Electromagnetic-Thermal-Fluidic Analysis of Permanent Magnet Synchronous Machine by Bi-directional Method

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This paper presents an electromagnetic-thermal-fluidic coupling model for the accurate evaluation of electromagnetic and thermal performance of a permanent magnet synchronous machine (PMSM). 2-D transient finite-element method (FEM) is used to investigate electromagnetic loss including copper loss, iron loss and magnet eddy loss. The calculated electromagnetic power loss is taken as the main source of the thermal-fluidic field and the materials property is in turn updated according to the temperature distribution. The simulation result of a rated 8 kW permanent magnetic machine is compared with the measuring result, which shows that the coupling analysis by the bi-directional method is more accurate than that by the unidirectional method. The calculation method will be helpful for the elaborate design of electrical machines.

***Index Terms*—Multiphysics, permanent magnet machines, electromagnetic analysis, thermal analysis**

I. INTRODUCTION

With a continuous improvement in PMSM performance, the interaction among various physical fields has become more and more complicated. Consequently, such factors as temperature rise, mechanical strength and vibration have been the main obstacles for further improving power density or torque density. Traditional design or analysis by the unidirectional method cannot satisfy the strict demand of power density. Many researchers have adopted bi-directional method for solving weak coupling problems and focused on combining electromagnetic finite-element methods or lumped methods with lumped parameter thermal network methods because of low cost and quite high accuracy [1-9]. In spite of its less computation, the method has obvious deficiencies. It is incapable of obtaining detailed temperature distribution and dealing with a great fluidic effect on the thermal field. This paper adopts the bi-directional method to investigate the PMSM electromagnetic-thermal-fluidic coupling model. The transient electromagnetic 2-D FEM and 3-D CFD method are used for the coupling model and different geometry models of different fields are used for the maximum reduction of computation time. The experiment verification shows that the coupling analysis by the bi-directional method is more accurate than that by the unidirectional method.

II. ELECTROMAGNETIC-THERMAL-FLUIDIC ANALYSIS

A rated 8kW interior V-shape PMSM with 36 slots and 10 poles is taken as a prototype, as shown in Fig. 1. NdFeB material is used because it is sensitive to temperature variation and has high energy products.

Fig. 1 Prototype stator and rotor

A. *Electromagnetic Modelling*

A 2-D transient electromagnetic FEM model is built based on the commercial software. Winding loss, iron loss and magnet eddy loss included in electromagnetic loss are the key points in the coupling analysis. By combining skin and proximity effect with thermal effect, the winding loss P_{Cu} (W) can be formulated as

$$P_{Cu} = \left(\mathrm{r_{ac}} / \mathrm{r_{dc}}\right)\big|_{T} \left(1+\alpha(T-T_0)\right)\rho_0 J^2 \tag{1}$$

where α is the temperature coefficient of copper, T_0 (℃) is the reference temperature, $\rho_0(\Omega \cdot m)$ is the resistivity at T_0 and J ($\mathrm{A \cdot m^{-2}}$) is the current density of the winding [10].

Similarly, magnet eddy loss can be expressed as

$$P_m = \rho_m J^2 \tag{2}$$

where P_m is magnet eddy loss, $\rho_{\mathrm{m}}(\Omega \cdot \mathrm{m})$ is the resistivity of the magnet.

The total iron loss P_t can be regarded as the sum of the hysteresis loss P_h, eddy-current loss P_c and excess loss P_e according to the principle of loss separation. The formula is

$$\begin{aligned} P_t &= P_h + P_c + P_e \\ &= \sum_{m=1}^{n} \left(C_h \left(mf_s\right) B_m^2 + C_c \left(mf_s B_m\right)^2 + C_e \left(mf_s B_m\right)^{1.5} \right) \end{aligned} \tag{3}$$

where B_m is the peak value of mth magnetic flux density, and the coefficients C_h, C_c and C_e in the above equations have been obtained by fitting the experimental data [11].

B. *Thermal Modelling*

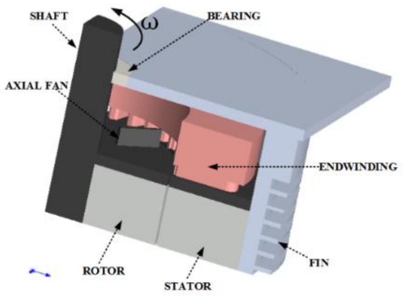

Fig. 2 CFD model

CFD model of the prototype is shown in Fig. 2. Only a radial and axial half-model is built by symmetry principle. The heat source contains mechanical and electromagnetic losses. Electromagnetic loss is mapped from the electromagnetic result and mechanical losses contains bearing and windage loss are directly measured by dummy rotor test. The main way of heat dissipation is through the heat convection of the machine surface, the heat dissipation can be expressed as

$$Q = hS\left(T_s - T_{amb}\right) \tag{4}$$

where Q (W) is the heat power, h (W ·m^{-2} ·K^{-1}) is the coefficient of heat convection, S (m^2) is the surface area, T_s (℃) is the surface temperature and T_{amb} (℃) is the ambient temperature.

C. Detailed Coupling Analysis Procedure

Electromagnetic loss significantly affects the distribution of temperature as the main heat sources. Temperature in turn influences the winding resistance, magnet remanence and intrinsic coercivity, thereby affecting the performance of electrical machine. In this paper, the magnet work point is on the reversible line and thus the influence of the temperature on magnet can be empirically expressed as

$$B_r\left(T\right) = \left[1 + \beta\left(T - T_0\right)\right] B_r\left(T_0\right) \tag{5}$$

where β is the temperature coefficients of remanence.

The main procedure of coupling analysis is shown in Fig. 3. Firstly, the temperature of winding and magnet is assumed to be 20℃ as initial value. Secondly, the material property is updated according to the current temperature and then electromagnetic loss distribution is calculated by 2-D transient FEM. Thirdly, the electromagnetic loss is loaded into thermal field as heat source to obtain temperature distribution by 3-D CFD. If a temperature difference lower than 1% appears in the successive iterations, the solution will converge and the procedure will end, otherwise the procedure will return to the second step.

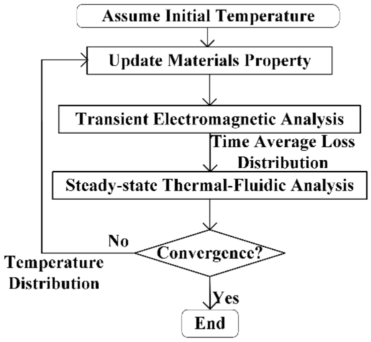

Fig. 3 The process chart of the coupling algorithm.

III EXPERIMENT VALIDATION

A load test has been carried out to prove the accuracy of the bi-directional coupling method. After the thermal state become stable, electromagnetic parameters and temperature rises are measured. As shown in TABLE I, the electromagnetic result shows that the bi-directional method is more accurate than unidirectional method because of the consideration of temperature influence on materials property. Table II compares the simulated and the measured temperature of different components. It can be seen that the bi-directional method is not more accurate than the unidirectional method because winding loss increases with the rise in temperature while iron loss decreases due to the reduction of the flux density. For this condition, the reduction in iron loss is more than the increasing amount of the winding loss, which results in that the simulated temperature by the unidirectional method is higher than that by the bidirectional method.

TABLE I

COMPARISON OF THE FUNDAMENTAL COMPONENT OF THE VOLTAGE AND CURRENT OBTAINED BY SIMULATION AND MEASUREMENT

	Measured	Unidirectional Method (Error%)	Bi-directional Method (Error%)
Phase Voltage/V	31.41	35.6 (13.3%)	31.45 (0.1%)
Phase Current/A	125.77	147.2 (17.0%)	125.41 (0.3%)

TABLE II

COMPARISON OF THE TEMPERATURE OF DIFFERENT COMPONENTS OBTAINED BY SIMULATION AND MEASUREMENT

	Measured	Unidirectional Method	Bi-directional Method
Enclosure	92.9℃	92.3℃	91.0℃
Slot Winding	106.7℃	105.3℃	102.9℃
End Winding	106.8℃	103.7℃	101.3℃

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