vector, W/m
H	burial depth, m
I	current load, A
gid_f	grid independence factor, –
K_e	Kersten number, –
k	thermal conductivity, W/(m K)
l	distance between conductor axes, m
n	porosity, –
N	total number of nodes in FEM model, –
q	quartz content, –
q_v	heat source per cable core unit volume, W/m^3
R_e	electric resistance, Ω/km
R_0	thermal resistance, (m K)/W
r	radius, m
S_r	degree of saturation, –
T	temperature at any point in the x–y plane around the underground cable, °C
$\overline{T}^e$	average temperature within a triangular finite element, °C
T_{max}	central cable core maximum temperature, °C
$T_{max,p}$	maximum allowable cable core temperature, °C
$\tan\delta$	insulation loss factor, –
U	peak voltage, kV
U_d	RMS voltage, kV
W_d	dielectric losses, W/m
w_n	gravimetric natural water content, %
w_{sat}	gravimetric saturation water content, %
x	distance from the symmetry plane, m
y	distance from the ground surface, m
y_s	skin effect factor, –
y_p	proximity effect factor, –

Greek symbols

α	temperature coefficient, –
ϵ	absolute value of relative error, %
ΔQ	heat losses from the power cable, W/km
ΔT	cable core and soil temperature difference, °C
ε	dielectric loss factor, –
ρ	density, kg/m^3
ρ_d	soil dry density, kg/m^3
ρ_s	solids unit weight, kg/m^3

Subscripts

AC	alternating current
c	cable conductor
DC	direct current
dry	dry soil
e	external
IEC	according to IEC Standards
ins	cable insulation
j	cable jacket
opt	optimal value
ref	reference value
s	solid
sat	saturated state
sh	cable sheath
w	water
wet	soil in a moist state

Superscript

e	element number
i	iteration number

Matrices and vectors (Appendix A)

$\{f\}$	global load vector, W/m
$\{J\}$	Jacobian matrix
$[K]$	global stiffness matrix, W/(m K)
$\{q\}$	nodal coordinates vector, m
$\{T\}$	nodal temperatures vector, °C
$\{\Delta T\}^i$	difference between nodal temperatures in i-th and $i-1$-th iterations
$\{\Phi\}$	functions vector used in Newton–Raphson algorithm

transfer through the porous extended surfaces [12–15]; flow through porous channels, pipes and cavities [16–21]; and combustion applications [22]. The modeling of flow and heat transfer processes in porous materials is a very complicated and challenging task. Therefore, the presented study attempts to propose an alternative approach that includes the effect of dry zones formation on soil thermal conductivity. The conductivity drop in a proximity of cables is modeled via the exponential function of temperature dependent thermal conductivity.

Heat dissipation process through the underground power cables and the surrounding soil was considered in [23–29], among others. Different authors performed both the numerical simulations and the experimental investigations on underground power cable systems. Hwang and Jiang [23] presented a combined nonlinear magnetothermal analysis, including radiation effects, for calculating the thermal fields of an underground cable system. Al-Saud et al. [24] performed the numerical computations of temperature distribution in soil and underground power cables. A new perturbed finite-element analysis technique was used. Al-Saud's approach involves the use of derived sensitivity coefficients associated with various cable parameters of interest, and use these coefficients to achieve optimal cable performance. De Lieto et al. [25] performed a numerical study based on a Control-Volume Formulation of the Finite-Difference Method. That technique was used to determine the thermal resistance existing between an underground electrical power cable and the ground surface. The thermal behavior of the cables system was studied for various dimensions of the trench, cable burial depth, two backfill layers thicknesses, and the cable bedding. The authors developed a semi-empirical correlating equation using multiple regression procedures and verified proposed model experimentally in [26].

The comprehensive approach to determining the cable ampacity was presented by Kroener et al. [5]. The authors developed the new numerical model of coupled liquid water, vapor and heat flow in a thermal system consists of underground cable buried in the soil. The transient computations performed using the Finite Element Method were verified experimentally and demonstrated the strong relation of the cable temperature on soil water content.

The serviceable simplified analytical model of transient heat dissipation from underground cable to surroundings was developed by Papagiannopoulos et al. [27]. The authors considered both the thermal impedances and the thermal resistances that influence the dynamic behavior of the thermo-electrical system. The analytical model results were further compared with the results obtained