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Thermal performance optimization of the underground power cable system by using a modified Jaya algorithm

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ABSTRACT

This paper presents a modified Jaya algorithm for optimizing the material costs and electric-thermal performance of an Underground Power Cable System (UPCS). A High Voltage (HV) underground cable line with three 400 kV AC cables arranged in flat formation in an exemplary case study is considered. When buried underground, three XLPE high voltage cables are situated in thermal backfill layer for ensuring the optimal thermal performance of the cable system. The study discusses the effect of thermal conductivities of soil and cable backfill material on the UPCS total investment costs. The soil thermal conductivity is assumed constant and equal to 0.8 W/(m K). The cable backfills considered in the study are as follows: sand and cement mix, Fluidized Thermal Backfill™ (FTB) and Powercrete™ a product of Heidelberg Cement Group. Constant thermal conductivities of the backfills in the dry state are assumed, respectively, 1.0 W/(m K), 1.54 W/(m K) and 3.0 W/(m K). The cable backfill dimensions and cable conductor area are selected as design variables in the optimization problem. The modified JAYA algorithm is applied to minimize material costs of UPCS under the constraint that the cable conductor temperature shall not exceed its optimum value of 65 °C. The cable temperature is determined from the two-dimensional steady state heat conduction equation discretized using the Finite Element Method (FEM). The performance of the modified Jaya algorithm was compared with classical Jaya and PSO algorithms. The modified Jaya algorithm, for the presented case study, allows one to obtain lower values of the cost function.

1. Introduction

The sustained growth of the global economy and increasing population, particularly in the developing countries, determine the increasing demand for electric energy supply. Electrical power worldwide is mainly transmitted with High Voltage (HV) Alternating Current (AC) overhead line technology. For instance, 96% of the onshore transmission network in Europe is build overhead, and only 4% is installed underground. Underground cables are mainly used over short distances, in areas where overhead lines are inexpedient or impossible to use, as well as for specific technical applications. Underground cabling is becoming increasingly attractive for use mainly for environmental and aesthetic reasons. Also, Underground Transmission Lines (UTL) are resistant to weather conditions and are installed when the use of overhead lines may result in an adverse impact on the environment, concerns over potential health issues, impact on property prices, or the condition of national parks or areas of natural beauty. UTL is also more reliable than overhead transmission lines when it comes to the cable line failure likelihood. Thus, UTL is recommended during design and installation in:

- densely populated urban areas (ease of network expansion, lower risk of electric shock, aesthetic reasons),
- electrical power outputs from power plants (i.e. conventional or renewable energy sources) and large energy consumers (i.e.

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Nomenclature

Roman symbols

A	cross-sectional area, m^2
A_{cal}	used in the FEM model equivalent cross-sectional area calculated based on the nominal cross-sectional area, m^2
a, c	exponential model coefficients of the unit cost factor
b	the distance between the conductor axis and the top of the cable bedding layer, m
C	sample length, m
C_{total}	total material costs (cable + thermal backfill material costs) per 1 km of the cable line, kEuro
d	diameter, m
F_o	objective (cost) function
f	frequency, Hz
H	computational domain height, m
h	burial depth of the transmission line, m
$hgrad$	mesh growth rate
I	current loading, A
K_s, K_p	skin and proximity effect correction factors
k	thermal conductivity, W/(m K)
l	horizontal distance between the cable conductors axes, m
m	number of design variables
n	number of solution candidates
PF	penalty function
p	the distance between the conductors axis and the bottom of the cable bedding layer, m
q_v	thermal load calculated with respect to 1 m^2 of a cable cross-section area, W/m^3
r_1, r_2	random numbers generated during each iteration of JAYA algorithm
R'	alternating current (AC) resistance, Ω/km
R_{io}	outer diameter of the cable insulation d_{ins} to the conductor diameter d_c ratio
s	spacing between the side edge of the bedding layer and the side cable axis, m
T	temperature, °C
$T_{\max}$	the maximum temperature of the central cable conductor, °C
T_{opt}	optimum temperature of the cable conductor, $T_{opt} = 65$ °C
T_{ref}	reference temperature, $T_{ref} = 20$ °C
$\tan\delta$	loss factor for the XLPE insulation
uc	unit costs, kEuro
ucf	unit costs factor
U	peak voltage for the considered AC circuit, V
W	computational domain width, m
X	vector of design variables
x, y	Cartesian coordinates
x_s, x_p	argument of a Bessel function used to calculate skin and proximity effect
y_s, y_p	skin and proximity coefficients

Greek symbols

α_{ref}	temperature coefficient
ε	relative permittivity of the XLPE insulation
ρ_{20}	specific electrical resistance of the copper conductor in 20 °C, Ω m
ΔQ	heat losses in a cable referred to 1 m of the cable length, W/m

Subscripts

b	backfill
$best$	best solution in the population
c	cable conductor
ext	cable external layer
g	ground
i	iteration number
ins	cable insulation
j	design variable id
k	k-th solution in population
m	number of design variables
max	maximum value of parameter
min	minimum value of parameter
$mean$	mean value of parameter
o	outer diameter
s	soil
SC	Sand-Cement mix
$worst$	worst solution in the population

Superscript

‘	updated position of design variable vector **X**

List of abbreviations

BF	Brute Force algorithm
FEM	Finite Element Method
FTB	Fluidized Thermal Backfill
HV	High Voltage
IEC	International Electrotechnical Commission
PC	Powercrete™
PSO	Particle Swarm Optimization
SCM	Sand-Cement mix
SGFC	Sand, Gravel, Fly ash and Cement-mix
UPCS	Underground Power Cable System
UTL	Underground Transmission Line,
XLPE	cross-linked polyethylene

mines, ironworks, manufactures, or even electrical grid interconnections between countries),

- interconnections in power stations (overhead lines are connected to an underground cable via a cable connection station [1]).

Nevertheless, use of underground cables in HV applications is still limited owing to their high installation and maintenance costs, as well as expensive repairs in case of an outage. It was estimated in Ref. [2] that underground lines could take from 48 to 480 h to be repaired during an outage, as compared to 8–48 h for overhead lines. The underground cables themselves also have a higher unit price due to their construction complexity and greater production costs [3].

Undergrounding is not a new trend, as underground cables have been used for low and medium voltage lines in urban areas for a long time. Several countries use underground Low Voltage (LV) distribution lines in almost their entire network, with a target of 100%, such as the Netherlands, Singapore, and Denmark. For instance, Denmark is planning to underground 75% of its electricity grid shortly. It should be noted that almost 10% of the underground power projected lines are 400 kV transmission lines [4].