Electrical Power and Energy Systems xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Electrothermal analysis and temperature fluctuations' prediction of overhead power lines

I. Theodosoglou [a,*], V. Chatziathanasiou [a], A. Papagiannakis [a], B. Więcek [b], G. De Mey [c]

[a] Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Greece
[b] Institute of Electronics, Technical University of Łódź, Poland
[c] Department of Electronics and Information Systems, Ghent University, Belgium

ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form 10 June 2016
Accepted 9 July 2016
Available online xxxx

Keywords:
Electromagnetic analysis
Fourier analysis
Thermal analysis
Thermal impedance
Overhead power lines

ABSTRACT

This paper presents an algorithm for the calculation of the thermal impedance of an overhead power transmission line (OHL), the temperature fluctuations due to its continuous load variations and the delay time in which they are noticed. The temperature fluctuations' prediction is resulting from the dynamic thermal analysis of a complete joined electrothermal problem using Fourier analysis. The problem has not only been solved analytically but it has also been simulated and solved with a software package. The comparison between the analytical solution results and the simulation ones shows that the difference between them is almost negligible.

The proposed algorithm's scheme is applied to measured rms current data obtained from two different lab experiments, in each one a different type of conductor was used, as well as from an operating OHL in Thessaloniki, Greece, for four indicative months spanning a whole year and covering all four seasons. However, only the results of the most representative month of these four have been chosen to be presented, as during this summer month there is great demand of power and the loads are ranging at really high levels. The results are presented both analytically and graphically through figures and tables.

1. Introduction

The demand for additional electric power is constantly increasing, year by year, and for that there is a corresponding requirement to increase the power transferred by OHLs. Although building new OHLs may be feasible on account of economic or environmental consideration, the increase of the load transfer capacity of the existing OHLs seems to be the best solution but this, on the other hand, can cause thermal problems and greatly affect the functioning of the OHLs. Consequently, the temperature increase in OHLs and its prediction is, very often, a major problem for electricity companies as the distance between the OHL and the ground is decreased and may be less than the minimum permissible one, so the sag clearance requirements are not met and this can cause several problems. This conductor expansion depends on both the OHL's load and the prevailing environmental conditions. So, during the summer, when the ambient temperature and the sun radiation are ranging at pretty high levels, especially in countries as Greece, the OHL's power transfer capability is influenced directly, as it is determined by its maximum permissible operating temperature [1]. Generally, as mentioned above, the conductor sags are designed to be within prescribed limits and for that a computational algorithm have already been proposed in order to determine the conductor sag levels from real time measurements of several OHL parameters through online monitoring [2]. Another alternative, for dynamical change of the thermal rating for increased power transfer in an OHL, can be performed by online estimation of the OHL's temperature and sag, using synchronized phasor measurement units in real time [3].

When an OHL is exposed to high temperatures a degradation in its strength is observed which is cumulative during its lifetime. The OHLs that have gone through several stresses, such as overloads, often present problems due to the loss of strength of the conductors, so that electricity companies need to know the thermal history of the OHL, up to a point, in order to decide when it must be substituted [4]. Not only the overloads but also the multiple and consecutive short circuits are, very often, another cause of thermal problems that occur in an OHL and increase its temperature [5]. A steady state modeling approach, which does not uses the distributed and lumped parameter model but proposes a model with multiple nonuniform segments in order to capture the

* Corresponding author.
E-mail addresses: theodosoglou_ioanna@hotmail.com (I. Theodosoglou), hatziath@auth.gr (V. Chatziathanasiou), agp@eng.auth.gr (A. Papagiannakis), boguslaw.wiecek@p.lodz.pl (B. Więcek), Gilbert.DeMey@elis.UGent.be (G. De Mey).

http://dx.doi.org/10.1016/j.ijepes.2016.07.002
0142-0615/

nonuniformity of the OHL parameters [6], has already been published. Real time overload capacity prediction of OHLs is an issue that had been also addressed in the recent years and methods identifying the nonlinear OHL thermal dynamics and predict its temperature [7] have been developed. The thermal problems, also, particularly concern the field of renewable energy, as the renewable energy sources induce power flow variability at the transmission level. Monte Carlo simulations, under a probabilistic approach, for estimating OHL temperatures being subject to various degrees of variability of the power has already been run showing the importance of the dynamic OHL temperature estimation [8]. The thermal problems are not only an important field of research for the OHLs but also for the cables, as their power transfer capability is highly affected by them. The transient temperature rises in cables has a direct impact in the current rating of the cable bundles, thus in [9] an algorithm using a two-fold summation of the Bessel functions for the analytical expression of them is proposed.

In recent years, the electrothermal approach in power system operation gains more and more ground, as the proposed models capture the dynamic behaviour of the OHL over time, in terms of environmental conditions, using real time processes and link these thermal quantities to the electrical power flow model through the OHL power losses [10,11].

If the power dissipated in the OHL is assumed to be constant, the temperature rises until it attains a constant value. In this case, the thermal behaviour of the OHL can be fully described by its thermal resistance, $R_{th} = T/P$, where T is the temperature rise above the ambient temperature and P is the power (Joule losses) per unit length.

However, in fact, the OHL's transmitted power is fluctuating significantly during a single day and this has a direct impact on the Joule losses. In this case, the transmitted power is considered, approximately, as a periodic signal with a period of one day. Consequently, a dynamic analysis is deemed necessary, in order to take into account all the dynamic thermal effects and specify the OHL's thermal behaviour.

The dynamic thermal alternating current (AC) analysis, where the phasor notation ($j\omega$) is used for both the temperatures and the heat fluxes, results in the calculation of the thermal impedance, $Z_{th}(j\omega)$, which is a complex function of frequency, ω, and is graphically depicted by a Nyquist plot (i.e. $\mathrm{Im}[Z_{th}(j\omega)]$ versus $\mathrm{Re}[Z_{th}(j\omega)]$, using ω as a parameter). The thermal impedance's curves describe fully the OHL and constitute its thermal blueprint which allows the prediction of the temperature fluctuations (value and delay) due to the OHL's load variations. Although this technique is well known and applicable in electrical engineering only in recent years is extended to thermal problems in electronics and microelectronics.

There are papers where the thermal impedance is calculated semi-analytically as a function of frequency and presented in a Nyquist plot [12] and others where is calculated, numerically, directly in the frequency domain using the boundary element method and the Green's function for the solution of the thermal conduction equation [13–15]. Fourier techniques, such as Fourier analysis, are, also, used in order to measure the thermal impedance from the transient temperature behaviour [16]. Even the thermal properties of various interface materials, which are used in electronic packages, have been investigated, using the thermal impedance represented in a Nyquist plot, showing that the material influences not only the thermal resistance but also the entire shape of the thermal impedance's Nyquist plot [17]. Moreover, a dynamic AC approach enables us to limit ourselves to phase measurements of the thermal signals which can be carried out with a much higher precision than amplitude ones. For instance, the heat transfer coefficient, which is usually measured under steady state conditions, can be measured, through a dynamic approach, by just measuring the phase difference between the thermal input and output signal with high accuracy [18]. The dynamic thermal analysis and the harmonic analysis seem to be very useful tools not only for the overhead lines but also for the buried cables as they lead to the prediction of the time delay in which the temperature rise appears when a load variation occurs [19].

As mentioned above, the dynamic electrothermal analysis and the temperature fluctuations' prediction is undoubtedly a useful tool in many fields and a lot of researchers use it in a wide range of problems. In this paper, the electrothermal problem of OHLs is solved analytically and the proposed algorithm's steps which lead to the calculation of: the thermal impedance, the temperature fluctuations and the delay time of the measured rms data are presented in full detail. The electrothermal problem has, also, been simulated and solved with a software package and its results are compared with the analytical solution's ones.

Then, the technique is assessed and tested through two sets of experiments and a test case. Furthermore, the presented time delay algorithm is applied to real data received from measurements in the High Voltage Substation in Thessaloniki, Greece, for four indicative months, spanning a whole year and representing all the seasons.

At last, in the concluding section, are presented the results of this work and the conclusions that are drawn.

2. Thermal impedance

The OHLs' analyzed geometries, in the present work, are the typical ones [20] for an AAC (*All Aluminum Conductor*) and an ACSR (*Aluminum Conductor Steel-Reinforced*) OHL (Fig. 1). As the AAC and the ACSR OHLs' problems admit analytical solution, a few approximations are accepted in the power frequency regime, for the electromagnetic field problem [21] in order to become solvable.

In Table 1 the required AAC and ACSR OHL's parameters used both in the electromagnetic field problem and in the thermal problem are presented. The Joule losses, the AC impedance and the DC resistance are calculated through the electromagnetic analysis while the thermal resistance and thermal impedance through the thermal analysis. It should be noted that, both configurations operate at frequency of 50 Hz, with air being their surrounding medium and are chosen so as to have the same equivalent copper cross-section, 92.5 mm^2. Furthermore, great attention should be paid for the value of the thermal capacity that is used in calculations. More specifically, extensive calculations showed that for both AAC and ACSR OHLs, of any cross-section, the actual value of their thermal capacity is about 23% lower than the one if they assumed to be solid.

From the analytical solution of the electromagnetic field problem and the numerical results of the configurations considered, it is noted that the DC resistance, R_{DC}, is about 0.21% lower than the real part of the thermal impedance, Z_{AC}, for the AAC OHL and 0.16% lower for the ACSR OHL.

Additionally, it is remarkable that, if the variables' values maintain constant, the power volume density of the Joule losses presents negligible variation within each conductive region and, thus, it can be approximated by a constant value. On the other hand, the difference in the power volume density of the Joule losses between the steel core and the conductive aluminum region is remarkable. As can be seen from Fig. 2, the amplitude of the Joule losses' density is slightly increased due to the skin effect as the outer surface of the OHL is approached. Also, another mathematical model that enables the determination of temperature distribution arising out of the current density distribution over individual layers of multilayer conductors, like the ones in this paper, through electromagnetic field analysis [22] come in agreement with the abovementioned results.