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Research on Performance of Two Different Structure Switched Reluctance Motors

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ABSTRACT

In order to study the influence of different structures of the same power motor on the performance of the motor, the experimental research method is used, based on An soft electromagnetic simulation software, from the aspects of winding self-inductance, winding mutual inductance, torque magnitude and pulsation effect, winding current, etc., the same rated parameters. The simulation performance of four-phase 8 / 6 pole switched reluctance motor and four-phase 16 / 12 pole switched reluctance motor were compared and analyzed. The results show that 8 / 6 pole switched reluctance motors have higher self-inductance value, larger mutual inductance value, larger torque, smaller torque ripple and lower current than 8 / 16 pole windings compared to 16 / 12 pole.

1. Introduction

Switched reluctance motor (SRM) is a new type of speed regulation motor. This speed regulation system has a large motor utilization factor. The system efficiency and power density are high in the low speed and load range. It is a high-tech, including power electronics technology, electromagnetic theory, design and production technology. Because of its advantages in starting performance and high efficiency operation, the switched reluctance motor system (SRM) is widely used in many fields, such as electric vehicles, paper machines, compressors, etc. [1].

Under the premise of determining the basic performance of the rated voltage, output power, speed, etc, what kind of internal structure of the motor can be selected to make the SRM performance better. At present, there is no selection standard of design. With less research, it is relatively difficult to determine the structure of the fixed rotor.

At present, the commonly used SRM structure types are mainly three-phase 6/4 pole, three-phase 12/8 pole, four-phase 8/6 pole and four-phase 16/12 pole [2]. A comparative analysis of the four-phase 8/6 pole SRD showed that, whether it is used as a motor or a generator, it is more advantageous to develop and apply a three-phase 6/4 pole switched reluctance motor from the perspective of improving the unit volume capacity and system efficiency of the motor. This is a study of SRMs with different phase numbers, but SRMs with the same phase number and different structures have not been studied[3].

In the case of the SRM parameters are given, the selection of different fixed rotor structures results in different performance of the motor. This article focus on the comparative analysis of the motor performance of the four-phase 8/6 pole and four-phase 16/12 pole SRM structure types to obtain a more reasonable SRM structure.

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2. Basic structure and principle of SRM

The switched reluctance motor has a double-salient pole structure. Only the stator has windings and no other components on the rotor, and the structure is simple. The structure of a 12/8 pole switched reluctance motor is typical, take it for example [4]. The opposite poles are called "one phase". Switched reluctance motors operate by changing the energization of each phase winding.

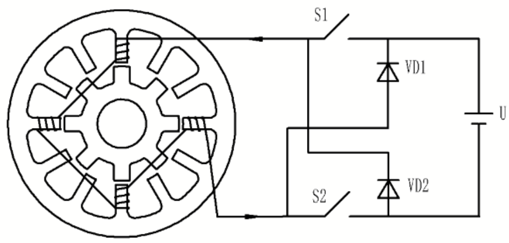


Fig.1. 12/8 pole switched reluctance motor structure (only one phase is drawn)

Switched reluctance motors are classified according to the number of phases. The single-phase switched reluctance motor has a simple structure and convenient control, but it has no self-starting ability when the stator pole axis coincides with the rotor pole axis.

Two-phase switched reluctance motors also have no self-starting capability [5]. Three-phase switched reluctance motors have self-starting capabilities. The motor structure and control are relatively simple and widely used. The application range of the four-phase switched reluctance motor is also relatively wide. Due to the increase in the number of phases, the operating performance is improved, but the cost is increased and the control complexity is increased. Five-phase and above switched reluctance motors have good performance, but the structure and control complexity are significantly improved, and they are rarely used.

The most commonly used motor types are 8/6 pole and 12/8 pole. The following table lists the commonly used switched reluctance motors, including the motor phase number, pole number and step angle.

Tab.1. Commonly used switched reluctance motors

Phase	Number of stator poles	Number of rotor poles	Step angle（°）
3	6	4	30
	12	8	15
4	8	6	15
	16	12	7.5

The relationship between stator and rotor pole number and phase number[6]:

$$\left.\begin{aligned} N_S &= 2km \\ N_S &= N_S \mp 2k \end{aligned}\right\} \tag{1}$$

Among them, N_s represents the stator pole number, N_r represents the rotor pole number, m represents the motor phase number, k represents the positive integer.

It can be seen from the above formula that the stator and rotor poles are unequal and they are even numbers. When the number of stator poles and rotor poles are close, the inductance change can be increased, thereby increasing the motor torque. In order to achieve the minimum switching frequency and reduce the minimum inductance as much as possible, the "—" sign is generally used in equation (1).

The step angle can be obtained according to the following formula[7]:

$$\theta_{\text{step}} = \frac{2\pi\left(N_s - N_r\right)}{N_s N_r} \tag{2}$$

where θ_{step} represents the step angle.

Switched reluctance motors rely on the change in reluctance between the stator and the rotor. When one of the stator windings is energized, if the stator pole axis and rotor pole axis do not coincide, there will be magnetic resistance acting on the rotor, causing the rotor to move. Until the axis of stator pole and rotor pole coincides, the magnetic resistance disappears. Continues to rotate a certain angle under the action of inertia, the adjacent winding is energized, so that the rotor continues to rotate.

The following illustrates the working principle of switched reluctance motor[8]. In the figure, the stator coil is on the stator pole. The winding marked with an arrow indicates that the phase winding is energized. The dashed line indicates the magnetic line of force. The angle of rotation before the rotor starts is 0 °.

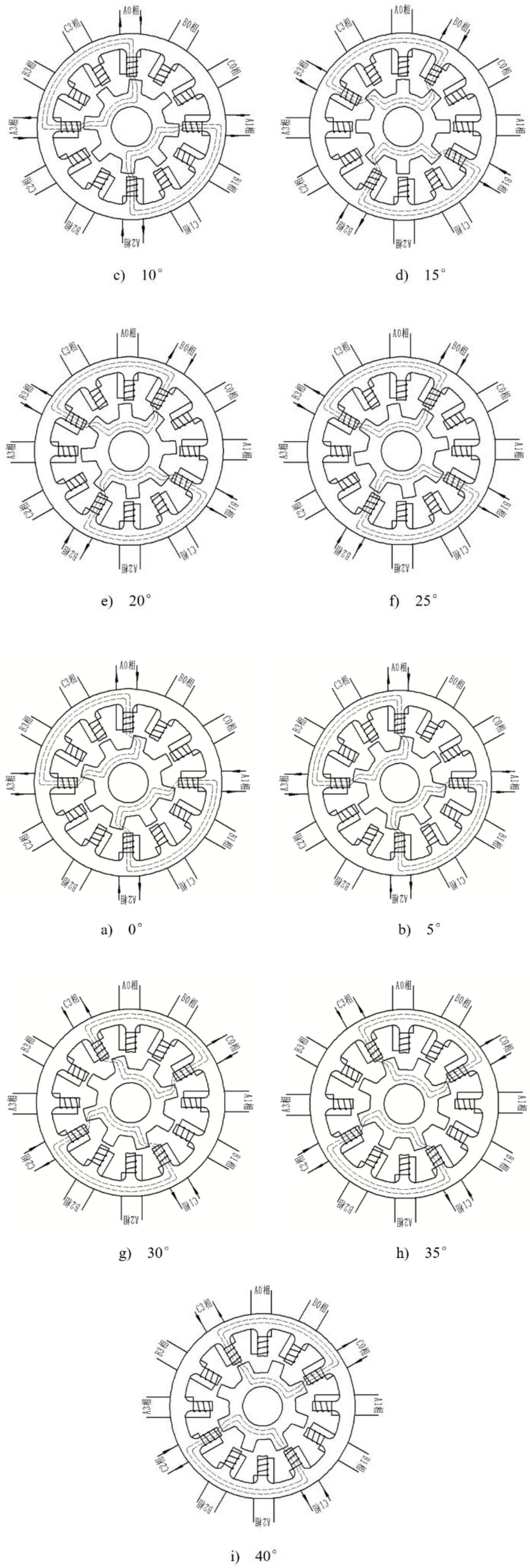


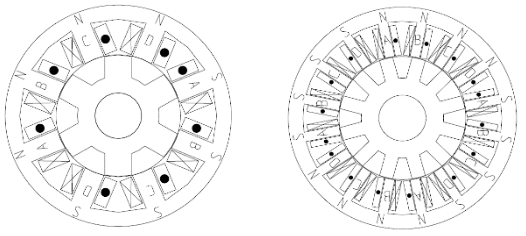
Fig.2. Schematic diagram of the working principle of 12/8 pole switch reluctance motor

At the initial position, the A-phase winding is energized. Under the action of the magnetic force, the rotor pole closest to the A-phase begins to rotate counterclockwise, making the reluctance smaller. The rotor rotates to 5 °, and then rotates 15 ° .So far, the rotor no longer rotates when the magnetic circuit is the shortest. In order to make the rotor continue to rotate, the A-phase power supply must be cut off when the rotor is not under force, and the B-phase is turned on at the same time, so the B-phase generates magnetic flux. Before turning to 30 °, turn off the B-phase winding power and turn on the C-phase winding to make the rotor continue to rotate. Turn on the A-phase winding power before turning to 45 °, and so on, and the motor will run. In this subject, the three-phase windings circulate electricity once, the rotor rotates counterclockwise π / 4 (that is, a pole pitch angle), and the stator magnetic field rotates clockwise π / 2[9].

As long as each phase is turned on in a certain order, the motor can work normally, regardless of the direction of the magnetic field lines, that is, regardless of the direction of the current, and the energizing sequence is opposite to the direction of rotation.

3. Four-phase 8/6 pole and four-phase 16/12 pole structure characteristics

The two types of motors are four-phase stator windings. The difference is that the number of stator poles and rotor poles. 8/6 poles have 8 stator poles and 6 rotor poles. 16/12 poles have 16 stator poles and 12 rotors poles. One-phase winding is wound on two teeth poles in the radial direction of the stator pole[10]. The schematic diagram of the structure of the two motors is shown in Figure 2.



(a) 8/6 poles (b) 16/12 poles

Fig.3. Four-phase 8/6 pole and four-phase 16/12 pole structure diagram

4. Two motor parameters and research methods

In the Ansoft electromagnetic simulation environment, input the necessary parameters of the motor, create a motor model to simulate two different structures of SRM, and compare and analyze the performance of the two motors. The values of the two motor parameters are shown in Table 2.

Tab. 2. Two main parameters of SRM

Parameter / Motor structure	4 phase 8/6 pole	Four-phase 16/12 pole
rated power /kW	5	5
Rated voltage /V	72	72
Rated speed /（r/min）	6100	6100
Stator outer diameter /mm	155	155
Rotor outer diameter /mm	85	86
Stator tooth width /mm	14.09	6.59
Rotor tooth width /mm	18.54	9.21
Iron core stack length /mm	102	102
First air gap /mm	0.4	0.4
Shaft diameter	32	32

It can be seen from Table 2: The rated power, rated voltage, and speed of the two motors are the same, and the motor volume is also the same. The difference is the design of the stator and rotor structure. By adjusting the stator inner diameter and rotor outer diameter, the motor performance is optimized.. In this way, when the performance of the two motors is the best, compare the performance of the two motors with the same rated parameters and different structures.

The research method adopts Ansoft finite element method. By comparing the analysis results, the motor structure with better motor performance when the rated parameters are the same is selected.

5. Comparative analysis

5.1 Winding inductance

In the switched reluctance motor, the relative position of the stator and rotor is different, and the inductance is different. The winding inductance value changes periodically between the maximum inductance and the minimum inductance. The maximum inductance value is at the position where the stator pole axis is aligned with the rotor pole axis, and the minimum inductance is at the position where the stator salient pole axis is aligned with the rotor slot axis.

Figure 4 shows the relationship between winding inductance and rotor position. The origin of the coordinate is the position reference point, and the phase inductance is the smallest at this time. The rotor starts rotate, and the stator pole and the rotor pole start to coincide at the position θ_2. The rotor continues to rotate, the overlapping area becomes larger, and at the position θ_3, the two salient poles completely coincide, when the phase inductance is the largest. From θ_3-θ_4 process, the two salient poles remain completely coincident, the θ_4 position is the end point of the two salient poles completely coincide. From θ_4-θ_5 process, the overlap of the two salient poles decreases until they do not completely coincide, and the position θ_1 and position θ_5 is the two salient poles from coincidence to Positions that do not overlap at all [11].

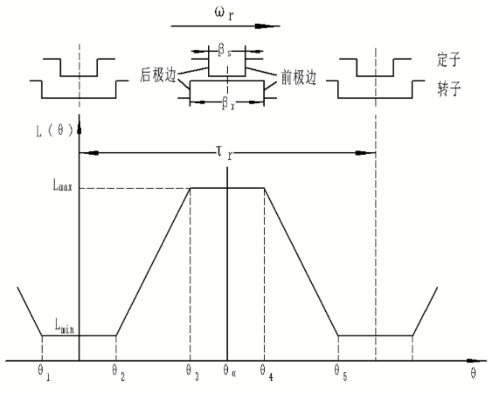


Fig.4. Curve of winding inductance and rotor position

From the above analysis, the relationship between inductance $L(\theta)$and rotor position angle θ can be obtained

$$L(\theta)=\begin{cases} L_{\min} & (\theta_1 \le \theta < \theta_2) \\ L_{\min}+K(\theta-\theta_2) & (\theta_2 \le \theta < \theta_3) \\ L_{\max} & (\theta_3 \le \theta < \theta_4) \\ L_{\max}-K(\theta-\theta_4) & (\theta_4 \le \theta < \theta_5) \end{cases} \tag{3}$$

$$K = \frac{L_{\max} - L_{\min}}{\theta_3 - \theta_2} = \frac{L_{\max} - L_{\min}}{\beta_s} \tag{4}$$

where K is the inductance change rate and β_s is the stator pole arc.

5.1.1 Winding inductance

The self-inductance characteristic curve of each phase winding of the two structure motors is shown in Figure 5.

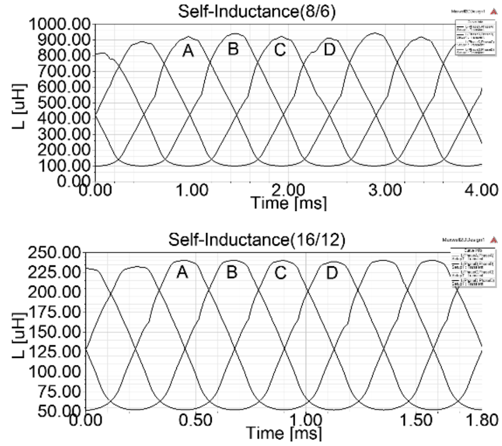


Fig.5. Self-inductance characteristic curve

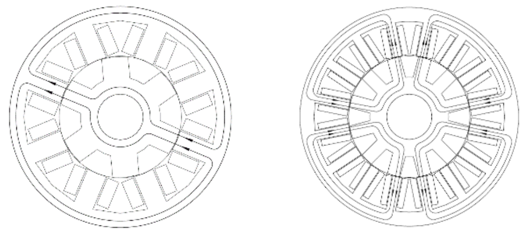
It can be seen from Figure 5, whether it is 8/6 pole SRM or 16/12 pole SRM, the self-inductance change rule of each phase winding in each structure is basically the same, and the self-inductance amplitude varies greatly [12]. Taking the D-phase winding as an example, the self-inductance parameters of the two structures are compared as shown in Table 3. In the table, Lmax represents the maximum self-inductance, Lmin represents the minimum self-inductance, and Lavg represents the average self-inductance.

Tab.3. Comparison of self-inductance parameters of two structures (Phase D)

Motor structure	Lmax/ μH	Lmin/ μH	Lavg/ μH	Rate of change
8/6	911.5	100.1	443.5	9.1
16/12	237.6	51.9	132.3	4.6

It can be seen from the values in Table 3: The difference between the maximum SRM self-inductance of the two different structures is about 700 H, and the minimum self-inductance is about 50 H. From the change rate of self-inductance, the change rate of 8/6 pole self-inductance is double of the 16/12 pole. The self-inductance change rate greater, and the torque of the motor is greater.

The air gap is the largest when the poles of the stator and rotor are completely non-overlapping. At this time, the saturation of the magnetic circuit is low, the magnetic resistance is large, the proportion in the magnetic circuit is large, and the magnetic resistance plays a dominant role. Because the air gap paths of the two motor structures when the magnetic poles do not overlap at all are similar, the self-inductance value is not much different. At the maximum self-inductance, the 8/6-pole SRM self-inductance magnetic circuit passes through twice of the air gap, as shown in Figure 6 (a), and the 16/12 pole SRM self-inducting magnetic circuit passes through the air gap four times. As shown in Figure5 (b). Through the air gap more times, the magnetic resistance will greater. Therefore, the 16/12 pole magnetic resistance is large and the maximum self-inductance is small [13].



(a) 8/6 poles (b) 16/12 poles

Fig. 6. Maximum self-inductance circuit

5.1.2 Comparison of mutual inductance between windings

When SRM is running normally, each phase winding conducts current in turn. During commutation, adjacent windings will conduct simultaneously, so the self-inductance generated by the two phases affects each other to form mutual inductance [14]. The mutual inductance curve of the adjacent winding simulated by Ansoft is shown in Figure 7.

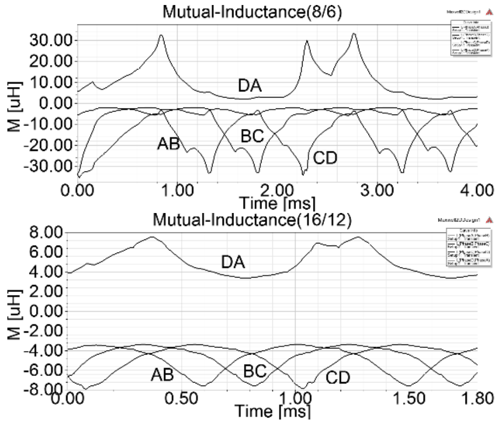


Fig.7. Mutual inductance characteristic curve

It can be seen from Figure 7 that the mutual inductances of different structural types SRMs is differ greatly, and the mutual inductance curve of each structure is irregular. There are positive and negative numerical values, and the amplitudes also differ greatly. In order to analyze the relationship between mutual inductance and self-inductance under two different structures and the effect of mutual inductance on self-inductance, the mutual inductance value between the two phases of DA and the self-inductance value of phase A are compared, in which the values involved are taken as absolute values [15] ,as shown in Table 4. Among them, Mmax represents the maximum mutual inductance, Mmin represents the minimum mutual inductance, and Mavg represents the average mutual inductance.

Tab.4. Comparison of mutual inductance parameters of two structures (DA phase)

Motor structue	DA mutual inductance /μH			Phase A /μH		
	Mmax	Mmin	Mavg	Lmax	Lmin	Lavg
8/6	32.9	2.0	9.6	911.5	100.1	443.5
16/12	7.5	3.4	4.9	237.6	51.9	132.3

It can be seen from Table 4 that the average value of the mutual inductance of 8/6 poles is about twice the average value of the mutual inductance of 16/12 poles. The maximum mutual inductance of the former is about 4 times of the maximum mutual inductance of the latter, and the minimum value of mutual inductance between the two is not much different.

According to Table 3 and Table 4, it can be seen that the 8/6 pole structure type motor has a large self-inductance value and a large mutual inductance value, and the 16/12 pole structure type motor has a small self-inductance value and a small mutual inductance value. The average value of 8/6 pole mutual inductance accounts for about 1% of the average value of self-inductance, and the average value of 16/12 pole mutual inductance accounts for 4% of the average value of self-inductance. So the latter mutual inductance has a greater impact on motor performance. From the perspective of increasing torque, the mutual inductance value should be positive value, and the larger the better.

5.2 Torque comparison

When the axes of the two salient poles coincide, the magnetic force between the stator and the rotor is radial, and the torque is zero. When the two axes do not coincide, torque is generated.

According to the electromechanical equation [16]

$$\mathrm{T_e}(\mathrm{i},\ \theta)=\frac{\partial W_{\mathrm{m}}{}'(\mathrm{i}_1,\ \mathrm{i}_2,\cdots,\ \mathrm{i}_m;\ \theta)}{\partial\theta} \tag{5}$$

Under linear conditions, when the rotor is at a certain position angle, the magnetization curve can be represented by OB in the figure 8. From the figure, it can be seen that the magnetic energy increases with the increase of current.

When the current increases from 0 to i1, the flux linkage φ increases from 0 to φ_1. The areas of triangle OBC and triangle OAB respectively represent the magnetic energy storage(W_{m}) and magnetic common energy(W'_{m}), $\varphi=\mathrm{f}(\mathrm{i})$, which is a straight line, and the slope is determined by the magnitude of reluctance.

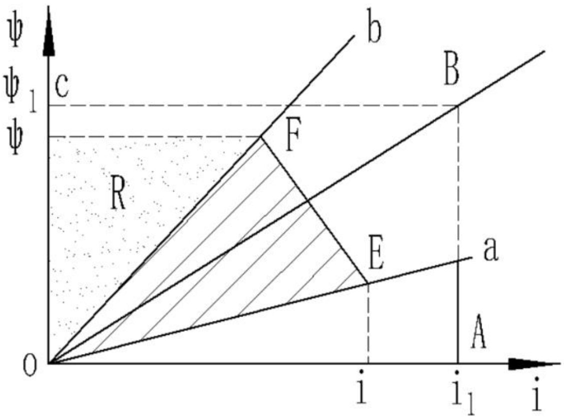


Fig.8. Flux-current relationship

According to the assumption of linear, simplify equation (5)

$$\mathrm{T_e}(\mathrm{i},\ \theta)=\left.\frac{\partial W_{\mathrm{m}}{}'(\mathrm{i},\ \theta)}{\partial\theta}\right|_{\mathrm{i=const}} \tag{6}$$

$$W_{\mathrm{m}}=W'_{\mathrm{m}}=\frac{1}{2}\mathrm{i}\psi=\frac{1}{2}\mathrm{Li}^2 \tag{7}$$

Substituting equation (7) into (6)

$$\mathrm{T_e}=\frac{\mathrm{i}^2}{2}\frac{\partial L}{\partial\theta} \tag{8}$$

Combined inductance expression

$$\mathrm{T_e}=\begin{cases}0 & (\theta_1\le\theta<\theta_2)\\ \frac{1}{2}K\mathrm{i}^2 & (\theta_2\le\theta<\theta_3)\\ 0 & (\theta_3\le\theta<\theta_4)\\ -\frac{1}{2}K\mathrm{i}^2 & (\theta_4\le\theta<\theta_5)\end{cases} \tag{9}$$

where K is the inductance change rate

It can be seen from the above formula that the inductance change rate is proportional to the torque, the torque is proportional to the square of the current. The drag torque is generated when the inductance rises, and the braking torque is generated when it falls. The required torque type can be obtained by adjusting the conduction angle. The relationship between phase inductance, electromagnetic torque and rotor position can also be obtained according to the above formula [17], as shown in Figure 9.

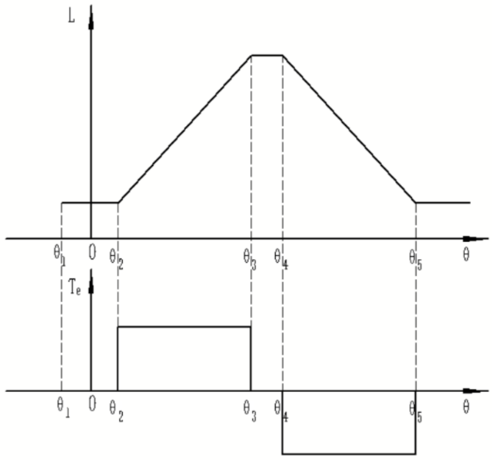


Fig.9. Relationship between phase inductance, electromagnetic torque and rotor position

The torque of the motor indicates the ability of the motor to drive the load. The greater the torque, the greater the power of the motor to drive the object. If the torque is too small, there will be a phenomenon that the motor cannot drive the object. So the torque is great significance for determines and controls the load of the drive shaft, the strength design of the working parts of the transmission system and selection of prime mover capacity. In addition, the size of torque ripple has a great influence on the performance of the motor. The torque waveforms of the two structures of motor torque are shown in Figure 10.

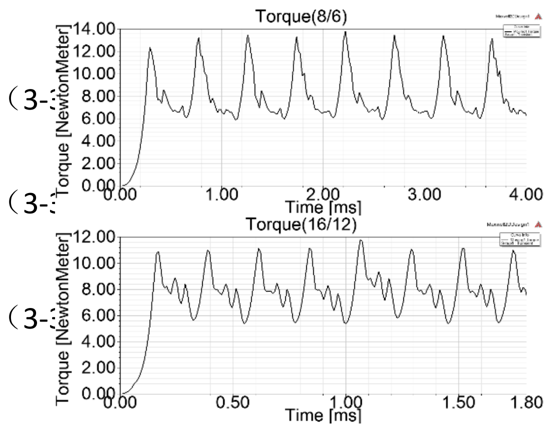


Fig.10.SRM torque curve of four-phase 8/6 pole and four-phase 16/12 pole

It can be seen from Figure 10: 8/6 pole SRM torque value fluctuates up and down around 9N • m, the maximum value of torque is 13.05 N • m and the minimum value is 5.85 N • m; 16/12 pole SRM torque fluctuates up and down around 8 N • m, the maximum value of torque is 11.90 N • m, and the minimum value is 5.38 N • m. Therefore, the average torque of 8/6 poles SRM is greater than 16/12 poles SRM, and the torque ripple of 8/6 poles is greater than 16/12 poles SRM.

From the perspective of the electromagnetic torque, the torque is determined by the difference between the maximum value and the minimum value of self-inductance. When the difference between the self-inductance values is greater, the torque is greater. The difference between the maximum and minimum values of the 8/6 pole self-inductance is 843 μH, and the difference between the maximum and minimum values of the 16/12 pole SRM's self-inductance is 187.6 μH. Therefore, the electromagnetic torque of 8/6 poles SRM is greater than that of 16/12 poles SRM.

From the torque ripple analysis, the larger the torque value drops, the greater the motor ripple. The torque drop occurs when the windings are commutated, The current phase off cannot generate torque and the next on phase cannot generate enough torque. 8/6 pole SRM's torque drops to 7.20 N • m, 16/12 pole SRM's torque drops to 6.52 N • m, and 8/6 pole SRM's torque drops are relatively large. Because of the difference in the internal structure of the two motors, the fixed rotor pole overlap ratio is different. Stator and rotor pole overlap ratio is different. Therefore, the torque ripple of 16/12 pole is smaller than that of 8/6 pole SRM.

5.3 Winding current comparison

When the motor is running, the EMF equation of the phase winding can be obtained[18]

$$\pm \mathrm{u_k} = \frac{\mathrm{d}\psi_\mathrm{k}}{\mathrm{dt}} + \mathrm{i}R \tag{10}$$

Where +uk represents the excitation phase voltage and -uk represents freewheeling phase voltage

Since the winding voltage drop is very small compared to the sag, ignoring the winding voltage drop has little effect on the calculation results.

Substitute $\psi_\mathrm{k} = L(\theta)\mathrm{i}(\theta)$ into formula (9)

$$\pm \mathrm{u_k} = \frac{\mathrm{d}\psi_\mathrm{k}}{\mathrm{dt}} = L\frac{\mathrm{di}}{\mathrm{dt}} + \mathrm{i}\frac{\mathrm{d}L}{\mathrm{dt}} = L\frac{\mathrm{di}}{\mathrm{d}\theta}\omega_\mathrm{r} + \mathrm{i}\frac{\mathrm{d}L}{\mathrm{d}\theta}\omega_\mathrm{r} \tag{11}$$

During the energization of the winding, the voltage is positive, and both sides are multiplied by the current i to obtain the power balance equation

$$\mathrm{u_k i} = L\mathrm{i}\frac{\mathrm{di}}{\mathrm{dt}} + \mathrm{i}^2\frac{\mathrm{d}L}{\mathrm{d}\theta}\omega_\mathrm{r} = \frac{\mathrm{d}}{\mathrm{d}\theta}\left(\frac{1}{2}L\mathrm{i}^2\right) + \mathrm{i}^2\frac{\mathrm{d}L}{\mathrm{d}\theta}\omega_\mathrm{r} \tag{12}$$

Equation (11) shows that the power is applied, if the loss is not counted, to increase the winding energy storage and mechanical power output.

According to Figure 4, $\theta_2 \le \theta < \theta_3$ stage, the inductance is rises, the electromotive force is positive, and the drag torque is generated; $\theta_3 \le \theta < \theta_4$ stage, the inductance remains unchanged, the electromotive force is zero, no torque is generated; $\theta_4 \le \theta < \theta_5$ stage, the inductance is decreases, the electromotive force is negative, the braking torque is generated. The energy is feedback to the power source, which is in the state of power generation [19]. Therefore, in order to obtain a larger torque, on the one hand, the current should be rapidly reduced when the inductance decreases to does not appear to be a braking torque, on the other hand, a larger current should be obtained when the inductance increases to improve the drag torque.

According to the above analysis, $\theta_1 \le \theta < \theta_2$ stage, the main switching device is triggered, $\theta_2 \le \theta < \theta_3$ stage, the main switching device is turned off, so the current waveform when the inductance changes is obtained, as shown in Figure 11.

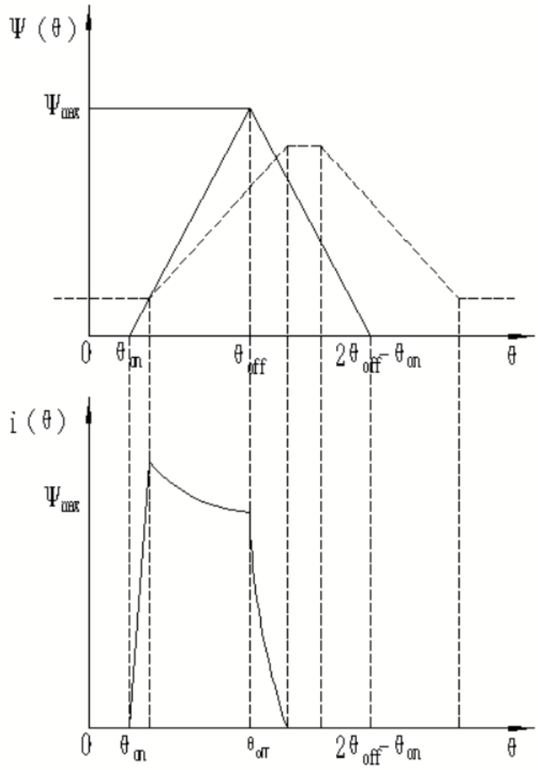


Fig.11. Current waveform when the inductance changes

(3-24)

The winding current expression can be obtained by derivation:

$$\mathrm{i}(\theta)=\begin{cases} \dfrac{U_\mathrm{s}}{\omega_\mathrm{r}}\dfrac{\theta-\theta_\mathrm{on}}{L_\mathrm{min}} & (\theta_1 \le \theta < \theta_2) \\ \dfrac{U_\mathrm{s}}{\omega_\mathrm{r}}\dfrac{\theta-\theta_\mathrm{on}}{L_\mathrm{min}+K(\theta-\theta_2)} & (\theta_2 \le \theta < \theta_\mathrm{off}) \\ \dfrac{U_\mathrm{s}}{\omega_\mathrm{r}}\dfrac{2\theta_{off}-\theta_\mathrm{on}-\theta}{L_\mathrm{min}+K(\theta-\theta_2)} & (\theta_\mathrm{off} \le \theta < \theta_3) \\ \dfrac{U_\mathrm{s}}{\omega_\mathrm{r}}\dfrac{2\theta_{off}-\theta_\mathrm{on}-\theta}{L_\mathrm{max}} & (\theta_3 \le \theta < \theta_4) \\ \dfrac{U_\mathrm{s}}{\omega_\mathrm{r}}\dfrac{2\theta_{off}-\theta_\mathrm{on}-\theta}{L_\mathrm{max}-K(\theta-\theta_4)} & (\theta_4 \le \theta \le 2\theta_{off}-\theta_{on} < \theta_5) \end{cases} \tag{13}$$

(3-25)

It can be seen from the above formula that when the power supply voltage and speed are constant, the current can be expressed by $\mathrm{f}(\theta)$, which is related to the parameters such as the on/off angle and the maximum inductance[20][21]. The current is adjusted by the conduction angle. The current rising stage has a great influence on the system performance. Generally, the current rises quickly and the output torque is large, but the torque ripple is large and the operation is unstable. The current characteristic curves of two different structures of motor windings are shown in Figure 12.

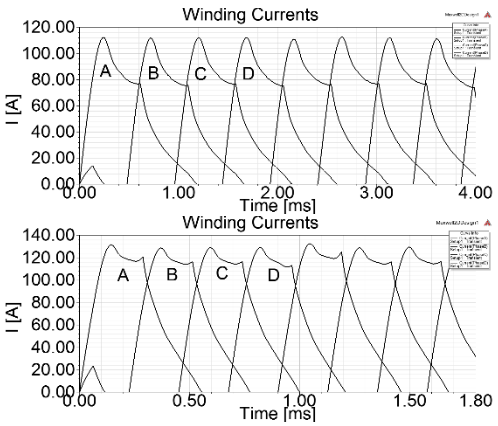


Fig.12. Winding current characteristic curve

The above figure shows that the 8/6 pole winding current is smaller than the 16/12 pole current, and the current density is relatively small, which is beneficial to reduce the volt-ampere capacity of the switch tube.

6. In conclusion

Through the above analysis, under the conditions of the same rated power, the same rated voltage, the same motor capacity, and the performance of the motor has reached the best, the following conclusions can be drawn:

1) The 8/6-pole SRM's self-inductance circuit is different with the 16/12 pole SRM, resulting in different self-inductance values. The 8/6 pole SRM's self-inductance value is large and the self-inductance change rate is large.

2) The influence of 8/6 pole SRM's mutual inductance on self-inductance is smaller than that of 16/12 pole SRM, but the mutual inductance value of 8/6 pole SRM is larger.

3) Since the 8/6 pole SRM's change rate of self-inductance and mutual inductance value are greater than 16/12 pole SRM, the electromagnetic torque of 8/6 pole SRM is greater than 16/12 pole, and the torque ripple of 16/12 pole SRM is smaller than that of 8/6 pole SRM.

4) The 8/6 pole SRM winding current is smaller than 16/12 pole SRM, which is beneficial to prolong the service life of the switch tube.

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