이중운전조건을 고려한 외전형 SRM의 구동특성

Drive Characteristics of Outer–rotor Type SRM Considering Dual Operating Modes

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Abstract – As a direct drive type washing machine requires two operating modes, washing and spinning modes, a design of the motor with high efficiency in each mode is not applicable to a conventional procedure. To achieve the requirements, a multi-pole outer rotor type switched reluctance motors are considered. To select a suitable motor type for the application, a static torque is compared based on the FEM analysis. The selected type is obtained for high and wide torque than other types of the motor. Further, the pole shape and arc are optimized to meet the required torque and torque ripple. To verify the proposed structure, the prototype is designed and manufactured. And the simulation and experimental results verify the validity of the proposed structure.

Keywords : Switched reluctance motor, Outer rotor type, Washing machine, Dual operating modes

I. INTRODUCTION

The requests of high performance washing machines are increased for various requirements of customers. Now in the home appliances market, the energy saving, environmental protection and low vibration and noise operation are hot issues. The motor, as a heart of washing machines, is a key component to meet the requirements and cannot be replaced.

At present, most of washing machines adopt direct drive technology. The direct drive in washing machine has many advantages such as reducing the friction and acoustic noise, eliminating the back lash, simplifying the mechanical structure, and increasing stiffness [1]. Also, with the direct drive motor to the appliance, the production cost could be reduced due to removing the gear for speed change. Nowadays, induction machine (IM), permanent-magnet synchronous machine, brushless DC motor (BLDC) are adopted frequently [1]-[5]. But, switched reluctance motor (SRM) also could be one of a possible candidate for its good features.

SRM is a double-salient and single-excited motor, in which windings are located on the stator and no windings or permanent magnets are used in the rotor. These mechanical structures cause the SRM to have many advantageous characteristics, such as good fault tolerance, robustness, low cost, high starting torque and applicability in harsh environments, such as high temperature or high speed [6]-[7]. With these advantages, SRM has become one of the strong candidates for washing machine drive systems.

Due to the requirement of self-start ability in two directions, and considering the cost of controller and advantage of the direct drive technology, three-phase outer rotor type SRM is chosen for the drive of a washing machine. In general, the three-phase SRM are 6/4 or 12/8 types of SRM. But higher number of poles such as 18/12, 24/16, 30/20 is also considered for the applications[8].

Fig. 1 Load characteristics of washing machine

In this paper, to satisfy the operation requirements of washing machine, dual operating modes and low speed direct drive, four three-phase outer rotor type SRMs, 12/8, 18/12, 24/16 and 30/20 type, are considered and analyzed for the application. The static characteristics of the proposed SRMs are compared to obtain the most suitable conditions. Through some considerations and
analysis results, 24/16 type SRM is selected for the application due to higher torque and lower torque ripple than other types.

Further, based on the analysis and design, the pole shape and arc of the SRM is further optimized to get optimized performance. Finally, the experiments are executed with the prototype, and the results verify the validity of the proposed structure.

II. Characteristic Requirements

Fig. 1 shows the load characteristics of direct drive type washing machine. As shown in Fig. 1, when it is in the washing mode, the laundry will alternatively rotate in forward or reverse directions at low speed to remove the substance from the clothes with a small amount of water. Due to frequently start and stop, the motor in this mode requires low speed/high torque characteristics. When the motor is in the spinning mode, to get enough centrifugal force to remove the water from the clothes, the laundry should be rotated in high speed low torque characteristics.

According to the conditions and Fig. 1, it can be found that the operation speed of the motor varies very large, which changes from 45 rpm to 1400 rpm according to each operation mode. So the motor should have wide speed range and self-start ability in two directions. Further, because washing machine always operate in the two modes: washing and spinning mode, the efficiency in both modes is very important. To consider the operation efficiency of the motor at washing and spinning mode, the rated speed is selected at 400 rpm, as shown in Fig. 2. Also when the motor is in the washing mode, the required motor speed and torque is 45 rpm and 20 N.m, respectively; when the motor is in spinning mode, the required motor speed and torque is 1400 rpm and 2 N.m, respectively. Table 1 shows the detailed design requirements.

III. Design of outer rotor type SRM

To satisfy the design requirements shown in Table 1 and obtain the power density, four three-phase outer rotor types of SRM, 12/8, 18/12, 24/16 and 30/20 types, are considered and designed. The design progress of the proposed SRMs is described in flow chart, as shown in Fig. 3.

A. Selection of Dimensions

Because the output equation relates the bore diameter, stack length, speed, and magnetic and electric loading to the output of a machine, the outer rotor type motor can be designed starting from the output equation (1),

\[ P_o = k_d k_s \left( \frac{x^2}{120} \right) (1 - \frac{1}{\sigma_s \sigma_u}) BA D^2 LN, \]

where,

\[ k_d = \frac{\theta_p P_r}{360} \]

\[ \sigma_s = \frac{L_s^a}{L_s} \]

\[ \sigma_u = \frac{L_u^a}{L_u} \]

\[ A_s = 2T_i \mu m / \pi D \]

in which, \( k_d \) is the efficiency, \( k_s \) is the duty cycle, \( \sigma_s \) and \( \sigma_u \) are the coefficients, respectively, \( B \) is magnetic loading, \( A_s \) is the specific electric loading, \( D \) is the bore diameter, \( L \) is the stack length, \( N \) is the rotor speed in revolutions per minute (rpm), \( \theta \) is the current conduction angle for each rising inductance profile, \( q \) is the number of stator phases, and \( P_r \) is the number of rotor poles, \( L_s^a \) and \( L_u^a \) is the aligned saturated inductance per phase and aligned but unsaturated inductance, respectively, \( L_s \) is the unaligned inductance per phase, \( T_i \) is the number of turns per phase, \( i \) is stator current, and \( m \) is the number of phases conducting simultaneously.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>AC 220 [V]</td>
</tr>
<tr>
<td>Speed</td>
<td>400 [rpm]</td>
</tr>
<tr>
<td>Current</td>
<td>5.5 [A]</td>
</tr>
<tr>
<td>Torque</td>
<td>20 [Nm]</td>
</tr>
<tr>
<td>Output Power</td>
<td>840 [W]</td>
</tr>
<tr>
<td>Volume</td>
<td>340 x 15 [mm]</td>
</tr>
</tbody>
</table>
Due to the considerations of mechanical robustness and minimization of vibration, it could be a in the range of (10)

$$\omega_{sp} > b_y \geq 0.5\omega_{sp}$$  \hspace{1cm} (10)

It is recommended to choose a higher value for $b_y$ than its minimum.

The rotor yoke thickness, $b_y$, is based on structural integrity and operating flux density. The range has to account for an air gap to provide a high ratio between the aligned and unaligned inductances, but at the same time it is desirable to have shorter rotor poles to generate minimum vibration in the rotor. Based on these considerations, the $b_y$ in terms of stator pole width is

$$0.5\omega_{sp} < b_y < 0.75\omega_{sp}$$  \hspace{1cm} (11)

Fig. 3 Flow chart for the design process

B. Selection of Pole Arc

According to the analysis, the motor used in washing machine should have self-start ability in two directions. Therefore, in order to make sure that the motor can self-start in the two directions, the stator pole arc $\beta_s$ and rotor pole arc $\beta_r$ should meet the following conditions.

$$\beta_s \geq \beta_r$$  \hspace{1cm} (6)

$$\min(\beta_s, \beta_r) \geq \frac{2\pi}{4P_r}$$  \hspace{1cm} (7)

$$\beta_s + \beta_r \leq \frac{2\pi}{P_r}$$  \hspace{1cm} (8)

where, $q$ is the number of stator phases, and $P_r$ is the number of rotor poles

C. Thickness of Stator and Rotor Yokes

The stator yoke thickness, $b_y$, is determined on the basis of maximum flux density in it and an additional requirement of a minimization of vibration to reduce acoustic noise. The flux density in the stator back iron is approximately half of the stator poles. An allowance is given to have a slightly greater share of the pole flux. The stator pole arcs have to be chosen to accommodate the pole flux density. If $\omega_{sp}$ is the pole width given in terms of pole arc as (9), the $b_y$ has to be a minimum of $0.5\omega_{sp}$.

$$\omega_{sp} = D \sin\left(\frac{\beta_r}{2}\right)$$  \hspace{1cm} (9)

Fig. 4 Flux distributions in the 4 types of SRM

D. Comparative Analysis of the Proposed SRMs

According to the above considerations and design process, the main parameters of the proposed structure are selected. Then, to check the designed results satisfy the design requirements, a finite element method (FEM) is employed to get the characteristics of the proposed four structures. At the same time, the characteristics of the proposed SRMs are compared to choose the most suitable type for the washing machine.

Fig. 4 shows the flux distribution of the four considered types with phase-A excited, and Fig. 5 shows the torque profile of the four types. From Fig. 5, it can be found that there is no torque dead zone in all types of the motors considered, so the four types could have a self-start ability in the two directions. Further, from Table 2, it can be found that 24/16 type SRM has...
highest torque and lowest torque ripple, so 24/16 type is chosen for further and detailed design for the optimization.

![Fig. 5 Torque profiles in the 4 types of SRMs](image)

### Table 2 Performance comparisons

<table>
<thead>
<tr>
<th>Motor type</th>
<th>12/8</th>
<th>18/12</th>
<th>24/16</th>
<th>30/20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque ripple (%)</td>
<td>76</td>
<td>63</td>
<td>54</td>
<td>58</td>
</tr>
<tr>
<td>Winding space (mm²)</td>
<td>369</td>
<td>294</td>
<td>265</td>
<td>227</td>
</tr>
<tr>
<td>Average torque (N.m)</td>
<td>21</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

### IV. Optimization of 24/16 Type

Through the above analysis, 24/16 type is selected as the drive motor, but the structure and dimension is not optimized. To get better performance, such as higher torque and lower torque ripple, optimization is executed including pole shape and pole arc optimization.

#### A. Pole Shape Optimization

1) Stator pole shape

Fig. 6(a) shows a conventional stator pole shape, and 6(b) shows the optimized pole shape. The optimized pole shape adopts T-shape, which keeps the same pole arc as before, but reduces the width at the bottom of stator pole. So it can keep the torque production ability as conventional type and increasing the winding space, as shown in Fig. 7 and Table 3.

![Fig. 7 Torque profile of T shape stator pole](image)

### Table 3 Torque and winding space

<table>
<thead>
<tr>
<th>Type</th>
<th>Conventional shape</th>
<th>T shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding space (mm²)</td>
<td>265</td>
<td>286</td>
</tr>
<tr>
<td>Average torque (N.m)</td>
<td>20</td>
<td>21</td>
</tr>
</tbody>
</table>

2) Stator pole tip

The height of stator pole tip will affect the saturation level and winding space. If the height of the stator pole tip is small, the motor is very easy to be saturated at the tip of the stator poles, but the winding space is increased, vice versa. Fig. 8 shows torque profile of proposed motor with the height of stator pole tip changing from 1 to 6mm. Based on analysis of Fig. 8, 2mm is selected to trade torque and winding space off.

![Fig. 8 Torque with height of stator pole tip from 1mm to 6mm](image)

### B. Pole Arc Optimization

1) Rotor and outside stator pole arc

The pole arc of the rotor and outside stator not only affects the self-start ability of the motor, but also the torque production. If keep the outside pole arc βs constant and only change the rotor pole arc βr, when βs > βr, the average torque of the motor will be increased.
with increasing $\beta r$ until $\beta s = \beta r$. When $\beta s < \beta r$, the average torque of the motor will be almost same as before, only the position of torque production is changed. But the condition is not always like that, if $\beta r$ is too large, the minimum inductance of the motor will be increased, which may decrease the average torque. The condition is the same when keep the rotor pole arc constant and only change the pole arc of outside stator.

Fig. 9 shows torque profile with rotor and outside stator pole arc changing from $8^\circ$ to $11^\circ$. Based on Fig. 9, both of the rotor and outside stator pole arcs are selected as $8.6^\circ$.

2) Inside stator pole arc

The pole arc of inside stator affects the torque production ability. If increasing the stator pole arc, the anti-saturation ability of the stator pole is increased, but the winding space will be decreased, which may reduce the winding turns, vice versa. Therefore, if the outside stator pole arc $\beta s$ is very small, the average torque of the motor will be increased with increasing pole arc until $\beta s$ getting to some value where the inductance increased by the pole arc equals to that decreased by the winding turns. At this time, if continue to increase $\beta s$, the average torque of the motor will be decreased. Fig. 10 shows torque profiles of proposed SRM with inside stator pole arc changing from $7^\circ$ to $10^\circ$. Based on the analysis, $7.7^\circ$ is selected as the pole arc of inside stator.

V. Simulation and Experiment

Based on the above optimization progress, the proposed SRM is optimally designed. Table 4 shows the detailed parameter. Meanwhile, the prototype is manufactured as shown in Fig. 11.

Table 4 Parameters of proposed SRM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>840</td>
<td>W</td>
</tr>
<tr>
<td>Outer rotor diameter</td>
<td>320</td>
<td>mm</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.35</td>
<td>mm</td>
</tr>
<tr>
<td>Rotor radius</td>
<td>133</td>
<td>mm</td>
</tr>
<tr>
<td>Stack length</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Stator weight</td>
<td>4.264</td>
<td>kg</td>
</tr>
<tr>
<td>Rotor weight</td>
<td>2.304</td>
<td>kg</td>
</tr>
<tr>
<td>Phase resistance</td>
<td>2.2</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Turns/polele</td>
<td>115</td>
<td>turns</td>
</tr>
</tbody>
</table>

Figs. 12 and 13 show the inductance and torque profile of optimized motor. Compared with the motor before optimizing, the out torque is increased and torque ripple is decreased.

Further, the motor could develop the required torque of 3N.m and 20N.m at 3A and 10A, which is used for washing and spinning modes, respectively.

To verify the validity of the proposed design, some experiments are executed. Fig. 14 shows the experimentally measure inductances. And the maximum and minimum inductances obtained by FEM and experiment are shown in Table 5. From Table 5, it can be found that the minimum inductance obtained by
The experiment has good match with that by FEM analysis, but the maximum inductance have about 10% error, which maybe some manufacturing errors.

The load tests are shown in Fig. 15 and 16. Phase voltages and currents according to control signals are in Fig. 15, drive efficiency are in Fig. 16, respectively. The measured efficiency is not met the calculated one because of some limitations and difficulties as well as errors in the prototype.

### Table 5 Simulation and experimental results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Inductance (H)</td>
<td>0.011</td>
<td>0.009</td>
</tr>
<tr>
<td>Max. Inductance (H)</td>
<td>0.043</td>
<td>0.041</td>
</tr>
</tbody>
</table>

In this paper, four outer rotor type SRMs for direct drive washing machine are proposed. To improve the output power density, the operation efficiency at both modes, washing and spinning mode, are considered. The design progress of SRMs is also described in detail. Based on the FEM analysis results, the most suitable motor for the washing machine is selected. Further, the pole shape and arc of the selected motor is optimized for obtaining optimized performance. Finally, the prototype is manufactured and tested to verify the validity of proposed structure.

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References


