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Application of thermal impedance to inverse heat transfer modeling of power cables

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Abstract

This paper presents the inverse heat transfer modeling in applications to the power cables. In order to simplify the calculations, the inverse modeling implements thermal simulations in frequency domain. Due to the cylindrical summery of the power cable, this model has an analytical solution, which simplifies using Bessel functions. The inverse model allows estimating the thermal parameters of the material the cable is made of. It can be used for defect detection and aging of the cable. The model was made in Matlab®, and compared with the results obtained from COMSOL® simulation software.

Keywords: IR thermography, power cables, thermal impedance, Fourier analysis, forward and inverse thermal modeling.

Zastosowanie impedancji termicznej do modelowania cieplnych problemów odwrotnych kabli energetycznych

Streszczenie

W pracy przedstawiono zastosowanie modelowania cieplnych zjawisk odwrotnych do wyznaczania wartości parametrów termicznych kabli energetycznych. W procesie modelowania odwrotnego struktury wykorzystano model w dziedzinie częstotliwości, który dla struktury o symetrii cylindrycznej ma rozwiązanie analityczne przy użyciu funkcji Bessela. Model termiczny wraz z optymalizacją opracowano w programie Matlab®. Wyniki modelowania odwrotnego zweryfikowano rezultatami uzyskanymi z symulacji 3D wykonanych za pomocą oprogramowania COMSOL® oraz za pomocą danych pomiarowych, uzyskanych z kamery termowizyjnej. Opracowana metoda może być wykorzystana w praktyce do oceny stanu kabli energetycznych, ich zużycia, do wykrywania defektów związanych np. z korozją oraz do oszacowania warunków odprowadzania ciepła z kabli do otoczenia. W konsekwencji na podstawie wyników termowizyjnych można wyuczyć wartość impedancji termicznej kabla, co pozwoli oszacować maksymalną wartość temperatury w określonych warunkach pracy. Na obecnym etapie badań wykonano model kabla z litego materiału. Kolejnym krokiem będzie opracowanie modelu kabla wielowarstwowego, w tym z izolacją o małej przewodności cieplnej.

Słowa kluczowe: Termografia w podczerwieni, impedancja termiczna, proste i odwrotne modelowania termiczne.

1. Introduction

The detection of defects and the aging estimation in power cables and overhead power lines using non-destructive techniques (like thermography) is useful for the electricity companies. It can reduce the cost of maintenance and /or forecasts faults. It is well known that the aging of these systems is a serious problem as it can reduce the power transfer ability or may cause damages and, consequently, power interruptions. The estimation of a defect can also prevent an undesirable event like short-circuit. So the estimation of the deterioration of materials through the estimation of the thermal properties seems to be very useful. The method that will be presented in this work generally gives an estimation of the thermal properties of the wires of an overhead line (Fig. 1a) or of the different layers of a cable (conductor, insulation, sheath etc.) as shown in Fig. 1b.

As a first presentation, we will present here two simple cases: an overhead AAC (All Aluminum Conductor) line and an overhead steel rod. In the first case the data (temperature vs. time) are obtained through simulation while in the second by measurement. The measurement system is shown in Fig. 2.

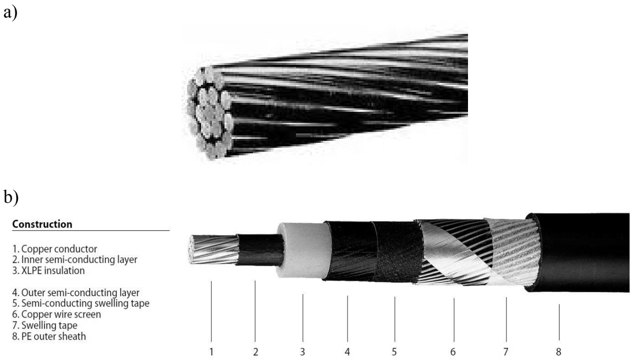

Fig. 1. a) AAC overhead power line, b) MV power cable
Rys. 1. Aluminiowy, napowietrzny kabel energetyczny, b) kabel linii średniego napięcia

An electrothermal analysis of overhead power lines is presented in [1]. Actually, the structure of an AAC line is a multicore one (Fig. 1a). For simplicity reasons it is modeled as a homogeneous one, as in [1]. In this case the problem can be analytically solved. The same model is also used for the simulation.

2. Thermal impedance of a single core conductor

The thermal impedance of a given object is typically measured using the step power function excitation and acquiring the temperature evolution in time as shown in Fig. 3. The impedance is simple a ratio of temperature and power, and it is the function vs. time – Eq. (1).

Fig. 2. The test stand for measuring the conductor temperature
Rys. 2. Stanowisko badawcze do pomiarów termicznych kabli energetycznych

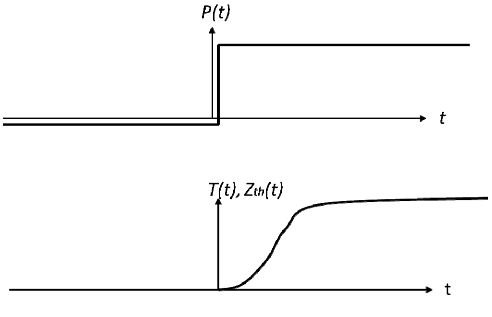

Fig. 3. The concept of thermal impedance measurement
Rys. 3. Koncepcja pomiaru impedancji termicznej

$$Z_{th}(t)=\frac{\Delta T(t)}{P},\quad \frac{K}{W} \tag{1}$$

where $\Delta T(t)$ is the temperature of the object with respect to the ambient and $P=P_0 1(t)$.

The thermal impedance is a quantity which thermally characterizes the investigated object, and it depends on the thermal conductivity and capacity as well as on cooling conditions described by the heat transfer coefficient. The convenient way of presenting the thermal impedance is its frequency dependent form (2), known as the Nyquist plot [1, 2, 3]. It takes the complex values and it can be presented by its magnitude and argument (angle) and/or real and imaginary parts.

$$Z_{th}(j\omega)=\frac{j\omega}{P_0}\int_0^\infty e^{j\omega t}\Delta T(t)dt \tag{2}$$

For a single core conductor presented in Fig. 4, the thermal impedance can be calculated by a simple two dimensional time-dependent thermal model – Eq. (3).

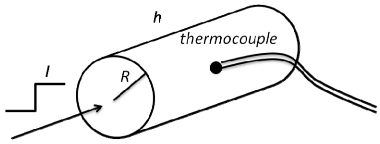

Fig. 4. Geometry of a single core conductor
Rys. 4. Geometria jednordzeniowego przewodnika

$$\lambda\nabla^2 T-\rho c_w\frac{dT}{dt}=-q_v \tag{3}$$

where λ, ρ, c_w denote thermal conductivity, density and specific heat, respectively, and q_v is a volumetric power density dissipated is the conductor.

In order to simplify the calculation and get the solution of Eq. (3) in an analytical form, one can present the model in frequency domain using the Laplace transform – Eq. (4).

$$\lambda\nabla^2 T-j\omega\rho c_w T=-q_v \tag{4}$$

Eq. (4) in general case for the complex geometry is difficult to be solved, even with use of numerical tools. In our case the object has the cylindrical symmetry. It results in the analytical solution (5) in Laplace domain.

$$T(j\omega)=\frac{q_v}{j\omega C_{thv}}+AI_0(\beta r) \tag{5}$$

where C_{thv} is the thermal capacity per unit volume, I_0 is the zero-order Bessel function and β is the parameter expressed by (6).

$$\beta=\sqrt{\frac{j\omega C_{thv}}{\lambda}} \tag{6}$$

Integration constant A can be calculated using the boundary condition (7).

$$\lambda\left.\frac{dT}{dr}\right|_R=h(T-T_a) \tag{7}$$

where T_a is the ambient temperature and h is the heat transfer coefficient modeling the heat removal to the ambient.

Finally, the temperature in frequency domain can be presented as in Eq. (8)

$$T(j\omega) = \frac{q_v}{j\omega C_{thv}} + \frac{T_a - \dfrac{q_v}{j\omega C_{thv}}}{hI_0(\beta r) + \lambda I_1(\beta r)} hI_0(\beta r) \tag{8}$$

and the complex thermal impedance takes a form (9).

$$Z_{th}(j\omega) = \frac{T(j\omega)}{FFT\{P(t)\}} = j\omega T(j\omega) \tag{9}$$

3. Inverse heat transfer model

The heat inverse thermal model was the final aim of this research. It allowed evaluating the values of the thermal parameters of the material, the object was made from. We propose the algorithm presented in Figs. 5 and 6.

The temperature measurement can be performed in 2 ways: using an IR camera or a contact thermometer, e.g. a thermocouple as shown in Fig. 3. In this research we measured the temperature using a thermocouple firmly attached to the cable. In order to verify the correctness of the proposed approach, the modeled data obtained from 2D commercial software [5] was also used as the input.

The inverse heat transfer model in based on the numerical modeling. The Euclidean distance between the time dependent temperature curves obtained both from experiment and simulations was chosen. The temperature vs. time in the simulation can be obtained using the inverse Fourier transform. In order to calculate the temperature from its frequency domain representation, it is necessary to modify slightly the thermal impedance. Due to the fact that the Fourier analysis is defined in the range of frequencies from minus to plus infinity, the additional part of Z_{th} for positive angles has to be concerned [1, 3].

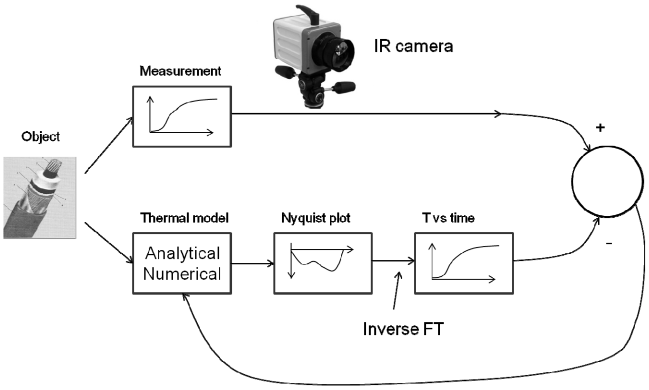

Fig. 5. Experimental procedure diagram
Rys. 5. Schemat prowadzenia badań termowizyjnych

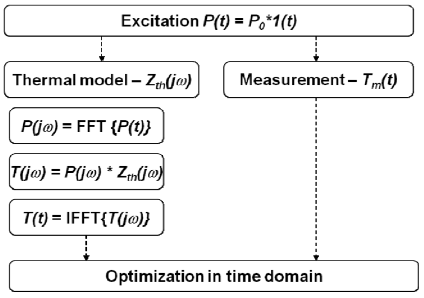

Fig. 6. Flowchart of the inverse heat transfer solver
Rys. 6. Algorytm rozwiązania termicznego problemu odwrotnego

The presented method was implemented in Matlab® software. There are many optimization algorithms that can be used for this problem, and most of them are available in commercial software. For this research we checked the gradient, genetic and pattern search algorithms, and the pattern search was selected, mainly because of reasonable computing time. For 6000 – 8000 samples of temperature, the inverse heat transfer model of a single core cable was calculates within about 1 min.

4. Experimental and simulation results

The experiments were preceded by simulations using the commercially available software for 3D physical modeling COMSOL® [5]. We modeled the single core conductor with the given values of parameters in order to compare the results with the known quantities. The results are presented in Table 1.

Tab. 1. Results for different conductors, MEA(SIM) – input data obtained from measurement (MEA) and 3D simulation in COMSOL [5], (SIM)
Tab. 1. Wyniki analizy dla różnych przewodników, MEA (SIM) wejściowe dane pomiarowe (MEA) i z symulacji przy użyciu programu COMSOL (SIM)

Case, material	λ W/m·K	C_v J/Km^3	h W/m^{2}K	Input data
Al r=6.91 mm I=300 A ρ=2.94e-8 Ωm	181.6	$2.51 \cdot 10^6$	9.9	SIM
Low conductive mat. r=6.91 mm I=300 A ρ=2.94e-8 Ωm	2.6	$1.91 \cdot 10^6$	10.1	SIM
Fe r=4 mm I=35 A ρ=1.64e-7 Ωm	49.6	$3.49 \cdot 10^6$	7.1	MEA

To get the input data, there were made various simulations for an aluminum conductor with thermal conductivity λ = 237 W/m·K, thermal capacity $C_{thv} = 2.45 \cdot 10^6$ J/m^{3}K and heat transfer coefficient h=10 W/m^{2}K. As it is seen from Table 1, in the 1st row, the thermal capacity was evaluated with a satisfactory accuracy, while the thermal conductivity takes the value with the larger error. In addition, an artificial material was chosen with thermal conductivity λ=1 W/m·K to verify the possibility of getting the correct values. It this case, both thermal capacity and conductivity were calculated with lower accuracy (2nd row in Table 1), but still showing the correct tendency. The value of the heat transfer coefficient is estimated very well with an error of the order of 1%. The 3rd case presented in Table 1 concerns the temperature measurement of a real steel rod. The estimated values of the thermal parameters are very realistic. The thermal conductivity is lower, while the thermal capacity is larger comparing with the cable made of aluminum. The fitting of the temperature curves vs. time for both simulated and measured input data is shown in Figs. 7 and 8. The fitting is acceptable.

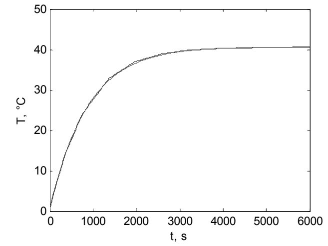

Fig. 7. Simulated (by 3D model) and fitted curve for an aluminum cable
Rys. 7. Wyniki dopasowania odpowiedzi skokowej kabla aluminiowego dla danych wejściowych uzyskanych z modelu 3D

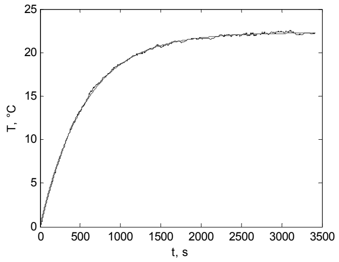

Fig. 8. Experimental and fitted curve for a steel cable
Rys. 8. Wyniki dopasowania odpowiedzi skokowej kabla stalowego dla danych wejściowych uzyskanych z pomiaru

The reason that the thermal conductivity is worse estimated is mainly due to the low sampling rate in temperature measurements. We performed the measurement at 1s rate. It resulted in losing the temperature variation at the very beginning of the thermal process. The thermal conductivity has the highest impact on the temperature at first seconds of the heating process. To achieve the better accuracy of estimation of the thermal conductivity, one has to augment the acquisition speed of measuring data.

5. Conclusions

In this paper we presented a novel approach to inverse thermal modeling for estimation of the power cable thermal parameters. A novelty of this method originates from the fitting of the simulation and measurement results in time domain but using the modeling in frequency domain. Such approach simplifies the calculation and makes it possible to solve the 1D thermal problem analytically. Then, the numerical optimization is used for fitting the step-function responses. It leads to obtaining the power cable thermal parameters and the convective heat transfer coefficient. The problem presented in this paper is simple, because the cable is of single core with cylindrical symmetry. Our future research will concentrate on multilayer power cable structures.

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