Improved Design and Performance Analysis of Permanent Magnet Transverse Flux Motors with Soft Magnetic Composite Core

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***Abstract*-This paper presents an improved design and analysis procedure for permanent magnet transverse flux motors (TFM) with soft magnetic composite (SMC) core, based on our previous experience with the study of a single-sided SMC TFM. Three-dimensional finite element analyses of magnetic field are conducted for key parameter computation; a hybrid thermal model with distributed heat sources is used for temperature rise calculation; an equivalent electric circuit is derived under optimum brushless DC control condition for motor performance prediction; and computer search techniques are applied for design optimization. All these computations and analyses have been implemented in a commercial software ANSYS for design and performance analysis of the SMC TFM prototype.**

I. INTRODUCTION

The soft magnetic composite (SMC) material produced by powder metallurgy possesses a number of advantages over the traditional laminated steels and the research about its application in electrical machines in the past few years has shown a promising prospect [1]. The main advantages of this material are the isotropic magnetic and thermal properties, low eddy current loss, and nearly net-shape fabrication process with good tolerance and surface finish. The isotropic magnetic property of the SMC allows new design freedoms and may be very suitable for construction of electromagnetic devices with three-dimensional (3D) flux and complex shapes such as claw pole and transverse flux machines [2, 3].

Permanent magnet (PM) motors with the transverse flux structure have attracted increasing attentions since Weh and May first proposed two versions of transverse flux motor (TFM) in 1986 [4]. Motors of this type are capable of producing very high specific torque at low speed and are thus suitable for direct-drive applications [4, 5]. The complex topology of a TFM will definitely benefit if the flux path does not have to be constrained in a two-dimensional plane. SMC materials offer this design flexibility and also the prospect of low-cost and environment-friendly manufacturing. In addition, the TFM has the cheapest possible winding, namely one or two (depending on TFM type) circular coils per phase.

The application of SMC in transverse flux geometry was first attempted by Newcastle University upon Tyne, UK, in 1996 [6]. SMC was used for the stator iron parts of a TFM prototype with a flux-concentrating PM rotor, double axial airgaps and a modified double-sided stator topology. Since the main magnetic flux in the stator core flows in all the three directions, laminated steels are not suited for the complex magnetic circuit and SMC is an ideal substitute. The authors also highlighted that SMC allows the armature core to be made much larger than laminations, as the available space on the flanks and core back can be used by SMC without increasing the overall machine volume.

Another investigation was reported by the University of Technology Aachen, Germany, in 2000 [7]. The paper described a TFM prototype with three phases magnetically coupled in the laminated stator to reduce the motor volume. The external rotor comprises PMs and flux concentrating iron parts, which are made by SMC as “the guidance of the flux in three dimensions is impossible with laminated steel” [7]. However, 3D finite element analysis (FEA) of magnetic field has shown that the flux in the stator core, particularly in the poles, has significant components in all the three directions and high eddy current losses may be produced by the varying field perpendicular to the direction of lamination [8]. Therefore, the authors further developed the prototype by using SMC in both stator and rotor cores [8].

Since 1998, our research group, the Centre for Electrical Machines and Power Electronics, University of Technology, Sydney, has conducted extensive research on measurement and modeling of the magnetic properties of SMC materials and development of SMC motors with different topologies, including a single-sided SMC TFM prototype [3, 9]. Based on the prototype, this paper aims to present an improved design and analysis procedure for PM transverse flux motors with SMC core by using a combination of 3D electromagnetic field FEAs for computation of key motor parameters, a hybrid thermal model with distributed heat sources for prediction of temperature rises, an equivalent electric circuit for prediction of motor performances, and computer search techniques for design optimization. The design and analysis method has been validated by the experimental results on the SMC TFM prototype.

II. 3D MAGNETIC FIELD FEA OF TFM

The equivalent magnetic circuit method can be used for determination of initial design variables which are important for fast convergence of optimization, but 3D FEAs of magnetic fields are necessary for accurate computation of major parameters such as the back electromotive force (*emf*), winding inductance, electromagnetic torque, cogging torque and core loss. Since the magnetic flux in a TFM is substantially 3D and the magnetic circuit is non-linear, conventional methods such as the magnetic circuit cannot obtain reliable design data although they are useful in approximate analysis.

A. Prototype Structure and FEA Solution Region

Fig. 1 illustrates the magnetically relevant parts of one pole-pair of one stack of the single-sided TFM prototype and the solution region for the magnetic field FEA at the zero rotor position, where one of the stator teeth is aligned with one of the rotor magnets [3, 9].

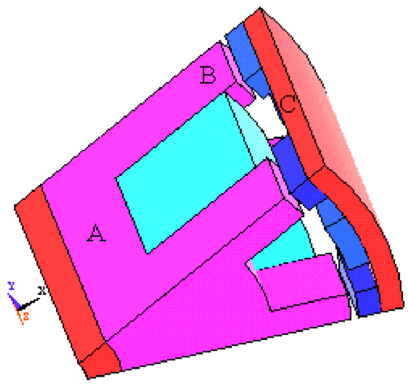

Fig.1 Region for field solution

The motor is of outer rotor structure and each phase consists of two arrays of PMs, which are mounted on the inner surface of the rotor. In the initial prototype, mild steel was used for the rotor yoke but it should be noted that the motor performance such as efficiency would be much better if SMC had been used due to the significant eddy current loss caused by the varying flux density in the yoke. The inner stator is stacked axially and each phase employs a simple toroidal winding. The SMC stator core of each stack is molded in two halves. To take advantage of the isotropic magnetic properties of SMC, the rotor magnets are designed to overhang the stator teeth both axially and circumferentially as the magnetic flux can also flow into the stator teeth via the side surfaces. In this way, the stator winding flux and the motor's specific torque per volume can be increased.

The three stacks of the motor are basically magnetically independent and each stack is periodically symmetrical for every pole-pair region. At the two radial boundary planes, the magnetic scalar potentials obey the periodical boundary conditions:

$$\varphi_m(r,\Delta\theta,z)=\varphi_m(r,-\Delta\theta,z) \qquad (1)$$

where $\Delta\theta=18^o$ mechanical is the angle of one pole pitch. The origin of the cylindrical coordinate is located at the center of the stack.

In the field analysis, separated fixed finite element meshes are created for the stator and rotor parts, and merged at the airgap. This provides an efficient calculation for torque, flux and back electromotive force (*emf*), inductance at various rotor angles, and core losses.

B. Major Parameter Computation

Based on the magnetic field FEA, several key parameters can be determined for performance prediction in the optimization loop. For example, the no-load magnetic field distribution is calculated to find out the magnetic flux linking the stator winding and hence the induced *emf* due to the rotation of the PMs on the rotor. Fig. 2 plots the calculated flux waveform of the SMC TFM prototype, which is almost perfectly sinusoidal.

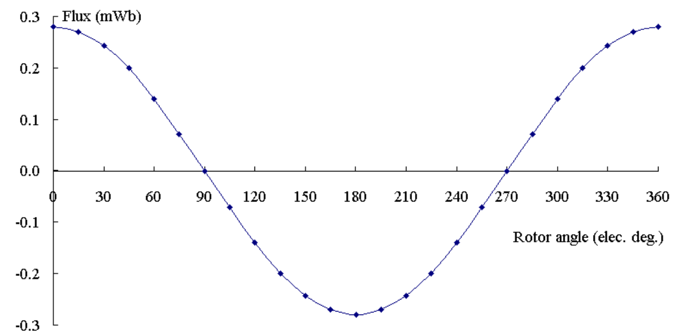

Fig.2 No-load flux per turn of a phase winding

To reduce the time of optimization iterations, the no-load magnetic field distribution is only solved for the rotor at the aligned position ($\theta = 0^o$) to find the maximum flux linkage of the stator coil produced by the rotor magnets and the back *emf*. Here, we assume that the flux curve versus rotor angle is sinusoidal, which has been justified by the calculation in Fig. 2. For accurate calculation, a series of magnetic field FEA are conducted at different rotor positions to obtain the whole curve (360^o or 180^o electrical taking advantage of the symmetry). The discrete Fourier transformation is used to obtain the fundamental and harmonics of the stator coil flux and back *emf*.

In addition, the curves of the cogging torque (without the stator current) against the rotor angle can also be computed from the no-load magnetic field solution by the virtual work or Maxwell stress tensor methods.

The second magnetic field FEA in the optimization loop is to calculate the winding inductance and reactance. The self-inductance of each phase winding can be calculated by the flux method, $L_1=N_1\phi_1/I_1$, where ϕ_1 is the magnitude of the flux linking the stator winding due to a stator current I_1 in each of N_1 turns. Alternately, the inductance can be calculated by the energy method, i.e. $L_1=2W_f/I_1^2$, where W_f is the magnetic energy stored in the motor. ϕ_1 and W_f can be obtained from the results of a field analysis with a stator current I_1 while the permanent magnets are "switched off", i.e. remanence is set to zero. For fast computation, only one calculation at the rotor position $\theta = 0^o$ is conducted. In surface-mounted PM motors, the winding inductance varies little against the rotor angle as the permeability of PM is close to that of air and the armature magnetomotive force applies the same circuit magnetically at different rotor positions. For accurate calculation, the inductance is computed at different rotor angles and the average value is used in the equivalent electric circuit for performance prediction. If the difference between the d-axis (θ = 0°) and the q-axis (θ = 90° electrical) values is significant, a model considering separately the d- and q-axis currents and inductances can be used. Furthermore, the maximum magnetic flux density in magnets produced by the armature current can be computed from this field analysis to check whether the magnets would be demagnetized.

The third FEA is to calculate the core loss by an improved method as described in [10, 11]. A series of 3D FEAs are conducted to determine the flux density locus in each element when the rotor rotates. An example is shown in Fig. 3. The total core loss is calculated by separating the hysteresis (with purely alternating, purely circular rotating or elliptically rotating flux density vectors), eddy current and anomalous losses in each element, and different formulations are used for different flux density patterns. This method can also calculate the core loss distribution, one of the key factors for accurate thermal analysis.

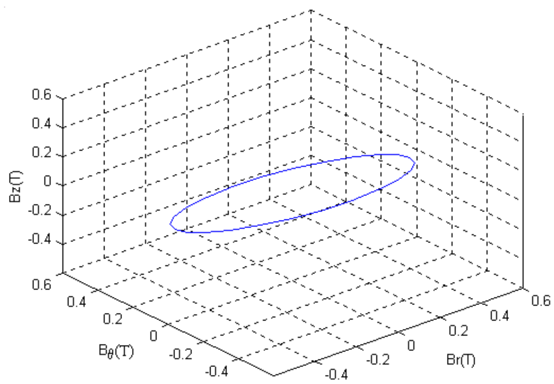

Fig.3 No-load flux density locus at Point B of the stator tooth

III. Thermal Analysis

To manufacture more compact and more efficient motors it is necessary to predict with reasonable accuracy the thermal performance at the design stage. In this paper, the temperature distribution is calculated by using a hybrid thermal model with distributed heat sources. Fig. 4 illustrates the schematic diagram of thermal network. For higher computation accuracy, any part, e.g. the airgap, can be divided into many small segments.

The thermal resistances of conduction in the following sections are calculated: rotor yoke (R_{ry}), magnets (R_m), glue between magnet and rotor yoke (R_{mg}), air gap (R_{ag}), stator yoke (R_{Fe1}), stator side discs (R_{Fe2}), stator teeth (R_{Fe3}), varnished copper wire (R_{cu}) and insulations (R_{I1}, R_{I2}, R_{I3}) between the winding and the stator yoke, the stator wall disc and the air gap, respectively. In addition, the thermal resistances of the stator shaft (R_{ss}), the aluminum end plates (R_{al}) and the stationary air (R_{sa}) between the side discs and the end plates are calculated separately.

The equivalent thermal resistances to the heat convection of the following sections are calculated: between the stator tooth surface and the inner air in the airgap (R_{FeA}), between the winding and the inner air (R_{WA}), between the magnet and the inner air (R_{mA}), between the rotor yoke and the inner air (R_{ryA1}), between the rotor yoke and the outer air (R_{ryA2}).

The heat sources include the stator coil copper losses (P_{cu}), the stator and rotor core losses (P_{Fes}, P_{Fer}), and the mechanical losses due to windage and friction (P_{mec}). The improved method for core loss calculation can obtain the loss distribution, which is a great advantage for the thermal calculation by the hybrid thermal model.

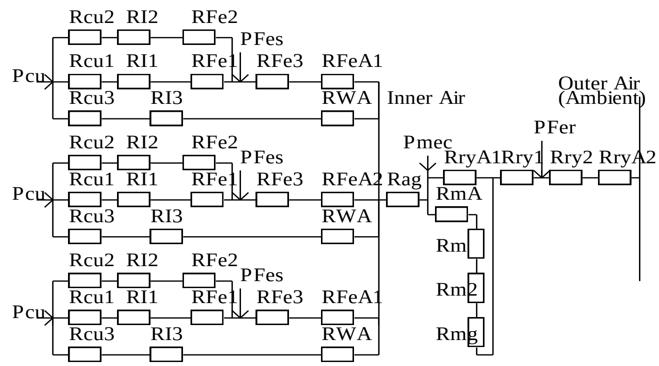

Fig.4. A schematic diagram of thermal network of the TFM prototype

IV. Performance Prediction

The motor is operated with a brushless DC drive scheme. At the optimum control condition, the current I_1 is in phase with the back *emf*, E_1 in the stator winding and an equivalent electric circuit is shown in Fig. 5, where R_1 and X_1 are the resistance and synchronous reactance of one phase winding, respectively.

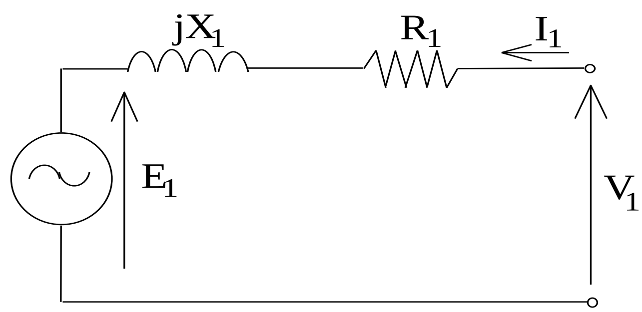

Fig.5. Equivalent electric circuit model of the TFM

The achievable maximum electromagnetic power P_{em} is

$$P_{em} = 3E_1I_1 \tag{2}$$

The output power P_{out}, output torque T_{out}, input power P_{in} and efficiency η of the total drive system can be calculated by

$$P_{out} = P_{em} - P_{Fe} - P_{mec} \quad (3)$$

$$T_{out} = P_{out} / \omega_r \quad (4)$$

$$P_{in} = P_{em} + P_{inv} + P_{cu} \quad (5)$$

$$P_{cu} = 3 I_1^2 R_1 \quad (6)$$

$$\eta = P_{out} / P_{in} \quad (7)$$

where P_{Fe} is the core loss, P_{mec} the mechanical loss, P_{inv} the inverter conduction loss, P_{cu} the copper loss, which is assumed here to be dominated by the fundamental component of current, and ω_r the rotor angular speed in mechanical rad/s.

V. Design Optimization

An optimization routine for the design of the single-sided TFM with SMC core has been set up, which includes three magnetic field FEAs for calculation of back *emf*, stator winding inductance and core loss, as described in Section II. The motor performance is predicted by an equivalent electric circuit under the optimum brushless DC control condition. The magnetic field FEAs, thermal analysis, performance prediction, and optimization searches are all implemented in a commercial comprehensive software package, ANSYS.

The dimensional variables are the motor outer diameter, effective axial length, rotor yoke thickness, PM dimensions (length, width and height), stator tooth width at top and at bottom, stator tooth height and stator yoke thickness. Considering the mechanical clearance requirement, the airgap length is chosen as 1 mm although smaller value could provide better electromagnetic performance. The design objective is to minimize the total drive cost including material (PMs, iron, copper) and power electronics within the temperature rise limit.

Table 1 lists the performance and major dimensions of the SMC TFM prototype [3]. Table 2 compares the predicted and measured key motor parameters, which validate the design and analysis procedure.

TABLE I
Motor Performance and Major Dimensions

Parameter and dimension	Value
Speed (rev/min)	1800
Frequency (Hz)	300
Output power (W)	640
Total drive efficiency (%)	79.5
Phase current (A)	5.5
Winding temperature rise (°C)	65
Stator outer radius (mm)	40
Effective stator axial length (mm)	93
Rotor (motor) outer radius (mm)	47
Rotor inner radius (mm)	41
Magnet dimensions	OD88 x ID82 x 9 mm arc 12°
Airgap length (mm)	1

TABLE II
Key Motor Parameters

Parameter	Predicted	Measured
Motor back *emf* constant (Vs)	0.247	0.244
Phase resistance at 20°C (Ω)	0.310	0.305
Phase (synchronous) inductance (mH)	6.68	6.53
Cogging torque maximum (Nm)	0.339	0.32
Winding temperature rise (°C)	65	66

VI. Conclusion

This paper presents a design and analysis procedure for transverse flux motors with SMC core, which combines 3D magnetic field FEAs, hybrid thermal model with distributed heat sources, and optimization techniques. The theoretical results by this procedure have been validated by the experiment on a single-sided SMC TFM prototype.

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