Comprehensive Performance Evaluation of a High Speed Brushless DC Motor Using an Improved Phase Variable Model

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This paper presents the performance evaluation of a high-speed surface mounted PM brushless DC motor by using an improved phase variable model. Magnetic field finite element analyses are conducted to accurately calculate the key motor parameters such as air gap flux, back electromotive force and inductance, and their dependence on rotor position and magnetic saturation. Based on the numerical magnetic field solutions, a modified incremental energy method is applied to effectively calculate the self and mutual inductances of the stator windings. In order to evaluate the comprehensive performance of the motor, especially the motor output at high-speed operation, which is affected by the dynamic inductances, an improved phase variable model is derived to simulate the motor performance. In the model, the rotor position dependence of key parameters is taken into account. The motor prototype has been constructed and tested with both a dynamometer and a high-speed embroidery machine, validating successfully the theoretical calculations.

Key Words: BLDC motor, Performance evaluation, Finite element analysis, Improved phase variable model.

1. Introduction

High speed permanent magnet (PM) motors with brushless DC (BLDC) control scheme have found wide applications in industrial and domestic appliance drive market because of their advantages such as high efficiency, high power density and high drive performance [1]-[3]. This paper presents the performance analysis of a surface mounted PM BLDC motor for driving high-speed embroidery machines by using an improved phase variable model. In the design of the motor, magnetic field finite element analysis (FEA) was conducted to accurately calculate key motor parameters such as air gap flux, back electromotive force (*emf*), and inductance, and cogging torque, etc. Based on the numerical magnetic field solution, a modified incremental energy method is applied to effectively calculate the self and mutual inductances of the stator windings.

The rise rate of armature current is limited by the winding inductances, and this may affect the output performance of the motor, especially when operating at high speed. Therefore, it is necessary to investigate whether or not the motor can reach the required electromagnetic torque and speed at a given voltage. Based on [4], an improved phase variable model [5] is developed and implemented in the Matlab/Simulink environment for evaluating the motor's dynamic and steady state performance. In the model, the real waveforms of back *emf* and inductances are taken into account.

The developed motor prototype has been fabricated and tested with both a dynamometer and a high-speed embroidery machine. Experimental results verify the theoretical analyses.

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2. Motor Structure and Major Dimensions

Fig. 1 illustrates the magnetically relevant parts of the motor prototype. The laminated stator has 12 slots, in which the three phase single-layer windings are placed (not shown for clarity). The rotor core and shaft are made of solid mild steel, and four pieces of NdFeB PMs are mounted and bound on the surface of the rotor. The stator core has an inner diameter of 38 mm, outer diameter of 76 mm, and axial length of 38 mm. The main air gap length and the height of PMs along the radial magnetization direction are chosen as 1 mm and 2.5 mm, respectively. The motor is designed to deliver an output torque of 1.0 Nm at a speed of not less than 5000 rev/min.

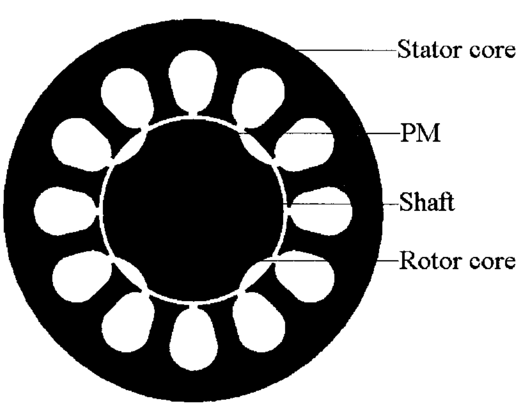

Fig. 1. Cross section of a PM BLDC motor

3. Parameter Computation

3.1 Winding flux, back emf, and cogging Torque

Magnetic field FEA can take into account the detailed structure and dimensions of the motor and the non-linearity of ferromagnetic materials, and hence can accurately compute the motor parameters and performance [6]. Fig. 2 illustrates the plot of magnetic flux density vectors at no-load at θ=0°, *i.e.* the rotor position shown in Fig. 1. From the no-load field distribution, the PM flux (defined as the flux of one coil produced by the rotor PMs), back *emf* of one phase winding, and cogging torque can be determined. The curves of these parameters against the rotor angular position or time can be obtained by a series of magnetic field FEAs at different rotor positions. Fig. 3 shows the no-load flux linking a coil (two coils form a phase winding) at different rotor positions. By applying the discrete Fourier transform, the magnitude of the fundamental of the coil flux was calculated as ϕ_1=0.543 mWb, and the *emf* constant can then be determined as 0.2457 Vs/(mech rad), by

$$K_E = \frac{p}{2} N_s \frac{\phi_1}{\sqrt{2}} \qquad (1)$$

where p=4 is the number of poles and N_s=320 the number of turns of a phase winding. The torque constant can be obtained by K_T=mK_E, where m=3 is the number of phases.

From the no-load magnetic field distribution, the cogging torque curve can also be calculated by the Maxwell stress tensor method, or the virtual work method. It was found that the cogging torque of this surface-mounted PM motor is very small with a maximum value of 0.014 Nm.

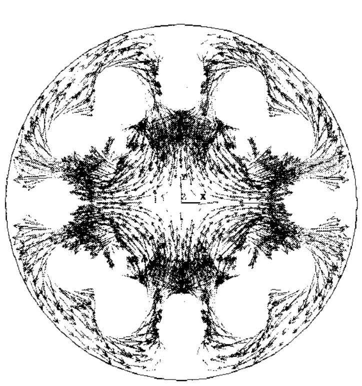

Fig. 2. Plot of no-load magnetic flux density vectors

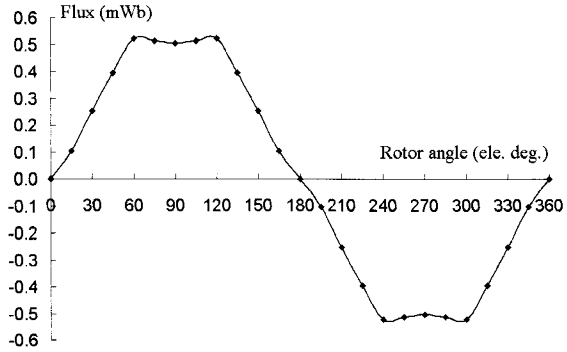

Fig. 3. PM Flux per turn versus rotor angle

3.2 Winding Inductance

The behavior of the motor equivalent electrical circuit is dominated by the incremental inductance rather than the apparent inductance. In this paper, the winding incremental inductances are calculated by a modified incremental energy method [7], which includes the following steps: (1) For a given rotor position θ, conduct a non-linear field analysis considering the saturation due to the PMs to find the operating point of the motor, and save the incremental permeability in each element; (2) Set the remanence of PMs to be zero, and conduct linear field analyses with the saved permeabilities under perturbed stator current excitations, *i.e.* assigning the 3 phase winding currents as (i_a,i_b,i_c) = $(\Delta i,\Delta i,0)$, $(\Delta i,0,\Delta i)$, $(0,\Delta i,\Delta i)$, $(\Delta i,0,0)$, $(0,0,\Delta i)$, and $(0,\Delta i,0)$, respectively; (3) Calculate the magnetic co-energy for each current excitation; and (4) Calculate the incremental inductances by

$$L_{aa}(\theta) = L_{bb}(\theta) = L_{cc}(\theta) = \frac{2W_c(\Delta i,0,0,\theta)}{(\Delta i)^2} \qquad (2a)$$

$$L_{ab}(\theta) = L_{ba}(\theta) = \frac{W_c(\Delta i,\Delta i,0,\theta) - W_c(0,\Delta i,0,\theta) - W_c(\Delta i,0,0,\theta)}{(\Delta i)^2} \qquad (2b)$$

$$L_{bc}(\theta) = L_{cb}(\theta) = \frac{W_c(0,\Delta i,\Delta i,\theta) - W_c(0,\Delta i,0,\theta) - W_c(0,0,\Delta i,\theta)}{(\Delta i)^2} \quad (2c)$$

$$L_{ca}(\theta) = L_{ac}(\theta) = \frac{W_c(\Delta i,0,\Delta i,\theta) - W_c(0,0,\Delta i,\theta) - W_c(\Delta i,0,0,\theta)}{(\Delta i)^2} \quad (2d)$$

Fig. 4 shows the calculated self and mutual incremental inductances at different rotor positions.

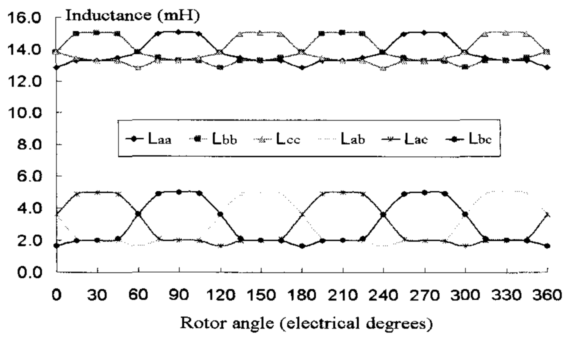

Fig. 4. Winding inductances versus rotor angle

4. Improved Phase Variable Model

The equation-based phase variable model of BLDC motor is given as

$$V_{abc} = r_{abc} i_{abc} + \frac{d\psi_{abc}}{dt} + e_{abc} \quad (3)$$

$$\psi_{abc} = L_{abc} i_{abc} \quad (4)$$

$$T_m = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} + T_{cog} \quad (5)$$

$$J\frac{d\omega_r}{dt} = T_m - B\omega_r - T_L \quad (6)$$

$$L_{ab} = L_{ba},\ L_{bc} = L_{cb},\ L_{ca} = L_{ac},\ r_a = r_b = r_c \quad (7)$$

$$i_a + i_b + i_c = 0 \quad (8)$$

All above variables are used as their conventional meanings. The profiles of L_{abc}, e_{abc}, and T_{cog} are obtained from the nonlinear time-stepping FEA solutions, in which the rotor position dependence and saturation effect are considered.

For dynamic performance evaluation, compared with an equivalent electric circuit model, the nonlinear time-stepping magnetic field FEA can give accurate results but is more time consuming. A phase variable model of BLDC motor based on FEA coupling with external circuits, which behaves much faster with the same level of accuracy, has been introduced and verified in [4]. However, the equation-based model cannot be applied to BLDC motors directly, so an additional model composed of several circuit components has to be employed.

In [5], we proposed a pure mathematical method to work out the central point potential (voltage) of the Y-connected three phase symmetrical windings, so that the port voltages of all phase windings in both energized and non-energized conditions can be estimated. In this way, the improved phase variable model can be directly applied to investigate the performance of BLDC motors.

5. Performance Simulation and Validation

The basic design requirement for the motor drive system is that for an output torque of 1.0 Nm, the steady-state speed should be no less than 5000 rpm when the inverter DC bus voltage is V_{dc}=310 VDC. By using the proposed model, the motor drive system is simulated under these conditions and some of the results are plotted in Figs. 5-8, showing that the motor can meet the design requirements.

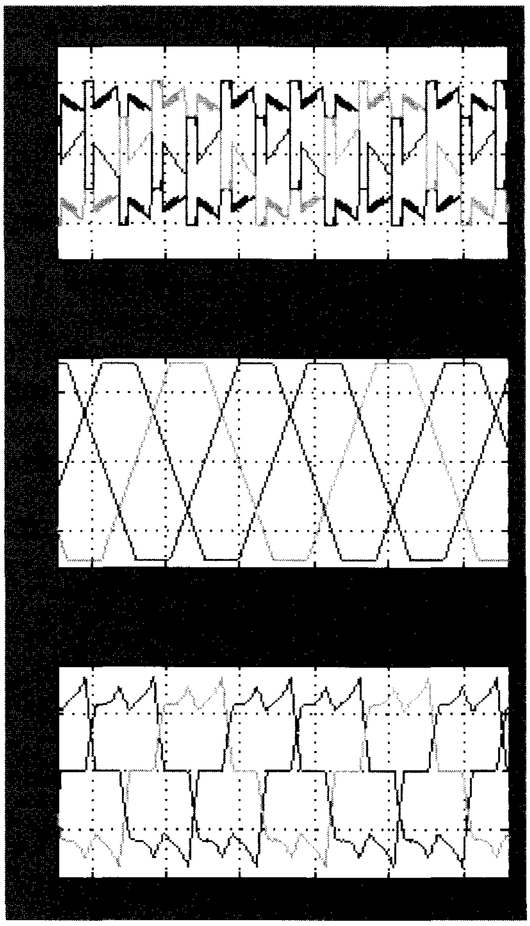

Fig. 5. Simulated steady performance

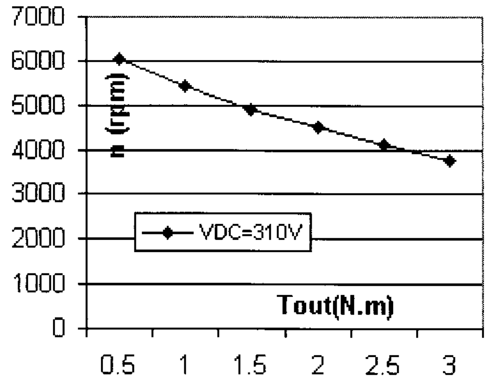

Fig. 6. Curve of steady speed versus output torque

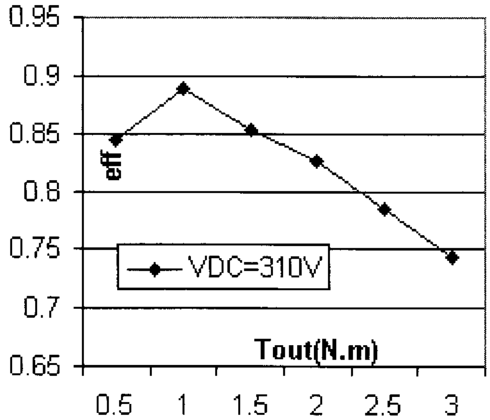

Fig. 7. Curve of motor efficiency versus output torque

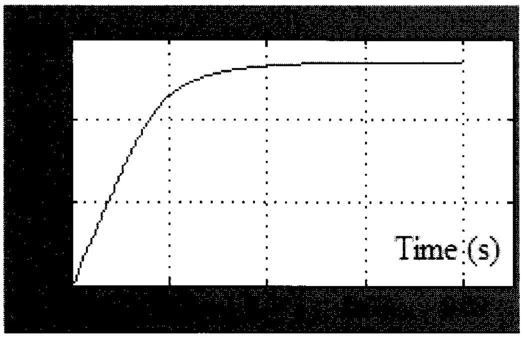

Fig. 8. Speed curve during start-up with T_L=1.0 Nm and V_{in}=310 VDC

The designed motor has been fabricated and successfully operated with a brushless DC control scheme. Experiments have been conducted on the prototype. The back *emf*, for example, was measured at different rotor speeds and the experimentally determined *emf* constant is 0.2464 Vs/rad, which is very close to the theoretical value. Other parameters, such as the inductances and torque/speed curves are also in substantial agreement with the theory.

6. Conclusion

This paper presents the comprehensive performance evaluation of a high-speed permanent magnet brushless DC motor by an improved phase variable model, which is implemented in Simulink surrounding. The rotor dependence and magnetic saturation effect on key motor parameters such as back *emf* and inductances are considered.

For accurate computation of the motor parameters, nonlinear time-stepping finite element magnetic field analysis is performed and improved formulations, *e.g.* a modified incremental energy method for calculating the self and mutual winding inductances, are employed.

The motor has been constructed and tested with a brushless DC control scheme, validating the theoretical design and analysis.

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