Sensitivity Analysis of Machine Components Thermal Properties Effects on Winding Temperature

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***Abstract*—This paper investigates the sensitivity analysis of winding temperature to key parameters in electrical machine thermal design. With a validated 3D thermal model based on an existing 75kW traction machine for an electric vehicle, the methodology of the sensitivity analysis study is conducted and presented. Finally, further research and practical guidelines on reducing the peak temperature of electrical machines are proposed.**

Keywords—sensitivity analysis, thermal network, thermal improvement, thermal management

I. Introduction

Improved thermal management is an essential element in the pursuit of higher performance electrical machines which push the various performance metrics [1, 2]. Thermal aspects of different materials are investigated in considerable amount of research. For example, steel lamination with different thickness and alloy contents thermal effects are discussed in [3]. Impregnation resin with different thermal conductivity is investigated in [4]. The material developments enable improved performance, while often at an increased cost.

Water jacket cooling is widely used for electrical machines, where a cooling jacket is placed surrounding the stator lamination. Enhanced cooling, such as slot cooling, or end-winding cooling, are investigated to achieve large temperature reduction in [5, 6]. However, the novel cooling methods typically come at a cost, whether financial or complexity, with complex arrangements leading to reduced reliability. Therefore, water jacket cooling is still a popular option for thermal engineers, especially for high reliability volume manufacturing, as in automotive. Different techniques are investigated to supplement this traditional cooling technologies, such as the recently presented back-iron extension (BIE), with thermal benefits of over 25% temperature reduction reported in [5]. For water jacket cooling, the equivalent thermal resistance between the hot spot in the slot and the coolant is made up of several separate resistive components, which include resistances passing through different materials, wire enamel, slot impregnation resin, air-pockets, the slot liner, stator lamination, contact resistance, water jacket and then to the coolant. Various parameters are critical in determining the component thermal resistance and therefore affect the temperature output of the motor. However, the equivalent formulas between the parameters and the winding temperature are difficult to be extracted, due to the large number of parameters required for the electrical machines. Sensitivity analysis is an available tool used to analyze the correlation issue between the temperature output and input parameters. Sensitivity analysis, as suggested by the name, studies how the uncertainty in the inputs contributes to its output of a mathematical model or systems [7]. It is time effective for pointing out research directions from thermal advantages perspectives. Four components that are considered to particularly affect the stator and rotor temperature are targeted in [8], including convection to the coolant, conduction through the stator winding, convection to the air-gap and convection to the rotor end regions. Different thermal improvements are suggested based on the sensitivity analysis results of the heat transfer.

Thermal analysis software is based on either analytical models or numerical methods. Thermal resistance networks are widely used in the thermal design for electrical machines, due to their simplicity, speed and flexibility in variations [8]. Therefore, due to large number of calculations requirement, Lumped Parameter Thermal Network (LPTN) is used for the sensitivity analysis with its quick solving nature [9]. The thermal model used for the sensitivity analysis is validated with DC thermal tests, with only copper DC losses considered. Simple theory, where one parameter is changed at one time is adopted for the sensitivity analysis. A Design of Experiments (DoE) is performed for the sensitivity analysis study in this paper. DoE is a field of research, which is originally

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developed to retrieve as much information as possible from minimum experimental practices. Exploiting the advantage and effectiveness of DoE, multiple input parameters for electrical machine design are simultaneously varying and the impact for each variable on the response of the highest winding temperature is extracted.

This paper provides sensitivity analysis of different parameters on the peak temperature of an existing traction machine, presents analytical theory for the cooling techniques, and proposes practical thermal design guidelines based on the findings. The following sensitivity analysis is conducted to find out the most essential factor in determining the highest winding temperature [9]. The paper is organized as follows, firstly section II presents the thermal model and the experimental validation of an existing traction motor. Section III investigates the sensitivity analysis of winding temperature to different parameters. Section IV concludes the research.

II. THERMAL MODEL VALIDATION

This section discusses the building of a 3D thermal model and thermal testing for an existing traction machine. Firstly, the traction machine and the thermal model are described, followed by the testing and the comparison of analytical and measured test results.

A. Thermal model

A 3D Lumped Parameter Thermal Network (LPTN) is built for a 75kW 12 slot, 8-pole traction motor on test bench shown in Fig. 1. Temperature sensors, used to capture the winding temperature, are placed in the slot, detailed in Fig. 2. For the slot, T1 is expected to record the slot hot spot temperature, while T2, and T3 are placed between the slot liner and the winding. Meanwhile, there are temperature sensors inserted in the middle of the end-winding region, where highest winding temperature for the electrical machine is expected.

Fig. 3 shows the 3D thermal model developed for the traction machine, including both radial and axial sections. The procedure of building the thermal model is as follows, (i) exploiting the motor symmetry, the thermal resistance network for the part corresponding to half stator slot and half magnet is firstly constructed, individually; (ii) Then the thermal network, each for the whole stator and the rotor, is modified based on the 'part' thermal network in step (i); finally, (iii) the two thermal networks are combined by the heat transfer in the air-gap region.

There are five axial sections for the thermal modelling, including three sections in the core machine and two end-winding sections. It can be seen that there are 5×5 nodes evenly distributed in the slot, with radial thermal resistance displayed between each two adjacent nodes. The stator back-iron, stator tooth, air-gap, rotor iron, magnet, and shaft are represented by a single node, respectively. Loss distribution are considered to be uniform within one corresponding node. Only conduction and convection heat transfer are considered in this paper, with formulas presented in [10].

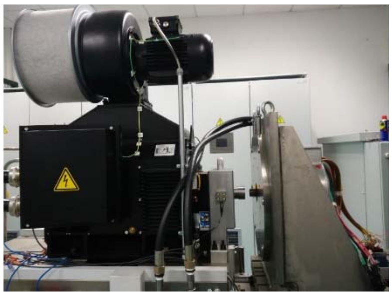


Fig. 1. Traction motor under test for thermal model validation

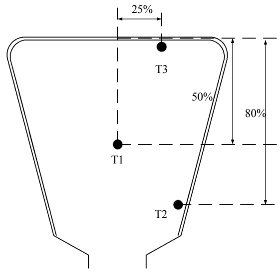


Fig. 2. Temperature sensor locations

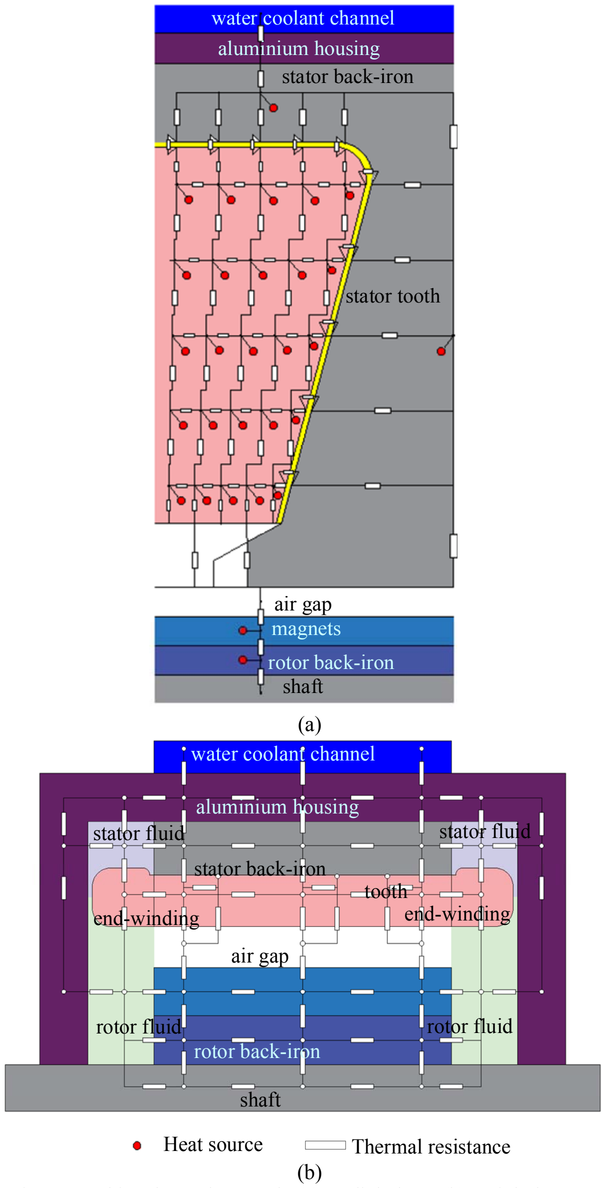


Fig. 3. Machine thermal network. (a) Radial plane, (b) Axial plane

B. Thermal network calibration

Short circuit tests have been conducted on the traction machine with rotor speed of 20 rpm, 40 rpm, and 60 rpm, with the test rig shown in Fig. 1. The current generated in TABLE I is 30% - 80% of the rated current, namely 30.56A, 55.19A, and 72.19A. At thermal steady state, the adsorbed electrical power and the temperatures of the stator windings are recorded. TABLE I indicates the input power for the test rig and output torque. It is worth noting that,

(i) Heat transfer between the traction machine and ambient air has been neglected;

(ii) Only DC copper losses account for the temperature rise in the machine, while iron losses and friction losses are neglected at low rotor rotation speeds.

For the thermal network shown in Fig. 3, it has been calibrated until the predicted winding temperature and the winding temperature distribution matches with the measured ones. The calibration has been conducted by modifying the following parameters:

(i) impregnation resin thermal conductivity (W/m·K), which affects the slot equivalent thermal conductivity;

(ii) contact resistance between the housing and stator lamination, which is translated to the equivalent air-gap thickness between the housing and the stator.

(iii) heat transfer coefficient in the coolant channel, which is calculated with standard dimensionless analysis formulas [11].

(iv) the impregnation resin goodness, ranging from '0' to '1'. Goodness with '1' indicates no air bubbles involved in the slot windings, while goodness with '0' means all air insulated between different slot windings.

C. Short circuit tests results

Fig. 4 plots the peak temperature at the end-winding obtained from the thermal network and on the same plot, the experimental results measured points at corresponding rotor speed are superimposed. The experimental results agree well with the simulation data within acceptable discrepancy, due to the thermocouple locations and manufacturing deviations. It can be seen that the increasing rate of '●'representing the experimental temperature is larger than that of the blue line '▬' representing the simulation results, due to friction losses in the practical case. In the thermal testing, friction losses are resulted due to the larger rotor rotation speed, corresponding to increasing current.

Meanwhile, Fig. 5 shows the temperature distribution comparison between the thermal model and experimental results. The node temperature marked with [●] represents the average temperature of the quadrilateral in ----. Fig. 5 (a) indicates that hot spot is located slightly below the centre of the slot. The difference between the simulation and experimental results are mainly resulted from the deviations of experimental temperature sensors locations. A slight temperature sensor location moving will lead to significant temperature difference in the slot, as shown in Fig. 5 (a).

TABLE I. MEASURED DATA

Rotor speed	*Torque*	*Input power*	*Current*
rpm	(Nm)	w	A
20	-40.7	84	30.56
40	-69	289	55.19
60	-82.26	517	72.19

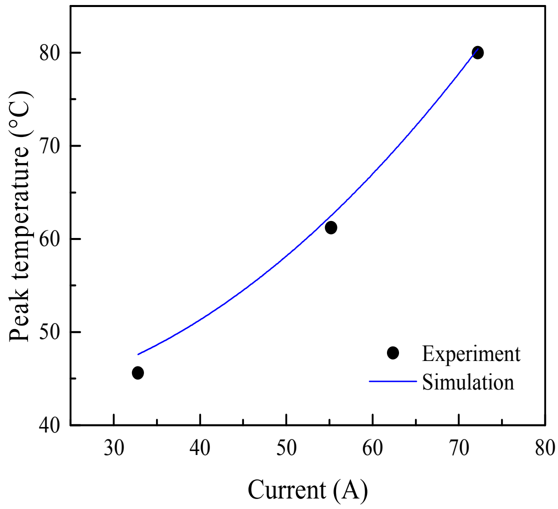
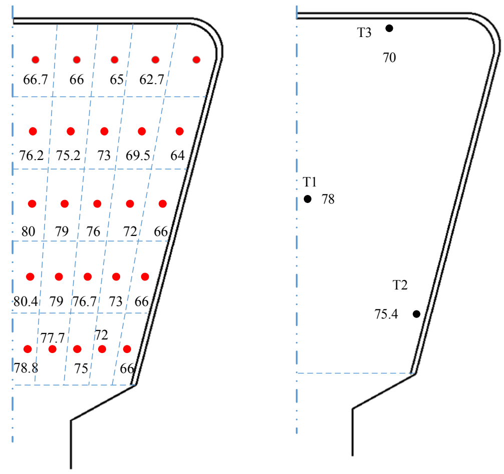


Fig. 4. Peak end-winding temperature experimental validation



(a) thermal model (b) experiment

Fig. 5. Temperature contour comparison with current 72.19A

III. SENSITIVITY ANALYSIS

The developed thermal model described in section II is used for sensitivity analysis in this section. Two level factorial analysis is used in this research. Firstly the input parameters and the corresponding high and low level values are introduced, followed by the sensitivity analysis results

A. Input parameters

For the developed thermal network in section II, various input parameters are influential over the winding temperature, such as stator geometry, material thermal properties or fluid flow dynamics. However, some parameters play critical roles on the output of the highest winding temperature, while changes in some parameters result into almost negligible difference. It is time consuming and computer power demanding for simulation and corresponding analysis conducted on all the input parameters.

There are 11 parameters selected for the sensitivity analysis, shown in TABLE II, ranging from material properties to certain fluid dynamics. For the input parameters shown in TABLE II, HTC_end-winding, HTC_coolant, HTC_air-gap represents the heat transfer coefficient for corresponding convection heat transfer in the following regions, i) end-winding region; ii) between stator lamination and housing; iii) in the air-gap. Different materials' thermal properties are also included, from slot liner thickness to impregnation resin thermal conductivity. Contact resistance between the stator lamination and housing is monitored, with equivalent air-gap thickness between them. Slot number is included and examined from thermal perspectives. The transformation considering slot number is as follows, the total slot area of the motor and the ratio of total copper area to slot area remain same. All the input variables are independent and any interaction effects are not considered. The selected 11 parameters in TABLE II. are randomized with Minitab factorial design and simulation results are generated with the thermal tool developed in section II.

B. *Sensitivity analysis results*

Fig. 6 plots the Pareto chart of standardized effects for aforementioned different input variables, with significant factors on the right side of the dotted red line. Fig. 7 presents the main effects of six key parameters factorial plot. The greater the gradient in the slot, the greater the impact of changing the variable on the highest winding temperature. It shows that the resulting value of peak winding temperature is particularly sensitive to slot number and contact resistance between the housing and stator lamination.

Slot number shows the largest potential in affecting the maximum winding temperature, followed by impregnation resin thermal conductivity, slot liner thickness and contact resistance between the housing and the stator. The DoE results agree with the expected results in the aforementioned resistance path analysis, where slot radial resistance has significant impacts on the hot spot of the electrical machine.

TABLE II. INPUT VARIABLES FOR DOE

Parameter	*Unit*	*Low level*	*High level*
slot number		12	24
HTC_end-winding	$(W/m^2{\cdot}K)$	10	20
HTC_coolant	$(W/m^2{\cdot}K)$	1000	2000
HTC_air-gap	$(W/m^2{\cdot}K)$	19.2	38.4
slot liner thickness	(mm)	0.15	0.5
slot liner thermal conductivity	(W/m·K)	0.1	0.2
housing frame thermal conductivity	(W/m·K)	100	300
stator thermal conductivity radially	(W/m·K)	15	30
stator thermal conductivity axially	(W/m·K)	0.87	1.74
impregnation resin thermal conductivity	(W/m·K)	0.1	0.2
equivalent air gap thickness between stator and housing frame	(mm)	0.05	0.1

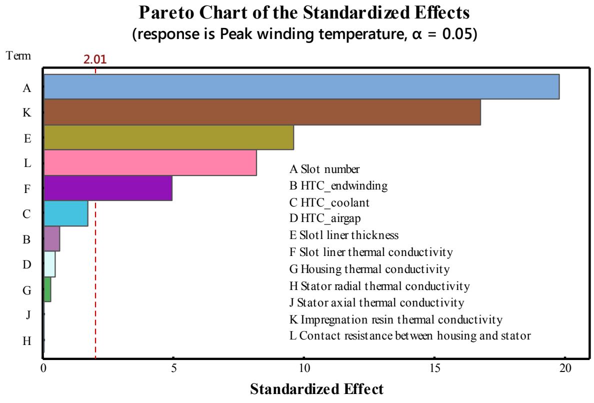


Fig. 6. Main effects for the peak temperature

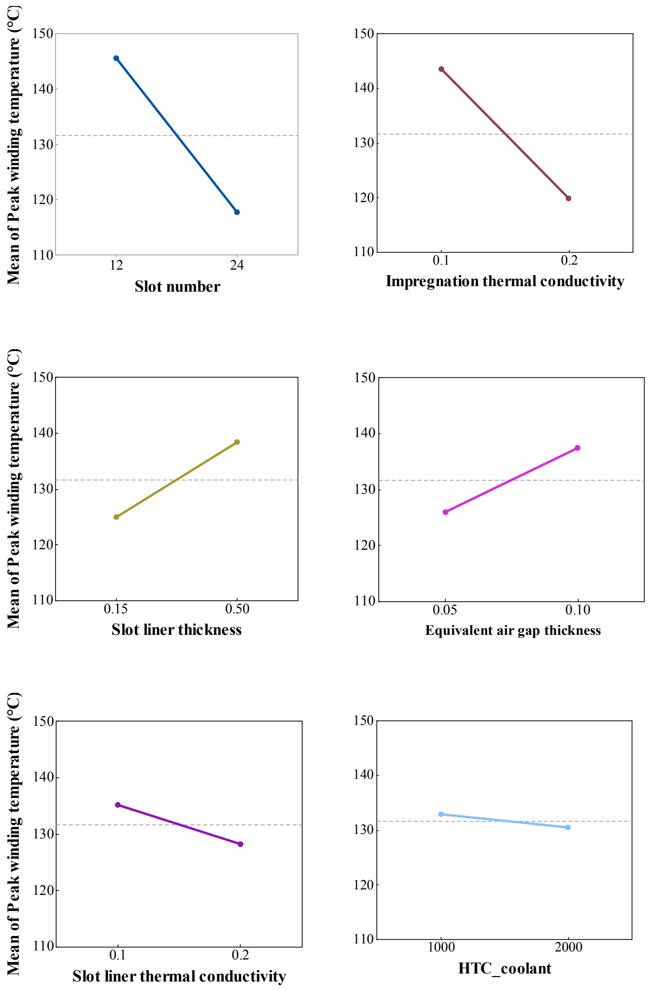


Fig. 7. Key parameters factorial plot

It is obvious that slot liner thickness, slot liner thermal conductivity, impregnation resin thermal conductivity affect the slot radial resistance. Slot number, which physically shortens the distance from the hot spot in the slot to the tooth and therefore slot thermal resistance is shortened. The temperature is more sensitive to impregnation resin thermal conductivity than slot liner thickness/thermal conductivity, as impregnation occupies a large percentage of the slot.

The impact of heat transfer coefficient between the coolant and frame on the winding temperature is not obvious in this case. Further increase in HTC_coolant improves the thermal condition slightly as the convection thermal resistance is very small. Other parameters effects are limited, such as the heat transfer coefficient in the end-winding region.

Stator and rotor are coupled with the heat transfer in the air-gap. Due to low rotating speed, friction losses in the air gap are ignored. It is indicated that there is weak link between stator and rotor in thermal aspect with the low sensitivity analysis of the HTC-air-gap. Therefore, further coefficients regarding rotor will not affect the stator thermal values, similar statement is also validated in [12].

IV. CONCLUSION

Thermal management is a key enabler for high power density electrical machines, which push thermal engineers to pursue large winding temperature reduction. Parameters that are highly influential on the winding temperature are merit more focus for the sake of simulation and experiment time reduction. Sensitivity analysis study investigates the response of output in the thermal system to the uncertainty in the fluctuations in the input parameters of the electrical machines. This paper presents a sensitivity analysis study on the winding temperature of a traction machine by using a developed thermal model. The slot number is shown to be critical in peak winding temperature determination. Slot liner and impregnation resin properties are also significant on the thermal effects of electrical machines.

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