Research on Electromagnetic Force Distribution and Vibration Performance of A Novel 10/4 Switched Reluctance Motor

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Abstract. Radial electromagnetic force is one of the main reasons causing the vibration and noise of the switched reluctance motor. Based on this, the novel structure of 10/4 pole switched reluctance motor is proposed, which increases the air gap flux and electromagnetic torque by increasing the number of stator poles. In addition, the excitation current of the stator winding is reduced by early turn-off angle. Through the finite element modelling analysis, the results show the superiority of the new type of switched reluctance motor. In the end, the vibration characteristics of the conventional motor and the new motor are compared and analysed, and the effect of the structure of this new type of switched reluctance motor is verified.

1. Introduction
Switched Reluctance Motor (SRM or SR Motor for short) is a structure of doubly salient. It is a new kind of variable speed drive system. When it is compared with the traditional motor, SRM has the advantages of simple structure, low cost and good regulating performance [1-6]. Since the 1990 s, it has been increasingly applied in electric vehicle, mine, oilfield, textile machinery and other industrial areas [7-9]. However, it has been found in the study of SRM that the serious problem of the noise and vibration has limited the popularization and application of it in some occasions [10-11]. The study shows that the effect on the stator radial force is the main cause of noise and vibration [12-15]. It has designed a kind of semi-anechoic chamber to isolate noise in literature [16]. However, the use of the semi-anechoic chamber have limitations which cannot fundamentally solve the problem of vibration. In literature [17], in order to reduce the noise and vibration, the gear of switched reluctance motor is designed as inclined structure to achieve the effect of flattening radial electromagnetic force. But it has higher requirements for the mechanical design. In literature [18], Based on the theory of magnetic permeability which can decrease the amplitude of radial force, the rotor has been set no filler ring holes to reduce the vibration and noise. But the round hole would make the stress concentration
problem obviously which has bad effect to the rotor structure. In literature [19], to achieve noise reduction and vibration damping by using the method of adding auxiliary coil, however, because of the existence of strong winding coupling, the reliability of motor is reduced, fault tolerant ability is decreased. In literature [20], the axial type switched reluctance motor is proposed. It can improve the electromagnetic torque. But it has no further ways to reduce the radial force.

This paper has designed a new type of five phase 10/4 structure of switched reluctance motor. By increasing the number of stator pole to increase the air gap flux and electromagnetic torque.

2. Basic principles and innovative approaches

2.1. Basic principles

The static torque of a switched reluctance motor (SRM) can be obtained by the partial derivative of its magnetic field energy or magnetic co-energy to the rotor position angle.

\[ n = \left. \frac{\partial W_m^\prime}{\partial \theta} \right|_{i = \text{const}} \]  

(1)

In formula 1, \( n \) is the static torque; \( W_m^\prime \) is magnetic co-energy; \( \theta \) is the position angle of the rotor; and \( i \) is the electric current of exciting winding.

When magnetic circuit of motor is not saturated, which means the magnetic circuit is assumed to be linear, then

\[ W_m = W_m^\prime = \frac{1}{2} i \psi = \frac{1}{2} i^2 L \]  

(2)

In formula 2, \( W_m \) is the magnetic energy of the whole magnetic field; \( \psi \) is the flux linkage of conduction phase windings; \( L \) is the inductance of conduction phase windings.

And then the calculation formula of torque \( T \) is obtained:

\[ T = \frac{\partial W_m^\prime}{\partial \theta} = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \]  

(3)

In formula 3, \( i, \psi, \) and \( L \) are the electric current, flux linkage and inductance which conduct phase windings.

The above equation shows that the torque of SRM is obtained because terminal inductance changes with the different spatial positions and the torque is always trying to maximize the inductance. When \( \frac{\partial L}{\partial \theta} > 0 \), a positive torque is generated. When \( \frac{\partial L}{\partial \theta} < 0 \), a braking torque is generated.

Accordingly, the torque characteristic \( T = f(\theta) \) can be obtained from the curve \( L = f(\theta) \) which shows that the inductance \( L \) of SRM varies with rotor position angle \( \theta \), as shown in Fig 1.
Fig. 1. Operating principle of SRM

Fig. 1. (a) is the inductance curve $L_A(\theta)$ of A-phase winding, and the inductance is the smallest when the stator polar axis is aligned with the rotor slot axis, now let $\theta = 0^\circ$; the inductance is the largest when stator polar axis is aligned with the rotor polar axis, and now set the mechanical angle $\theta = 45^\circ$ (the electrical angle is 180 degrees). On this basis, the combined torque of the final SRM (Fig. 1 (d)) is obtained according to different winding lead-on time (Fig. 1 (c)). This paper studies the distribution rule of electromagnetic force of a new type of SRM with this basic idea.

2.2. Innovative approaches

In conventional SRM, commutation often occurs when the stator polar axis and the rotor polar axis coincides with each other. And since the radial electromagnetic force reaches the maximum value at this moment, large noise and vibration of the SRM are generated when running. Given that, this paper proposes a new method for designing the structure of the 5-phase 10/4 SRM by increasing the number of stator poles to increase the air-gap flux and the circumferential electromagnetic force and by turning on and off in advance the stator windings current to reduce the radial electromagnetic force. In this way, not only electromagnet torque of SRM can be increased, but the vibration and noise of it can be reduced.

Fig. 2 shows the structural diagram and operating principle of the new five-phase 10/4 SRM in which the pole pairs of the stator poles is 5 and that of rotor poles is 2. When $\alpha A = 20^\circ$ is detected (Fig. 3-1 (a)), A-phase winding is turned on and the rotor is rotated by the electromagnetic force. When the rotor rotates to $\alpha D = 20^\circ$ (Fig. 3-1(b)), A-phase winding is turned off, D-phase winding is turned on and generates electromagnetic force to drive the rotor to continue its rotation. When the rotor rotates to $\alpha B = 20^\circ$ (Fig. 3-1(c)), D-phase winding is turned off, B-phase winding turns on and generates electromagnetic force to drive the rotor to continue its rotation. When the rotor rotates to $\alpha E = 20^\circ$ (Fig. 3-1(d)), B-phase winding is turned off, E-phase winding is turned on and generates electromagnetic force to drive the rotor to continue its rotation. When the rotor rotates to $\alpha C = 20^\circ$
(Fig.3-1(e)), E-phase winding is turned off, C-phase winding is turned on and generates electromagnetic force to drive the rotor to continue its rotation. When the rotor rotates to $\alpha_A=20^\circ$ (Fig.3-1(f)), C-phase winding is turned off, A-phase winding is turned on and generates electromagnetic force to drive the rotor to continue its rotation. The rotor will continue to rotate with the repetition of the process showed above.

![Image of operating principle](image)

**Fig.2.** Operating principle of the new five-phase 10/4 SRM
3. Distribution Character of Electromagnetic Force

Whether this new type of switched reluctance motor can achieve the effect of vibration and noise reduction depends on whether it can effectively reduce the radial electromagnetic force. In this paper, the finite element model of the traditional switched reluctance motor and the new type of switched reluctance motor is established, the distributions of inductance, torque and radial electromagnetic force are analyzed respectively, and the rationality of the new switched reluctance motor is verified.

1/2 axisymmetric model is established by ANSYS simulation software; B-H curve is used for stator and rotor material, and relative permeability is 1 in other areas. The field winding applies a DC load that is applied to the different field windings depending on the rotor position. In this study, the number of pairs of stator poles of conventional switched reluctance motor is 3 and the number of pole pairs of rotor is 2. The number of pairs of stator poles of the new switched reluctance motor is 5 and the number of rotor poles is also 2. As shown in Fig.3.

The inductance of the SRM is obtained by the electromagnetic energy method, that is, the magnetic energy in the whole region is obtained by the finite element analysis, and the inductance is finally determined according to the loaded current value. The electromagnetic torque is obtained by the ANSYS macro command TORQSUM, and the radial electromagnetic force is obtained by getting the coordinate transformation after acquiring the relevant force data.

According to the above-mentioned basic principle, the change law of the inductance of the switched reluctance motor in an electric cycle is analyzed, as shown in Fig.4. The maximum value of the inductance of the switched reluctance motor appears near the electrical angle of 0 and the minimum occurs at an electrical angle of approximately 180 degrees; the rapidly decreasing inductor area occurs within an electrical angle range of 30 to 90 and the rapid increase in inductance occurs at an electrical angle of 270 to 330. The above-mentioned principle shows that the electrical angle and the mechanical angle meet the condition of Nr times (the number of pole pairs of the stator); for the number of stator poles of new switched reluctance motor is 5, and the mechanical angle of one electrical cycle is 72 degrees; the relative distance between the stator and rotor is shorter, so the inductance rising or falling area appears more steep change.

The distribution of inductance directly affects the electromagnetic torque of the switched reluctance motor. The electromagnetic torque of the switched reluctance motor is mainly determined by the spatial change of the motor inductance. The specific distribution is shown in Fig.5. The electromagnetic torque of the switched reluctance motor is almost zero in the region where the rate of change of inductance is small (electrical angle between 120 to 240 degrees); the electromagnetic torque of the switched reluctance motor is negative in the region where the inductance decreases fastest; In the region where the inductance rises fastest, the electromagnetic torque of the switched reluctance motor is positive, and the positive torque region is the normal working range of the switched reluctance motor. At the same time, the new switched reluctance motor inductance change rate is greater, so in the same excitation conditions it can obtain greater electromagnetic torque, an increase of 51.7%.

![Fig.3. new switched reluctance motor geometric model and grid division](image-url)
In order to verify the distribution of the radial force of the new SRM, the distribution of the radial electromagnetic force of SRM is analyzed in an electric cycle, as shown in Fig.6. The results show that, compared with the conventional switched reluctance motor, the amplitude of the radial electromagnetic force decreases by 45.3%, while the new SRM achieves 51.7% increase of the electromagnetic torque. The result shows the superiority of the new SRM.

Based on the analysis of the electromagnetic torque of single-phase loading, single-cycle SRM and distribution law of radial electromagnetic force, combined with the characteristics of SRM excitation, we further study the electromagnetic torque of SRM in multiphase loading and the distribution character of radial electromagnetic force. In order to more clearly reflect the difference between the electromagnetic torque and the radial electromagnetic force distribution between the traditional motor and the new motor, Fig. 7 shows the comparison between these two. Red lines represent the new motor, black lines represent the traditional motor; it can be seen that the new SRM has greater electromagnetic torque capacity and smaller radial electromagnetic force, and its overall performance is much better.
4. Response analysis under excitation of radial electromagnetic force

In order to verify the effect of the new SRM on vibration and noise reduction, we compare the traditional motor with the new motor and analyze the response of the traditional motor and the new motor under excitation of radial electromagnetic force. In the analysis, the radial electromagnetic force obtained from the above analysis is applied to the stator pole, and only a set of excitation windings are energized when the motor run normally. Fig.8 shows the response of traditional motors and new motors under excitation of radial electromagnetic force. For traditional switched reluctance motor, the maximum displacement of first-order, second-order, third-order response were $2.92 \times 10^{-2}$mm, $4.83 \times 10^{-2}$mm, $8.41 \times 10^{-1}$mm respectively; For new switched reluctance motor, the maximum displacement of first-order, second-order, third-order response were $1.30 \times 10^{-2}$mm, $2.89 \times 10^{-2}$mm, $1.02 \times 10^{-1}$mm respectively. Taking the most easily occurring first-order response as an example, the maximum displacement of new switched reluctance motor is 55.48% less than traditional switched reluctance motor. The results have verified the structure of new switched reluctance motor on vibration and noise reduction.

![A traditional motor response](image1)
![The second order response of traditional motor](image2)
![Traditional motor third-order responses](image3)

![A new type motor response](image4)
![New type of motor second order response](image5)
![Three new motor response](image6)

**Fig.8.** Traditional motor and a new type under the radial electromagnetic force excitation response analysis.

5. Conclusion

In this paper, the finite element method, the contrast analysis of the new type 10/4 switched reluctance motor with traditional 6/4 switched reluctance electric magnetic force distribution. Results show that under the condition of the same excitation, a new electromagnetic torque of switched reluctance motor than traditional electromagnetic torque of switched reluctance motor increases by 51.7%, while the radial electromagnetic force is decreased by 45.3%. Finally by comparing the analysis of the vibration of the traditional motor with new motor, taking the most easily occurring first-order response as an example, the maximum displacement of new switched reluctance motor is 55.48% less than traditional switched reluctance motor, proving the effect of damping noise reduction of the new switched reluctance motor. In general, the new type of switched reluctance motor has a larger electromagnetic...
torque output capacity and smaller radial electromagentic force, can effectively achieve the purpose of damping noise reduction.

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