Design of 3-Step Skew BLAC Motor for Better Performance in Electric Power Steering System

Subrato Saha, Yun-Hyun Cho

Abstract—In Electric Power Steering (EPS), spoke type Brushless AC (BLAC) motors offer distinct advantages over other electric motor types in terms of torque smoothness, reliability and efficiency. This paper deals with the shape optimization of spoke type BLAC motor, in order to reduce cogging torque. This paper examines 3 steps skewing rotor angle, optimizing rotor core edge and rotor overlap length for reducing cogging torque in spoke type BLAC motor. The methods were applied to existing machine designs and their performance was calculated using finite element analysis (FEA). Prototypes of the machine designs were constructed and experimental results obtained. It is shown that the FEA predicted the cogging torque to be nearly reduce using those methods.

Keywords—EPS, 3-Step skewing, spoke type BLAC, cogging torque, FEA, optimization.

I. INTRODUCTION

In recent years, energy savings in vehicles has been issues in the worldwide so that electric vehicles and hybrid electric vehicles, which are driven by electric motors, are being launched in the market. In addition, some hydraulic controlled mechanical systems have been replaced by electric driven systems, such as power steering and brake system. The existing power steering system for vehicles can be categorized into three types, the hydraulic power steering that obtains steering assistant power directly from hydraulic pump driven by the engine, the EPS (Electric Power Steering) that is driven by an electric motor, and the EHPs (Electric Hydraulic Power Steering) that the hydraulic pump for steering assistance is driven by an electric motor. Compared to the hydraulic power steering system, the EPS has shown better fuel efficiency, better steering feel, environment friendly, reduced manufacturing time on the production line, and it also offers more space in engine compartment due to the down-sizing with the reduced component [13]-[15]. Due to these benefits, the EPS shared about 35% of the power steering world market in 2007 and its portion in the market share has been continually increased [14]. Moreover, cogging torque is one of the important drawbacks of EPS, spoke type BLAC motors, which results in shaft vibration and noise. Particularly, cogging torque causes pulsating in motor torque and prevents having a smooth rotation, especially at low speeds and light loads. The cogging torque and its reduction techniques in PM brushless AC machines have been broadly investigated over the past decades. Up to date, there have been various studies devoted to 3-D analytical modeling and prediction of cogging torque in surface-mounted PM brushless machines with regular geometric shapes [6], [7] and the versatile finite-element analysis (FEA) is widely employed to evaluate the cogging torque in all kinds of PM brushless AC machines [8], [9]. Recently brushless spoke type machines are becoming increasingly popular in industrial applications. They offer a highly efficient, high power-density, low size alternative to conventional machines, and as their cost continues to decrease they have the opportunity to become a dominant force in the industrial applications market [1], [2]. One major drawback to spoke type machines is the torque ripple that is inherent in their design. This ripple is parasitic, and can lead to mechanical vibration, acoustic noise, and problems in drive systems. Minimizing this ripple is of great importance in the design of a BLAC spoke type machine [3]. However, in many case of vehicle applications, a cogging torque of the electric motor is of basic concern. There is no exception for the BLAC motor employed as the EPS system. Therefore, the cogging torque minimization of the BLAC motor is becoming necessary since its low torque ripple is required in the EPS application. This paper presents the rotor Shape optimization of a 3-step skewing [5] spoke type BLAC motor, which is designed for an electric power steering application. The design specification of the BLAC motor for the EPS application is listed in Table I, and proto type of the spoke type BLAC motor is illustrated in Fig. 1 (a).

II. REDUCING COGGIN G TORQUE

In its most fundamental form, cogging torque can be represented by

$$\tau_{\text{cog}} = \frac{1}{2} \phi_g R \frac{dR}{d\theta}$$  \hspace{1cm} (1)

where $\phi_g$ is the air-gap flux, $R$ is the air-gap reluctance, and $\theta$
is the position of the rotor [1]. This supports the idea that
cogging torque is the interaction between the magnets (the
source of the air-gap flux since cogging torque is considered
with an unexcited stator) and the stator teeth (the source of the
varying air-gap reluctance). The air-gap reluctance varies
periodically, thus causing the cogging torque to be periodic [7]. Because of this periodicity, cogging torque can be
expressed as a Fourier series:

\[ T_{cog} = \sum_{k=1}^{\infty} T_{mk} \sin (mk \theta) \]  

(2)

where \( m \) is the least common multiple of the number of stator
slots (\( p_s \)) and the number of poles (\( N_p \)), \( k \) is an integer, and \( T_{mk} \)
is a Fourier coefficient [2]. It is seen that the cogging torque
has \( m \) periods per mechanical revolution of the rotor and has a
direct relationship to the number of slots and poles.

### TABLE I

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P )</td>
<td>Phase number</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>( D_{so} )</td>
<td>Stator outer diameter</td>
<td>mm</td>
<td>88.8</td>
</tr>
<tr>
<td>( D_{ro} )</td>
<td>Rotor outer diameter</td>
<td>mm</td>
<td>50.8</td>
</tr>
<tr>
<td>( l_s )</td>
<td>Stack length</td>
<td>-</td>
<td>39</td>
</tr>
<tr>
<td>( p_s )</td>
<td>Stator slot number</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>( p_r )</td>
<td>Rotor slot number</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>( N_{coil} )</td>
<td>Coil turn number</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>( PM )</td>
<td>Magnet Material</td>
<td>-</td>
<td>Ferrite</td>
</tr>
<tr>
<td>( g )</td>
<td>Air gap length</td>
<td>mm</td>
<td>0.62</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Skewing step number</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>( N_p )</td>
<td>No. of poles</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>( T_r )</td>
<td>Rated Torque</td>
<td>Nm</td>
<td>3.26</td>
</tr>
<tr>
<td>( P_r )</td>
<td>Rated power</td>
<td>Watt</td>
<td>420</td>
</tr>
<tr>
<td>( N_r )</td>
<td>Rated rotational speed</td>
<td>rpm</td>
<td>1230</td>
</tr>
<tr>
<td>( V )</td>
<td>Voltage</td>
<td>Volt</td>
<td>12</td>
</tr>
<tr>
<td>( A )</td>
<td>Current</td>
<td>Amp</td>
<td>70</td>
</tr>
</tbody>
</table>

To theoretically eliminate cogging torque via machine
design, one must examine the equations that define it. From
the inspection of (1), it is seen that cogging torque can be
eliminated by forcing either the air-gap flux, \( \phi_g \) or the rate of
change of the air-gap reluctance, \( dR/d\theta \) to be zero. Making \( \phi_g \)
zero is not possible since the air-gap flux is needed for the
alignment and reluctance torque components that drive the
machine. Therefore, cogging torque can be cancelled by forcing the air-gap reluctance to be constant with respect to
rotor position. In practice, cogging torque cannot be easily
eliminated, but it can be greatly reduced [1].

Examination of (2) reveals that cogging torque can be
represented as a Fourier series so it is a summation of
harmonic sinusoids. In traditional machines with no cogging
torque reduction design techniques, the rotor magnets have an
additive effect when contributing to cogging torque because
each magnet has the same relative position with respect to the
stator slots [2]. The torque from each magnet is in phase with
the others, and thus the harmonic components of each are
added. By designing a machine in such a way that the cogging
effects from the magnets are out of phase with each other,
some of the harmonics seen in (2) can be eliminated, thus
reducing cogging torque. An alternative is to skew the rotor.
With a full-ring magnet this can be done by imposing a
skewed magnetization pattern, using a magnetizing fixture
with skewed poles. With arrays of magnets such as shown in
Fig. 2. This supports the idea that cogging torque is the
interaction between the magnet and the stator teeth. Therefore
it is possible to reducing cogging torque by changing rotor
skew model and rotor pole shape. Whether it is applied to the
rotor, skewing reduces the winding factor and the fundamental
EMF by the so-called skew factor.

The following design technique is a combination of
methods that utilize the aforementioned cogging torque
reduction theories. It should be noted that although these
techniques are successful in reducing the undesired cogging
torque, when used alone, they also reduce the desired mutual
torque. Along with the higher manufacturing costs associated
with the generally more complex machine designs, these are
the two main tradeoffs in reducing cogging torque [1].
where \( \tau \) and \( \theta_i \) are the skewing step number and mechanical skewing angle between the adjacent two steps. By inspection, all the harmonics of the cogging torque can virtually be eliminated except those which are multiples of \( \tau \) with the step skewing angle as:

\[
\theta_i = \frac{2k\pi}{\tau_{cm}} \left( N_i - p_r \right) \quad k = 1, 2, 3 \ldots
\]

where \( k \) normally should be kept as small as unity in order to prevent the machine performance from excessive deterioration. Based on the 2-D FEA results, the initial cogging torque and after optimization waveform of the magnetic field of the BLAC motor, the response surface model of the peak to peak value of the cogging torque. The design parameters, from \( x_1 \) to \( x_3 \), are described in Table II.

The design-space to make an appropriate response surface model is screened in Table III. From the design-space, designs of experimental (DOE) are listed in Table II. A central composite design (CCD), which is one of DOE, is applied to obtain the approximate selection of the calculating points, because of providing a systematic and efficient approach in order to build the second-order fitted model. The next step in design process for the reduction of the cogging torque is to apply an optimization procedure.

### Table II

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Items</th>
<th>Variable Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_1 )</td>
<td>Permanent magnet skew angle (PM_AG)</td>
<td>6°~14°</td>
<td>deg.</td>
</tr>
<tr>
<td>( x_2 )</td>
<td>Rotor core edge-length (RC_EL)</td>
<td>1.0~1.5</td>
<td>mm</td>
</tr>
<tr>
<td>( x_3 )</td>
<td>Rotor overlap length (RC_OVL)</td>
<td>1.9~2.4</td>
<td>mm</td>
</tr>
</tbody>
</table>

### Table III

<table>
<thead>
<tr>
<th>No.</th>
<th>( x_1 ) (degree)</th>
<th>( x_2 ) (mm)</th>
<th>( x_3 ) (mm)</th>
<th>( Y_{\text{BEMF}} ) (V)</th>
<th>( Y_{\text{CogT}} ) (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14°</td>
<td>1.25</td>
<td>2.15</td>
<td>2.15</td>
<td>0.01230</td>
</tr>
<tr>
<td>2</td>
<td>6°</td>
<td>1.50</td>
<td>2.40</td>
<td>3.01</td>
<td>0.02500</td>
</tr>
<tr>
<td>3</td>
<td>10°</td>
<td>1.25</td>
<td>1.90</td>
<td>1.75</td>
<td>0.00950</td>
</tr>
<tr>
<td>4</td>
<td>6°</td>
<td>1.25</td>
<td>2.15</td>
<td>1.95</td>
<td>0.01230</td>
</tr>
<tr>
<td>5</td>
<td>14°</td>
<td>1.50</td>
<td>1.90</td>
<td>2.10</td>
<td>0.02500</td>
</tr>
<tr>
<td>6</td>
<td>10°</td>
<td>1.25</td>
<td>2.15</td>
<td>1.62</td>
<td>0.00723</td>
</tr>
<tr>
<td>7</td>
<td>6°</td>
<td>1.50</td>
<td>1.90</td>
<td>1.56</td>
<td>0.00780</td>
</tr>
<tr>
<td>8</td>
<td>6°</td>
<td>2.00</td>
<td>1.90</td>
<td>1.56</td>
<td>0.00780</td>
</tr>
<tr>
<td>9</td>
<td>10°</td>
<td>2.00</td>
<td>2.40</td>
<td>1.56</td>
<td>0.00780</td>
</tr>
<tr>
<td>10</td>
<td>10°</td>
<td>1.00</td>
<td>2.40</td>
<td>1.86</td>
<td>0.00850</td>
</tr>
<tr>
<td>11</td>
<td>1.00</td>
<td>2.15</td>
<td>1.95</td>
<td>1.95</td>
<td>0.00900</td>
</tr>
<tr>
<td>12</td>
<td>1.00</td>
<td>2.15</td>
<td>1.90</td>
<td>1.96</td>
<td>0.19000</td>
</tr>
<tr>
<td>13</td>
<td>10°</td>
<td>2.15</td>
<td>2.40</td>
<td>1.82</td>
<td>0.09500</td>
</tr>
<tr>
<td>14</td>
<td>14°</td>
<td>2.15</td>
<td>2.40</td>
<td>1.75</td>
<td>0.01200</td>
</tr>
<tr>
<td>15</td>
<td>10°</td>
<td>2.00</td>
<td>2.15</td>
<td>2.20</td>
<td>0.00980</td>
</tr>
</tbody>
</table>

\( Y_{\text{BEMF}} \) = Coefficient of Back-EMF (BEMF), \( Y_{\text{CogT}} \) = peak to peak of cogging torque.

The constrained optimization problem can be written mathematically as:

\[
\begin{align*}
\text{Minimize:} & \quad f(x) = Y_{\text{CogT}} = 0.02315x_1^2 + 0.188x_1x_2 - 0.3412x_2^2 \\
& \quad - 0.03789x_1 - 4.613x_2^2 + 4.709x_1x_3 + 2.006x_2 + 0.001825x_3^2 \\
& \quad - 0.03122x_1 + 0.8408
\end{align*}
\]

where \( f(x) \) is the objective function and \( f(x) \) is estimated by the response surface model of the peak to peak value of the cogging torque.

### V. RESULTS AND DISCUSSION

The prediction of the second order polynomial models, which is obtained by the RSM, is illustrated in Fig. 3. In order to minimize the cogging torque in the design space, the value...
of rotor step skew angle, rotor core edge length, rotor overlap length depth turned out to be an existence. Fig. 4 (a) shows the response surface of the cogging torque and Fig. 4 (b) shows the coefficient of back EMF at 1230 rpm according to design variables respectively. From the response surfaces of the cogging torque, the two local minimum areas turned out to be an existence. After optimization with response surface method we get our optimum point for spoke type BLAC motor. The results of computational optimization compared with the results of the initial design are shown in Table IV. These results compare very well with those obtained using FEA analysis directly. The results of the FEA analysis correspond to optimum design variables, which are the cogging torque, torque ripple and torque curves shown in Fig. 7 and the BEMF comparison between initial designs and after optimization design waveform shown in Fig. 6.

**Fig. 4 (a) Response surface cogging torque (b) Response surface BEMF**

**TABLE IV**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Initial designed motor</th>
<th>Optimum designed motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>mm</td>
<td>6.0°</td>
<td>6.30°</td>
</tr>
<tr>
<td>$x_2$</td>
<td>mm</td>
<td>1.2</td>
<td>1.21</td>
</tr>
<tr>
<td>$x_3$</td>
<td>mm</td>
<td>2.0</td>
<td>1.93</td>
</tr>
<tr>
<td>BEMF</td>
<td>V</td>
<td>1.37</td>
<td>1.58</td>
</tr>
<tr>
<td>Cogging torque</td>
<td>N-m</td>
<td>0.017</td>
<td>0.0080</td>
</tr>
</tbody>
</table>

**Fig. 3 Optimization analysis of BEMF and Cogging Torque in RSM**

The harmonic are analyzed by fast Fourier transform (FFT), as shown in Fig. 5 back EMF for (a) various PM skew (b) various Rotor core Edge Length (c) various Rotor overlap Length
various rotor core edge length (c) various rotor overlap length respectively. The P-P cogging torque value can be reduced from 0.017 to 0.0080 Nm (nearly 53%) by rotor optimization. Therefore the results of the optimum design for the cogging torque reduction are contented with the demanded motor specification for the EPS application.

VI. EXPERIMENTAL RESULTS

The spoke type BLAC motor with optimized rotor has been prototyped for the experimental validation of the FEA results and the verification of the rotor optimization techniques for cogging torque minimization. Fig. 8 shows the photos of (a) optimized rotor shape (b) three step rotor skew and (c) assembled prototype. The measured and 3-D FEA predicted (a) cogging torque and (b) BEMF waveforms of the prototype are compared in Fig. 9. However, comparison results confirmed that cogging torque is reasonably good agreement as well BEMF. The measured cogging torque from the machine with optimize rotor is about similar than the 3-D FEA estimated one. Therefore the agreement of the predicted and measured cogging torque result is considered satisfactory. Furthermore, an alternative current motor has been used to drive the rotor of the prototype machine at rated speed in order to measure the back EMF waveforms. It can be found from Fig. 9 (b) that is relatively close agreement between the predicted and measured result.
Cogging torque is very important factor in high performance and precise electrical motor. This paper described the shape optimization in order to reduce the cogging torque in the SPOKE type BLAC motor. The experimental results obtained from the prototype demonstrate satisfactory agreement with the estimated by FEA approaches, and underpin the findings of the study. And optimum design for the cogging torque reduction is satisfied with the required motor specification for the EPS application. 

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIP) No: NRF-2014R1A2A2A01003368 and by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Knowledge Economy, Republic of Korea under Grant 20134030200320.

REFERENCES