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Optimizing of the underground power cable bedding using momentum-type particle swarm optimization method

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A B S T R A C T

Thermal performance optimization of underground power cable system is presented in this paper. The analyzed system consists of three underground power cables situated in an in-line arrangement. The HDPE (High-Density Polyethylene) casing pipes, filled with SBM (Sand-Bentonite Mixture), covers the cables to protect them from heavy mechanical loads (e.g. vibrations). The FTB (Fluidized Thermal Backfill) layer is applied to prevent the cables from overheating. Due to the substantial costs of FTB backfill material (in relation to the native soil or dry sand), the cross-sectional area of FTB bedding layer has to be minimized. Furthermore, the maximum cable conductor temperature is expected not to exceed the optimum operating temperature. Therefore, the optimization procedure i.e. momentum-type PSO (Particle Swarm Optimization) is applied. The FEM (Finite Element Method) is used to solve the two-dimensional steady-state heat conduction problem. As a result, temperature distribution is determined for the native soil, FTB bedding, and cables. The performed computations considered the temperature dependent current rating and volumetric heat generation rate from cable conductor. The applied optimization procedure resulted in determination of the optimum cable spacing and cross-sectional area of the rectangular-shaped FTB bedding layer. Moreover, the obtained maximum temperature for the cable core do not exceed the allowable value.

1. Introduction

In recent years, the thermal analysis of underground power cable system attracted a broad scientific attention. In most instances, the electric energy transmission line operates at the maximum possible conductor electric current. According to first Joule's law, heat generated in power cable core depends on its electric resistance and flowing electric current. An accurate analysis of heat dissipation process from the underground power cables to the surrounding soil plays a crucial role in designing the electricity transmission lines in modern power plants [1,2].

Ampacity is defined as the maximum electrical current that a conductor can safely carry without exceeding its insulation temperature limitations. Power cable ampacity is also described as a current carrying capacity. The current carrying capacity mostly depends on the temperature of the cable conductor. Excessive conductor temperature leads to cable overheating and the improper operation of the power transmission line. Furthermore, the better conditions of heat dissipation process from a cable to its surroundings, the lower cable diameter may be used for the same electrical load. Therefore, the unit costs associated with underground transmission line installation decreases significantly.

The traditional method used in calculations of the thermal resistance between the cable system and the external environment [3,4] assumes that the soil is a homogeneous material with constant thermal conductivity. In fact, the heat transfer processes associated with heat dissipation from the power cable to the surrounding soil are more complex. The soil is a multilayered porous material and consists of e.g. quartz, organic matter, clay minerals, air, water in the liquid and vapor phase, among others. Moreover, the heat transfer conditions depend strongly on the thermal conductivity of each soil layer. Thus, soil thermal conductivity exhibits a distinct dependence on porosity, liquid vapor transport, and temperature, among others [5]. The thermal conductivity increases with soil porosity since the pores are filled with water and the air

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Nomenclature

A	cross-section area (m^2)
b	distance between conductor axis and top edge of the FTB bedding layer (m)
d	diameter (m)
f	alternating current (AC) frequency (Hz)
$F(\mathbf{x})$	cost function
H	burial depth (m)
I	current load (A)
k	thermal conductivity (W/(m K))
l	distance between conductor axes (m)
p	distance between conductor axis and bottom edge of the FTB bedding layer (m)
q_v	heat source per unit volume (W/m^3)
rand()	random number between 0 and 1 (−)
R_e	electrical resistance (Ω/km)
R_{th}	thermal resistance ((m K)/W)
r	radius (m)
s	distance between conductor axis and lateral edge of the FTB bedding layer (m)
T	temperature (°C)
T_{cmax}	maximum central cable core temperature (°C)
$T_{c,FEM}$	cable core temperature determined from FEM model (°C)
$T_{max,p}$	maximum allowable cable core temperature (°C)
$\mathbf{v}_i^n$	i-th particle velocity in n-th iteration (m/s)
$\mathbf{x}$	design variables vector (or particle position vector) (m)
$\mathbf{x}_i^n$	i-th particle position in n-th iteration (m)
y_s	skin effect factor (−)
y_p	proximity effect factor (−)

Greek symbols

α	temperature coefficient (−)
ΔQ	heat losses from the power cable per unit length (W/m)

Subscripts

AC	alternating current
b	cable bedding layer
c	cable conductor
DC	direct current
g	at ground level
ins	XLPE cable insulation
ja	cable jacket
max	maximum value (related to the central cable core temperature T_{cmax} or cost function $F(\mathbf{x})$)
mean	mean value (related to the central cable core temperature T_{cmax} or cost function $F(\mathbf{x})$)
min	minimum value (related to the central cable core temperature T_{cmax} or cost function $F(\mathbf{x})$)
opt	optimum cable core temperature
pf	constants of dynamic penalty function $C(n)$ and the penalty factor $H(\mathbf{x})$
PSO	constants of particle swarm optimization (PSO) algorithm
ref	reference value
sh	cable sheath
soil	soil

Superscripts

n	iteration number

List of shorts

FTB	fluidized thermal backfill
FEM	finite element method
PSO	particle swarm optimization
HDPE	high-density polyethylene
SBM	sand-bentonite mixture
PE	polyethylene
PVC	polyvinyl chloride
SGFC	sand, gravel, fly ash and cement-mix
IEC	international electrotechnical commission
XLPE	cross-linked polyethylene

[6,7]. The higher soil water content, the better heat dissipation process conditions occur. However, water existing in pores may locally evaporate in the immediate vicinity of the cable thus the so-called 'dry zones' are created. Dry zones are usually formed around underground power cables under loading conditions due to the moisture migration within the soil [8]. The presence of dry zones around the cable results in a significant soil thermal conductivity drop since the thermal conductivity is over 20 times lower for a vapor than for liquid. Therefore, when temperature is rising, and dry zones are formed, it leads to a significant reduction in soil thermal conductivity.

Geometrical configuration of the cable system (i.e. cable spacing, shape of the trench, backfill layer cross-sectional area) influences the cable core temperature. In thermal engineering practice, it is possible to enhance the heat transfer from the solid materials to its surroundings by different methods. In particular cases: extended surfaces [9–11], porous structures [12–14] and multiphase materials [15,16] are utilized. During the underground transmission line placement, the heat dissipation from power cables to the surrounding soil shall be enhanced.

In order to circumvent the power cable overheating problems the specially designed bedding material, e.g. FTB (Fluidized Thermal Backfill), exhibiting higher thermal conductivity than the mother ground, is often used. Moreover, the thermal conductivity of the dry FTB material is over three times greater than for the dry soil. Therefore, underground power cables placement in the FTB bedding instead of the mother ground may circumvent the problems associated with a considerable thermal conductivity drop in soil, especially in the vicinity of the cable. On the other hand, the material costs related to FTB backfilling are significantly higher, comparing to the mother ground. Approximate cost of FTB is about $130 per cubic meter [17] and strongly depends on the cable line installation location and availability of raw materials, among others. Hence, when designing the shape of FTB layer (the optimum cross-sectional area of the bedding layer), the optimization work has to be done.

This paper presents an optimization of the FTB bedding layer cross-sectional area for underground power cable system that is planned to be installed in one of the Polish power plants. The analyzed system consists of three underground power cables situated in an in-line arrangement. Minimization of the FTB bedding cross-sectional area is performed by employing the momentum-type PSO (Particle Swarm Optimization) Method [18]. Moreover, the cable conductor temperature cannot exceed the optimum operating temperature i.e. 65 °C, which is specified by the cable producer. The Finite Element Method [5,19,20,23,24] is applied to determine the temperature distribution in underground power cable system. The methods for thermal analysis of underground power cable systems can be also found in Refs. [21,22].