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THE INNOVATIVE DESIGN CONCEPT OF THERMAL MODEL FOR THE CALCULATION OF THE ELECTROMAGNETIC CIRCUIT OF ROTATING ELECTRICAL MACHINES

INNOWACYJNA KONCEPCJA BUDOWY OBLICZENIOWEGO MODELU CIEPLNEGO DLA OBWODU ELEKTROMAGNETYCZNEGO WIRUJĄCYCH MASZYN ELEKTRYCZNYCH*

Operating parameters and reliability of rotating electrical machines are connected to a large extent with their thermal state. The high temperature of these devices has an impact on the life of such elements as bearings, windings, andalso efficiency and possibility of their use. More often, during the analysis of the existingand new designs of electrical machines,the thermal and mechanical calculations are carried out. The finite element method which uses spatial models is commonly used in such calculations. The correct formulation of boundary conditionsand the appropriate model simplifications are the key problems. Parameters calibration of thecalculation model in order to obtain adequate calculations results to the actual device operation is necessary to performed. The innovative conception for determining the thermal parameters of the numerical model for the most complex structure of electrical machinery, which is the electromagnetic circuit, is presented in this paper. During the preparation of the thermal spatial computational models of rotating electrical machines, this method can be used. The proposed simplified monolithic model of the electromagnetic circuit with base on simple experiment calibration method allows to preparethe effective computational model which can be successfully applied in the programs which use the finite element method.

Keywords: *numerical computation, thermal analysis, FEM, operation ofelectrical machines.*

Parametry eksploatacyjne oraz niezawodność wirujących maszyn elektrycznychzwiązane są w znacznymstopniu z ich stanem cieplnym. Wysoka temperatura tych urządzeń ma wpływ na żywotność takich elementów jakłożyska, uzwojenie, oraz sprawność i możliwości ich zastosowania. Podczas analizy istniejących konstrukcji maszyn elektrycznych oraz na etapie projektowania nowychprowadzone sąoraz częściejobliczeniawytrzymałościowe i termiczne.Przy obliczeniach takich powszechnie stosowana jest metoda elementów skończonych wykorzystująca przestrzenne modele obliczeniowe, w których zagadnieniem kluczowym jest sformułowanie poprawnych warunków brzegowych oraz przyjęcie właściwych uproszczeń. W celu otrzymania wyniku adekwatnego do rzeczywistej pracy analizowanego urządzenia niezbędne jest przeprowadzenie kalibracji parametrów modelu obliczeniowego. W niniejszej pracy przedstawiono innowacyjną koncepcję określania parametrów cieplnych modelu numerycznego dla najbardziej złożonej struktury maszyn elektrycznych, jaką jest obwód elektromagnetyczny. Metoda ta ma zastosowanie podczas budowy przestrzennych termicznych modeli obliczeniowych wirujących maszyn elektrycznych. Zaproponowany uproszczony monolityczny model obwodu elektromagnetycznego wraz z metodą jego kalibracji za pomocą prostego doświadczenia pozwala na szybkie przygotowanie efektywnegomodelu obliczeniowego, który z powodzeniem może być użyty w programach wykorzystującychmetodę elementów skończonych.

Słowa kluczowe*:* *obliczenia numeryczne, obliczenia cieplne, MES, eksploatacja maszyn elektrycznych.*

1. Introduction

Growing demands on the efficiency of electric motors, as well as economic aspects and diversity of application cause that in the design of electrical machines not only electrical parameters are important.The higher reliability, minimize weight and dimensions, high strength, and appropriate vibration, noise and thermal stateparameters are required from actually designed and manufactured electrical machines [1, 4-6, 10]. In other words, electrical machines should be optimized to working conditions in which they are operated. This approach necessitate development of newer and more elaborate design. At the same time in the design process of modern electrical machines the interdisciplinary knowledge in the field of electrical engineering, electronics, strength

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** of materials, thermodynamics, fluid mechanics and acoustics is required from constructor.

The development of computer technology and constantly increasing computing capabilities have contributed to the development of numerical methods and increasing popularity of programs supporting the work of design engineers. Skillful use of specialized software in the design of electrical machines can increase the efficiency of project work and motor durability simultaneously reducing their weight, vibration, noise and temperature. In the available publications, it can be seen that more often to thedesign analysis of electrical machine researchers use sophisticated computational programs. In addition to the mechanical analysis, software for thermal and flowanalysis based on *FEM* and *CFD* or the Lumped Parameter Modelingis becoming more popular[2].

In the literature related to this subject, different ways of modeling and calibration of computational models and related problemscan bealso found [1, 4-8, 10, 12, 13, 15]. However, in the most recent publications Lumped Parameter Modelingmethodsare described and used to the electrical machines thermal calculations [1, 4-6].

These analyzes allow for the development of innovative solutions of designhigh efficiency electric motors, as well as designing new efficient ways of cooling. For a variety of models, it is possible to create electrical computational models on which we can perform theheat and flow calculations. The most known and developed software forthermal analysisof electrical motors is the *Motor-CAD*. It uses the method of lumped parameter modeling, but also has modules which use*FEA* and *CFD* [1, 4-8, 10, 12, 13, 15]. However, regardless of thesoftware we use to obtain correct simulation results of the thermal condition of electric machines,it is necessary toproperlyidentify the actual or replacement value of thermal parameters of the structural materials and preparing of appropriate computational model.

2. Aims and assumptions of the work

Stator is the one of main element of rotating electrical machine and itis located inside the machine. It consists of a coil made of insulated copper wires, impregnation and lamination stack. These elements createelectromagnetic circuit and they are the main source of heat and at the same time they are responsible for heat energy dissipation from the machine. However,from the point of view of computational techniques, these elements are a complex set of parts and thus adopting appropriate computational model and selecting the right parameters has a huge impact on efficiency and accuracy of the calculation results.

The purpose of this study is to determine the appropriate thermal parameters of the elementary electromagnetic circuit component which isthe part of the whole machine. These parameters will be used to build acomputational thermal model of the complete electromagnetic assembly and developing the correct method for cooling electrical machines.

Thermal properties of the electromagnetic circuit depend on the characteristics of the components as well as their production technology. The most accurate way to determine the replacement thermal properties of components is to carry out tests on samples taken from the materials used in electrical machines built according to the technology used in the manufacturing plant. Such studieswere presented in the work [3],in which the research was conducted on samples using expensive, specialized measurement stations.

This paper proposes a method for determining the thermal parameters of the electromagnetic circuit based on a simple experiment. Such an experiment is possible to carry out in each production facilities and does not require the use of highly specialized measuring equipment.

3. The preparation of the computational model of electromagnetic circuitmethod

3.1. Sampling and verification of the thermal conductivity parameter across thelamination stack

For proper thermal properties selectionof an elementary circuit, lamination stack sample made of *M400-50A* sheet, was prepared (Fig.1). This materialis commonly used in the production of electrical machines' cores. For thermal measurements, special holes in the lamination stack sample were made.

Fig. 1.Sample of the lamination stack

In the most of the publications two-dimensional heat transfer calculation, based on Lumped Parameter Modeling, can be found. Often in these calculations one-dimensional heat distribution along lamination stack is assumed. In the three-dimensional thermal analys is the thermal conductivity parameter across the lamination stack is important. The value of this parameter depends on silicone steel type, kind of insulation and lamination pressure, which is confirmed by the studies presented in [3].

For the determination of the thermal conductivity parameter across the lamination stack the simple experiment was carried out. In the next step the experiment was modeled and solved numerically. On the basis of the experiment results, the thermal parameters were determined by the cyclic numerical simulation. The obtained computational model may be used to the thermal calculation of the complete electrical machine.

During the experiment the heating plate with a power of 125 W was used. The lamination stack sample was placed on the heating plate surface after achievement the temperature of 160°C. To ensure proper contact and heat distribution between the plate and lamination stack sample, the heat carrier plate and thermal paste were used. During the experiment, the temperature was measured by Pt100 sensors at the points shown in Fig. 2. Thermovision camera which is often used to monitor the technical condition of electric machines [9, 11] was also used.

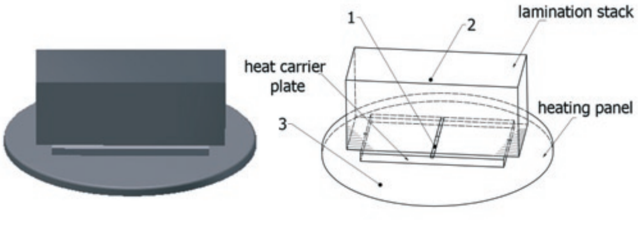

Fig. 2. Thermocouples location: 1-bottom surface of the lamination stack, 2-top surface of the lamination stack 3-heating panel surface, 4-ambient temperature

To provide heat transfer only by natural convection and radiation, the measuring position has been protected from air flow. The temperature registration continued until steady state was reached. Steady state thermogram is shown in Fig. 3.

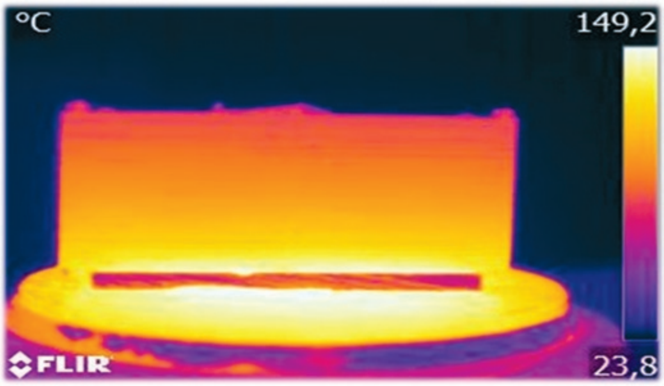

Fig. 3. Steady state thermogram of the thermal conductivity test across the lamination stack

Next the measurement position was modeled in Autodesk Inventor (Fig. 2).Prepared model was imported into Autodesk Simulation CFD to simulate the heat flow. As boundary conditions, parameters corresponding exactly to the conditions prevailing during the experiment were assumed.

They included: initial temperature of the heating plate (~160°C), the heating plate power (125 W), initial temperature of the sample which was equal to ambient temperature (~21°C), the properties of the aluminum heat carrier plate (Cp = 896 J/kgK, l = 203 W/mK) and thermal grease (Cp = 465 J/kgK, l = 0,78 W/mK). Also the phenomenon of radiation and convection were taken into account. The value of the convection parameter was assumed to 7 W/m^2.

For such prepared calculation model, in order to itscalibration, series of transient numerical simulations were performed. During calibration, the value of the thermal conductivity parameter across the lamination stack in the range of 1 to 5,6W/mK was changed. According to [3, 6, 13] the specific heat was set up at 490 J/kgK. The best compatibility experiment results with simulations were obtained for lb$_z$ = 3 W/mK. The comparison of the results obtained from the numerical analysis and experiment is shown in Fig. 4 and 5.

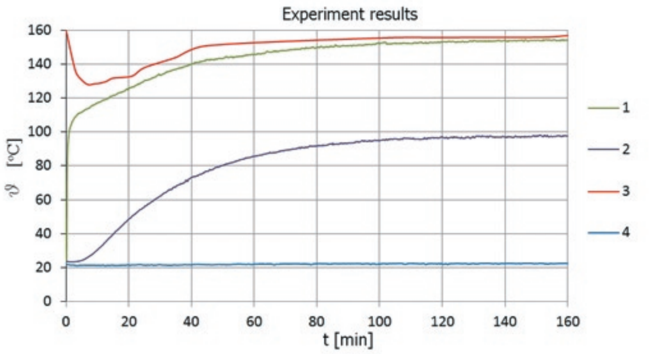

Fig. 4. Temperature distribution at the measuring points 1-4 obtained from laboratory measurements

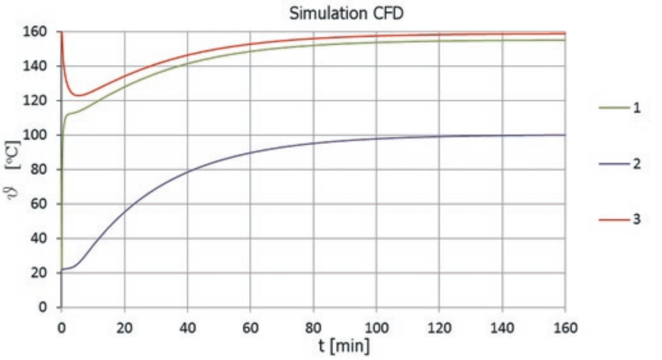

Fig. 5. Temperature distribution at the measuring points 1-3 obtained from numerical simulation

Comparing thegraphsin Fig.4 and 5,the agreement of the numerical simulations results with experiment can be seen. On the basis of this comparison the correctness of the assumed computational model, material properties and methods for model calibration is confirmed.

3.2. Sampling and verification of the thermal conductivity parameter along the lamination stack

In order to determine the equivalent thermal conductivity along the lamination stack, similar to that described in section 3.1, experiment was conducted, which then was modeled and solved numerically. A method and procedure for experiment were the same as in the case of determination the thermal conductivity parameter across the lamination stack. During the experiment temperature at the measuring points, shown in Fig. 6, was monitored byPt100 sensors. Steady state thermogram is shown in Fig. 7.

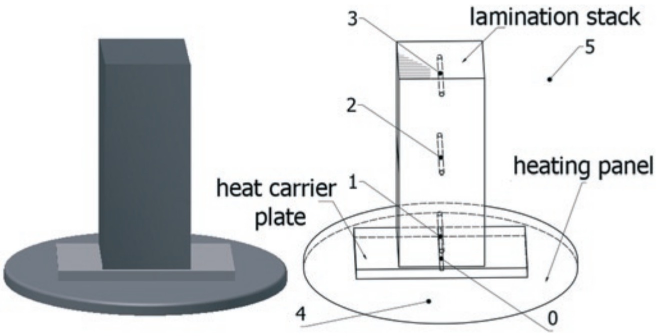

Fig. 6.Thermocouples location: 0-top surface of heat carrier plate, 1,2,3-at holes in the lamination stack 4-heating panel surface, 5-ambient temperature

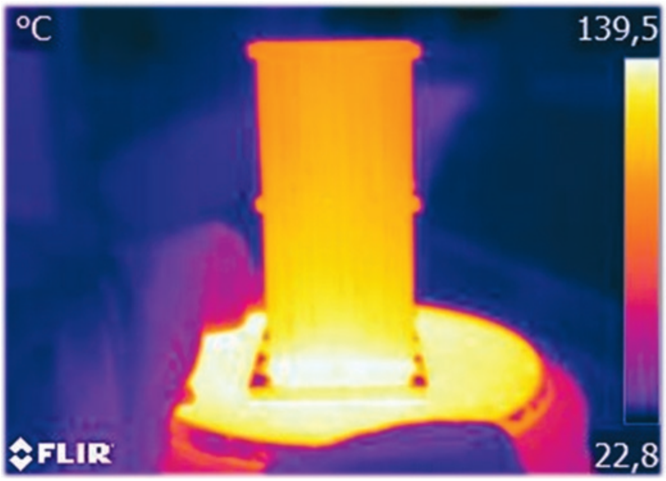

Fig. 7.Steady state thermogram of the thermal conductivity test along the lamination stack

In the numerical simulations thermal conductivity parameter along the lamination stack $\lambda b_{x,y}$ was changed in the range of 20 to 30 W/ mK. Specific heat Cp$_b$ as previously was set up at 490 J/kgK. As a result of model calibration, the best simulation compatibility with the experiment results obtained for λb_z=30 W/mK can be observed by comparing the temperature distributions shown in Fig.8 and Fig.9.

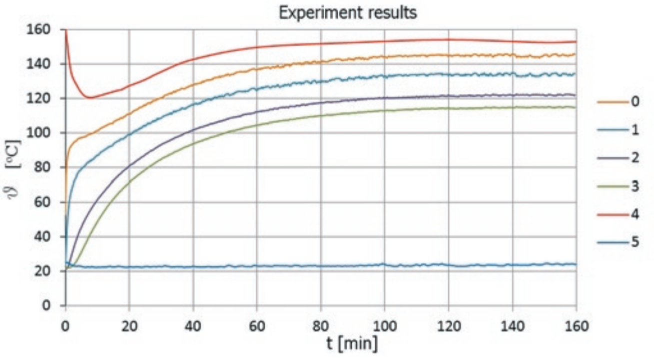

Fig. 8. Temperature distribution at the measuring points 0-5 obtained from laboratory measurements

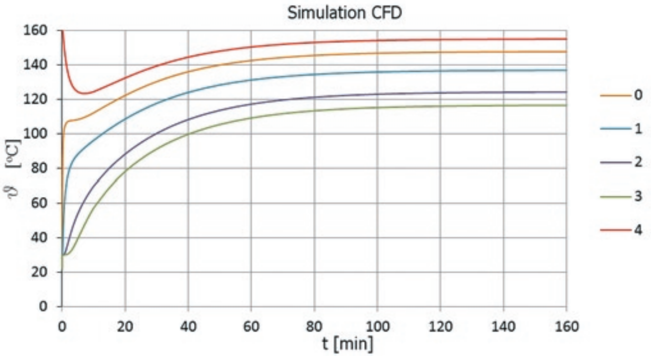

Fig. 9. Temperature distribution at the measuring points 1-3 obtained from numerical simulation

3.3. Accuracy verification of the determination of the slot insulation thermal resistance substitute and coil model parameters replacement

In order to determinethe substitute parameters of slot insulation thermal resistance and thermal properties of electromagnetic circuit model, which is shown in Fig.10, the same as for lamination stack, an experiment was conducted. Also the experiment was modeled and solved numerically.

Fig. 10. Sample of the electromagnetic circuit

A sample of the electromagnetic circuit was prepared according to the most commonly used in manufacture technology stators. Lamination stack was made from laser-cut electrical sheets. The coil windings were made from a round wire ∅0,71 mm. As a slot insulation, a flexible laminate with thickness 0,23 mm was used. Then, the sample was impregnated.

During the experiment the coil winding of the prepared electromagnetic circuit sample was fed with direct current and generated 20 W of losses. The temperature was monitoring by Pt100 sensors at the measuring points shown in Fig. 11.

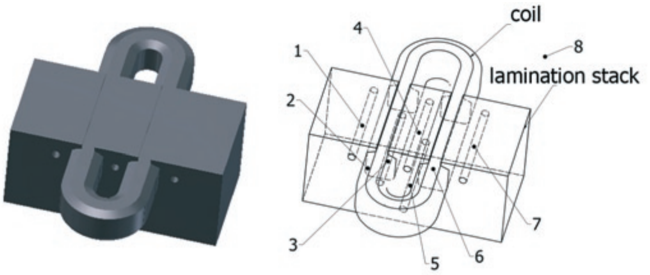

Fig. 11. Thermocouples location: 1,3,4,5,6,7- at holes in the lamination stack, 2-at the bottom of the slot, under slut insulation , 8-ambient temperature

Measuring position has been covered from an air flow to provideheat transfer by natural convection. The study was carried out to achieve a steady state. The steady state thermogram is shown in Fig. 12.

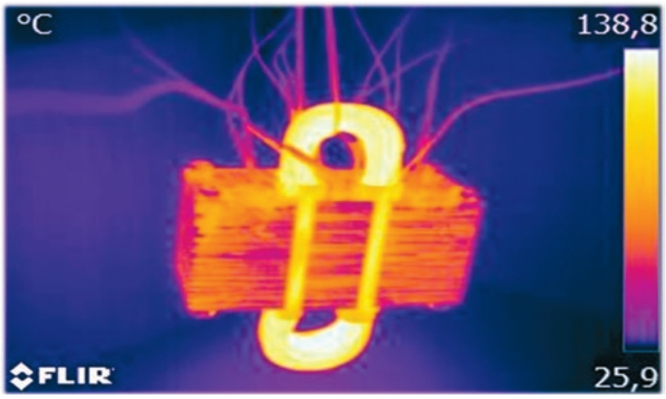

Fig. 12.Thermogram of the sample of electromagnetic circuit

As boundary conditions for the numerical simulation, the same parameters which were measured at the time of conducting research, were set up. The initial temperature of the sample which was equal ambient temperature (~ 21°C), the power supplied to the coil (~ 20 W), and the material properties of lamination stack determined as was described above were determined. The heat exchange to the environment, as in 3.1 and 3.2, includes radiation and convection phenomenon.

A key step in the construction of the numerical model was to develop a model of the winding and slot insulation. Winding was modeled as a monolith. Modeling the slot insulation as a solid causes formation of a thin structure which has an impact on mesh size, and finally the computational time. During the analysis of the spatial model of the whole machine it will increase the number of elements that will make it impossible to carry out effective calculations. Moreover, there is difficulty in determining the effect of slot insulation adhesion to lamination stack and winding, and influence of the applied impregnation and gaps filled with air for final values of the thermal parameter of such insulation. Because of that, in the calculation model a solid model of the slot insulation was replaced by equivalent slot insulation contact thermal resistance parameter $Rc_{\dot{z}}$, calculated on the basis of the known heat flow through the surface of the insulation and temperature drop obtained in steady-state [14, 16]. This alternative method for determining the equivalent thermal resistance of slot insulation is commonly used to determine the thermal parameters of computational models, however, concerns the complete electromagnetic circuit [5, 6], not as in this study a representative sample.

$$Rc_z = \frac{\Delta T}{\dot{Q}/A} \tag{1}$$

In the calculation model, the following thermal properties were set up:

- For the lamination stack:

  Cp_b=490 J/kgK,

  lb_z=3 W/mK,

  lb_{xy}=30 W/mK.
- For the winding:

  Cp_u=380 J/kgK,

  lu_{xy} =190 W/mK,

  lu_z =0,45 W`/mK,

  $Rc_{\dot{z}\,=}$ 0,0073 Km^2/W.

The equivalent thermal conductivity of the coil across winding-was determined by using the Richter formula, which is valid for the coil with round wires tightlywound and adjacent to each other with the assumption that all voids are filled with varnish.

$$lu_z = cl \tag{2}$$

The c coefficient depends on the ratio of the diameter ***d*** of the wire without insulation and insulated wire diameter ***d'***. For the wire used in the sample winding with a diameter *d* =0,7 1 and *d'*=0,789, Richter's factor takes the value *c* =4,5. With the assumed thermal conductivity of the wire insulation l_i=0,1 W/mK equivalent thermal winding conductivity across winding lu_ztakes the value 0,45 W/mK.

Temperature distribution obtained from laboratory measurements is shown in Fig.13 and obtained by numerical simulation is shown in Fig.14.

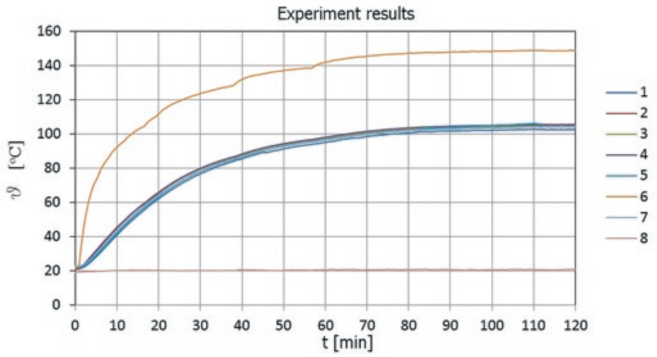

Fig. 13. Temperature distribution of the electromagnetic circuit sample obtained from laboratory measurements

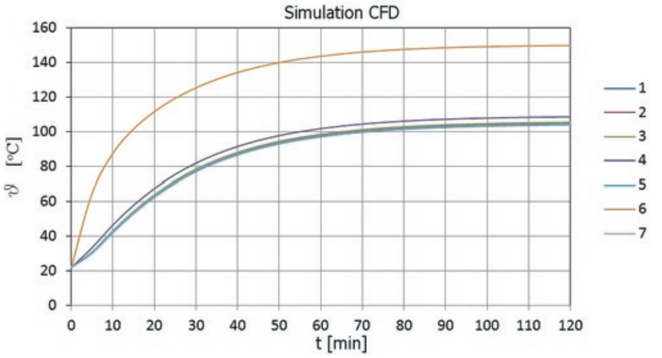

Fig. 14. Temperature distribution of the electromagnetic circuit sample obtained from numerical simulation

Comparing the temperature distribution obtained by numerical simulations and experiment, convergence can be seen. That confirms correct assumption of the calculation model and method of determining the replacement valuesof material properties. Calibrated model of the electromagnetic circuit can be further used to develop a complete electrical machine model.

4. Conclusion

Spatial modeling software allows at the design phase to obtain a virtual machine models. These models are then used for strength and flow calculation which base on the finite element method. However, in the electrical machines analysis it is necessary to select a suitable strategy for construction of computational model. The appropriate simplifications and implementation of adequate parameters are important for correct calculations.

In this paper the possibility of proper preparing of calculation model of the most complicated structure of the electrical machine, which is the electromagnetic circuit, was pointed out. Lamination stack modeling as a body with a thermal conductivity determined by the calibration base on the experiment results, and monolithic coil model with the slot insulation replacement by the substitute thermal contact resistance parameter which is experimentally determined, led to development ofthe effective computational model of electromagnetic circuit. The comparison of the temperature distributions logged during the experiments (Fig. 8 and 13) and the one obtained from numerical calculations (Fig. 9 and 14) conducted with the parameters assumed from the calibration, it can be confirmed that the method of model construction and calibration is correct. The proposed spatial simplified model of the electromagnetic circuit and method of calibration can be used to develop a computational model of the complete electrical machine which will allow for the efficient design of electrical machines with greater reliability using the finite element method.

In the works with similar content, descriptions of different ways of modeling and calibrating computational models and problems associated with them can be find. In the most of the papers, the possibility of use the calculation based on Lumped Parameter Modelingis described [1, 4-8, 10, 12, 13, 15].

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