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Calculation of thermal coefficients of a metal partition wall by FEM analysis

***Abstract**. Thermal coefficients, used in numerical analysis of the thermal field, are usually given by tables. The values are also given with lower and upper bound that presents an additional dilemma when determining, which value to choose. This paper describes a calibration of the thermal coefficients on the test object with a Particle swarm optimization algorithm (PSO). The thermal field, which has been discussed in this research, is a consequence of eddy currents that occur in metal parts of switchgear.*

***Streszczenie.** Współczynniki transferu ciepła używane w analizie numerycznej pola cieplnego są zwykle przedstawiane w tabelach. Te wartości są także podawane w postaci górnych i dolnych wartości, co generuje dodatkowy dylemat, która wartość wybrać. Artykuł opisuje kalibrację współczynników przepływu ciepła na obiekcie testowym z użyciem algorytmu optymalizacyjnego PSO. Pole cieplne, które jest dyskutowane w artykule, wynika z prądów wirowych występujących w częściach metalowych aparatu. (**Obliczenia współczynników przepływu ciepła w metalowych ścianach metodą elementów skończonych**)*

Keywords: eddy currents, electrothermal effects, finite element analysis, optimization methods.
Słowa kluczowe: prądy wirowe, efekt elektrotermiczny, metoda elementów skończonych, metody optymalizacji

Introduction

Partition wall is located between two medium voltage switchgear cells, where busbars (conductors) go through. Partition wall consists of a metal plate and three bushing elements that go through it [1].

Eddy currents indirectly affect heating of medium voltage cell. Depending on conductivity and permeability of the metal plate, eddy current density varies. The whole physical process could be explained with proximity effect. The source conductors generate time-harmonic magnetic field, which is assessed with Biot-Savart law. Variable magnetic field has some influence on conductive materials. According to Faraday's Law time-harmonic magnetic field that crosses materials induces voltage and consequently the current. The closer the source conductors are, the greater is the influence on the rest of the conductive materials. Effective current value of conductors is the second significant parameter that determines magnetic field impact on the conductive areas located near the source (busbars).

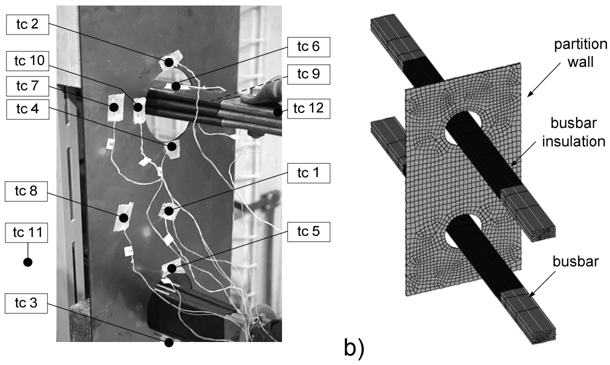
Parameters that represent some material properties (for example, conductivity, permeability, heat transfer coefficient) are obtained from tables and are given under certain boundaries. For the exact calculation of the temperature values, it is necessary to calibrate the numerical model. The calibration [2] is carried out with an optimization algorithm [3], which estimates the correct input parameters of numerical model for the eddy current and for thermal calculation.

Parameters are calculated with a prepared simplified test object of the partition wall. Material parameters, which are obtained on the basis of the test object calibration, are used further for temperature FEM calculation of the real three-phase partition wall of the switchgear cell.

Test object and numerical model of the metal partition wall

The test object has been prepared for temperature analysis, which is a consequence of eddy currents in metal parts of medium voltage switchgear. The test object of the partition wall consists of a 3 mm thick metal plate and contains two holes, through which busbars are placed (Fig. 1a).

Numerical analysis presents a coupled problem of eddy currents phenomenon through a thermal field observation [4]. Since the calculation is based on FEM, it is crucial to define a proper numerical model (Fig. 1b). The complete numerical model is built with two parametric preprocessors (eddy currents and thermal one) and two postprocessors (numerical and graphic one). The FEM calculations are carried out with EleFAnT3D solver [5]. The numerical model consists of 52,100 finite elements, which are 20-nodal isoparametric hexahedrals.



a) b)
Fig.1. a) Test object with 12 thermocouples, b) 3D FE model

Temperature measurements are carried out with twelve thermocouples, positioned as it is shown in Fig. 1a. Measurement results of temperature for all 12 thermocouples at the RMS current of 400 A through the busbars are shown in Fig. 2.

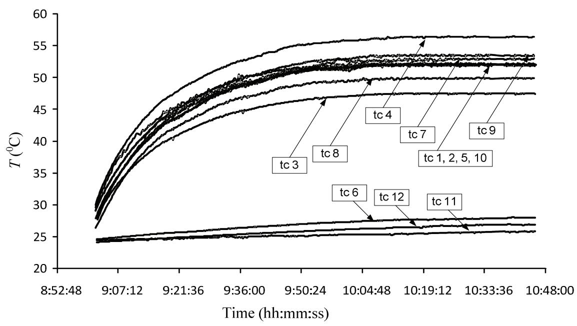


Fig.2. Measured temperature values at RMS current 400 A.

Calibration procedure for thermal coefficients

Calibration procedure for thermal coefficients runs inside the Particle swarm optimization algorithm (PSO) [3] in Matlab and it is schematically shown in Fig. 3. Due to the non-uniform eddy currents distribution, a numerical postprocessor is designed to calculate the average eddy current density value in each finite element. Joule losses are obtained from previous calculations, and are applied further on in the second part of the process (thermal analysis).

```
Begin
Temperature measurements obtained with thermocouples
Parametrically written FEM model of partition wall
Create initial population for particle swarm optimization (PSO)
  While the stopping criterion is not reached Do
    For i=1 to size of the swarm nD Do
      Create preprocessor_1 (materials, boundary conditions,
                              effective current in conductors)
      Solve the eddy current problem
      Numerical post processor (current density and Joule losses
                                  in each FE)
      Create preprocessors_2 (materials, boundary conditions,
                              Joule losses in each FE)
      Solve the thermal field (temperature distribution)
      Evaluate the objective function fi (RMS between calculated and
                              measured temperature values in n points)
    End
    If (fi < required condition) Then
      The numerical model is calibrated.
      Optimal parameters of the optimization process-the actual
                    material properties of the test model
    Else
      Use of particle swarm optimization (PSO) algorithm
      New values of optimization parameters (conductivity,
                 permeability, heat transfer coefficient)
    EndIf
  End
End
```

Fig.3. Pseudo-code of the calibration process for optimization parameters

The minimal difference between measured and calculated (FEM) values in all (n=12) points represents the objective function. It is defined as RMS value:

$$f = \sqrt{\frac{1}{n} e_i^T e_i} \quad i = 1,...,n \tag{1}$$

where error vector $\mathbf{e}_i$, is defined as difference between FEM calculated ($T_{C,i}$) and measured temperature values ($T_{M,i}$) in the i^{th} point of the model:

$$e_i = T_{C,i} - T_{M,i} \, . \tag{2}$$

The PSO algorithm searches the minimum of the objective function because the agreement between numerical results and results obtained with the test object is the main goal.

Particle swarm optimization (PSO) algorithm

Particle swarm optimization algorithm is placed in population-based stochastic search technique. Various evolution optimization methods, which belong to this group of stochastic methods, imitate genuine evolution. Evolution methods change a population of the individuals, which contains the problem solution, by different processes: mutation, cross-over, reproduction. The best solution is carried over generations. In a counterweight to the evolution algorithms, PSO algorithm imitates social behaviour of the birds while they fly and does not contain genetic operators. Instead of the genetic operators, the population members are exposed to the cooperation between each other, at the same time, throughout generations they compete with each other. Each and every particle adjusts its flying ability to the leading particle-the best individual. Each particle of the population, which represents a possible solution to the problem, is treated as a point in the D-dimensional space. The i^{th} particle is presented as $x_i=(x_{i1}, x_{i2}, \ldots, x_{iD})$. The best former position (position, which gives the best result) of the each and every particle is stored and presented as $p_i=(p_{i1}, p_{i2}, \ldots, p_{iD})$. The velocity of the i^{th} particle is presented as $v_i=(v_{i1}, v_{i2}, \ldots, v_{iD})$.

The velocity change v_i and the new position x_i of the i^{th} particle change in accordance with the (3) and (4):

$$\begin{aligned} v_i(t+1) &= w \cdot v_i(t) + c_1 \cdot rand() \cdot (p_i(t) - x_i(t)) + \\ &+ c_2 \cdot Rand() \cdot (p_g(t) - x_i(t)) \end{aligned} \tag{3}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{4}$$

where t indicates the iteration, c_1 and c_2 are positive constants, rand() and Rand() are random functions that choose values from range [0,1]. Equation (3) is used for calculation of the new particle velocity on the basis of the former particle velocity and the distance between its instantaneous distance and distance of the leading particle. Equation (4) represents a flight of the particle towards the new position.

Equation (3) contains three parts. The first part is a former velocity of the particle and second and the third part influence on the velocity change. Weight w balances global and local search. The small weight w (<0.8), causes the PSO algorithm to behave as a local algorithm and it finds a global minimum very fast. The great weight w (≥1.2), causes the PSO algorithm to behave more as a global algorithm. The time of the search increases. The weight between those two values gives the best possibility to find the global optimum and at the same time the search is reasonably short to accept.

When the new population is entirely formed, the algorithm is being carried out until the interruption criterion is reached. The quality of each particle is evaluated on the basis of the defined objective function.

Improvements of the PSO algorithm introduce the genetic operator mutation to achieve global minimum reliably [6]. However, it is possible that particles simply fall into the local minimum, if they reach convergence too fast to the position of the best individual (the leading particle).

Results

The complete process of the numerical model calibration is realizable in regards to the electromagnetic calculation in two ways. In the case of linearity, electromagnetic parameters (permeability and conductivity) and temperature parameters (thermal coefficients of different materials) are calibrated. In the case of non-linearity, the calibration of the temperature parameters is possible. Of course, in that case BH curve and conductivity must be familiar. Note that only the case of non-linear eddy current analysis is discussed.

Optimization process of the partition wall model parameters calibration with PSO algorithm has been performed under the settings shown in Table I.

Table 1. PSO settings

parameter	value
constant $c1$	2
constant $c2$	2
weight w	1.1
size of the swarm n_D	20

At the non-linear calculation thermal model parameters represent four optimization parameters. Behaviours of the objective function for the non-linear analysis throughout the optimization procedure is shown in Fig. 4 (at RMS current 400 A). Fig. 4a shows all evaluations for the objective function and Fig. 4b shows currently best value of the objective function for each iteration.

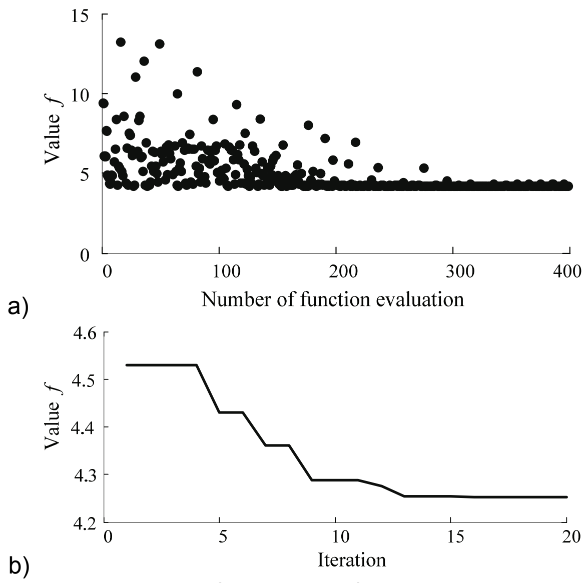


Fig.4. a) All evaluations of the objective function, b) currently best values of the objective function throughout the individual iterations

Behaviours of best individuals throughout the optimization process for each iteration are shown in Fig. 5. The parameters are calculated on their relative values. Optimization process runs until it reaches the maximal number of iterations, respectively until the convergence is reached. Therefore, the parameter values in the last iteration also represent the final result.

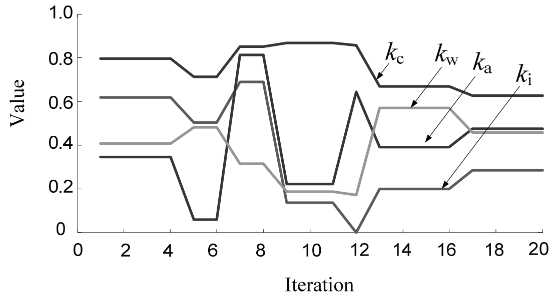


Fig.5. The best individuals (relative value) throughout the optimization process for each iteration

The final results of calibration of the numerical model with the optimization algorithm PSO are give in Table II.

Table 2. Parameters obtained with calibration (optimization)

Parameter	Variable	Lower value	Upper value	Identified value (nonlinear)
Thermal coefficient of air	k_a [W/mK]	0.022	0.03	0.0278
Thermal coefficient of partition wall	k_w [W/mK]	30	85	61.8
Thermal coefficient of insulation	k_i [W/mK]	0.1	0.2	0.142
Thermal coefficient of copper	k_c [W/mK]	385	410	396.4

If the parameters of the calibrated model are used for thermal analysis on different parts of the switchgear, more accurate results would be obtained in comparison to the well known data.

The test object of the partition wall is made out of steel with a mark J.0146.P3, which has a conductivity σ=7e6 S/m and B-H curve is obtained from experimental measurements.

Conclusion

The aim of this research is to improve parameters of the numerical thermal model. Numerical model is calibrated when calculated and measured results achieve good agreement. Determined parameters (thermal coefficients) gained from the test object have been used on the realistic partition wall with three conductors. Therefore, the greater accuracy of the calculation is almost sure in comparison with the coefficients written in tables. Obtained results can be used in further analysis and other calculations regarding a medium voltage cell.

Particle swarm optimization algorithm has proven as an effective and fast for minimum search between calculated and measured temperature values. This is extremely important, because numerical calculation is very time-consuming.

Through the optimization process many problems have occurred. It has also happened that the optimization algorithm had produced an illogical result, respectively an incorrect combination of the electro thermal parameters (note that the problem has been a huge number of the measuring points and consequently larger averaging!).

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