Applied Thermal Engineering 60 (2013) 256–260

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Dynamic thermal analysis of underground medium power cables using thermal impedance, time constant distribution and structure function

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HIGHLIGHTS

- Investigation of dynamic thermal behavior experimentally and theoretically.
- Measurement of thermal impedance.
- Evaluation of time constant spectrum and structure function.
- Comparison between theoretical analysis and measurements.

ARTICLE INFO

Article history:
Received 14 February 2013
Accepted 8 July 2013
Available online 17 July 2013

Keywords:
Underground power cables
Dynamic thermal analysis
Thermal impedance
Time constant
Structure function
Differential structure function

ABSTRACT

The thermal behavior of a laboratory model for an underground cable has been investigated experimentally. Temperatures are recorded as a function of time so that the dynamic thermal properties could be investigated. The results are represented by thermal impedances. Two new representations, the thermal time constant distribution and the structure functions, will be introduced as well. It will be shown that with the help of a simple analytical model a lot of new information can be gained.

1. Introduction

Due to the inevitable Joule losses, underground power cables are being heated and operate at elevated temperatures. This problem has been treated in many papers. In Ref. [1] Vollaro et al. presented a numerical study for the determination of the thermal resistance existing between an underground electrical power cable and the ground surface and proposed a semi-empirical correlating equation for the design of buried electrical power cables. In Ref. [2] Vollaro et al. investigate the inaccuracies in calculation of thermal flux from buried cables system to the ground surface through the soil. In Ref. [3] Canova et al. deal with a new concept of technology for the mitigation of the magnetic field produced by underground power lines called High Magnetic Coupling Passive Loop (HMCPL) and investigate the thermal behavior of HMCPL directly buried in the ground, both in transient and in steady-state conditions. In Refs. [4], Kovac et al., assess the generated heat per unit time and volume within cable sheaths for underground power cables using the filament method and the simple analytical IEC relations and compare the results. Most of the publications concerning underground power cables are limited to a thermal steady state analysis, i.e. it is assumed that the Joule losses and hence the cable temperature are constant in time. The thermal properties are then represented by a quantity called the thermal resistance. In practice

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http://dx.doi.org/10.1016/j.applthermaleng.2013.07.009

Nomenclature

C_p	specific heat per mass unit (J/kg K)
C_v	specific heat per unit volume (J/m^3 K)
C_{th}	thermal capacity (J/K)
H	laboratory setup height (m)
h	heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity (W/mK)
L	length of the cable (m)
P	power (joule losses) (W)
R	electric resistance (Ω)
R_{th}	thermal resistance (K/W)
r	radial distance (m)
r_o	radius of the cable (m)
T	temperature (°C)
t_1	thermal time constant (conduction) (s)
W	laboratory setup width (m)
Z_{th}	thermal impedance (K/W)
α	buried depth (m)
ρ	density (kg/m^3)
τ_{th}	thermal time constant (convection) (s)
$\varphi(\tau)$	time constant distribution (K/J)
ω	angular frequency (rad/s)

the Joule losses are varying all the time. Even when the thermal time constant of an underground cable is quite high, its temperature can vary considerably because the Joule losses are time dependent. Consequently a dynamic thermal analysis is required to get a full understanding of the problem.

In a recently published paper, the authors presented a thermal impedance evaluation of underground cables [5]. Thermal impedance, in contrast to thermal resistance, depends on the frequency so that dynamic aspects can be represented. It is similar to electric impedance just like thermal resistance is analogous to electric resistance. It should be emphasized that thermal impedance is a totally different representation of dynamic thermal phenomena as compared to a temperature plotted versus time. In this paper other representation will be also added: the time constant distribution and the structure functions.

The techniques used in this paper have been developed to investigate the thermal properties of electronic and microelectronic [6]. The approach has been used to characterize substrates [7], cooling fins [8], thermal interface materials [9]. Heat transfer coefficient could also be measured using the thermal impedance [10]. The representation of the thermal impedance in a Nyquist plot has proved to be a thermal fingerprint of electronic packages [11]. This method has been elaborated by V. Szekely and his team. A first application was a detailed view of the thermal path between a heat source and the ambient [12]. The monitoring of electronic packages was a second application of this method [13]. A mathematical analysis has also been carried out by V. Szekely [14]. First of all the thermal step response of an electronic component is recorded. Starting at a given moment $t = 0$, a constant power is dissipated in a component and its temperature rise is measured to obtain the thermal step response $T(t)$. From the thermal step response the thermal impedance $Z_{th}(j\omega)$ can be calculated. This is a major difference with electric impedance, which can be easily measured directly because AC or pure sinusoidal voltage sources are available. A sinusoidal temperature source with variable is not existing so that one has to use an indirect method based on the thermal step response. From the impedance $Z_{th}(j\omega)$ or from the step response $T(t)$ the time constant distribution $\phi(\tau)$ can be obtained using a mathematical transformation. From the time constant distribution one can construct a Foster RC equivalent network. The input impedance of this network is just $Z_{th}(j\omega)$. The Foster network is then converted into an equivalent Cauer RC network. The Cauer network allows a physical interpretation called the structure function.

2. Experimental measurements

In the laboratory a down scaled model for simulating underground cables has been constructed (Fig. 1). A cubic shaped box (each side approximately 50 cm) is filled with dry sand. A cable with a core radius of 1.13 mm and an electric insulation of 1 mm thickness was positioned at a depth of 2 cm as shown in Fig. 1. The length of the cable in the sand was $L = 50$ cm. The cable has a series resistance of 4.19 mΩ/m. The cable was heated with two different currents, $I = 33.33$ A and $I = 50$ A, giving rise to power generations of 4.654 W/m and 10.475 W/m respectively.

A thermocouple was attached to the cable to measure its temperature. The results of the transient temperature are shown in Fig. 2. The cable having a series resistance of 4.19 mΩ/m (or $R = 2.095$ mΩ for the buried part), produces a power of $P = RI^2 = 2.327$ W for $I = 33.33$ A and $P = 5.237$ W for $I = 50$ A. From the transient curves one can observe that the steady state temperature is around 35.50 °C for $I = 33.33$ A whereas for $I = 50$ A a value 45.90 °C is found. Taking the ambient temperature of 27.34 °C one gets temperature rises of 8.16 °C and 18.56 °C above ambient. This gives rise to $R_{th} = 8.16/2.327 = 3.507$ K/W and $R_{th} = 18.56/5.237 = 3.544$ K/W respectively.

From the transient curves $T(t)$ one can obtain the thermal impedance by evaluating the following integral:

$$Z_{th} = \frac{j\omega}{P}\int_0^{\infty} e^{j\omega t} T(t)\mathrm{d}t \qquad (1)$$

The Nyquist plot of the impedance Z_{th} is shown in Fig. 3 and was produced by the T3ster software from MICRED company. This plot is the representation of the imaginary part versus the real part of Z_{th} using the angular frequency ω as a parameter. One observes that both impedance curves are not perfectly coinciding. In principle the thermal impedance measured with 33.33 A and 50 A

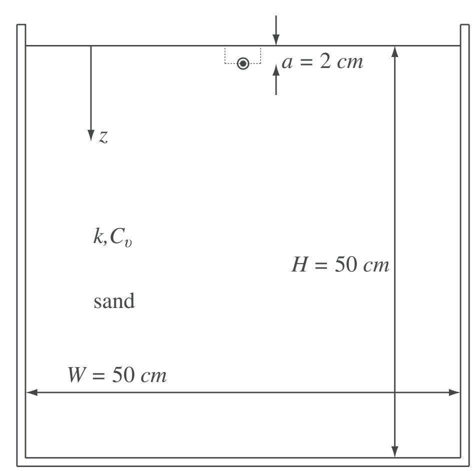

Fig. 1. Schematic view of the laboratory setup of a buried cable.