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Tool to identify parameters of insulation system in electrical machines

Streszczenie. *W artykule przedstawiono problem identyfikacji parametrów schematu zastępczego układu izolacyjnego maszyny elektrycznej. Zaproponowana metoda identyfikacji wykorzystuje zarejestrowane przebiegi napicia i algorytm roju pszczelego (Artificial Bee Colony Algorithm). Zamieszczono przykład obliczeniowy.*

Abstract*. The issue of the equivalent scheme parameter identification for the insulation system in an electrical machine is discussed in the paper. The presented method is based upon a recorded voltage waveform, and Artificial Bee Colony algorithm is used in calculations. A numerical example is presented. (**Narzędzie identyfikacji parametrów układu izolacyjnego maszyny elektrycznej**).*

Słowa kluczowe: maszyna elektryczna, izolacja, identyfikacja parametrów, algorytm pszczeli (ABC)
Keywords: electrical machines, insulation, parameter identification, artificial bee colony algorithm (ABC).

Introduction - insulation testing

The electrical machine is a key element responsible for the correct performance of the machine. The technical condition of the insulation practically dictates the useful life of the device. Insulation is subjected to mechanical, chemical, electromagnetic, and thermal stresses; it is characterized by its resistance to heat, electrical strength, and heat conductivity coefficient. The problem of diagnosing the current state of the insulation and forecasting its progress of degradation is most important for all users of electrical machines and drives. At present, there are numerous insulation diagnostic methods exist; they can be classified e.g. on the basis of applied diagnostic voltage [2,3,4]. Among the most popular tests run with AC voltage, we may list the dielectric loss tangent tanδ measurement, partial discharge tests or the dielectric frequency response [5,7]. Among DC voltage tests, we can list the polarization method (recovery voltage test and insulation discharge current); quantities such as the polarization index (PI), capacitance of insulation system C, and the dielectric discharge DD are evaluated. Insulation may also be tested with step voltage (the voltage magnitude increases with time). When insulation-to-ground (that is, the main insulation in the machine) has been tested, turn-to-turn insulation measurements may also be performed [1,5,6]. Here, we may list the test of discharge current flowing when a loaded capacitor has been connected to the winding to the winding – surge test) or the test with voltage induced in the winding when constant current flowing through the winding has been switched off (recording of voltage waveform, assessment of induced voltage frequency and logarithmic decrement). The application of a given method depends on the goal of the measurements, available facilities/measurement devices, competence of diagnosing person/s, as well as the condition (age, wear) of insulation. Methods should be inexpensive and effective, easy to implement, and interpret. Often, more or less complex equivalent schemes are used to describe the insulation system. Such schemes take into account elements such as winding resistances and inductances, capacitances-to-ground and turn-to-turn capacitances. In practice, each different machine should be represented by its own (dedicated) equivalent scheme. An example of an equivalent scheme is shown in Fig.1. The values of the parameters in the scheme will be time-dependent (in particular, in the case of old insulation parameters, will depend on applied voltage). However, the problem is how to identify these parameters. If the present values of the parameters were determined and compared with the previous ones, it would be possible to predict the future performance of the insulation system. This would be an interesting diagnostic tool.

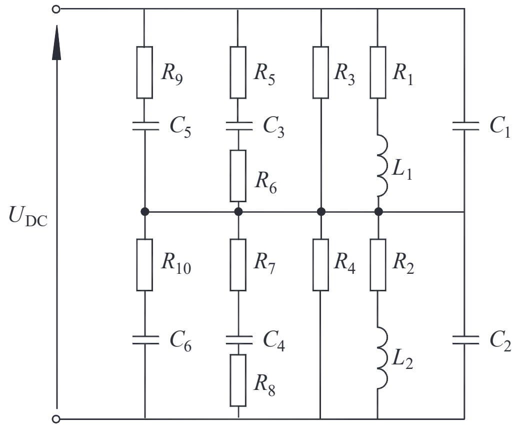

Fig. 1. Example of an equivalent scheme for insulation system - for a coil consisting of two turns: R_1, R_2 – turn resistances, L_1, L_2 - turn inductances, C_1 to C_6 - capacitances of insulation-to-ground, R_3 to R_{10} – resistances of insulation-to-ground

Description of the proposed test method

The main issue is how to reproduce the parameters of the proposed model (circuit) of the insulation system on the basis of relatively simple measurements. We propose a procedure divided into two stages. During the first stage, the insulation system should be performed using the reflected wave method. Roughly, this method consists of supplying the circuit with DC voltage in such a way that the current flowing through the winding should not exceed 10% of the winding's rated current. The circuit is opened, and the waveform of voltage induced at the winding is recorded. An example of a recorded waveform is shown in Fig.2.

In conventional methods, the recorded waveform is used to determine voltage oscillation frequency, waveform envelope (logarithmic decrement), and maximum value of the induced voltage. In our procedure, during the second stage we shall try to mathematically reproduce the parameters of the equivalent scheme of the insulation system.

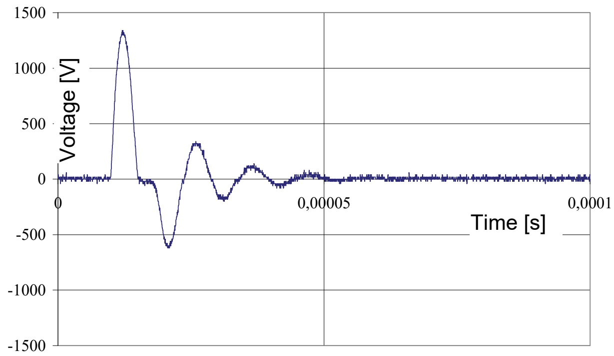

Fig.2. Voltage waveform recorded at the winding of a low-power electrical machine; winding insulation has been impregnated by VPI

Reproduction of equivalent scheme parameters using the artificial bee colony (ABC) algorithm
Problem formulation

If we want to propose a novel method for reproducing parameters of an equivalent scheme of electrical machine, the first step will be to check this method with a simple trial electric circuit. This is shown in Fig.3.

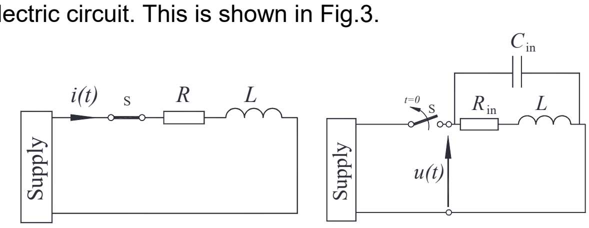

Fig.3. a) Model of a simple real inductor (coil), supplied from a DC source, switch *s* closed, $t < 0$; b) model with switch open, $t \geq 0$; R, L, resistance and inductance, R_{in}, Cin, resistance and capacitance of the insulation system, $u(t)$ – voltage induced at the terminals (energy stored in the magnetic field and later discharged through the insulation system)

It has been assumed that this circuit should be supplied by DC current until steady-state is reached; then, switch is tripped (opened), and voltage will be induced at circuit terminals. This voltage may be expressed by the following relationship:

(1) $$u(t) = \frac{2e^{-\frac{R_{in}}{2L}t} I_0 L \sinh\left(\frac{\sqrt{C_{in}R_{in}^2 - 4L}}{2L\sqrt{C_{in}}}t\right)}{\sqrt{\left(R_{in}C_{in}\right)^2 - 4LC_{in}}},$$

where: $u(t)$ – voltage induced at the circuit terminals after the switch has been opened, I_0 – current (DC) flowing in the circuit before opening the switch, R_{in}, C_{in} – resistance and capacitance of coil insulation, respectively, L – coil inductance.

The elements shown in Fig.3a are solely the coil parameters, i.e., wire resistance and coil inductance. The resistance and capacitance of the insulation have been taken into account in Fig3b, while the resistance has been neglected, since it is much lower than the insulation resistance. For simulation purposes, we assumed that R_{in} = 20 kΩ, C_{in} = 2 nF, L = 0.2 H, I_0 = 0.5 A. An exemplary waveform has then been generated for the purpose of testing the computation method. This voltage is shown in Fig.4.

In the next step, we have formulated an algorithm for reproducing parameters of the scheme shown in Fig.3b solely on the basis of the discretized values of waveform shown in Fig.4.

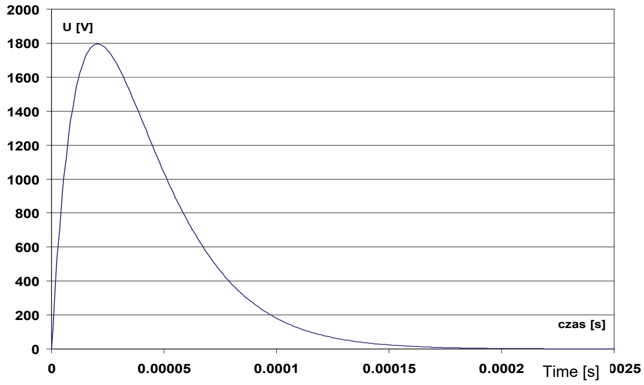

Fig.4. Voltage waveform generated for the scheme shown in Fig.3

Proposed computational method – swarm algorithm

The ABC algorithm was proposed by Karaboga in 2005 [8]. It has been formulated on observation of a a behaviour of swarm of bees searching for food. The exact description of the algorithm may be found elsewhere [9,10]. The algorithm may be implemented in, e.g. Mathematica software, and this procedure has been adopted here.

The initial stage of the algorithm consists of setting the general algorithm parameters, setting the starting point, and first calculating the equivalent scheme parameters.

1.Parameter setting
SN *(Swarm Number)* – this is equal to the number of 'bee-scouts'. We set SN at 20.
D *(Dimension)* – this is the number of 'food sources' discovered (equivalent to the size of the vector x^i , i =1,...,SN). In our case, since we search for values of parameters R_{in}, L, and C_{in}, D = 3.
lim – this is the number of corrective explorations around the food source x^i (corrections of the 'nectar source position'; in this case the location of the food corresponds to the values of the equivalent scheme parameters); it is assumed that $lim = SN{\cdot}D$ (here it is equal to 60).
MCN *(Maximal Cycle Number)* – maximum number of cycles (iterations). We set MCN at 20.

2. Determination of the 'starting point'
The initial population of 'bees' is defined; in other words, some parameters of the equivalent scheme are randomly selected. They are represented by the vector x^i ,i =1,...,SN.

3. The values of the function $F(x^i)$ are calculated, i = 1,...,SN. The function $F(x^i)$ is defined as a deviation of the waveform calculated on the basis of calculated scheme parameters (provided at the starting point) from waveform input to the procedure (Fig.4). The comparison of solutions achieved by different (subsequent) iterations is based upon comparing the obtained values of this deviation. The best possible solution – from among these calculated! – is the one where deviation is the least.
Main part of the algorithm: the first 'location of nectar sources' (corresponding to randomly selected values of the equivalent scheme parameters) will be corrected. The values of the parameters in iteration #2 will be chosen close to the values of the parameters selected in iteration #1.

1. Modification of equivalent scheme parameters
a) Formula (2) is adopted by each 'bee-scout' and position x^i (parameter set) is thereby modified.

(2) $$v_j^i = x_j^i + \varphi_{ij}(x_j^i - x_j^k), \text{ where } j \in \{1,...D\}$$

where

$$k \in \{1,\ldots,SN\},\ k \neq i \quad \varphi_j \in [-1,1] \tag{3}$$

are numbers selected at random.
b) Now the deviation in this step $F(v^i)$ is compared with the previous deviation $F(x^i)$ and if the following relationship

$$F(v^i) \leq F(x^i) \tag{4}$$

is true, then new parameters (vector v^i) replace previous parameters (vector x^i). If not, the parameters x^i remain unchanged and the procedure shown in Step 6 is adopted. Steps (a) and (b) are repeated lim times (we try to find slight divergences of the parameters from their previous values).

2. The probabilities P_i for the positions x^i selected in step 1 are calculated:

$$P_i = \frac{fit_i}{\sum_{j=1}^{SN} fit_j}, \text{ where } i = 1,\ldots SN \tag{5}$$

where

□□□ $$fit_i = \frac{1}{1+F(x^i)}$$

3. Each onlooking bee (i.e. bee-viewer) selects one 'food source', i.e. the parameter set x^i, $i = 1,\ldots,SN$ (from all possible sources), with probability P_i . One set may be selected by any number of bees.

4. Next, another modification of the parameter set is performed (each onlooking bee modifies the set according to the procedure presented in Step 1).

5. The important step is to select the BEST 'food source position', i.e. the best parameter set x^{best} from among all the calculated sets. If this new x^{best} is better than the one selected in the earlier iteration, then it is assumed as the x^{best} location for the entire algorithm.

6. The alternate procedure, if the parameter set has not been improved (relationship (4) has been found to be false). The new parameter set is adopted in accordance with the following formulas:

$$x_j^1 = x_k^{\min} + \varphi_{ij}\left(x_k^{\max} - x_k^{\min}\right), \tag{7}$$

where $j = 1,\ldots,D$ and $\varphi_{ij} \in [0,1]$.

Steps (1-6) must be repeated MCN times.

Calculation results

The selected calculation results are shown below. Since the number of full computational cycles was 20, only a few results are presented. Fig.5 presents the results in graphical form, the selected numerical results are set out in Table 1.

Table 1. Calculated equivalent scheme parameters - selected results (parameters of the reproduced waveform were R_{in} = 2 kΩ, L = 0.2 H, C_{in} = 2 nF)

Cycle number	R_{in}	L	C_{in}	Deviation $F(x^i)$
	Ω	H	F	-
1	24569.4	120.31	$6.39259 \cdot 10^{-7}$	$1.19 \cdot 10^{8}$
10	18860	0.203674	$2.14777 \cdot 10^{-9}$	102601
15	19558.3	0.200165	$2.09759 \cdot 10^{-9}$	30.274
20	19519.6	0.200038	$2.10002 \cdot 10^{-9}$	0.00549285

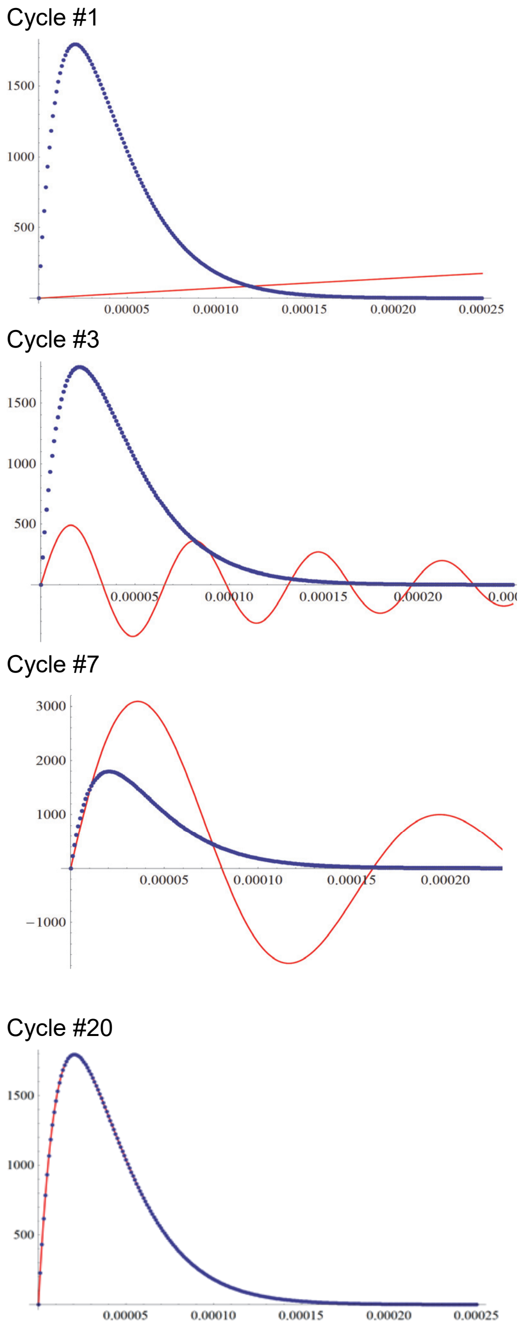

Fig.5. Calculation results: blue line – voltage waveform *u(t)* input into the algorithm; red line – waveform reproduced on the basis of parameters R_{in}, L, C_{in} calculated in the given cycle (parameters of the reproduced waveform were R_{in} = 2 kΩ, L = 0.2 H, C_{in} = 2 nF)

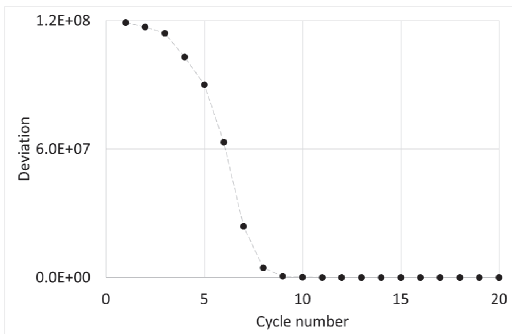

Fig.6. Deviation of the calculated waveform in a given calculation cycle (from the 1 to MSN = 20) from input waveform (numerical data as in Table 2)

To test the influence of noise on algorithm performance, randomly-generated “disturbance” was added to the original waveform, the magnitude of the noise magnitude equal to not more than 4% of the original values. The algorithm was run, and results are shown in Fig.7.

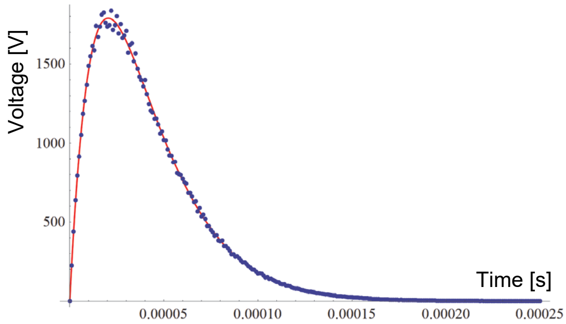

Fig.7. Calculation result for waveform with added noise: blue dots – voltage waveform input into the algorithm; red line – waveform reproduced on the basis of calculated parameters R_{in}, L, C_{in} best fit, calculation cycle #20; deviation $F(x^i)$ = 69737.2, parameters R_{in} = 19597.4 Ω, L = 0.199462 H, C_{in} = 2.09422 nF

Table 2. Comparison of calculated equivalent scheme parameters for smooth and noisy input waveform

	R_{in}	L	C_{in}	Deviation $F(x^i)$
	Ω	H	nF	
Input waveform	20000	0.2	2	-
Reproduced waveform	19519.6	0.200038	2.10002	0.00549285
Reproduced waveform with added noise	19597.4	0.199462	2.09422	69737.2

Conclusions

We wanted to provide a tool for identification of electrical circuit parameters when a single signal waveform for this circuit is known. The proposed end purpose is to diagnose machine insulation (basing on equivalent parameters of the insulation scheme). We have applied swarm-type mathematical algorithm (ABC) to the task of identifying three parameters of electrical circuit, with induced voltage waveform acting as input data. Two cases have been analysed: with a smooth input waveform and a waveform ‘contaminated’ by random noise. The proposed algorithm performed well. Future investigations will be centred on increasing the number of circuit elements and on possible attempts to reproduce real-life signals obtained from existing insulation systems.

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