COMPUTATIONAL AND EXPERIMENTAL MODELING OF CONTROL OF STATOR WINDING SLOT COOLING BY WATER

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This project is concerned with non-convectional direct stator winding slot cooling using water. The aim is to find optimal algorithm for control of water cooling. The control algorithms are tested on the experimental device, which is part of real synchronous machine with permanent magnets. The thermal model was built as a base for computational model of a machine without thermal sensors. The thermal model is possible used as predictor of machine heating in real time. This type of water cooling shows better effect on the machine heating than common water cooling system on the cover.

Key words: *heating, cooling control, electric machine*

1. Introduction

The project is concerned with computational and experimental simulations of stator winding heating of synchronous machine. The synchronous machine operates as high-torque machine with maximal torque 675 Nm at 50 rpm.

At the present time the cooling water flows in the channels, which are made on the cover. New cooling system has small channels in each stator winding slot (Fig. 1), where cooling water flows. Thus cooling water removes heat losses directly from stator winding. This is a main advantage of new cooling system.

Common water cooling system | Non-conventional water cooling system

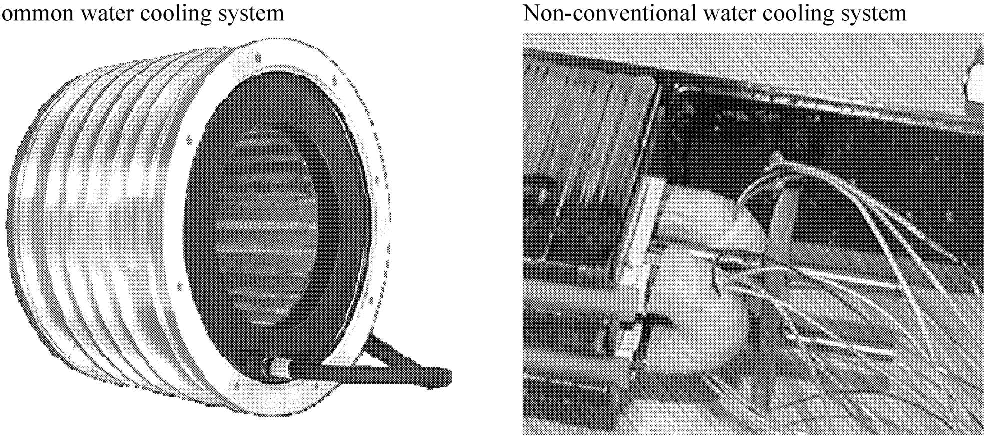

Fig.1: Cooling systems of synchronous machine

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The aim was to find algorithm for pump drive, so that the temperature of stator winding was below safe limit.

Software MATLAB/SIMULINK and ANSYS were used for computational simulation of water cooling drive. Computational simulations describe direct stator winding cooling by water.

Experimental device was used for verification of computational simulations and drive algorithm.

2. Computational model

The computational model geometry arises from real synchronous machine. It describes the heat of a part of synchronous machine mainly stator winding. The machine has 36 pairs of winding slots and permanent magnets on the rotor. Rotor with magnets is not modelled, because the heat loss is only in the stator winding and rotor effect is negligible on the heating of stator. The brass tubes were comprised in the middle of each winding slot. Cooling water flows in the brass tube. Symmetry of machine was assumed so only one pair of winding slot is modelled.

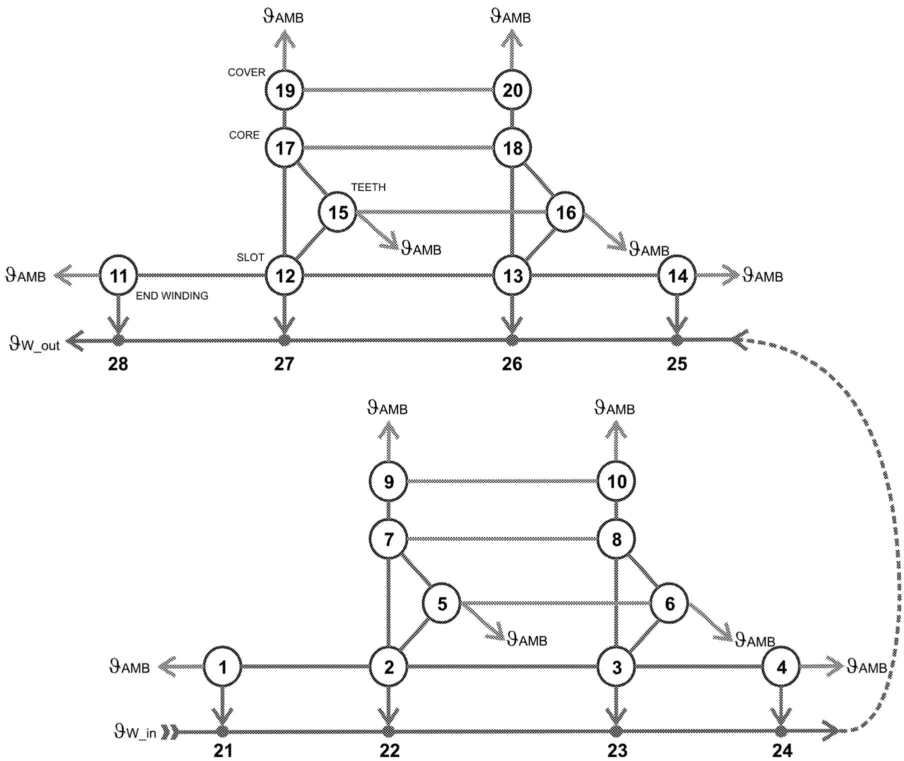

Fig.2: Thermal network of synchronous machine

The thermal network method [1] was used for description of machine heating. Thermal network describes heating of stator packet segment with two slots. Thermal networks (Fig. 2) consist from twenty-eight nodes. Last eight nodes (from 21 to 28) are used for description of cooling water heating. Thermal model describes transient state, because machine operates with varying load.

Thermal network is possible to be described by the system of differential equations:

$$C_i \frac{\mathrm{d}\vartheta_i}{\mathrm{d}t} + A\,\vartheta_i = b_i \ , \tag{1}$$

where is C_i thermal capacity concentrated in node i, A matrix of thermal conductivities, b_i heat loss in node i and heat flux to ambient.

Temperatures of nodes describing heating of cooling water are given by:

$$\vartheta_i \left(a_\mathrm{Q} + \sum_j a_{ij} \right) - \vartheta_{(i-1)} \left(a_\mathrm{Q} + \sum_j a_{(i-1)j} \right) - \sum_j \vartheta_{ij}\, a_{ij} - \sum_j \vartheta_{(i-1)j}\, a_{(i-1)j} = 0 \ , \tag{2}$$

where is ϑ_i temperature of water node i, a_Q thermal conductivity of flowing water, a_{ij} thermal conductivity between nodes i (water node) and j (solid parts), ϑ_{ij} temperature of solid parts, which is connected via conductivity a_{ij} to node ϑ_i (temperature of water node).

Thermal model was compared with finite elements method model [2]. Parameters of thermal model were corrected so difference between both models was minimal.

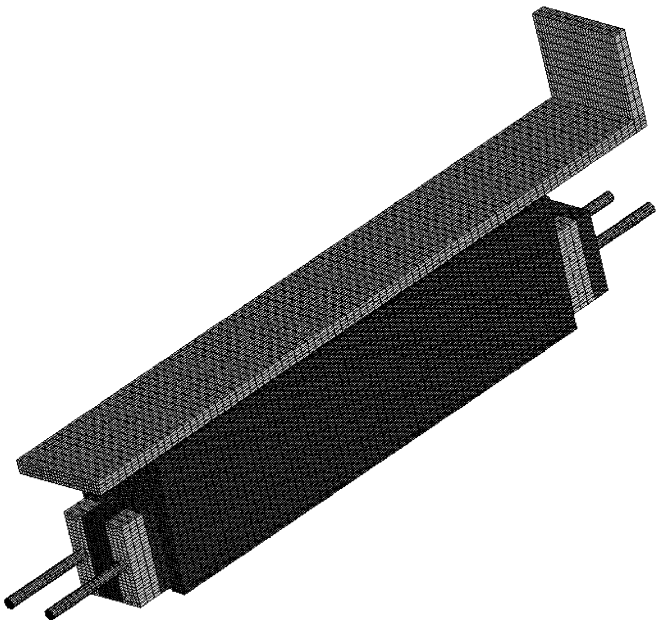

Fig.3: FEM model of stator winding heating

FEM model describes distribution of temperatures and heat fluxes in individual parts of model in detail. It is more detailed and computational time is too long so thermal network is more acceptable for control of water cooling in real time.

3. Experimental device

Experimental device (Fig. 4) was created for verification of computational simulations. The six thermocouples were placed to each winding slot. The first three thermocouples are above brass tube and other three thermocouples are below brass tube as shown Fig. 5. Infra thermometer was used for the measuring surface temperature.

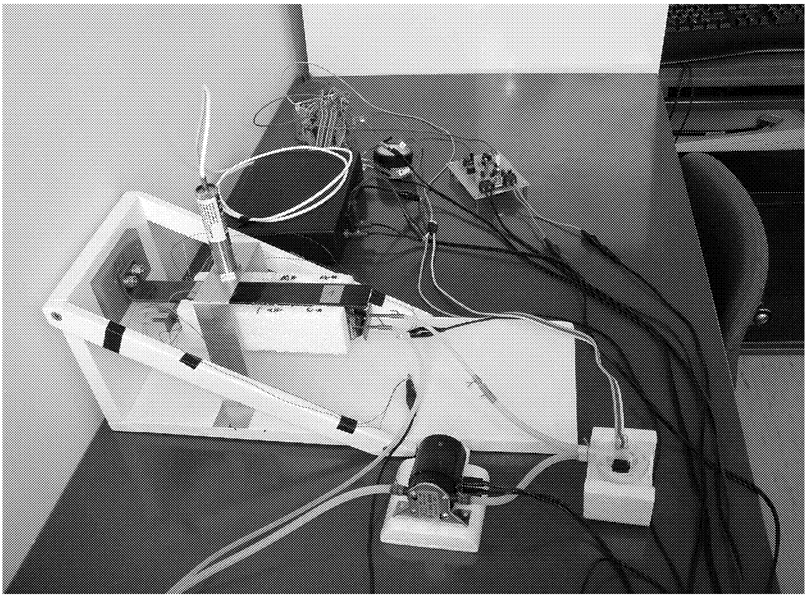

Fig.4: Experimental device

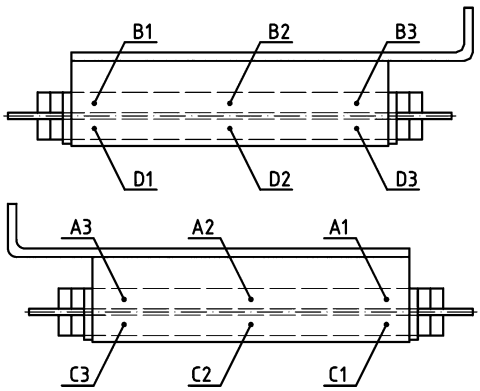

Fig.5: Placing of thermocouples in the stator winding

The revolutions of pump motor are controlled by pulse width modulation (PWM) switching converter with power transistor. The right pump capacity is checked by pulse flowmeter.

Signals from thermocouples, infra thermometer and flowmeter are connected with PC via multifunction analog I/O board (Acquitek). The pump is controlled via multifunctional board too. The user interface was created in software Matlab (toolbox GUI). The user interface make possible to monitor of individual part device temperatures and set pump capacity. The control algorithm of pump and thermal model is easy added to the interface.

4. Measurements

The aim of measurements was to compare of two systems of machine cooling. The first system (common) is the cooling only by means radiation and natural convection. The second system (new) is using direct water cooling in winding slot. The results are summarized in the following Table 1.

Winding current [A]	Heat losses (cold) [W]	Heat losses (heat) [W]	Heat losses in the water [W]	Winding temp. [°C]	Surface temp. [°C]	Pump capacity [l min-1]	Ambient temp. [°C]
1.5	13.8	16.8	—	84.5	82.6	—	27.4
2.0	24.6	34.0	—	135.8	127.4	—	27.0
2.0	24.6	27.1	17.7	49.3	46.0	0.5	22.7
3.0	55.4	69.8	52.2	90.3	85.9	0.5	22.8

Tab.1: Results of measurements

Heat losses (cold) in Tab. 1 mean heat losses at the beginning of heating. Similarly heat losses (heat) mean heat losses at the end of heating. Surface temperature is average temperature through full surface. The measurement error is ±0.5 °C.

The experimental device thermal phenomena were determined from measurements. Experimental results are used also for correction of thermal model parameters.

5. Identification of thermal model parameters

The measurements were used for verification of thermal model. Thermal network parameters were identified by using genetic algorithm, so that temperature differences between measurement and simulation are minimal. The result of identification is summarized in Tab. 2.

	Heat losses (cold) [W]	Heat losses (heat) [W]	Winding temp. [°C]	Surface temp. [°C]	Input water temp. [°C]	Output water temp. [°C]
Measuring	55.4	69.8	90.3	85.9	27.7	31.2
Simulation	55.4	70.1	91.4	84.1	27.7	31.6
Error [%]	—	−1.19	−1.19	2.08	—	−1.01

Tab.2: Results of identification of thermal model parameters

6. Control of water cooling

Figure 6 shows the scheme of water cooling control. Signals from thermocouples are amplified by operational amplifier INA125. Amplified voltages from thermocouples are evaluated by PC to get temperatures. The control algorithm calculates flow rate from the temperatures. The value of flow rate is converted to reference voltage, which is used as input to PWM switching converter. This process is still repeated.

Two control algorithms were tested on the experimental device. The first algorithm is ON-OFF regulation and second algorithm is *continuous* regulation.

6.1. ON-OFF controller

In this case was used ON-OFF controller with switching hysteresis for temperature regulation. If maximal temperature of winding reaches 60 °C then the pump is switched-on. The pump capacity was set on 0.7 l min^{-1}. If maximal temperature of winding reaches 55 °C then the pump is switched-off.

Figure 7 shows part of ON-OFF regulation. The winding temperature varies between 55–60 °C except first part of graph, where temperature goes up slowly from initial point.

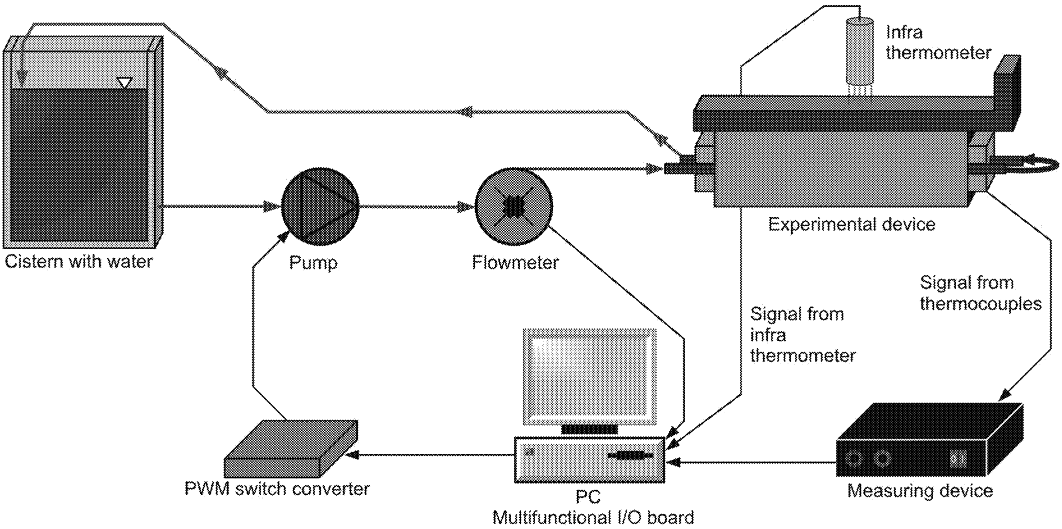

Fig.6: Scheme of water cooling control

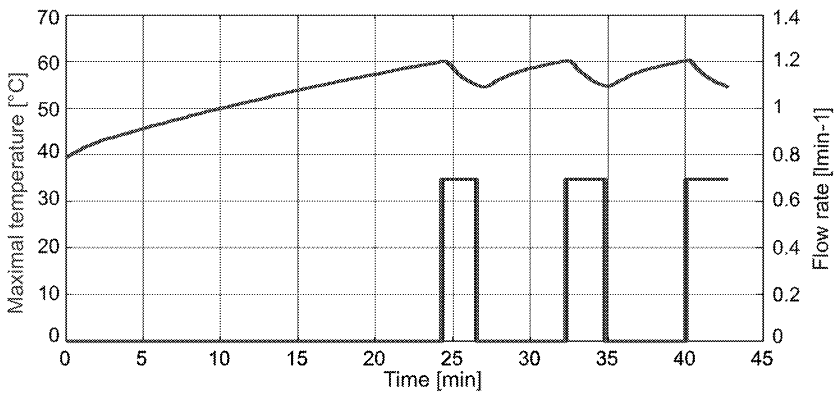

Fig.7: Simulation with ON-OFF controller

6.2. Continuous controller

In this case the pump capacity depends on the actual winding temperature. The control algorithm has three zones. If maximal temperature of winding is below 40 °C then the pump is switched-off. If maximal temperature of winding is more than 100 °C then the pump is switched on maximal flow rate ($0.7\,\mathrm{l\,min^{-1}}$). Two flow rate-temperature relationships were tested in the range of winding temperature from 40 °C to 100 °C. These relationships between flow rate and winding temperature are linear and exponential.

The random load current (heat loss) was generated for testing both continuous controllers. Figure 8 shows simulation results comparison with linear and exponential controller.

Steady state temperature is the same for both controllers at constant load current 3 A. The exponential regulation is better than linear, because flow rate is smaller for the same temperature. Other simulations show possibility of long time overloading with exponential controller as showing Fig. 9. The maximal temperature reaches 90 °C for the exponential pump control approximately ten minutes later then for linear pump control.

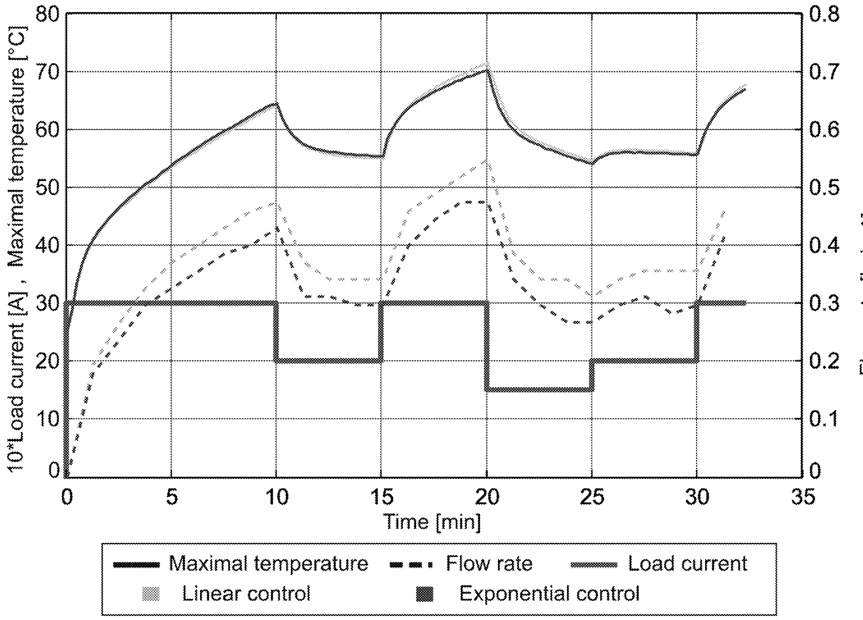

Fig.8: Simulation with continuous controllers

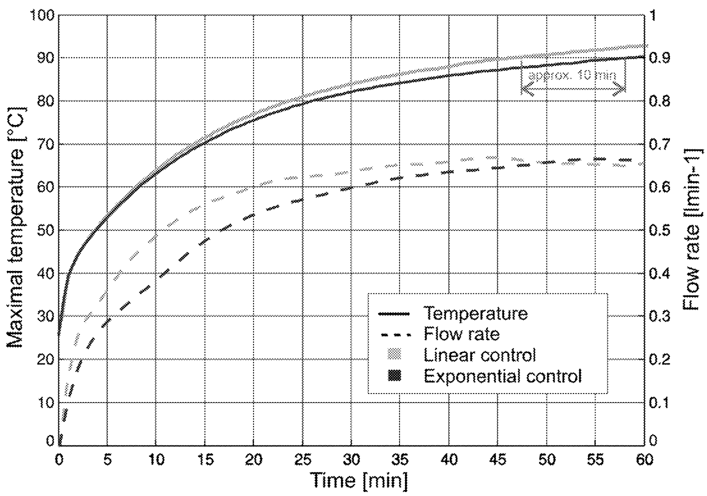

Fig.9: Comparison linear and exponential regulation

7. Conclusion

Paper describes the drive of direct winding slot cooling by water. The intensity of cooling depends on actual temperature of winding. The experimental results will serve as a base for computational model of a machine without thermal sensors. The thermal model is possible to be used for prediction temperature of machine individual parts in real time, so that algorithm of pump capacity control will be better.

Direct water cooling of winding slot is proved to be effective. This new cooling system responds faster than common cooling system on the machine load. The water requirement was reduced to 60 % using pump capacity control in comparison to cooling with constant flow rate $0.5\,\mathrm{l\,min^{-1}}$.

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References

[1] Hak J., Oslejsek O.: Computed of Cooling of Electric Machines, 1. Volume, VUES Brno 1973, Czech Republic
[2] Vlach R.: Computational and Experimental Modelling of Non-Convectional Winding Slot Cooling, International Conference Mechatronics, Robotics and Biomechanics 2005, Trest, 26.–29. 9. 2005, Czech Republic
[3] Holan V.: Non-Convectional Winding Slot Cooling of Synchronous Machine using Heat Pipe and Water Cooling, Diploma project, FSI TU Brno, 2006
[4] Ondruska E., Malousek A.: Ventilation and Cooling of Electric Machines, SNTL Praha, 1985

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