

Analysis of cogging torque of permanent magnet synchronous motor with different pole slots

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Abstract. Using Maxwell finite element analysis software, the harmonic contents of no-load magnetic field and load magnetic field of three permanent magnet synchronous motors with 8 poles, 24 slots, 36 slots and 48 slots are calculated, and the radial force wave analysis is carried out. The influence of chute on cogging torque of integer slot motor and the influence of different pole arc coefficients and eccentricity of magnetic steel on sinusoidal distortion rate of magnetic field are analyzed. The analysis and calculation results show that, compared with fractional slot motor, the radial electromagnetic force and cogging torque of integral slot motor can be reduced more effectively by selecting the inclined slot and the appropriate magnetic steel shape, which provides a theoretical basis for reducing the vibration and noise of permanent magnet synchronous motor.

Keywords: Permanent magnet synchronous motor, Radial force wave, Vibration, Noise.

1. Introduction

The vibration and noise of permanent magnet motors have always been a puzzle for people. In serious cases, they can become the key factor to determine the stable operation of products and the bottleneck to meet the standard limit^[1]. The radial electromagnetic force generated by the interaction of various harmonic magnetic fields in the air gap magnetic field of the motor is the main source of electromagnetic noise. The cogging torque causes periodic torque pulsation, which causes motor vibration and affects the control accuracy of the system. At present, the analysis of motor noise mainly focuses on mature induction motor and electrically excited synchronous motor^[2-4], while permanent magnet synchronous motor is a new type of high-efficiency special motor, but there are few comprehensive and in-depth studies on its noise and vibration characteristics. Reference [6] analyzes the influence of different pole-slot coordination on the vibration and noise of permanent magnet synchronous motor, and reference [8] analyzes the influence of permanent magnet magnetizing mode, eccentricity, different pole arc coefficient combinations and pole-slot coordination on ripple torque and cogging torque.

In this paper, the air-gap magnetic field of the motor is decomposed into the no-load rotor magnetic field and the loaded armature magnetic field. The harmonic content of the air-gap magnetic field of the permanent magnet synchronous motor with different pole slots is simulated and calculated in Maxwell 2D, and the force wave analysis is carried out. The cogging torque of the motor with and without different slot slots is calculated, and the influence of different pole arc coefficients and eccentricity of magnetic steel on the no-load harmonic magnetic field is also analyzed.

2. Principle of radial force wave analysis of permanent magnet synchronous motor

The noises produced by permanent magnet motors mainly include electromagnetic noise, aerodynamic noise and mechanical noise. The exciting force of motor electromagnetic noise depends on the stator and rotor winding magnetic potential and air gap permeability^[5]. Therefore, the radial electromagnetic force of permanent magnet synchronous motor can be transformed into the analysis of stator and rotor magnetic field.

2.1. Permanent magnet synchronous motor magnetomotive force and harmonic of magnetic field

According to Maxwell's law, the instantaneous value of radial electromagnetic force per unit area in motor air gap can be expressed as:

$$p_r = \frac{b(\theta, t)^2}{2\mu_0} \quad (1)$$

type: $b(\theta, t)$ -- air gap magnetic density, μ_0 -- air permeability

When the influence of core reluctance and saturation is not considered, the expression of air gap flux density is:

$$b(\theta, t) = f(\theta, t)\lambda(\theta, t) \quad (2)$$

type: $f(\theta, t)$ Is the air gap magnetomotive force; $\lambda(\theta, t)$ Is air gap specific permeability.

When the permanent magnet motor is powered by sine wave, its stator and rotor magnetomotive force can be divided into stator fundamental magnetomotive force, stator harmonic magnetomotive force and rotor permanent magnet harmonic magnetomotive force. Among them:

$$\begin{aligned} f(\theta, t) &= f_0(\theta, t) + \sum_v f_v(\theta, t) + \sum_\mu f_\mu(\theta, t) \\ &= F_0 \cos(p\theta - \omega_0 t - \varphi_0) + \sum_v F_v \cos(v\theta - \omega_0 t - \varphi_v) + \sum_\mu F_\mu \cos(\mu\theta - \omega_0 t - \varphi_\mu) \end{aligned} \quad (3)$$

When the stator of permanent magnet synchronous motor has cogging and the rotor has surface permanent magnet structure, the air gap specific permeability can be approximately expressed as^[6]:

$$\lambda(\theta, t) = \Lambda_0 + \sum \lambda_{i_1} \quad (4)$$

Among $f_0(\theta, t)$ 、 $\sum_v F_v(\theta, t)$ 、 $\sum_\mu F_\mu(\theta, t)$ They are stator fundamental magnetomotive force, stator harmonic magnetomotive force and rotor permanent magnet harmonic magnetomotive force. ω_0 : frequency of fundamental current of stator, v : polar pairs of stator harmonics, μ : polar number of rotor harmonics, Λ_0 Is a constant part of air gap permeability per unit area, λ_{i_1} Is the periodic component of harmonic specific permeability caused by stator slot. Substitute formulas (3) and (4) into (2) and ignore the periodic component. λ_{i_1} The influence of, get:

$$b(\theta, t) = f(\theta, t)\lambda(\theta, t)$$

$$= B_0 \cos(p\theta - \omega_0 t - \varphi_0) \sum_v B_v \cos(v\theta - \omega_0 t - \varphi_v) + \sum_\mu B_\mu \cos(\mu\theta - \frac{\mu\omega_0 t}{p} - \varphi_\mu) \quad (5)$$

Substituting (5) into (1) gives:

$$\begin{aligned} p_r &= \frac{1}{2\mu_0} \left\{ \frac{B_0^2}{2} \cos 2(p\theta - \omega_0 t - \varphi_0) + \sum_\mu \frac{B_\mu^2}{2} \cos 2(\mu\theta - \frac{\mu\omega_0 t}{p} - \varphi_\mu) + \right. \\ &\left. \frac{1}{2} (B_0^2 + \sum_v B_v^2 + \sum_\mu B_\mu^2) + \sum_v \frac{B_v^2}{2} \cos 2(v\theta - \omega_0 t - \varphi_v) + \sum_v \sum_\mu B_v B_\mu \cos[(\mu \pm v)\theta - (\frac{\mu}{p} \pm 1)\omega_0 t - \varphi_{\mu v}] \right\} \end{aligned} \quad (6)$$

In formula (6), the order of the force wave generated by the stator harmonic and the force wave generated by the rotor harmonic is high, and its function can be ignored. The part with constant radial force will not cause the stator core to bend and deform. The electromagnetic force wave generated by the interaction between stator fundamental wave and stator and rotor harmonic wave is the main factor causing motor vibration and noise.

2.2. Harmonic of stator magnetic field of permanent magnet synchronous motor

(1) Harmonic polar number of air gap magnetic field of integer slot permanent magnet synchronous motor.

Its stator harmonic magnetic field contains only odd harmonics, $v=(2mk+1)p$, where $k = 0, 1, 2, 3 \dots$, m is the phase number of permanent magnet synchronous motor, and p is the polar logarithm.

(2) polar number of harmonic waves in air gap magnetic field of fractional slot permanent magnet synchronous motor.

The number of slots per pole per phase is $q = \frac{Z_1}{2mp} = b + \frac{c}{d}$, where $\frac{c}{d}$ It's simplest fraction. For a three-phase fractional slot permanent magnet synchronous motor, when d is even, the number of unit motors is $t = 2p/d$, and the number of harmonic magnetic fields in the stator winding can be expressed as: $v=(3k+1)t$; When d is odd, the number of unit motors is $t = p/d$, and the number of harmonic magnetic field of stator winding can be expressed as: $v = 6(k+1)t$. Where $k = 0, 1, 2, 3 \dots$

3. Finite element analysis and calculation of air gap magnetic field

The air-gap magnetic field of the motor under load can be composed of the superposition of the no-load permanent magnet magnetic field and the loaded armature magnetic field. In this section, Maxwell software is used to calculate the waveforms of permanent magnet magnetic field at no-load and stator armature magnetic field at rated load of three permanent magnet synchronous motors with 8 poles and 24 slots, 8 poles and 36 slots and 8 poles and 48 slots, respectively. Then, Fourier decomposition is carried out to calculate the amplitudes of harmonics, and the calculation results are shown in Tables 1 and 2.

When analyzing motor vibration and noise, it is customary to take the 2-pole wave with wavelength equal to the armature circumference $2p\tau$ as the reference wave, while the traditional fundamental wave (P-pole) of the motor is equivalent to $2p\tau/2\tau=p$ -th wave, which is now called the fundamental wave, that is, the fundamental wave of the motor in this paper is p -th wave, and the times of other harmonics are correspondingly increased to p times.

3.1. Calculation of magnetic field harmonics of no-load permanent magnet

In Maxwell 2D model, the stator winding current is set to zero, so that the rotor magnetic field waveform can be obtained, which is decomposed into harmonics by Fourier. The amplitude of harmonics is shown in Table 1:

Table 1 Harmonic frequency and amplitude of rotor no-load magnetic field

Polar logarithm of harmonics	Harmonic amplitude /T		
	24 slots	36 slots	48 slots
4	0.929	0.955	0.940
12	0.046	0.127	0.031
20	0.045	0.038	0
24	0	0.0097	0
28	0.061	0	0
32	0	0.064	0
36	0.012	0	0
40	0	0.079	0
44	0.043	0.012	0.042
52	0.047	0.012	0.056
60	0.016	0.019	0
68	0.029	0.068	0
76	0.029	0.016	0
92	0	0	0.048
100	0	0	0.050

Table 2 Harmonic Frequency and Amplitude of Stator Armature Magnetic Field under Rated Load

Polar logarithm of harmonics	Harmonic amplitude /T		
	24 slots	36 slots	48 slots
4	0.1963	0.2009	0.1999
8	0	0.0066	0
16	0	0.0098	0
20	0.0633	0.0086	0.0041
28	0.0389	0.0038	0.0035
32	0	0.0569	0
40	0	0.0226	0
44	0.0407	0.0012	0.0505
48	0	0	0
52	0.0151	0.0037	0.0158
56	0	0.0035	0
64	0	0.0018	0
68	0.0179	0.0269	0.0011
76	0.0043	0.0033	0.0011
92	0	0	0.0183
100	0	0	0.0061

3.2. Calculation of stator armature magnetic field harmonics at rated load

In Maxwell 2D model, the rotor magnetic steel material is set as air, and the rated current is applied to the stator winding, so that the armature magnetic field waveform can be obtained, and then it is decomposed into harmonics by Fourier, and the amplitude of harmonics is shown in Table 2:

3.3. Influence of magnetic steel shape on sine distortion rate of air gap magnetic field

It can be known from formula (1) that the amplitude of radial force wave is directly proportional to the amplitude of air gap magnetic density between stator and rotor, so when the harmonic number of air gap magnetic field is constant, the amplitude of radial force wave can be reduced by reducing the sinusoidal distortion rate of magnetic field, that is, by reducing the amplitude of harmonic magnetic field between stator and rotor. Figs. 1 and 2 are curves of sinusoidal distortion rate of air gap magnetic field of three motors under different pole arc coefficients and different eccentricity of magnetic steel.

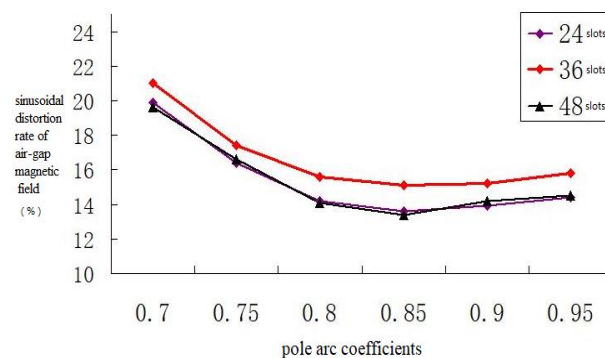


Fig. 1 sinusoidal distortion rate of air-gap magnetic field under different pole slots and different pole arc coefficients

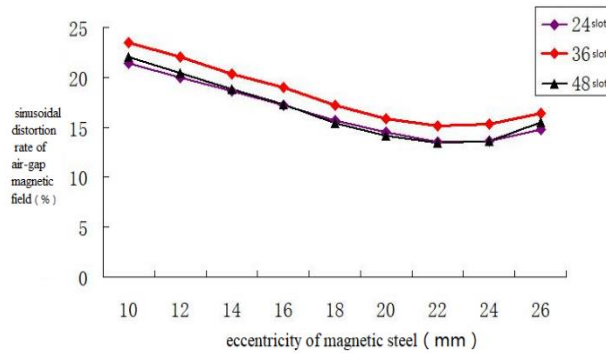


Fig. 2 sinusoidal distortion rate of air-gap magnetic field under different pole slots and different eccentricity of magnetic steel.

As can be seen from the above figure, the harmonic content is different with different polar slots, among which the harmonic distortion rate of slot 24 and slot 48 is the same, and the distortion rate of slot 36 is the largest. With the increase of polar arc coefficient and eccentricity, the sine distortion rate first decreases and then increases. When the polar arc coefficient is 0.85 and the eccentricity is about 22mm, the sine distortion rate is the smallest. Therefore, in order to reduce the influence of radial electromagnetic force on electromagnetic noise of permanent magnet synchronous motor, the pole arc coefficient and eccentricity of magnetic steel should be reasonably selected.

4. Radial force wave analysis

Generally speaking, the bending deformation of the stator core is inversely proportional to the fourth power of the force wave, and directly proportional to the amplitude of the force wave. Therefore, the low-order electromagnetic force wave with larger amplitude is the main source of electromagnetic vibration noise^[7]. Therefore, to reduce the electromagnetic noise of permanent magnet motors, it is necessary to increase the number of electromagnetic force waves, so as to avoid electromagnetic force waves below 4 times, while electromagnetic force waves above 4 times can be neglected in approximate calculation. The harmonic distribution of stator magnetic field and main pole magnetic field of fractional slot winding is denser than that of integral slot winding, and their interaction makes it easier to generate radial force waves of 4 times or less, thus increasing vibration noise. The radial force wave calculation table is based on the formula of harmonic frequency of stator and rotor. $r = \mu \pm \nu$ It is calculated that the radial force waves with times of 4 or less are shown in Table 3~ Table 5.

Table 3 Main force wave times of 8 poles and 24 slots

$\mu \backslash \nu$	4	12	20	28	44	52
4	0					
(-20)			0			
(28)				0		
[-44]					0	
[52]						0

The second-order stator tooth harmonics are listed in the table. Where () represents the first-order tooth harmonic and [] represents the second-order tooth harmonic, the same below.

Table 4 Main force wave times of 8 poles and 36 slots

$\mu \backslash \nu$	4	12	20	24	32	40	44	52	60	68	76
4	0										
-8	-4	4									
16		-4	4								
-20			0	4							
28				-4	4						
(-32)					0						
(40)						0	4				
-44						-4	0				
52								0			
-56								-4	4		
64									-4	4	
[-68]										0	
[76]											0

Table 5 Table of Main Force Wave Times of 8 Poles and 48 Slots

$\mu \backslash \nu$	4	12	44	52	92	100
4	0					
-20						
28						
(-44)			0			
(52)				0		
-68						
76						
[-92]					0	
[100]						0

It can be seen from the table that the times of force waves of 8 poles, 24 slots and 48 slots (integer slot windings) are all zero, and the zero-order force waves will not cause the bending deformation of the iron core, while the influence of higher-order force waves larger than the fourth order can be neglected in the analysis of motor vibration noise. For the 36-slot fractional slot motor, it contains 8 0-order force waves and 13 4-order force waves. This is because the harmonic spectrum of stator and rotor of fractional slot motor is denser than that of integer slot motor, especially the first-order tooth harmonic of stator, which reacts with rotor to generate 4 times of radial force waves, which will cause larger vibration and noise.

5. Analysis of cogging torque

Cogging torque is the torque generated by the interaction between the permanent magnet and the iron core when the permanent magnet motor is not energized. Under the same conditions, the cogging torque of fractional-slot motor is generally smaller than that of integral-slot motor. To weaken the cogging torque, inclined slot is the most effective method^[9]. In this section, the cogging torque of three kinds of permanent magnet synchronous motors with pole slots are simulated and calculated respectively.

5.1. Cogging torque without chute

In Maxwell 2D model, the stator winding current is set to zero, and the cogging torque of permanent magnet synchronous motor with three kinds of pole slots is simulated as follows:

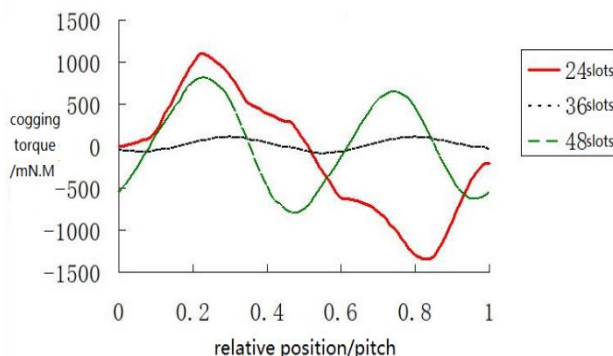


Fig. 3 Cogging torque of different pole slots without chute

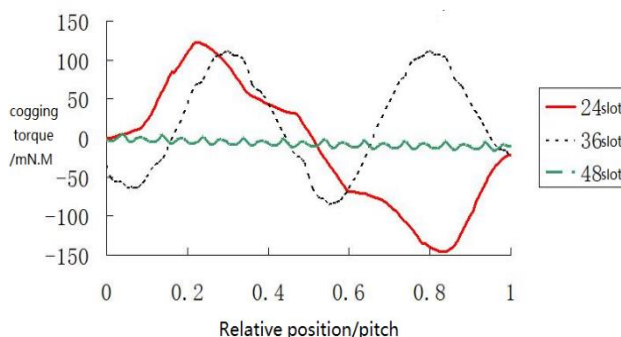


Fig. 4 Cogging torque of 24, 48 slot motor when inclined slot

In the above figure, the maximum cogging torque of 24, 36 and 48 slots is 1100mN.M, 110mN.M and 810mN.M, respectively. The cogging torque of fractional slot is the smallest, and the cogging torque of integral slot is obviously much larger than that of fractional slot.

5.2. Cogging torque in chute

In order to reduce cogging torque, 24-slot and 48-slot motors are respectively inclined by a stator pitch, and the simulation results are shown in Maxwell 2D. The results are as follows:

In the above figure, the cogging torque of 24-slot and 48-slot motors is 145mN.M and 15mN.M respectively, which is significantly lower than that of the non-slotted motor. Among them, the cogging torque of 48-slot motors is already very small, and the cogging torque of 24-slot and 36-slot fractional slots is 110 mN. m. Therefore, the cogging torque of integer slot motor can be weakened by the inclined slot, approaching or exceeding the level of cogging torque of fractional slot motor.

6. Conclusion

In this paper, the air gap magnetic field of the motor under load is divided into no-load permanent magnet magnetic field and loaded armature magnetic field. By calculating the harmonic content of the no-load rotor magnetic field and stator magnetic field under rated load of three permanent magnet synchronous motors with 8 poles, 24 slots, 36 slots and 48 slots, the radial force wave analysis is carried out, and the effects of cogging torque, different pole arc coefficients and eccentricity of magnetic steel on the sinusoidal distortion rate of magnetic field are simulated and analyzed. The analysis and simulation results show that the integer slot motor is better than the fractional slot motor in reducing the radial electromagnetic force that affects the vibration and noise of the motor. The cogging torque of integer-slot motor is larger than that of fractional-slot motor, but it can be significantly reduced by chute measures. The analysis method and results of this paper provide a

reference for the research of vibration and noise of permanent magnet synchronous motor and the design of permanent magnet synchronous motor, and have certain engineering reference significance.

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