Performance Analysis of an SMC Transverse Flux Motor with Brushless DC Control Scheme

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Due to their unique properties such as magnetic isotropy and low eddy current loss, soft magnetic composite (SMC) materials are particularly suitable for electrical machines with complex structure and three-dimensional (3-D) flux such as transverse flux motors (TFMs). This paper presents the performance analysis of a TFM with SMC stator core operating in a brushless DC control scheme. 3-D magnetic field finite element analysis is conducted to accurately compute the motor parameters. Equivalent electrical circuit and Simulink-based simulation model are derived to predict the motor's steady state and dynamic performances. Experiments are conducted on the prototype, validating the theoretical calculations and analyses.

Key Words: Transverse flux motor (TFM), Soft magnetic composite (SMC), Brushless DC control, Magnetic field finite element analysis (FEA), Performance simulation.

Introduction

Soft magnetic composite (SMC) materials and their applications in electromagnetic devices have achieved significant progress in the past decade [1]. The unique properties of SMC include magnetic and thermal isotropy, very low eddy current loss and relatively low total core loss at medium and high frequency, net-shape fabrication with smooth surface and good finish (no need of further machining), and prospect of low cost mass production. The base material of SMC is iron powder with high purity and high compressibility. The powder particles are bonded with a coating of an organic material, which produces high electrical resistivity. The coated iron is then compacted in a die to form a solid and finally heat-treated to anneal and cure the bond [2].

The powdered nature implies isotropic magnetic properties, which create crucial design benefits [3]. The constraints imposed by laminated steels, such as that magnetic flux must flow within the lamination plane, can be ignored. Electrical machines can now be designed with three-dimensional (3-D) fluxes, providing great design flexibility and possibility for novel structures. Typical examples of SMC applications are 3-D flux machines [4].

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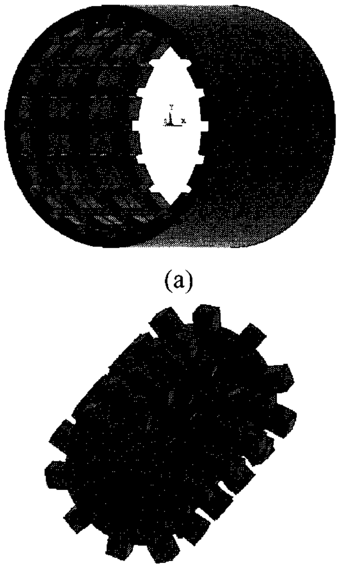
To investigate the application potential of SMC in electrical machines, a permanent magnet (PM) transverse flux motor (TFM) with SMC stator core has been developed by the authors, as illustrated in Fig. 1 [5]. Since it is very difficult to construct TFMs using laminated steels, which can carry time varying magnetic flux only in the plane of laminations in order to avoid excess eddy current loss, SMC is an ideal candidate for the core.

The three phases of the motor are stacked axially with an angular shift of 120° electrical from each other to generate a three-phase symmetrical electromotive force (*emf*) in the three windings and to minimize the cogging torque. Each phase has a simple concentrated winding (not shown in the figure for clarity) around an SMC core, which is molded in two halves. The outer rotor comprises a mild steel cylinder with two arrays of magnets per phase mounted on the inner surface.

The major parameters of the prototype include: 20 poles, an outer diameter of 94 mm, an active axial length of 93 mm, a main airgap length of 1.0 mm, and an average airgap diameter of 81 mm. The motor is designed to operate in a brushless DC (BLDC) control scheme, delivering a torque of 3.4 Nm at 1800 rev/min.

Due to the complicated structure, 3-D magnetic field finite element analysis (FEA) is required for accurate parameter calculation, taking into account the structure details, non-linear material properties and flux fringing.

Based on the TFM prototype, this paper presents the performance analysis by both an equivalent electrical circuit and a Simulink-based simulation model. The theoretical analyses are validated by experimental results on the prototype.



(a)

(b)

Fig. 1. Magnetically relevant parts of the TFM: (a) rotor and (b) stator.

2. 3D FEA of Magnetic Field

Considering the structural symmetry and the almost independent magnetic circuits between stacks, only one pole-pair region of one stack is required for the FEA solutions. On the two radial boundary planes, the magnetic scalar potentials obey the periodical boundary conditions.

From the magnetic field FEA solutions, key motor parameters such as winding flux, back *emf*, inductance and core loss, can be properly determined [5]. The winding flux is found to be a nearly perfect sinusoidal waveform with a magnitude of 0.290 mWb, and the back *emf* constant is K_E=0.247 Vs. The core loss at no-load and 1800 rev/min is 69 W, and increases to 112 W at load. The secant self-inductance of one phase winding is computed as 6.68 mH, which is almost constant at various rotor positions. The mutual inductance between phases can be considered as zero due to the almost independent magnetic circuit of each stack.

Since the behavior of an electrical circuit is governed by the so-called incremental inductances, rather than the secant ones [6], this paper computes the incremental inductances by using a modified incremental energy method [7]. The self incremental inductance of one phase winding is calculated as 5.66 mH, which is smaller than the secant one. This agrees with the fact that the incremental inductance corresponds to the tangential line at the operating point on the flux-linkage versus current curve, while the secant inductance corresponds to the line through the origin and the operating point.

3. Steady-state Performance Analysis by Equivalent Electrical Circuit

When operating in synchronous mode, the motor's steady-state characteristics can be predicted by an equivalent electrical circuit, as shown in Fig. 2, where E_1 is the induced back *emf*, V_1 the applied voltage, ω_1 the angular frequency, R_1 the resistance, and L_1 the synchronous inductance which equals the phase winding self inductance here. At the optimum BLDC control condition, the phase current I_1 is in phase with E_1, so the electromagnetic power can be calculated by

$$P_{em} = mE_1I_1 \tag{1}$$

The input power, output power, electromagnetic torque, output torque, and efficiency can be computed by

$$P_{cu} = mI_1^2R_1 \tag{2}$$

$$P_{in} = P_{em} + P_{cu} \tag{3}$$

$$P_{out} = P_{em} - P_{Fe} - P_{mec} \tag{4}$$

$$T_{em} = \frac{P_{em}}{\omega_r} = K_TI_1 \tag{5}$$

$$T_{out} = P_{out} / \omega_r \tag{6}$$

$$\eta = P_{out} / P_{in} \tag{7}$$

where m=3 is the number of phases, P_{cu} the copper loss, P_{Fe} the core loss, P_{mec} the mechanical loss, ω_r the rotor angular speed, and K_T=mK_E the torque constant.

From the electrical circuit, the steady-state mechanical characteristic, i.e. the relationship between the rotor speed and electromagnetic torque, can be derived as

$$\omega_r = \frac{\sqrt{\left(\frac{R_1T_{em}}{m}\right)^2 + \left[\left(\frac{P}{2}L_1\frac{T_{em}}{K_T}\right)^2 + K_E^2\right]\left[V_1^2 - \left(\frac{R_1T_{em}}{K_T}\right)^2\right]} - \frac{R_1T_{em}}{m}}{\left(\frac{P}{2}L_1\frac{T_{em}}{K_T}\right)^2 + K_E^2} \tag{8}$$

where P=20 is the number of poles. Fig. 3 illustrates the computed mechanical characteristics at different terminal voltages.

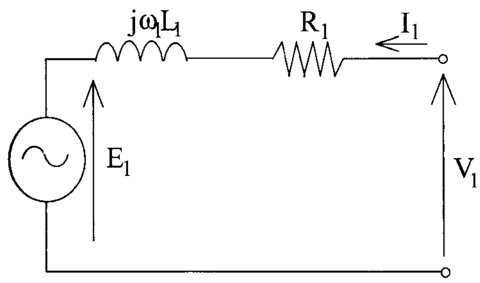


Fig. 2. Per-phase equivalent electrical circuit of the TFM

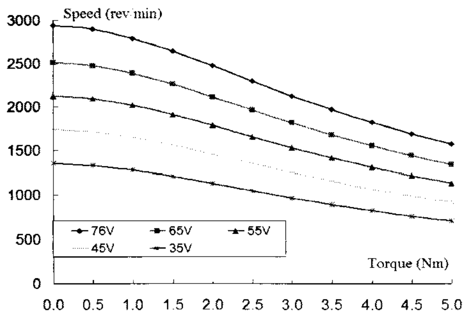


Fig. 3. Speed versus electromagnetic torque curves at various terminal voltages

4. Dynamic Performance Analysis by a Simulink-based Simulation Model

As the TFM prototype has an almost perfect sinusoidal *emf* waveform, the steady-state mechanical characteristics can be well predicted by the equivalent electrical circuit [5]. However, TFMs have quite large inductances, which may limit the state current rise rate and deteriorate the motor output, especially at high speed operation [8]. This paper also investigates the output capacity, such as the maximum steady-state speed that the motor can reach under a given load and inverter voltage, by employing a Simulink-based simulation model.

4.1 BLDC motor model with sinusoidal emf

The voltage equations of the three phase windings may be described as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ab} & L_b & M_{bc} \\ M_{ac} & M_{bc} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{9}$$

where v_a, v_b, and v_c are the terminal voltages of three phase windings, R_a, R_b, and R_c the three phase resistances, i_a, i_b, and i_c the three phase currents, e_a, e_b, and e_c the three phase back *emfs*, L_a, L_b, and L_c the three phase winding self inductances, and M_{ab}, M_{bc} and M_{ac} the mutual inductances.

For simplification, the three phases of the TFM prototype can be considered as three-phase symmetrical. The winding inductance is considered to be a constant, e.g. the average value over a cycle. The mutual inductance between phases is ignorable.

The three sinusoidal phase back *emfs* are:

$$\begin{cases} e_a = E_m \sin(\omega t) \\ e_b = E_m \sin(\omega t - 120^\circ) \\ e_c = E_m \sin(\omega t - 240^\circ) \end{cases} \tag{10}$$

where $E_m = \sqrt{2} K_E \omega_r$ is the magnitude of the sinusoidal back *emf*, ω the angular frequency, and $\omega = (P/2)\omega_r$.

The electromagnetic torque and the motion equation are

$$T_{em} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} \tag{11}$$

$$\frac{d\omega_r}{dt} = \frac{T_{em} - T_L - \delta_0 \omega_r}{J} \tag{12}$$

where T_L is the load torque, δ_0 the friction coefficient, and J the total inertia of rotating parts.

4.2 Performance simulation

According to the above equations, a Simulink-based simulation model is built [8], as illustrated in Fig. 4. Fig. 5 shows the simulated start-up speed curve with the rated load of 3.4 Nm when the inverter voltage is 192 VDC. It can be seen that the motor can reach the required rated speed of 1800 rpm. Figs. 6 and 7 plot the steady state electromagnetic torque, and applied voltage, back *emf* and current of a phase winding, respectively.

The simulated results, e.g. the steady state speed, are validated by the experiments on the TFM prototype [5].

5. Conclusion

This paper presents the performance analysis of a PM transverse flux motor with SMC core by using an equivalent electrical circuit and a simulink-based simulation model. For accurate computation of magnetic field distribution and key motor parameters such as winding flux, back *emf*, incremental inductance and core losses, 3-D finite element magnetic field analysis is conducted. The parameter computation and performance simulation have been validated by the experimental results on the TFM prototype.

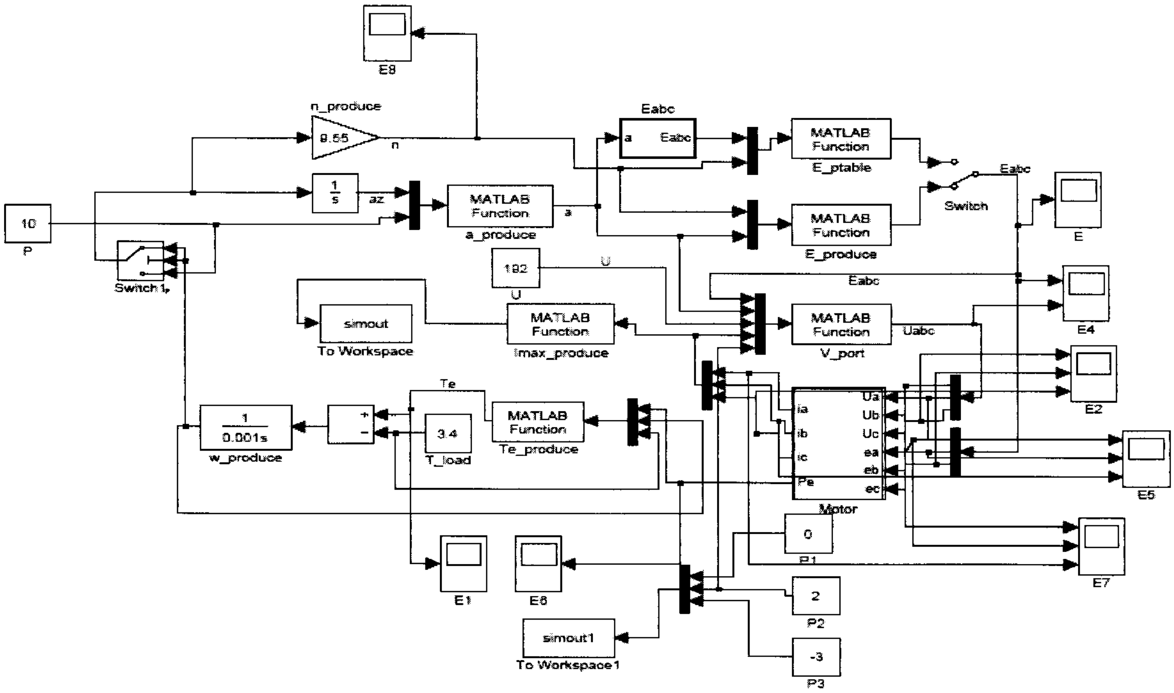


Fig. 4. Simulink-based simulation model of the TFM with sinusoidal back *emf* under BLDC control

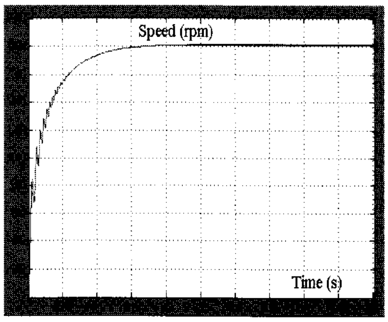


Fig. 5. Speed curve during start-up

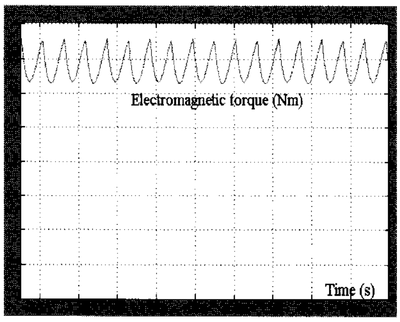


Fig. 6. Electromagnetic torque at the steady state

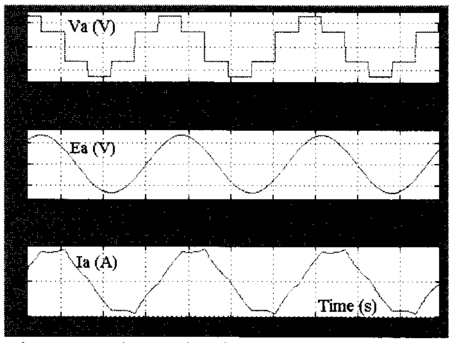


Fig. 7. Voltage, back *emf* and current of a phase winding at the steady state

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