

A Novel magnetic-thermal bidirectional coupled model of permanent magnet motors based on subdomain methods and 3D thermal network

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A computational model is proposed to consider the magnetic-thermal bidirectional coupled (MTBC) phenomenon in permanent magnet motors, based on the electromagnetic subdomain method and three dimensional (3D) thermal network. Compared with the traditional finite element (FE) and analytical methods, this model has the advantage of fast calculation speed and high precision. Firstly, independent models are established for the motor electromagnetic and thermal fields based on the subdomain method and 3D thermal network, respectively. Then, the remanent flux density of the permanent magnet (PM) is changed from an invariant value in the traditional electromagnetic subdomain model to a variable determined by the thermal network temperature in the coupled model. In this way, the interaction between the motor electromagnetic field and node temperatures of 3D thermal network can be realized. The steady-state temperature rises of the arc linear flux switching permanent magnet motor (AL FSPM) is calculated to verify the effectiveness of the MTBC model.

Index Terms—Magnetic field, thermal field, bidirectional coupled, permanent magnet motor.

I. INTRODUCTION

THE FE and analytical models are commonly applied in the current MTBC calculations of the motors [1-2]. However, the physical mechanism, boundary conditions and mesh quality requirements of the electromagnetic and thermal fields are different. Also, there are difficulties in correspondence of grid nodes and data interaction between the magnetic and thermal fields in the FE software. As for the analytical model, the MTBC is usually based on the electromagnetic loss formula and 2D thermal network [3]. Significant errors are introduced into the MTBC due to the low precision of these two models in the analysis of the electromagnetic and thermal fields.

The accuracy of the subdomain method depends on that of the FE method in magnetic calculations. In the motor thermal analysis, 3D thermal network can consider both the axial and radial heat transfer, which is more practical and accurate than 2D thermal network. Owing to the well performance of the subdomain method and 3D thermal network in the analysis of the motor magnetic and thermal fields, these two methods have potential in the MTBC calculation. However, feasible MTBC models based on the subdomain method and 3D thermal network have not been developed.

In this paper, a temperature-dependent remanent flux density of the PM is introduced into the subdomain model, and a MTBC iteration model is established. Based on this model, the steady-state temperature rise of the AL FSPM is calculated, and the model accuracy is verified by prototype tests.

II. STRUCTURE OF AL FSPM

An AL FSPM is designed for scanning devices, as shown in Fig. 1. The characteristic of the AL FSPM is discontinuous arc shaped stator. The advantages of the arc stator are flexibly distributed in the circumferential direction and space saving. Therefore, the AL FSPM is suitable for direct driving of large sized loads and robotic joints. At the same time, since the arc stator is based on the principle of flux switching, the

utilization rate of PM is higher than that of the previous arc motors with PM on the rotor [4]. The structural parameters of the designed AL FSPM are listed in Table I.

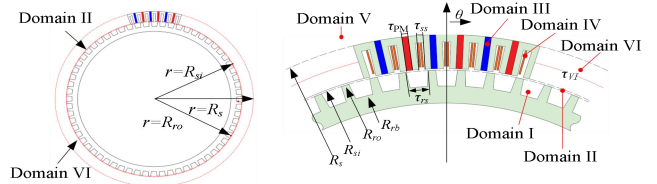


Fig.1. Division of the solving domain in AL FSPM and one arc stator.

TABLE I
PARAMETERS OF PROPOSED DOUBLE 3-PHASE AL FSPM

Rated power (kW)	0.414	Air gap (mm)	0.7
Peak voltage (V)	110	Rotor inn.diameter (mm)	160
Rated current (A)	3	Stator ext.diameter (mm)	208.8
Rated speed (r/min)	300	Rotor teeth width τ_{r0}	1.48°
Number of rotor teeth	64	PM height h_{PM} (mm)	11.8

III. MAGNETO-THERMAL BIDIRECTIONAL COUPLED MODEL

Due the PM and windings of the AL FSPM are both located on the stator, the temperature rise of the PM is easily affected by the copper loss of the winding. The MTBC phenomenon is obvious in the AL FSPM.

A. Subdomain Model of the Motor Magnetic Field

The partition of the solution regions is shown in Fig. 1. According to different sources of the magnetic potential, the solution regions of single arc stator is divided into 6 regions, including the arc end region in the circumferential direction between the arc stator. The general solution of the vector magnetic potential A_{III} in the PM (Domain III) is

$$A_{III}(r, \theta) = a_j^{III} + b_j^{III} \ln(r) - (-1)^j B_r \cdot r + \sum_{n_{III}=1}^{\infty} \left(c_{n,j}^{III} \left(\frac{r}{R_{si}} \right)^{\frac{n_{III}\pi}{\tau_{PM}}} + d_{n,j}^{III} \left(\frac{r}{R_s} \right)^{\frac{n_{III}\pi}{\tau_{PM}}} \right) \cos \left(\frac{n_{III}\pi}{\tau_{PM}} \left(\theta + \frac{\tau_{PM}}{2} - \theta_j \right) \right) \quad (1)$$

Where B_r is the remanent flux density of a PM, r is the radius, θ_j is the central line angle of the j -th PM.

B. 3D Thermal Network of the Motor Thermal Field

Due to the open housing of the motor end, the network branches have to be added in 3D thermal network to consider the axial heat transfer from the motor to the base and air. Also the heat transfer between the rotor and arc end region in the circumferential direction is discussed. In a word, parts of the rotor heat are transferred to the stator by the air gap, and other rotor heat is transferred to arc end region directly.

C. MTBC Model of the Subdomain Method and 3D Thermal Network

Power losses are affected by the temperature of the motor winding since the resistivity of copper wire increases with the temperature. Meanwhile, the variation of the remanent flux density with the temperature of the PM is considered. Thus, the vector magnetic potential equation of the PM evolves from equation (1) to equation (2).

$$\nabla^2 A = \frac{(-1)^{j-1}}{r} B_r(20^\circ\text{C}) \cdot (1 + \beta \cdot T_{\text{PM}}) = \frac{v}{r} \cdot (1 + \beta \cdot T_{\text{PM}}) \quad (2)$$

Where v is the base value of the vector magnetic potential of the PM at 20°C , T_{PM} and β are temperature and temperature coefficient of the PM, respectively.

The general solution of the vector potential A_{III} in one PM is

$$A_{III}(r, \theta) = a_j^{III} + b_j^{III} \ln(r) + v \cdot r \cdot (1 + \beta \cdot T_{\text{PM}}) + \sum_{n_{III}=1}^{\infty} \left[c_{n,j}^{III} \left(\frac{r}{R_{si}} \right)^{\frac{n_{III}\pi}{\tau_{\text{PM}}}} + d_{n,j}^{III} \left(\frac{r}{R_s} \right)^{\frac{n_{III}\pi}{\tau_{\text{PM}}}} \right] \cos \left(\frac{n_{III}\pi}{\tau_{\text{PM}}} \left(\theta + \frac{\tau_{\text{PM}}}{2} - \theta_j \right) \right) \quad (3)$$

D. Iterative Method of the MTBC Calculation During Steady State Operating

The iterative method of MTBC calculations during steady-state operation is shown in Fig. 2. First, various motor losses calculated at the initial temperature (room temperature), and these losses are used as initial thermal sources in 3D thermal network model to calculate the average temperatures of the PM and winding. Then, T_{PM} in the equation (3) and winding resistance are updated for the subdomain model based on the results of the thermal network. Finally, the motor losses are recalculated and updated for the thermal network. Iterative processes are repeated until the temperature calculation errors of the PM and winding are less than the allowable value.

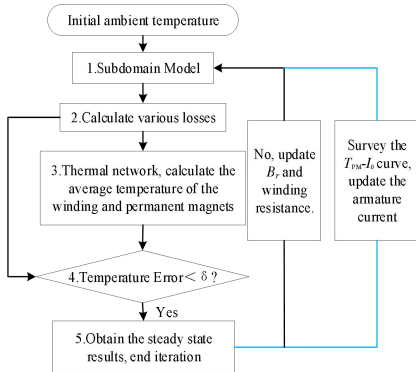


Fig.2. MTBC flowchart under steady-state operating.

Under the condition of constant torque, since B_r of the PM decreases with the temperature, the armature current has to be increased to maintain the output torque. Thus, the iteration of

T_{PM} and the armature current I_0 must be considered, which is represented by the blue line in Fig. 2. In this case, additional losses will be generated by the armature current, affecting the temperature rise of the motor.

IV. VALIDATION OF THE MTBC MODEL

This results of the temperature rises are compared, as shown in Fig. 3. There are obvious errors when the MTBC is ignored. Under the condition of constant current, the temperature rise errors are -12.8 K, -22.46% and -20.4 K, -23.53% for the housing and winding, respectively. Under the condition of constant torque, the MTBC phenomenon is more significant, due to the increases of the current and copper losses. Compared with the constant current condition, it can be seen the current had been increased by 9.89%. The steady-state temperature rises are increased by 10.5 K, 18.45% and 17.0 K, 19.61% for the housing and winding, respectively.

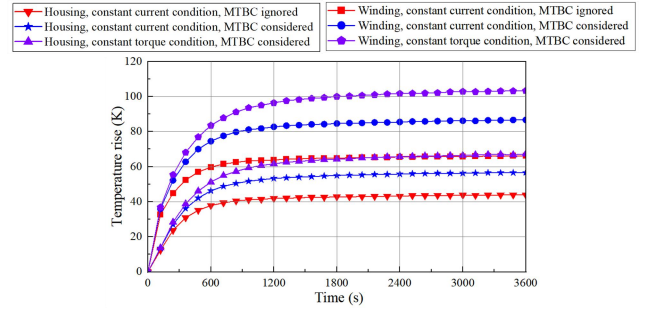


Fig.3. Temperature rise curves.

V. CONCLUSION

In this paper, an innovative MTBC model is proposed by utilizing the advantages of the magnetic subdomain model and 3D thermal network. This model can quickly calculate the coupled process of the motor losses and temperature rises, and the accuracy is close to that of the FE method. As a result, the proposed model can reduce the error in the design of the permanent magnet motors with obvious MTBC phenomenon, such as the flux switching motor, submersible motor and high power density motor, etc. Meanwhile, due to the universality of the subdomain method and 3D thermal network, the MTBC model proposed in this paper is not limited to the AL FSPM, but also suitable for other familiar permanent magnet motors.

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