Abstract—This paper presents the development of a permanent magnet (PM) brushless DC motor for driving high speed embroidery machines by employing advanced design and analysis techniques. In the design of the motor, magnetic field finite element analyses are conducted to accurately calculate the key motor parameters such as the air gap flux, back electromotive force ($emf$), and inductance, etc. Based on the numerical magnetic field solutions, a modified incremental energy method is introduced to effectively calculate the self and mutual inductances of the stator windings. A phasor diagram is derived to compute the motor’s steady state characteristics. To predict the dynamic performance and increase the prediction accuracy, a Simulink-based model is built to simulate the motor performance with the real waveforms of applied phase voltage, back $emf$ and current. The motor prototype has been constructed and tested with both a dynamometer and a high speed embroidery machine, which validates successfully the theoretical calculations.

Index Terms—High speed motor, brushless DC motor, magnetic field finite element analysis, incremental inductance, performance simulation.

I. INTRODUCTION

HIGH SPEED permanent magnet (PM) motors with brushless direct current (BLDC) control scheme have found wide applications in industrial and domestic appliance drive market in the past few decades, thanks to their advantages such as high efficiency, high power density and high drive performance [1-3]. Among the many applications are hard disk drives [4, 5], automotive fuel pumps [6], turbo-compressors [7], embroidery machines [8] and etc. The rapid development of BLDC motor drives has been in line with the advancement of PM materials, power switching devices, and control techniques [2]. To further improve the performance of BLDC drives, recent efforts have also been paid to the motor design and analysis by applying numerical techniques for accurate parameter prediction [9, 10], phase variable model including the effect of parameter variation [11, 12], performance simulation considering the real waveforms of back electromotive force ($emf$) [13], etc.

In this paper, a PM brushless DC motor is developed for driving high speed embroidery machines by employing various advanced techniques. In order to accurately compute the key motor parameters such as the air gap flux, back $emf$, and inductance, magnetic field finite element analyses (FEAs) are carried out. Based on the numerical magnetic field distribution, a modified incremental energy method is applied to effectively calculate the self and mutual inductances of the stator windings [14, 15].

To predict the motor performance, a phasor diagram with the sinusoidal waveforms (e.g. the fundamental components) of the applied phase voltage, back $emf$ and current is derived under the optimum BLDC control condition. However, this method cannot predict the dynamic performance and the calculated steady-state characteristic is only an approximate as the harmonics are not taken into account. Therefore, a Simulink-based simulation model is also built to simulate the motor performance with the real waveforms of the applied phase voltage, back $emf$ and current.

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. This is studied by the proposed simulation model.

The developed motor prototype has been fabricated and tested with both a dynamometer and a high speed embroidery machine. Theoretical calculations are validated by the good agreement with the experimental results.

II. MOTOR CONFIGURATION 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. 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.
III. COMPUTATION OF PARAMETERS AND PERFORMANCE

A. 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 [9]. Fig. 2 illustrates the magnetic field distribution at no-load at the rotor position shown in Fig. 1, from which the phase winding flux produced by the rotor PMs, back emf, 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 the discrete Fourier transform, the magnitude of the fundamental of the coil flux was calculated as $\phi_1=0.543 \text{ mWb}$, and the emf constant can then be determined as $0.2457 \text{ Vs/rad}$, by

$$K_E = \frac{p}{2} \frac{N_s \phi_1}{\sqrt{2}},$$

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.

B. Winding Inductance

The behavior of the motor equivalent electrical circuit is dominated by the incremental inductances rather than the apparent ones [16]. In this paper, the winding incremental inductances are calculated by a modified incremental energy method [14, 15], which includes the following steps: (1) For a given rotor position $\theta$, 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 $\left(\Delta i_a,\Delta i_b,\Delta i_c\right)$, $\left(\Delta i_b,\Delta i_c,\Delta i_a\right)$, $\left(\Delta i_c,\Delta i_a,\Delta i_b\right)$, $\left(\Delta i_a,0,0\right)$, $\left(0,\Delta i_b,\Delta i_c\right)$, $\left(0,0,\Delta i_a\right)$, respectively; (3) Calculate the co-energy for each current excitation; and (4) Calculate the incremental inductances by

$$L_{ac}(\theta) = L_{ba}(\theta) = L_{cb}(\theta) = \frac{2W_c\left(\Delta i_a,0,0,\theta\right)}{(\Delta i)^2}$$

$$L_{al}(\theta) = L_{lb}(\theta) = L_{lc}(\theta) = \frac{W_c\left(\Delta i_a,\Delta i,0,0\right) - W_c\left(0,0,\Delta i,0\right) - W_c\left(\Delta i,0,0,\Delta i\right)}{(\Delta i)^2}$$

$$L_{bc}(\theta) = L_{ca}(\theta) = \frac{W_c\left(0,\Delta i,\Delta i,0\right) - W_c\left(0,0,0,\Delta i\right) - W_c\left(\Delta i,0,0,\Delta i\right)}{(\Delta i)^2}$$

$$L_{cb}(\theta) = L_{ab}(\theta) = \frac{W_c\left(\Delta i,0,\Delta i,0\right) - W_c\left(0,0,0,\Delta i\right) - W_c\left(\Delta i,0,0,\Delta i\right)}{(\Delta i)^2}$$

Fig. 4 shows the calculated self and mutual incremental inductances at different rotor positions.
C. Calculation of Steady State Characteristics

To predict the motor’s steady state characteristics with the optimum BLDC scheme, a phasor diagram is derived as shown in Fig. 5, where $E_i$ is the back emf, $R_i$ stator winding resistance, $L_i$ synchronous inductance which equals the self inductance plus half of the mutual inductance, $V_i$ the rms values of the stator phase voltage, $I_i$ the phase current, and $\omega$ the angular frequency.

For simplicity, the winding inductances can be considered as constants, e.g. the average values. From Fig. 4, the average self-inductance of a phase winding is $L=13.8$ mH, and the average mutual inductance between two phase windings is $M=3.0$ mH.

The motor is assumed to operate in the optimum brushless DC mode, i.e. $I_i$ in phase with $E_i$, so that the electromagnetic torque can be obtained by

$$T_{em} = \frac{mE_i I_i}{\omega_r} \quad (3)$$

where $\omega_r$ is the rotor speed in rad/s. The rms value of the back emf is determined by $E_{rms}=k_L\omega_r$. For a given terminal voltage, $V_i$, the torque/speed curve can be derived as

$$\omega_r = \sqrt{\left[\frac{R T_{em}}{m}\right]^2 + \left[\frac{P}{2} L_i \frac{T_{em}}{K_I} \right]^2 + K_E^2} \sqrt{\left[\frac{R T_{em}}{m}\right]^2 + \left[\frac{P}{2} L_i \frac{T_{em}}{K_I} \right]^2}$$

$$- \frac{R T_{em}}{m}$$

(4)

Fig. 5. Phasor diagram when the motor is in optimum BLDC condition

Fig. 6 illustrates the torque/speed curves with different values of terminal voltage.

IV. PERFORMANCE SIMULATION

In Section III, the motor’s steady state characteristics were predicted based on sinusoidal flux, back emf, and current. In this section, the motor performance is also studied with the square wave voltages and trapezoidal wave emfs by a Matlab/Simulink-based model. This study aims to investigate the dynamic performance, e.g. whether or not the motor can reach the specified speed with the rated load at a given voltage since the motor output can be limited by the winding inductance, especially at high speed operation.

A. Modeling of the Brushless DC Motor with Square Waveform Voltage

The voltage equations of the three phase windings can be written as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_1 & 0 & 0 \\ 0 & R_1 & 0 \\ 0 & 0 & R_1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} \frac{d}{dt} i_a \\ \frac{d}{dt} i_b \\ \frac{d}{dt} i_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix}$$

(5)

where $V_a$, $V_b$, and $V_c$ are the phase voltages, $i_a$, $i_b$, and $i_c$ the phase currents, and $E_a$, $E_b$, and $E_c$ the phase back emfs. For the symmetrically distributed star connected three phase windings, the phase currents obey

$$i_a + i_b + i_c = 0 \quad (6)$$

For the motor operating with square waveform voltages, the conduction region of phase current corresponds to the peak value segment of the back emf, $E_{rms}$.

The electromagnetic torque is calculated by

$$T_{em} = E_d i_a + E_d i_b + E_d i_c$$

$$\omega_r$$

(7)

The motion equation is

$$\frac{d\omega_r}{dt} = \frac{T_{em} - T_l - \delta_0 \omega_r}{J} \quad (8)$$

where $T_l$ is the load, $\delta_0$ the friction coefficient, and $J$ the total inertia of the rotating parts.

B. Simulink-based Simulation of the Motor Drive System

According to (5)-(8), a Simulink-based model, as shown in Fig. 7, is built for the brushless DC motor.
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. 8-13, showing that the motor can meet the design requirements.

![Simulink-based model of the BLDC motor](image)

**Fig. 7.** Simulink-based model of the BLDC motor

**Fig. 8.** Start-up speed curve with a load of 1.0 Nm when $V_{dc}=310$ V DC

**Fig. 9.** Steady-state torque when $V_{dc}=310$ V DC

**Fig. 10.** Voltage of phase $a$

**Fig. 11.** Back emf of phase $a$

**Fig. 12.** Current in phase $a$
V. EXPERIMENTAL VALIDATION

The designed motor has been fabricated and successfully operated with a brushless DC control scheme. Experiments have been conducted on the prototype. The back \textit{emf}, for example, was measured at different rotor speeds and the experimentally determined \textit{emf} constant is 0.2464 V/s/\text{rad}, which is very close to the theoretical value. Fig. 14 shows the measured \textit{emf} waveform, obtained by recording the open-circuit terminal voltage when the motor is driven at a certain speed. It can be seen that the \textit{emf} waveform is similar to that of the computed flux in Fig. 3.

Fig. 15 shows the measured phase current, which agrees with the simulation (Fig. 11) in both waveform and magnitude. The steady-state mechanic characteristic is also measured as shown in Fig. 16. The speed has been normalized with the base of 6000 rpm. It can be found the motor can operate in a steady speed of more than 5000 rpm with the rated torque of 1.0 Nm when the input voltage is 220 VAC (310 VDC). The corresponding efficiency curve is also plotted in the figure.

Other parameters, such as the inductances are also in substantially agreement with the calculations.

VI. CONCLUSION

This paper reports the design and analysis of a permanent magnet motor for driving high speed embroidery machines. The motor is operated by a brushless DC drive scheme. The motor performance is investigated with the fundamental components of the applied phase voltage, back \textit{emf} and current by a phasor diagram, and with the real voltage, back \textit{emf} and current waveforms by a Simulink-based simulation model.

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

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

REFERENCES


