Fast Computation of the Performance of Lunar Rover Drive Motor with Skewed Stator Slots Based on 2D FEM

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Abstract—In order to study the performance of rare earth PM brushless DC motor with skewed stator slots for lunar rover driving wheel at extreme temperatures of lunar surface rapidly and accurately, a computational method based on 2D FEM was proposed. The skewed motor was equivalent to a certain number of straight slot motor units in series and the mathematical expression of calculation accuracy was deduced. In order to make the winding current of motor units in the same slot equal, a circuit with ideal current source was proposed to couple with the geometric model in 2D FEM. No-load back-EMF and electromagnetic torque were calculated for the prototype and the calculation accuracy was estimated according to the spectra of air-gap flux density at different relative positions of the stator and rotor in axial direction of the skewed motor. The proposed method is simpler and much more timesaving than 3D FEM. The calculated results closely match those of 3D FEM with the relative error less than 3.7%. The effectiveness of the method is verified by comparing with experimental results of multiple prototypes and the absolute error is less than 0.014Nm.

Index Terms—lunar rover drive motor, fast computation, skewed stator slot, PM brushless DC motor, 2D FEM

I. INTRODUCTION

Rugged Lunar surface in severe environment is covered with a layer of lunar dust [1] [2]. When traveling on the lunar surface, the sinkage and slippage of lunar rover driving wheels cannot be avoided and the rovers are hard to move [3]. For this reason, the wheel drive motors have to possess a strong ability to output torque. Rare earth PM brushless DC motor is one of the ideal choices of drive motor due to its high power density, reliable structure and extended speeding range. As the mobile platform of multitudinous precision instruments for lunar exploration, lunar rovers should operate smoothly if possible and the torque ripple of drive motor ought to be minimized. There are three main causes of torque ripple for PM brushless DC motors: (1) the waveforms of back-EMF are not ideal trapezoidal; (2) the slew rates of switching-in and switching-out phases are different; (3) cogging torque. With regard to the first two causes, many documents have proposed new approaches in motor control strategy [4]-[7]. In order to minimize the cogging torque, many methods in motor design are proposed [8]-[13] and skewed slot is the most commonly used in engineering practice.

The direct research method for skewed motor is 3D FEM. However, the number of meshed elements in 3D model is huge and the computational process is extremely time-consuming. In order to solve the above problem, the multi-slice model based on 2D FEM is adopted [14]-[17]. In consideration of the characteristics of PM brushless DC motor driven by trapezoidal current, a computational method is proposed. The method is simple and timesaving. The comparisons with simulation results of 3D model and experimental results indicate that the method has high calculation accuracy.

II. MULTI-SLICE MODEL AND ITS CALCULATION ACCURACY

The relative positions of the stator and rotor in different cross sections in the axial direction of skewed motor are different and accordingly, the magnetic field distributions in different cross sections are different. Consequently, 2D FEM cannot be adopted to study the skewed motor directly. In multi-slice model, a skewed slot motor is equivalent to a certain number of straight slot motor units in series. In that way, the sum of back-EMF of all the straight slot motor units is equal to the back-EMF of the skewed slot motor and the winding currents of straight slot motor units in the same slot are equal. The multi-slice model can be described as follows:

\[
\nabla \times (\nabla \times A_i) + \sigma \frac{\partial A_i}{\partial t} = J_i, \quad i = 1, \ldots, n
\]

\[
E = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} \frac{d\psi_i}{dt}
\]

where \( n \) is the slice number, \( J_i \) is the current density, \( E \) is the back-EMF of the skewed slot motor, \( E_i \) is the back-EMF of \( i \) straight slot motor unit, \( A_i \) is vector...
magnetic potential of \( i \) straight slot motor unit, and \( \psi_i \) is the winding flux of \( i \) straight slot motor unit.

Figure 1 shows an electrified wire and its multi-slice model in the \( k \)-order harmonic magnetic field. In the figure, \( B_{mk} \) is the amplitude of the \( k \)-order harmonic magnetic field, \( \alpha_k \) is the position angle of the wire’s one end, \( \beta \) is the skew angle of skewed motor, and \( L \) is projected length of the wire in the axial direction of skewed motor.

The electromagnetic force and back-EMF of the electrified wire can be calculated by:

\[
F_k = \int_{\alpha_k}^{\alpha_k + \beta} (B_{mk} \sin \theta) \frac{L}{k\beta} d\theta = \frac{2k\beta}{B_{mk} L} \sin(\alpha_k + \frac{k\beta}{2}) \sin \frac{k\beta}{2}
\]

\[
E_k = \int_{\alpha_k}^{\alpha_k + \beta} (B_{mk} \sin \theta) v \frac{L}{k\beta} d\theta = \frac{2k\beta}{B_{mk} L} v \sin(\alpha_k + \frac{k\beta}{2}) \sin \frac{k\beta}{2}
\]

where \( I \) is the current flowing through the wire, and \( v \) is the velocity of the wire.

In multi-slice model, the electromagnetic force and back-EMF can be calculated by:

\[
F_k' = \frac{1}{n} \sum_{i=1}^{n} F_{ki} = \frac{1}{n} \sum_{i=1}^{n} B_{mk} \frac{L}{n} \sin \kappa_{\alpha_i}
\]

\[
E_k' = \frac{1}{n} \sum_{i=1}^{n} E_{ki} = \frac{1}{n} \sum_{i=1}^{n} B_{mk} \frac{L}{n} v \sin \kappa_{\alpha_i}
\]

where \( F_{ki} \), \( E_{ki} \) and \( \kappa_{\alpha_i} \) are electromagnetic force, back-EMF and position angle of \( i \) straight slot motor unit, respectively.

Figure 2 shows the position angle of straight slot motor unit in the fundamental magnetic field. In the figure, the oblique bold line indicates a certain segmented wire of the skewed motor and the straight bold line indicates the wire in the straight slot of corresponding motor unit.

In the \( k \)-order harmonic magnetic field, \( \kappa_{\alpha_i} \) can be expressed as:

\[
\kappa_{\alpha_i} = \alpha_i + \frac{k\beta}{2} (i-1) + k\chi
\]

(4)

If (4) is brought into (3), \( F_k' \) and \( E_k' \) can be calculated by:

\[
F_k' = B_{mk} L \frac{\sin[(\alpha_i + \frac{k\beta}{2}) + (k\chi - \frac{k\beta}{2})] \sin \frac{k\beta}{2}}{n \sin \frac{k\beta}{2n}}
\]

\[
E_k' = B_{mk} L \frac{\sin[(\alpha_i + \frac{k\beta}{2}) + (k\chi - \frac{k\beta}{2})] \sin \frac{k\beta}{2}}{n \sin \frac{k\beta}{2n}}
\]

(5)

If \( k\beta \) is equal to integral multiples of \( 2\pi \), both \( F_k' \) and \( E_k' \) are equal to zero. In this case, it is meaningless to study the calculation accuracy of \( F_k' \) or \( E_k' \). When \( k\beta \) is not equal to integral multiples of \( 2\pi \), the relative error of \( F_k' \) or \( E_k' \) is given by:

\[
\varepsilon_k = \frac{E_k' - F_k'}{F_k'} = \frac{E_k - E_k'}{E_k} = \frac{k\beta \sin[(\alpha_i + \frac{k\beta}{2}) + (k\chi - \frac{k\beta}{2})]}{2 \sin(\alpha_i + \frac{k\beta}{2}) \sin \frac{k\beta}{2n}} - 1
\]

(6)

If \( \chi \) is equal to \( \beta/(2n) \), the position of straight slot motor unit is at the midpoint of segmented wire in skewed slot and \( \varepsilon_k \) has nothing to do with \( \alpha_i \). (6) can be simplified as:

\[
\varepsilon_k = \left(\frac{k\beta}{2n} - 1\right) \times 100\%
\]

(7)

III. 2D MODEL OF STRAIGHT SLOT MOTOR UNIT

According to the main parameters given in Table 1 and
the material properties given in Table 2, the 2D model of a straight slot motor unit of the prototype is built and the model consists of geometric model and circuit model. By means of modifying the material properties, the 2D models at different operating temperature are obtained.

<table>
<thead>
<tr>
<th>Parameter names/Unit</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated speed/rpm</td>
<td>1350</td>
</tr>
<tr>
<td>Rated voltage/V</td>
<td>28</td>
</tr>
<tr>
<td>A phase winding resistance/ ohm</td>
<td>5.17 (20°C)</td>
</tr>
<tr>
<td>Outside diameter of stator /mm</td>
<td>30.3</td>
</tr>
<tr>
<td>Inner diameter of stator /mm</td>
<td>17.5</td>
</tr>
<tr>
<td>Length of air gap/mm</td>
<td>1</td>
</tr>
<tr>
<td>Magnet thickness /mm</td>
<td>2.75</td>
</tr>
<tr>
<td>Outer diameter of rotor/mm</td>
<td>11</td>
</tr>
<tr>
<td>Effective length of iron core /mm</td>
<td>24</td>
</tr>
<tr>
<td>Shaft diameter/mm</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component names</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent magnet</td>
<td>NSC27G</td>
</tr>
<tr>
<td>Iron core</td>
<td>DW230-35</td>
</tr>
<tr>
<td>Winding</td>
<td>copper</td>
</tr>
<tr>
<td>Shaft</td>
<td>stainless steel</td>
</tr>
</tbody>
</table>

Figure 3 shows the shrink process of the studied region. In order to minimize the number of finite element mesh nodes, only one-eighth of the cross section of skewed prototype motor is taken as the geometric model in the light of periodicity condition and symmetrical characteristic.

The circuit powered by ideal voltage source as shown in Figure 3 (a) is commonly used in finite element models for motors. In order to make the winding currents of motor units in the same slot equal, the circuit powered by ideal current source as shown in Figure 3 (b) is proposed. Accordingly, the waveforms of phase winding currents are ideal rectangle so that the current of the switching-out phase winding is zero immediately and the current of the switching-in phase winding is in steady state directly. Consequently, it is not necessary to consider the torque ripples caused by commutation current. In addition, compared with the circuit with voltage source, the component number of the circuit with current source is less and the computational burden is eased ulteriorly.

![Figure 3. Shrink of the studied region.](image)

![Figure 4. Circuit model](image)
For the 2D models of all the motor units, there are only two different properties including the initial position of the stator and rotor in geometric model and the switch turn-on intervals of circuit model. With regard to the first difference, it is unnecessary to modify the geometric model before finite element simulation and it just needs to translate the calculated waveforms. Therefore, the 2D model of every motor unit can be obtained by modifying the switch turn-on interval of the 2D model of any one motor unit. In accordance with the even or odd quality of the slice number, two different computational methods are present as shown in Figure 5. In the figure, $\rho_i$ is the offset angle of the switch turn-on intervals.

\[
\rho_i = \frac{\beta}{2} + \frac{\beta}{2j(i-j-1)} \quad i = 1, \ldots, 2j + 1 \quad (8)
\]

IV. ADVANCE ESTIMATE OF CALCULATION ACCURACY

A. Magnetic Field Analysis of the Skewed Motor

The 3-D model of the skewed motor is built in the FluxSkewed module of Flux_v10.3. Compared with the slotless structure, the slot-harmonics caused by slotting will be superimposed in the magnetic field. As a result of armature reaction, the magnetic field will be warped and all the harmonic components will change.

Due to the slot effect, the waveforms of air-gap flux density at different relative positions of the stator and rotor are different. Figure 6 shows the waveforms and spectrum of normal no-load air-gap flux density along the axial direction of the skewed motor. It can be seen from the figure that the amplitudes of low harmonic components are far smaller than those of high harmonic components throughout, even though the waveforms are changing. Therefore, higher calculation accuracy can be obtained when the multi-slice model is adopted to calculate the no-load back-EMF, even though small slice number is chosen.

\[
\rho_i = \frac{\beta}{4j} + \frac{\beta}{2j}(i-j-1) \quad i = 1, \ldots, 2j \quad (9)
\]
Compared with the waveforms of no-load air-gap flux density, the loaded waveforms are distorted due to the armature reaction. Figure 7 shows the waveforms and spectrum of normal air-gap flux density along the axial direction of the skewed motor with 1.2A winding current. It can be seen from the figure that the amplitudes of low harmonic components are far smaller than these of high harmonic components throughout, even though the waveforms are seriously distorted. Therefore, higher accuracy can be obtained when the multi-slice model is adopted to calculate the electromagnetic torque and it is unnecessary to choose a big slice number.

B. Choice of Slice Number

With the increased slice number, the calculation accuracy is improved. However, large slice number can result in the tremendous amount of calculation. There have to be genuine trade-offs between calculation accuracy and workloads. In consideration of the prototype structure, the cogging torque can be eliminated.
completely, supposing that the skew angle is equal to an angular pitch and end magnetic field is ignored. The relative error of the multi-slice model for the prototype is given in Figure 8. It can be seen from the data in the figure that high calculation accuracy can be obtained when the slice number is greater than 10.

V. COMPARISON BETWEEN CALCULATED RESULTS AND SIMULATION RESULTS OF 3D MODEL

When rotating at the constant speed of 2000 rpm, the waveforms of no-load back-EMF of the multi-slice model and 3D model are shown in Figure 9. It can be seen from the figure that the no-load back-EMF of the multi-slice model closely match those of 3D model.

The relationship curves of currents and electromagnetic torques of the multi-slice model and 3D model are shown in Figure 10. Under the same conditions of operating temperature and winding current, the electromagnetic torque of multi-slice is greater than that of 3D model and the relative error is less than 3.7%, however.

VI. COMPARISON BETWEEN CALCULATED RESULTS AND EXPERIMENTAL RESULTS

According to the prototype parameters, four motors are produced and their photographs are shown in Figure 11. Three motors selected from the four randomly are tested at room temperature (about 20°C). The calculated results and experimental results are given in Figure 12. Because it is difficult to acquire the precise mathematical description of friction torque, the calculated results refer to the electromagnetic torques and the experimental results refer to the output torques. The six relationship curves of experimental results are almost coincident and it indicates that the machining accuracy of the prototypes is high and the experimental results are dependable. When the friction factor is reckoned, the calculated results closely match the experimental results and the absolute error is less than 0.014Nm.
VII. CONCLUSIONS

Taking into account magnetic saturation, winding distribution mode, slot effect and armature reaction, a calculation method for the performance of rare earth PM brushless DC motor with skewed stator slot for lunar rover driving wheel at extreme temperatures on lunar surface is proposed and has the following advantages:

1. Timesaving. It is unnecessary to build 3D model and half of the minimum repetitive unit of the cross section of the skewed motor is taken as the geometric model of 2D model. The component number of the proposed circuit model with current source is far less than that of the circuit model with voltage source.

2. Simple realization. The 2D model of any other motor units can be obtained by modifying the switch turn-on intervals merely.

3. High accuracy. Compared with the simulation results of 3D model, the no-load back-EMF are nearly identical and the relative error of electromagnetic torque is less than 3.7%. Compared with the experimental results, the absolute error of output torque is less than 0.014Nm.

REFERENCES


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