Parameter Computation and Performance Prediction of a Claw Pole/Transverse Flux Motor with Soft Magnetic Composite Core

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Abstract This paper presents the parameter computation and performance prediction of a flux-concentration claw pole/transverse flux motor with soft magnetic composite (SMC) core by using magnetic field finite element analysis and equivalent electrical circuit techniques. The magnetic field distribution in the motor is really complicated, and hence three-dimensional (3D) magnetic field finite element analysis is conducted for accurately determining the key motor parameters such as winding flux, back electromotive force, winding inductance, and core loss. To predict the motor performance, an equivalent electrical circuit is derived. The computation and analysis techniques used in the paper are also helpful for developing other novel machines with new structures and new materials.

Keywords: Claw pole/transverse flux motor, parameter computation, performance prediction, 3D finite element analysis, equivalent electrical circuit, soft magnetic composite.

1. INTRODUCTION

Transverse flux machines (TFMs) have aroused strong interests of research since they were proposed by Weh and May in 1980s [1]. TFMs are capable of producing very high specific torque provided that the pole number is high and hence suitable for direct drive applications featuring high torque at low rotational speed.

However, there are some shortcomings that should be carefully considered in the TFM design and application. Due to the large armature leakage fields, the power factor of TFMs is quite low, especially for the single-sided type [2]. The double-sided topology has higher power factor and specific output, but all the designs reported are considered as too complicated to manufacture [3]. In addition, the three-dimensional (3D) property of magnetic field makes the lamination of iron cores very difficult.

A large amount of work has been conducted for overcoming the shortcomings and a notable example is the development of high performance TFMs by claw pole geometries [4]. The claw pole/TFM features both the simplicity of the single-sided type and the high performance of the double-sided one [5]. To improve the power factor, the claw poles are axially shortened to reduce the armature interpolar flux leakage. The decrease in the axial length of the stator pole will not necessarily reduce the stator winding flux when a permanent magnet (PM) flux-concentrated rotor is used. The core construction could be easily realized by using soft magnetic composite (SMC) materials due to their unique properties such as magnetic and thermal isotropy, low eddy current loss, and nearly net-shape fabrication process with good tolerance and surface finish [6-8].

To investigate the application potential of SMC in electrical machines, the authors of this paper have conducted extensive research in the past decade and some progress has been achieved, such as the measurement and modeling of magnetic properties of SMC under rotating magnetic field excitations [9-11], development of several SMC motor prototypes [12-14], and preliminary study of some novel structure machines including the claw pole/TFM [15-16]. One of the successful experiences is the 3-D flux design concept, which provides great flexibility for designing high performance motors. SMC removes the constraints imposed by conventional laminated steels, e.g. the magnetic flux must flow with the lamination plane (2D) because the flux component perpendicular to the plane may cause excessive eddy currents.

As discussed above, SMC materials are particularly suitable for application in electrical machines with complex structure and 3D flux path [17]. Taking the claw pole/TFM as an example, this paper aims to present a general procedure for the design and analysis of 3D flux SMC electromagnetic devices.

Conventional techniques such as the equivalent magnetic circuit method and empirical formulae cannot properly analyze a 3D flux machine, especially one with novel structure and new materials like SMC. There is little existing experience and knowledge with the motor and the material. Therefore, advanced numerical techniques like finite element analysis (FEA) is necessary for correctly computing the magnetic field distribution and parameters of the motor. In addition, the magnetic properties of the new material with 3D flux excitations should be properly investigated, modeled and applied in the motor design [11, 16]. These data cannot be obtained from the material manufacturers who only provide the properties under one-dimensional (1D) alternating excitation.

2. CLAW POLE TFM PROTOTYPE AND 3D MAGNETIC FIELD FEA

Fig. 1 shows the layout of a claw pole/transverse flux motor and the field solution region of one pole pitch of one stack. The simple toroidal winding is enclosed by an SMC core, which is molded in two halves. In the flux-concentrating rotor, the PMs are magnetized tangentially and the fluxes produced by the two adjacent magnets aid in the SMC part between them and then flow to the stator via the air gap (in the figure, only one PM is shown for one pole pitch FEA model while the main magnetic circuit has the lowest reluctance).

The designed claw pole TFM uses Somaloy™ 500 (+0.5% Kenolube) core [18] and NdFeB permanent magnets. The major parameters and dimensions include 12 poles, stator outer diameter of 110 mm, stator inner diameter of 56 mm, effective axial length of 102 mm, and main air gap length of 1 mm. The arc-shape PM takes one third of the circumference of the rotor with a radial height of 14 mm. The coil window dimensions are 20 x 10 mm^2.

Because the magnetic flux in a CPTFM is substantially 3D and the magnetic circuit is non-linear, conventional approaches such as the equivalent magnetic circuit cannot obtain reliable design data. Compared with the laminated steel, SMC has lower magnetic permeability and saturation flux density. The lower permeability is not a serious problem for PM motors, but it does encourage leakage fields, which are naturally 3D. Therefore, 3D FEA of magnetic field is conducted for accurately computing the motor parameters such as the back electromotive force (*emf*), winding inductance, electromagnetic torque, cogging torque and core loss.

The magnetic circuit of each stack (or phase) is basically independent. For each stack, because of the symmetrical structure, it is only required to analyze the magnetic field in one pole pitch, as shown in Fig. 1. At the two radial boundary planes of one pole pitch, the magnetic scalar potential obeys the so-called half-periodical boundary conditions:

$$\varphi_m(r,\Delta\theta/2,z) = -\varphi_m(r,-\Delta\theta/2,-z) \qquad (1)$$

where $\Delta\theta = 30^{\circ}$ is the angle of one pole pitch. The original point of the cylindrical coordinate is located at the center of the stack.

Fig. 2 illustrates the plot of no-load magnetic flux density vectors produced by the rotor PMs where the magnetic circuit has the highest permeability and the stator winding links the maximum flux, i.e. $\theta=0^{\circ}$, as shown in Fig. 1. It can be seen that the major path of the flux is along the north pole of PM – rotor flux-concentrating iron between two PMs – main air gap – claw pole – stator side wall and yoke – another claw pole – main air gap – another flux concentrating iron – then the south pole of PM to form a closed loop. There is also a considerable amount of flux leakage between the side and end surfaces of the claw poles of two separated pieces.

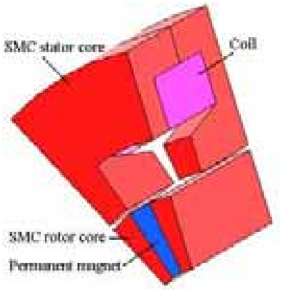

Fig. 1. Layout and FEA region of a claw pole TFM

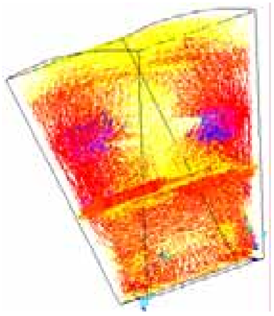

Fig. 2. Plots of no-load magnetic flux density vectors

3. PARAMETER COMPUTATION

From the magnetic field distributions, a number of key motor parameters can be accurately determined. For example, the PM flux, defined as the flux of a stator phase winding produced by the rotor PMs, can be obtained from the no-load magnetic field distribution. As shown in Fig. 3, the flux waveform is computed by rotating the rotor magnets for one pole pitch in 12 steps, which is an almost perfect sinusoid.

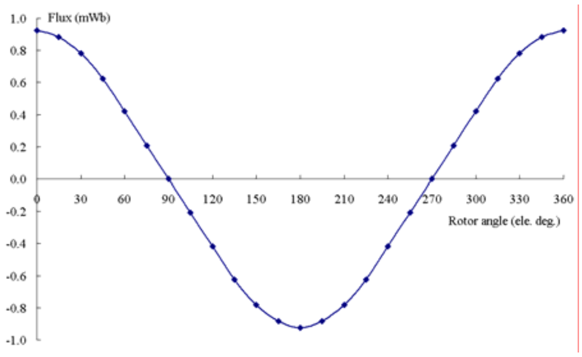

Fig. 3. Per-turn PM flux against rotor angle

When the rotor rotates, the PM flux varies and an *emf* is induced in the stator winding. The *emf* frequency depends on the rotor speed, while its waveform is determined by the waveform of the flux. The *emf* constant is found to be 0.267 Vs/rad, by

$$K_E = \frac{P}{2} N_1 \frac{\phi_1}{\sqrt{2}} \tag{2}$$

where P=12 is the number of poles, N_1=68 the number of turns of a phase winding, and ϕ_1 =0.925 mWb the magnitude of the flux fundamental component.

The behavior of an electrical circuit is governed by the incremental inductance instead of the secant inductance. Here, the phase winding incremental inductance of the claw pole TFM is calculated by a modified incremental energy method [19]. Due to the structural and magnetic saturation saliencies, the winding inductance varies against the rotor position. The averaged self-inductance of one phase winding is computed to be 4.06 mH. The mutual inductance between two phase windings can be considered as zero because of the almost independent magnetic circuit of each stack.

Unlike normal machines in which the copper loss dominates, SMC motors have comparable core loss and copper loss. Therefore, it is important to accurately predict the core loss. An accurate method has been proposed by the authors, which is based on flux density locus of each element and is capable of considering the rotational core loss [20-21]. By using this method, the core loss of the SMC claw pole TFM is computed to be 184.9 W at 3000 rpm [16].

4. PERFORMANCE PREDICTION

When running in synchronous mode, the steady-state performance of the claw pole TFM can be predicted by an equivalent circuit model as shown in Fig. 4, where E_1 is the induced stator *emf*, R_1 the stator winding resistance, $X_1=\omega_1 L_1$ the synchronous reactance, ω_1 the operating angular frequency, and L_1 the synchronous inductance which equals the self inductance of the phase winding here. The motor is assumed to operate in the optimum brushless dc mode, i.e. I_1 in phase with E_1, so that the electromagnetic power and torque can be calculated by

$$P_{em} = mE_1 I_1 \tag{3}$$

$$T_{em} = \frac{P_{em}}{\omega_r} = K_T I_1 \tag{4}$$

where m=3 is the number of phases, $\omega_r=\omega_1/(P/2)$ the rotor speed in mechanical rad/s, and $K_T=mK_E$ the torque constant. The rms value of the back *emf* is determined by $E_1=K_E\omega_1$.

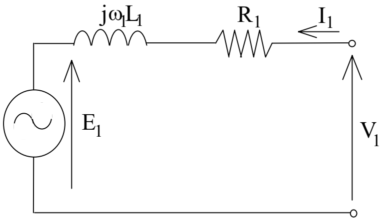

Fig. 4. Per-phase equivalent electrical circuit

For a given terminal voltage V_1, the torque/speed curve can be derived as

$$\omega_r = \frac{\sqrt{\left(\frac{R_1 T_{em}}{m}\right)^2 + \left[\left(\frac{P}{2} L_1 \frac{T_{em}}{K_T}\right)^2 + K_E^2\right]\left[V_1^2 - \left(\frac{R_1 T_{em}}{K_T}\right)^2\right]} - \frac{R_1 T_{em}}{m}}{\left(\frac{P}{2} L_1 \frac{T_{em}}{K_T}\right)^2 + K_E^2} \tag{5}$$

Fig. 5 plots the torque/speed curves with different values of terminal voltage, and Fig. 6 plots the curves of the input and output powers and efficiency versus the electromagnetic torque when the terminal voltage is 123 V (rms). In the optimum brushless dc operating mode, this motor can output 2850 W with an efficiency of 90% at 3000 rpm when the terminal voltage is 123 V.

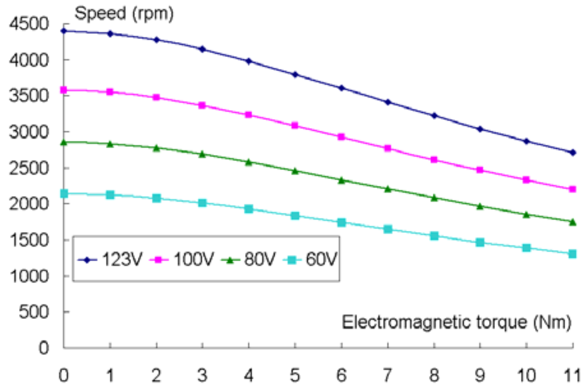

Fig. 5. Speed against electromagnetic torque

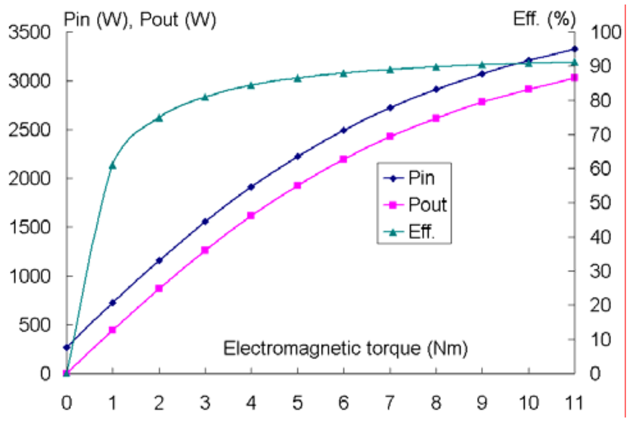

Fig. 6. Input power, output power and efficiency versus electromagnetic torque

5. CONCLUSION

This paper presents the analysis of a three-phase three-stack claw pole transverse flux motor with soft magnetic composite core and PM flux-concentrating rotor. Three-dimensional non-linear magnetic field finite element analysis is conducted to accurately compute the motor parameters. An equivalent electrical circuit is applied to predict the motor performances under the optimum brushless dc control. The analysis techniques, which were validated by the experimental results of a claw pole motor [13] and a transverse flux motor [14], can be helpful for designing and analyzing novel machines with complex structures and new materials.

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