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Harmonic analysis of dynamic thermal problems in high voltage overhead transmission lines and buried cables

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ABSTRACT

In this contribution a dynamic thermal analysis of an overhead transmission line and a buried power cable is presented. The temperature is calculated as a function of time using a realistic power input obtained from field data measurements. For both the temperature and the power a harmonic analysis is performed. The phase shift between the Fourier components corresponding to a one day period turns out to be a good indication of the temperature delay time with respect to the power peaks. In order to validate and assess the proposed method a lab experiment has been conducted.

1. Introduction

The problem of temperature increase and its prediction is an interesting one for the electricity companies. It is one of the crucial parameters that have direct influence to the power transfer capability. Many papers have been published concerning thermal problems of overhead [1–8] and buried [9–15] power transmission systems. Assuming constant dissipated power for the transmission system, the temperature rises until it attains a constant value. In this case, the thermal behavior of the system can be fully described by its thermal resistance $R_{th} = T/P$, where T is the temperature rise above ambient and P the power (Joule losses) per unit length. However, the power transmitted along the transmission system, and hence the Joule losses, are fluctuating strongly during a single day. So, a dynamic analysis of the thermal behavior is needed. The transmitted power can be considered approximately as a periodic signal with a period of one day. Consequently, a steady state thermal analysis based on the evaluation of a thermal resistance will only give the average temperature. The fluctuating components of the power losses give rise to time dependent temperatures as well. Due to the large thermal time constants, the phase shifts between the peak power and the peak temperature can be quite substantial. Hence, for a thermal analysis the thermal impedance, Z_{th}, has to be evaluated in order to include dynamic thermal effects. Two high voltage (HV) transmission systems will be compared in the present work: an ACSR (Aluminum Conductor Steel-Reinforced) overhead transmission line and a circuit of two 3-phase underground cables. The problem is treated analytically in the case of the ACSR structure and numerically in the case of the underground structure.

Well known, in electrical engineering, is the so called phasor notation ($j\omega$) also denoted by AC. Recently, this approach has been extended to thermal problems in electronics and microelectronics [16–21]. The same method is used in this contribution. The final result for all cases is then a thermal impedance, which is represented in a so called Nyquist plot (imaginary part versus the real part using ω as a parameter). The data for thermal impedance are subsequently used in a dynamic thermal analysis scheme which allows the prediction of temperature fluctuations (value and delay) due to load variations.

Dynamic analyses are normally carried out by solving the related differential equations in order to obtain the temperature as a function of time. In this contribution a harmonic analysis is presented. The Joule losses and the temperatures are represented by Fourier series. It is pointed out that the day night period turns out to be the most important one.

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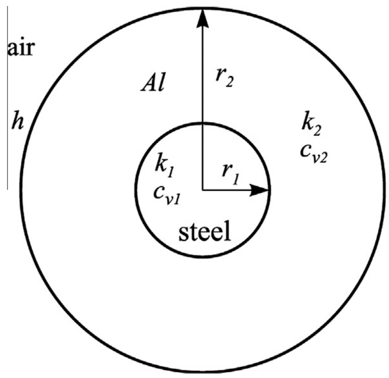

Fig. 1. Cross sectional view of an overhead transmission line.

2. Complex thermal impedance of an overhead transmission line

First of all we consider an ACSR overhead transmission line with a cross sectional view as shown in Fig. 1. Actually, the structure is a multicore one, but for simplicity reasons we consider it to be homogeneous. The structure consists of a central core made of steel in order to guarantee mechanical strength. The core is surrounded by a cylinder made from aluminum and acting as the electric conduction current medium. The parameters of the ACSR overhead transmission line are listed in Table 1 where k denotes the thermal conductivity, ρ the density, c_p the specific heat per unit weight, $c_v = \rho c_p$ the specific heat per unit volume and σ the electric conductivity.

Next a simple thermal model for the overhead line will be presented. High voltage overhead lines are placed at a sufficiently high altitude and are not electrically insulated. Being made from metal, one can assume that the line materials are all good thermal conductors so that a uniform temperature throughout the cross section can be assumed. The only way of heat transfer to the ambient is convection and radiation from the outer surface. Taking a global heat transfer coefficient h into account one gets the following thermal resistance:

$$R_{th} = \frac{1}{h2\pi r_2 L} \tag{1}$$

where r_2 is the radius of the line and L its length. Without loss of generality we can assume $L = 1$ m for our purposes.

The thermal capacity is easy to evaluate as the specific heat per unit volume c_v times the volume of the line:

$$C_{th} = c_v \pi r_2^2 L \tag{2}$$

Although the overhead line is composed of steel and aluminum, an average value of the specific heat of both metals has to be used here. With the knowledge of R_{th} and C_{th} it is quite straightforward to set up the equivalent thermal network shown in Fig. 2. P is the dissipated power or the Joule losses in a piece of line of length L. T denotes the line temperature rise above ambient. The ambient air temperature is taken as the zero reference value.

Using elementary electric network analysis, the thermal impedance Z_{th} of the line is given by:

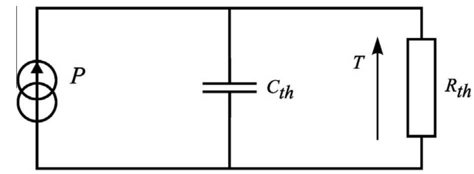

Fig. 2. Simplified thermal model of the overhead transmission line.

$$Z_{th} = \frac{R_{th}}{1 + j\omega R_{th} C_{th}} = \frac{R_{th}}{1 + j\omega \tau_{th}} \tag{3}$$

where $\omega = 2\pi f$ is the angular frequency and $\tau_{th} = R_{th}C_{th}$ the thermal time constant also found to be:

$$\tau_{th} = R_{th} C_{th} = \frac{1}{h2\pi r_2 L} c_v \pi r_2^2 L = \frac{c_v r_2}{2h} \tag{4}$$

The following set of input data has been used: $h = 10$ W/m^2 K, $c_v = 2619$ kJ/m^3 K, $r_2 = 12.489$ mm and $L = 1$ m in order to make the plot of Z_{th} shown in Fig. 3. The value $c_v = 2619$ kJ/m^3 K is a weighted average of the c_v values given in Table 1. It can be easily proved that the Nyquist plot of Z_{th} (i.e. the imaginary part of Z_{th} vs. the real part of Z_{th} using ω as a parameter) is exactly a semicircle. Obviously, at zero frequency one gets the steady state condition $Z_{th}(0) = R_{th}$, the numerical value being $R_{th} = 1.275$ K/W. For the thermal capacity one gets $C_{th} = 1281$ J/K so that the time constant turns out to be $\tau_{th} = 1636$ s or about 27 min.

In order to verify the assumption that the cross section of a line may be treated as isothermal due to the high thermal conductivities of the metals, the same line was also calculated taking the finite thermal conductivity k of the metals into account. Considering that it is consisting of homogeneous parts, the heat equations for the line structure can be written using phasor representation as:

$$k_1 \nabla^2 T_1(r) - j\omega c_{v1} T_1(r) = 0 \quad 0 < r < r_1 \tag{5}$$

$$k_2 \nabla^2 T_2(r) - j\omega c_{v2} T_2(r) = -p(r) \quad r_1 < r < r_2 \tag{6}$$

where k is the thermal conductivity (W/m K), c_v the specific heat per unit volume (J/m^3 K), $p(r)$ the power density (W/m^3) and $T(r)$ the temperature (K). Since the variation of the power density along the radius r is small, almost negligible, it is considered constant. The general solution of Eqs. (5) and (6) are [22]:

$$T_1(r) = AI_0(\beta_1 r) \tag{7}$$

in the steel core whereas in the Al part one has:

$$T_2(r) \frac{p}{j\omega c_{v2}} + BI_0(\beta_2 r) + CK_0(\beta_2 r) \tag{8}$$

in which I_0 and K_0 are the zeroth order modified Bessel functions of the first and second kind, respectively, and

$$\beta_i = \sqrt{\frac{j\omega C_{vi}}{k_i}} \tag{9}$$

The temperature T at a given point can be calculated from Eqs. (7) and (8). If the mean value of the total Joule losses is P Watts, the thermal impedance Z_{th} is now defined by:

Table 1
Physical parameters of the overhead transmission line.

Material	Radius (m)	k (W/m K)	ρ (Kg/m^3)	c_p (J/kg K)	c_v (kJ/m^3 K)	σ (S/m)
Steel	$r_1 = 0.004549$	44.1	7850	475	3728	4.13×10^6
Al	$r_2 = 0.012489$	237	2707	905	2449	35.3×10^6