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2D Magneto-thermal analysis of synchronous generator

***Abstract**. This paper presents a method for calculation of temperature distribution during the steady state operation of synchronous generator. The method is based on the 2D FEM coupled with external circuit and thermal network. Coolant temperature contribution through ventilation conditions is taken into account as well as the influence of radial cooling channels. Thermal calculation is coupled with the cooling calculation and complete procedure is solved iteratively. The calculation results with temperature distribution in stator of a synchronous generator.*

***Streszczenie.** W artykule zaprezentowano metodę obliczeń rozkładu temperatury podczas pracy ustalonej generatora synchronicznego. Metoda oparta jest na dwuwymiarowej analizie metodą elementów skończonych sprzężoną z obwodem zewnętrznym i siecią cieplną. Wzięto też pod uwagę rozkład temperatury czynnika chłodzącego; pełny model rozwiązany został iteracyjnie. Wyniki obliczeń rozkładu temperatury w stojanie generatora zostały przedstawione. (**Dwuwymiarowa magnetotermiczna analiza generatora synchronicznego**)*

Keywords: magneto-thermal analysis, finite element method, synchronous generator
Słowa kluczowe: analiza magnetotermiczna, metoda elementów skończonych, generator synchroniczny

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Introduction

Temperature determination and estimation of heating is an important aspect in designing of the synchronous generator. The active part of the medium sized synchronous machines mainly consists of radial channels which improve machine cooling. Their complex geometry makes it difficult to determine the thermal conditions inside the machine. For the synchronous generator temperature estimation, it is necessary to know the distribution of losses and both ventilation and thermal conditions inside the machine.

The most common method for electric machine thermal analysis is the use of thermal network. Hak [1] modeled the yoke and teeth region using the equivalent thermal resistances. Present-day papers use the larger and more complex resistance networks in order to describe the machine thermal image more accurately. The application of the finite element method (FEM) for heat conduction calculation has been recently in use in the research of temperature distribution inside the machine. Depending on machine type, ventilation type and predominant direction of heat conduction, it can be modeled in the 2D or 3D domain. Since the heat conduction is present predominantly in the axial direction, the 2D calculation with the external circuit included may be used for the electric machines instead of time consuming 3D modeling.

Generally, the losses in synchronous generator are mainly made up of the losses in winding, losses in iron, friction losses, ventilation losses and additional losses [2]. These losses generate heat inside the machine. To determine the losses in the synchronous generator, the analytic expressions [2] are usually used. To determine the losses in iron, there are various models that are used in the numerical electromagnetic calculation. One of them is the three-component method [3], which divides the losses in iron into the losses due to the hysteresis, classical eddy currents losses and additional excess loss component.

In this paper, the calculation model for temperature distribution of synchronous generator stator under the steady-state condition is presented. Calculation is based on coupling of an equivalent thermal network and FEM 2D solution, which includes an external circuit. Thermal calculation is coupled with the cooling calculation, and the whole calculation is performed iteratively. Radial heat paths of each laminated stator stack are calculated using the 2D FEM while the axial paths are modeled by thermal network. For this purpose, a program for temperature distribution calculation by the 2D FEM with external circuit included and spice model for thermal network calculation have been developed. The losses are taken from the electromagnetic calculation.

Thermal network of machine

When the ventilation and thermal conditions allow it, the thermal calculation using one slot pitch is made, as shown in Fig.1.

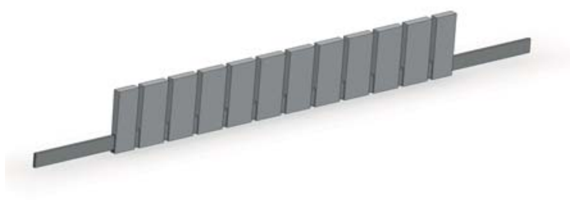

Fig.1. 3D calculation model

The shape in Fig.1 is modeled in the calculation by the combination of the thermal network technique and 2D FEM with the external circuit included. The equivalent thermal resistances R_{ekv} and sources T_{ekv} of each stator stack are obtained by FEM. Having included the equivalent thermal resistances and sources of each stator stack in the global thermal circuit of the machine together with heat source and resistance of the end windings and conductors in the radial channels, the global thermal circuit of the whole machine is obtained, Fig. 2.

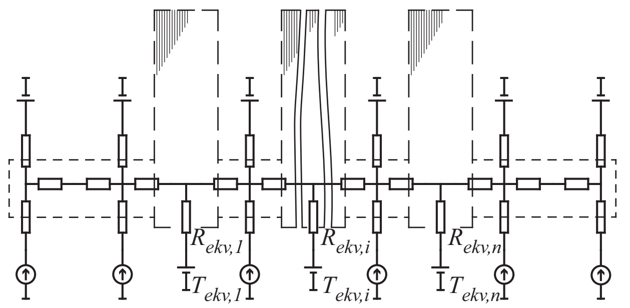

Fig.2. Generator stator core axial cross-section and global equivalent thermal circuit

Applying Kirchhoff's law to the thermal circuit nodes the results of steady state condition of temperature calculation could be expressed in matrix form as follows:

$$[G]\{T\} = \{Q\} \tag{1}$$

Where, $[G]$ is thermal conductivity matrix obtained from the thermal resistances, $\{Q\}$ is heat source, and $\{T\}$ is temperature. Temperatures in each node are obtained by:

(2) $$\{T\} = [G]^{-1}\{Q\}$$

Temperature distribution in radial direction for each laminated stator stack is obtained by the transfer of heat flow values from the global thermal network into 2D FEM calculation.

2D FEM with external circuit

Temperature distribution and heat flow in radial direction can be determined using the 2D FEM for the thermal field calculation. Naturally, a part of the heat flow escapes through lateral sides of each laminated stator stack. Hence, heat dissipation through lateral sides of core laminations is also included into 2D FEM. Values of temperature in the 2D are obtained by solving the thermal equation for a steady state condition.

(3) $$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) = -q$$

where k_x, k_y are thermal conductivities, q is the heat generation per unit volume, T is temperature.

Modeling region is divided into each laminated stator stack separately and each laminated stator stack is separately calculated using the 2D FEM. Axial thermal circuit over the yoke and teeth region is modeled by the conduction thermal resistance together with the thermal transfer by convection in the axial direction, Fig.3. Temperature source $T_{f(av)}$ represents the coolant temperature in cooling region, temperature source T_y and T_t represents the thermal source in yoke and teeth. Laminated stator stack losses in axial direction are uniformly distributed and that is why the T thermal model [4] of the external circuit is used. Stator core yoke and teeth region are divided in several internal regions and modeled with additional axial thermal circuit to achieve more accurate calculation.

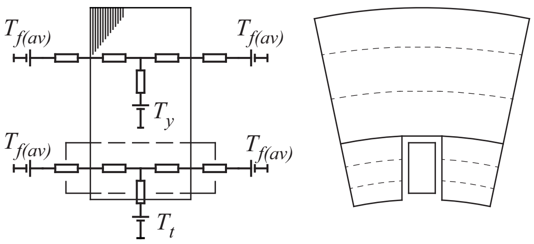

Fig.3. Thermal circuit of a single laminated stator stack

Using the variation calculation for the heat conduction problem with the convection boundary condition, and using FEM technique, the solution for the temperature inside the nodes is obtained. The system of equations is obtained and represented in the matrix form as

(4) $$[K]\{T\} = \{F\}$$

where $[K]$ is the thermal conductivity matrix, $\{T\}$ is the unknown vector of temperatures at nodes; $\{F\}$ is the vector of thermal sources. Furthermore, the equation for the element matrix form is:

(5) $$\left([k1]_e + [k2]_e\right)\{T\}_e = \left(\{f_Q\}_e + \{f_\alpha\}_e\right)$$

where $[k1]$ is the thermal conductivity matrix, $[k2]$ is the convection matrix on boundary condition, $\{f_Q\}$ is the internal heat source vector, and $\{f\alpha\}$ is the convection vector on boundary condition. Coupling Eq.(5) with the external thermal circuit presented in Fig.3 results in the system of equations. The coupling is represented as a contribution of external circuit $[k_{ext}]$ $\{f_{ext}\}$ to the matrix $[K]$ and $[F]$.

(6) $$\left([k1]_e + [k2]_e + [k_{ext}]_e\right)\{T\}_e = \left(\{f_Q\}_e + \{f_\alpha\}_e + \{f_{ext}\}_e\right)$$

Presented technique enables the calculation of the temperature distribution over the whole stator core with windings, if no radial channels exist. Radial channels among stator stacks make difficult the direct calculation using the presented 2D FEM on whole stator core. Therefore, an approximation is introduced by the introduction of the equivalent thermal resistance and equivalent thermal source of individual stator stacks. Said approximation enables the temperature distribution to be calculated over only one stator slot and stator conductor, as presented. It is possible to obtain the equivalent resistance R_{ekv} and equivalent temperature source T_{ekv} by applying the 2D FEM with the external thermal circuit included for each stator stack, Fig.4. The method is similar to the Thevenin model for electric circuit.

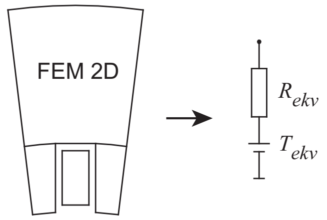

Fig.4. Equivalent thermal resistance and heat source for laminated stator stack

Ventilation conditions and coupling with thermal calculation

Ventilation conditions could significantly affect the temperature distribution inside the machine. The synchronous generator, which is analyzed in this paper, consists of radial ventilation channels where the heat is conducted by air. For the presented machine, the 1D ventilation calculations is made. For the heat transfer coefficient determination on end winding the literature [5] is used. Heat transfer coefficients from the air gap and radial channels are determined based on Gazley's research [6] who was researching fluid flow between the concentric cylinders and Roberts research [7] who was researching the heat transfer coefficient from the electric machine radial channel surface. Since the synchronous generator with constant speed is involved, fluid flow rate is constant. Therefore, the constant values of heat transfer coefficients are assumed and the influence of temperature on heat transfer coefficient is neglected.

The coolant temperature value is obtained from the value of absorbed losses P_n in each part of the control volume of the cooling circuit calculation [8]. Cooling circuit calculation is performed by using the data of fluid flow rate from ventilation calculation and data of absorbed losses which are known after the thermal network has been solved. Temperature rise at node of control volume is assumed to be equal to the mean value of temperature rise $T_{f(av),n}$ in the observed region, Eq.(7).

(7) $$T_{f(av),n} = T_{f(out),n-1} + \left(\frac{P_n}{\rho \cdot C_p \cdot V_n}\right)/2$$

where ρ is coolant density, C_p is specific heat capacity, and V_n is fluid volume flow rate, $T_{f(out),n-1}$ is temperature at outlet of control volume ($n-1$).

That value of coolant temperature is included in the new calculation of thermal network and FEM. The process continues iteratively until final values of temperatures are achieved, and the process is represented in block diagram, Fig.5. Coolant temperature is represented in the thermal network by the temperature source.

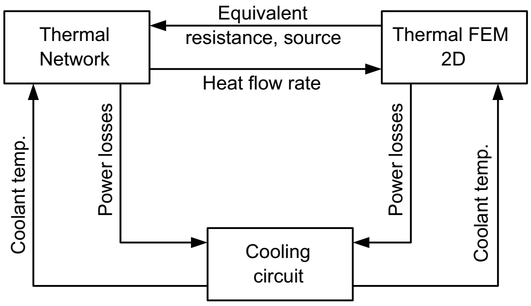

Fig.5. Block diagram of cooling circuit and thermal calculation coupling

To simplify the calculation, the thermal network nodes and cooling network nodes are matched as presented in Fig.6. At the same time, the nodes matching enables thermal and cooling network coupling.

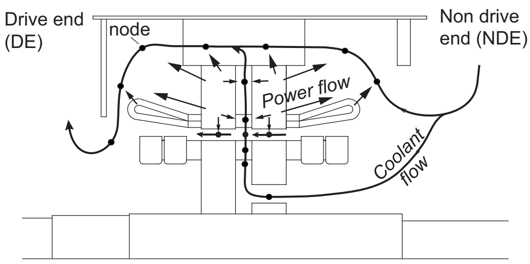

Fig.6. Coolant flow and power flow with cooling circuit nodes in radial channel and end space

Electromagnetic calculation and determination of losses

The rated operating point modeling is performed by a time domain finite element techniques including the rotor movement and an external electrical circuit is coupled [9]. The fundamental equations for the magnetic field are represented by

$$\frac{\partial}{\partial x}\left(\upsilon\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\upsilon\frac{\partial A}{\partial y}\right)=-J-J_i \quad (8)$$

where, A is vector magnetic potential, J is the current density vector, J_i is the induced current density in the conducting material, v is reluctivity.

Losses in ferromagnetic part are calculated by the numeric electromagnetic calculation while the additional losses are calculated by the analytical expressions [2]. Ohmic losses in winding P_w are calculated for the stranded conductor of stator and rotor winding and the eddy currents are neglected in the FEM analysis. AC contribution in ohmic losses is separately calculated through the analytical expression [3] as the contribution through the factor k_R.

$$P_{wa}=k_R\cdot I^2\cdot R_{DC} \quad (9)$$

where, I is current, R_{DC} is the DC value of resistance, k_R is the AC losses contribution factor.

Stator core laminations losses are calculated using the 2D time stepping finite element technique. Total iron loss P_t is made up of the hysteresis P_h and eddy current components losses P_e, plus an excess loss component P_x.

$$(10)\ P_t=P_h+P_e+P_x=k_h f B_m^{\beta}+k_c\left(fB_m\right)^2+k_e\left(fB_m\right)^{1.5}$$

where B_m represents peak magnetic flux density, f represents frequency. The constants k_h, k_c, k_e, β are the loss constants and are determined by iron loss material data. Flux density is recorded for each time step and each finite element. Losses are calculated as a sum of individual component losses for both orthogonal axis, tangential and radial. After time cycle is over, the harmonic evaluation of the flux density waveform in each FEM element is performed using Fourier analysis. Losses in iron Eq.(10) are calculated using the flux density harmonics for each element and a results are shown in Fig 7.

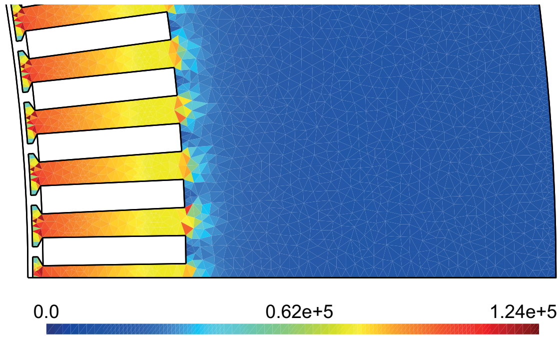

Fig.7. Stator core laminations losses density (W/m^3)

Losses are transferred from the electromagnetic into thermal calculation for each geometry segment. Winding average temperature is obtained from the thermal calculation and it affects the R_{DC} resistance change. It also affects the winding losses according to Eq.(9). The flow diagram of analysis, which includes the transfer of losses and temperature, is shown in Fig.8.

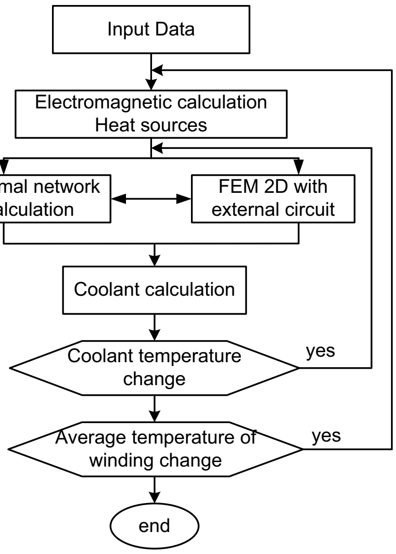

Fig.8. Flow diagram of the analysis

Results

A 10-pole synchronous generator rated 1MVA, 450V is used as a model. The presented method is verified in two ways. In the first part, the results of model calculation with the coolant constant temperature are compared with the 3D thermal model, while in the second part the results of model calculation with the dependent temperature of coolant are compared with the results of measurements on the machine.

One slot pitch of the 3D stator core laminations with coil is modeled with 3D Thermal FEM as shown in Fig.1. Coolant temperature is constant and identical over the whole model. Coolant temperature value is 20˚C and is equal to temperature of ambient. Comparisons of the results of temperatures for the 2D and 3D model can be found in the Table 1. Comparison of values of results in the 2D and 3D calculations shows the results very good agreements.

Table 1. Conductor temperature at constant coolant temp.

Conductor Temperature	Model 2D (˚C)	Model 3D (˚C)
End winding	54.9	54.7
1st laminated stator stack	57.0	56.8
7th laminated stator stack	63.5	63.2

Obtained mean value of conductor temperature of the numerical 2D model with external circuit is 59.1°C.

Since the winding temperature is more dependent on the coolant temperature, the temperature measurement on the examined machine is performed by the resistance method and the resistance thermometer in the end winding. In the Table 2, the comparison of the measured values with the results of the 2D numerical calculation and with the coolant temperature dependency included is presented.

Table 2. Temperature at coolant temp. dependency included

	Model 2D (°C)	Measure
End winding, drive end (DE)	83.4	86.5
Average conductor temp.	86.3	84.8

It is evident from this that there is a smaller deviation of measurement results and calculation results. This deviation is partially due to the unknown values of the heat transfer coefficients and material data.

The coolant temperature changes with the thermal and ventilation conditions inside the machine and consequently the winding temperature as presented in Table 3.

Table 3. Temperature in conductor at coolant temp. dependency included

	Model 2D (°C)
End winding, non drive end (NDE)	69.8
1st laminated stator stack slot	76.6
7th laminated stator stack slot	97.1
12th laminated stator stack slot	87.1
End winding, DE	83.4

The results of temperature distribution in the first laminated stator stack and central laminated stator stack using the 2D FEM and thermal network are shown in Fig.9. Temperature distribution results show that the highest temperatures appear in conductor around the center of the stator core while the values are somewhat lower on end winding. Asymmetric temperature distribution from DE and NDE can also be seen, which is the result of coolant non-uniform temperature in axial direction. Calculation difference of winding mean temperature between two models with the dependent temperature of coolant and with the coolant constant temperature is 27.2°C.

Conclusion

In this paper, the thermal analysis method that uses the 2D FEM calculation with external circuit and the thermal network model for temperature distribution calculation for the synchronous generator steady state condition is presented. Coolant temperature contribution through the machine ventilation conditions is also included so that the thermal calculation and cooling calculation are coupled and the result is iteratively obtained. Temperature distribution calculation is introduced over one stator slot considering radial channels.

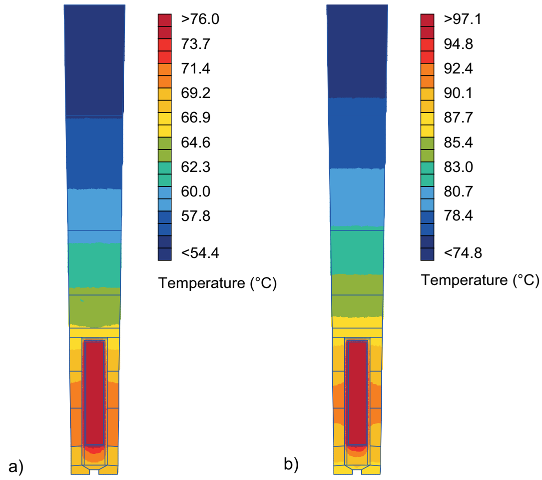

Fig.9. Temperature distribution in the 1st (a) and 7th (b) laminated stator stack

The results of two cases are verified. The calculation is compared with the 3D FEM thermal model without the coolant temperature dependency included. Results of modeling using the presented method and the 3D calculation provide similar results. With the ventilation contribution and coolant temperature dependency included, the model results are compared with the measurement results. Results obtained by the presented method show a good agreement with the measured values. The results show the temperature distribution in both radial and axial direction.

REFERENCES

[1] Hak, H.; "Die Warmewiderstand zwischen Zahn und Joch", Archiv fur Elektrotechnik, vol.45, Number 3, 1960
[2] Sirotić, Z; Krajzl, V.; "Upute za proračun sinhronih strojeva", Sveučilište u Zagrebu, Elektrotehnički fakultet, Zagreb 1972.
[3] Bertotti, G.; "General properties of power losses in soft ferromagnetic materials", Magnetics IEEE Transactions on, vol.24, no.1, pp.621-630, 1988
[4] Mellor, P.H.; Roberts,D.; Turner,D.R.; "Lumped parameter thermal model for electrical machines of TEFC design", Electric Power Applications, IEE Proceedings B, vol.138, no.5, pp.205-218, 1991
[5] Schubert, E.; "Warmeubergangszahlen on Wickelkopfen und Lagerschilden geschlossener Asynchronmaschinen", Elektrie, vol.22, pp.160-162, 1968
[6] Gazley, C.; "Heat-Transfer Characteristics of the Rotational and Axial Flow Between Concentric Cylinders", Transactions Asme, pp.79-89, 1958
[7] Roberts, T.J.; "Determination of the thermal constants of the heat flow equations of electrical machines", Proceedings-Institution of Mechanical Engineers London, vol.184, pp.84-92, 1969
[8] Jokinen, T.; Saari, J.; "Modeling of the coolant flow with heat flow controlled temperature sources in thermal networks", Electric Power Applications, IEE Proceedings, vol.144, no.5, pp.338-342, 1997
[9] Vilijan Matosevic, "Application of the Finite Element Method to the Calculation of Sudden Short Circuits in a Synchronous Generator", Master thesis., Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia, No. 3, 1998

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