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Evaluation of a buried power cable's thermal behavior using phase diagrams and calculation of the phase difference between temperature and power

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HIGHLIGHTS

- A dynamic thermal analysis of an underground power cable.
- Calculation of the increase in the cable's temperature over one year period.
- Presentation of the Temperature–Power phase diagrams for various time periods.
- Calculation of the phase difference between power and temperature.

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ABSTRACT

As most of the studies about thermal behavior of cables perform the steady state thermal analysis, a dynamic analysis of these problems can be proved very interesting. In the current study, a dynamic thermal analysis of an underground cable which operates under a continuously changing load and thus continuously changing Joule losses is carried out. With the Joule losses as the input signal it is proved that the thermal time constants in the range up to several hours are possible. It is also observed that the dynamic analysis, presented in this work, indicates an increase on the peak value of the cable's temperature that can reach up to 81%. This increase proves the importance of a dynamic analysis. Furthermore, the comparison between the steady state and dynamic analysis resulted in the conclusion that it is practically impossible to achieve steady state condition for power losses other than the mean value, thus steady state analysis cannot determine the instantaneous temperature of the cable. The analysis is based on the Temperature–Power (*T*–*P*) phase diagrams which are proved to be a more suitable representation method of the results comparing to the Temperature–Time plots. Lastly, the phase difference between the power and the temperature vectors is calculated.

1. Introduction

Underground power cables are subject to high temperatures due to the fact that the serial ohmic losses cannot be neglected. Moreover, the cables being buried at a depth of about 1 m (or more for HV cables), a high thermal resistance can be expected as well.

Several papers have been devoted to the study of thermal fields in underground cables. In most papers the related thermal problems are only studied under the steady state conditions. In 2011, Vollaro et al. performed a numerical study under the steady state conditions to determine the thermal resistance existing between an underground power cable and the ground surface [1], while in a more recent study in Ref. [2] they have compared experimental results in non-homogeneous soils with the numerical ones, leading to an acceptable convergence between them. Another interesting study focuses on the improvement of the evaluation of heat losses, compared to the methods of IEC-IEEE standards [3]. Furthermore, in Ref. [4] the authors have worked under steady state conditions

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Nomenclature

T	temperature (K)
P	power (W)
P_{DC}	mean value of power (W)
T_{DC}	mean value of temperature (K)
h	heat transfer coefficient (W/m^2 K)
R_{th}	thermal resistance (K/W)
ω	angular frequency (rad/s)
P_c	complex representation of power
T_c	complex representation of temperature
$\Delta\Phi$	phase difference (rad or °)
arg	argument (rad or °)

on a non-linear coupled electric-thermal model indicating again the need for the re-evaluation of the IEC standard. In 2005, J. Desmet et al. performed a thermal analysis of parallel underground cables validating their results with test set ups [5]. Lastly, models with multilayered soil can also be found in the literature, such as the study performed by Hanna et al. in Refs. [6] and [7].

On the other hand, scientific papers that deal with the dynamic thermal effects are rather limited. From the existing ones, in Ref. [8] the authors present a transient analysis of power cables thermal dynamic by interval mathematic and in Ref. [9] finite elements methods are used for the simulations of both steady state and transient analysis of cables, in order to determinate the current carrying capacity of the cables. In a published work by Cimini Jr. et al. in 2013, the authors point out the challenges that the Brazilian transmission system is facing and perform experimental work on the variation of temperature on conductors, in order to compare the results with numerical studies [10]. A very interesting study was published in 2013 in which the significance of the CFD technique, in order to determine the thermal state of a distribution network for performing a dynamic analysis, is demonstrated [11]. In Ref. [12] I. Papagiannopoulos et al. presented a theoretical analysis followed by an experimental study to determine the behavior of the thermal impedance of buried power cables. They concluded that the thermal impedance, in contrast to the thermal resistance, depends on the frequency and therefore is a good way of representing the dynamic behavior of the cables. In the same way, in Ref. [13] authors present an experimental study, performing a dynamic thermal analysis of underground cables using not only the thermal impedance but also two new representations, the thermal time constant distribution and the structure functions. A harmonic analysis of dynamic thermal problems in an overhead transmission line and a buried power cable is presented in Ref. [14] and the temperature delay time with respect to the power peaks is calculated.

In this contribution a dynamic thermal analysis of underground power cables is carried out. It will be proved that the thermal time constants in the range up to several hours are possible. On the other hand the input signal to the system we are dealing with, is nothing else than the electric power losses in the cable. These Joule losses being proportional to the square of the transmitted power are changing continuously making a dynamic analysis necessary.

If one considers the power transmitted through a cable observes that this time function has a periodicity of roughly 24 h. One can limit the transient thermal simulation to time constants up to 24 h which regarding ground corresponds to a depth of roughly 50 cm.

In our approach the superposition principle will be used throughout. The power losses $P(t)$ will be written as the algebraic sum of the mean value P_{DC} and a variable part $P_A(t)$ such that the mean value for the latter one is exactly zero. In a similar way the temperature T of the cable will also be written as the superposition of a mean value T_{DC} and a variable part $T_A(t)$.

Dynamic analysis focuses on the high fluctuations of the temperature that can rise due to the fluctuations of the cable's losses. The importance of the results is in the direction of pointing out that very instant temperatures, which are not predicted by a steady state analysis, can appear. Those high temperatures are crucial for choosing the appropriate cable and checking its durability. By assuming an average power loss for the cable we can come up with results in terms of temperature that at some time steps can be even 81% lower than the appeared temperature. Thus, there is no other way than a transient analysis in order to calculate the instantaneous temperature fluctuations.

In this contribution the steady state (DC) problem will not be considered for the obvious reason that many papers have already treated this problem. The current research work is limited to the time variable aspect of the heat transfer. A specific property is that the time variable temperature field is limited to a cylindrical shell around the cable so that convection at the ground level has almost no influence on the dynamic part of the heat transfer. In this paper the results are depicted in a so called phase diagram showing the temperature versus the power using time as a parameter. This diagram turns out to be more convenient than a plot of the temperature or power as function of time.

2. Dynamic analysis

For the simulations, a realistic power input has been used. The transmitted power data for a typical cable were provided by the Public Power Corporation of Greece. A plot of the transmitted power data in half-an-hour time steps, after the subtraction of the average power value, is shown in Fig. 1.

The cable that was used is a commercial MV underground power cable buried at a depth of 0.8 m. The details of the cable can be found in Table 1. However, in the framework of this study, only a simplified version of the single phase power cable was simulated, taking into consideration only the conductor and the insulation and neglecting all the other layers as well as the metallic sheath losses.

The radius of the conductor was 9.15 mm and the outer radius of the cable 19.5 mm. The cable and the trench, that the cable was buried, are presented in Fig. 2. It should be highlighted that the

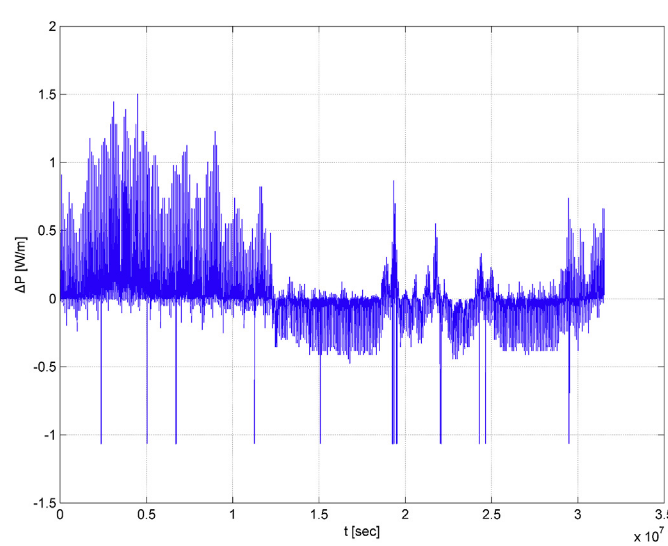

Fig. 1. Transmitted power data after the subtraction of the average power value.