Analysis and Optimization of Electromagnetic Noise of Interior Permanent Magnet Synchronous Motor for Vehicle

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Abstract. This paper takes an interior permanent magnet synchronous motor (IPMSM) of electric vehicle as the research object. Firstly, the flux density of the air gap, the electromagnetic force wave on the stator surface and the torque ripple of this motor are analysed from the perspective of electromagnetic field. Secondly, the modal analysis is carried out from the aspect of the structure of the motor, and the electromagnetic noise of the IPMSM under no-load condition and load conditions is studied from the above two aspects. Combined with the electromagnetic simulation software, the order, frequency and amplitude of the electromagnetic force wave under no-load condition and load conditions are calculated accurately. The modal frequencies and structural vibration of the stator are obtained by finite element simulation. To achieve the ultimate effect of reducing electromagnetic noise, the electromagnetic noise is optimized by slotting the outer circle of the rotor. The research provides a way to optimize the electromagnetic noise of the interior permanent magnet synchronous motor (IPMSM) for electric vehicles.

1. Introduction

The electric vehicles worldwide market is highly competitive today. Until now, most studies have focused on the traction performances of the driving motors [1-2]. NVH (noise, vibration and harshness) of vehicles are very important for vehicle manufacturers. It contributes to the safety, quality and driving pleasure [3]. The electromagnetic noise of the motor stems from the electromagnetic vibration, which is produced by the radial electromagnetic force generated by the magnetic field acting on the stator and the rotor. When the frequency and order of the electromagnetic force wave are close to the natural frequency of the stator structure, the motor will resonate and cause the electromagnetic vibration to produce noise. Therefore, the motor electromagnetic vibration and noise is determined by the radial electromagnetic force wave imposing on the structure of stator and the radial modes of stator’s structure. In this paper, the electromagnetic noise and vibration of the interior permanent magnet synchronous motor (IPMSM) in EV under no-load and load conditions are studied and analyzed.

2. Electromagnetic force calculation of motor

Electromagnetic force waves and natural frequencies of motor’s structure are two critical factors that decide the electromagnetic vibration/noise of motor [4-5]. The radial electromagnetic force acting
on the stator teeth is the main cause of electromagnetic vibration/noise [6]. According to Maxwell's law, the radial electromagnetic force of the motor is equal to:

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

Where, $P_r(\theta,t)$ is electromagnetic force density, unit: $N/m^2$; $b(\theta,t)$ is Motor gap flux density, unit: $T$; $\mu_0$ is vacuum permeability, $\mu_0 = 4\pi \times 10^{-7}$.

Space harmonics that induce radial electromagnetic force waves can be classified into 3 types [7]: 1) Produced by stator harmonics; 2) Produced by rotor harmonics; 3) Produced by the harmonics interaction of the rotor and the stator. When the saturation effect of the motor iron core is ignored, the air-gap flux density of the motor depends on the product of the air gap magnetic conductivity and the air gap magnetic potential. The expression is:

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

For permanent magnet synchronous motors under no-load condition, there is no stator current and the air gap magnetic potential are determined only by rotor magnetic potential, so:

$$f(\theta,t) = \sum_{\mu} F_{\mu} \cos(\omega_\mu t - \mu \theta) = \sum_{\mu} F_{\mu} \cos(\frac{\omega_\mu}{p} t - \mu \theta) \quad (3)$$

Where, $\mu$ is harmonic number of magnetic potential, $\mu = (2r+1)p$, $r = 0,1,2,3...$, $w_\mu$ is fundamental frequency angular frequency of current.

When calculating the permeability, only the slotted stator and the smooth surface of the rotor are considered, so the air gap permeability is:

$$\lambda(\theta,t) = \Lambda_0 + \sum_{k=1}^{\infty} \Lambda_k \cos kz\theta \quad (4)$$

By formula (2) ~ (4), the magnetic field distribution of air gap under no-load is obtained as follows:

$$b(\theta,t) = f(\theta,t)\lambda(\theta,t) = \sum_{\mu} A_{\mu} F_{\mu} \cos \left( \mu \frac{w_\mu}{p} t - \mu \theta \right) + \sum_{\mu} \sum_{k} A_{\mu} F_{\mu} \cos \left( \mu \frac{w_\mu}{p} t - (\mu \pm kZ) \theta \right), k = 1,2,3... \quad (5)$$

When the load is running, a symmetrical three-phase current is introduced into the three-phase winding, and the armature reaction magnetic field is:

$$f(\theta,t) = \sum_{\nu} F_{\nu} \cos(w_\nu t - v \theta - \varphi_\nu) \quad (6)$$

Where, $\nu$ is harmonic number of stator winding.

By formula (2)-(6), the air magnetic field under loading:

$$b(\theta,t) = f(\theta,t)\lambda(\theta,t) = \left[ \sum_{\mu} f_{\mu}(\theta,t) + \sum_{\nu} f_{\nu}(\theta,t) \right] \times \left[ \Lambda_0 + \sum_{k=1}^{\infty} \Lambda_k \cos kz\theta \right]$$

$$= \sum_{\mu} A_{\mu} F_{\mu} \cos \left( \mu \frac{w_\mu}{p} t - \mu \theta \right) + \sum_{\mu} \sum_{k} A_{\mu} F_{\mu} \cos \left( \mu \frac{w_\mu}{p} t - (\mu \pm kZ) \theta \right) + \sum_{\nu} \sum_{k} A_{\nu} F_{\nu} \cos \left( w_\nu t - (v \pm kZ) \theta - \varphi_\nu \right) \quad (7)$$

By formula (2)-(7), we can get the motor radial electromagnetic produced by harmonic magnetic field interaction between the rotor and the stator, which is the main cause of the electromagnetic vibration/noise.
vibration and noise for PMSM. Therefore, researches on the motor vibration and noise can be transformed into the analysis of the harmonic magnetic field between the rotor and the stator.

3. The order and frequency of radial force wave

The radial electromagnetic force generated by harmonic magnetic field interaction in air gap is the main cause of the motor electromagnetic noise[8]. The radial force wave generated by the interaction of the rotor harmonic magnetic field and the stator harmonic magnetic field, the radial force wave with large amplitude and low force wave order and polar logarithm plays a major role in the vibration and noise of the motor. So for the radial force wave with large or small order, the radial force wave with small amplitude can be neglected, and the radial force wave order and corresponding radial force wave frequency is:

\[ n = \mu + v \]
\[ f_r = (\mu + 1)f \]

Where, \( \mu \) is harmonic number of permanent magnet magnetic field, \( v \) is harmonic number of stator winding, \( f_r \) is the radial force wave frequency, \( f \) is electrical frequency.

The harmonic number of permanent magnet magnetic field is

\[ h = \frac{1}{2} (2h + 1)p, \quad h = 0, 1, 2, 3... \]

For each integer slot winding at each pole,

\[ \nu = (6k + 1)p, \quad k = \pm 1, \pm 2, \pm 3... \]

Table 1. Radial electromagnetic force order

| \( \mu \) | \( \nu \) | 3 | -15 | 21 | -33 | 39 | -51 | 57 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 3   | 0   |     |     |     |     |     |     |
| 9   | 6   | -6  |     |     |     |     |     |
| 15  | 0   | -6  |     |     |     |     |     |
| 21  | 6   | 0   |     |     |     |     |     |
| 27  | 6   | -6  |     |     |     |     |     |
| 33  | 0   | -6  |     |     |     |     |     |
| 39  | 6   | 0   |     |     |     |     |     |
| 45  | 6   | -6  |     |     |     |     |     |

The order of the radial electromagnetic force wave of the motor is shown in Table 1, from the Table 1, we can know:

1) The 0th order electromagnetic wave is composed of rotor harmonic and stator harmonic, \( \mu / v = 3/3, 15/-15, 21/21, 33/-33, 39/39, 51/-51... \), the interaction generation, the frequency distribution is 0f, 6f, 12f, 18f...

2) The sixth order electromagnetic wave is composed of stator harmonics and rotor harmonics, \( \mu / v = 9/3, 9/-15, 15/21, 21/-15, 27/21, 27/-33, 33/39, 39/-33... \), the interaction generation, the frequency distribution is 2f, 4f, 8f, 10f, 14f...

We mainly observe the gap magnetic density waveform, and analyze the sine of air gap magnetic density under no-load condition of the motor, and reduce the harmonic content of air gap magnetic density. As shown in the Figure 1, rotor outer circular is slotted.
As shown in Figure 2, the magnetic density of the motor air gap is optimized by a circular slotting of the rotor. The no-load air gap flux density and FFT decomposition diagram before and after slotting are as follows (blue is the result after slotting). The THD of no-load air gap flux density decreases from 4.16% before slotting to 2.63% after slotting.

As shown in the Figure 3, the electromagnetic wave under the overload and weak magnetic condition (70kw@8000rpm), the left figure shows the electromagnetic wave spatiotemporal analysis before optimization, and the right figure shows the electromagnetic wave analysis after optimization.

Torque waveform under rated condition (35kw@3000rpm) are compared in Figure 4(a). Torque fluctuation decreases from 2.44% to 1.25%; Torque waveform under overload condition (70kw@3000rpm) are compared in Figure 4(b). Torque fluctuation decreases from 3.24% to 2.44%.

Torque waveform under the rated weak magnetic condition (35kw@8000rpm) are compared in Figure 4(c), the torque fluctuation decreases from 17.3% to 9.8%; Torque waveform under the overload weak magnetic condition (70kw@8000rpm) are compared in Figure 4(d), the torque fluctuation decreases from 26.3% to 16.8%.
4. Model of Permanent Magnet Synchronous Motor

The goal of modal analysis is to simulate natural mode shapes and predict natural frequencies of structure [9]. In this paper, a simplified model of motor is established, and the windings are added as additional mass to the stator teeth.

Table 2. Radial electromagnetic force order

| Components       | Density/(kg/m3) | Modulus of Elasticity/Pa | Poisson ratio |
|------------------|-----------------|--------------------------|---------------|
| Iron core        | 7232            | $E_X=E_Y=2.06E+11, E_Z=1.5E+11$ | 0.3           |
| Equivalent winding | 4926           | $E_X=E_Y=9.5E+10, E_Z=1.4E+10$ | 0.3           |
| Equivalent insulation | 1889       | $E=1.4E+8$               | 0.3           |
| Shell            | 2956            | $E=7.0E+9$               | 0.33          |
| Cover            | 2956            | $E=7.0E+9$               | 0.33          |

The materials with the above-mentioned mechanical parameters, as shown in the table2, were added to each part of the stator core, equivalent winding and shell structure model respectively, and the obtained modes calculated by the finite element method were shown in the Figure 5 below.
Modal analysis focuses on modes consider low-order electromagnetic force waves. The simulation results show that the fourth-order mode and above frequency is high and it is not easy to cause vibration. However, the natural frequencies of second-order mode, third-order mode are lower, the rotational speed range of the motor is 0 to 8000rpm. Because of the existence of the components of the electromagnetic force wave of order 0 and order 6 at multiple frequencies, it may cause greater vibration and noise when the force wave frequency is close to the modal frequency.

5. Finite element analysis and test of noise

When the motor is running at low speed and high torque, the load current is large and it is easy to cause the saturation of magnetic field. In order to study the electromagnetic noise of the motor under different working conditions, the different working point are shown in figure 6.

![Figure 6. Selection of working points in noise analysis cloud map](image)

Finite element analysis was carried out for each working point of the motor, and the noise map was generated. As can be seen from figure 7, slotting on the rotor surface is conducive to reducing the motor noise, especially the lower order noise.

![Figure 7. Noise analysis cloud map](image)

![Figure 8. Motor noise measurement point](image)
As is shown in the figure 8, four microphones are arranged at the position 1 meter away from the enveloped surface of the motor. The measured microphone's bandwidth is set as 25600Hz, the resolution is 1Hz, and the order bandwidth is 0.5 order. After optimizing, noise is reduced by about 4dB.

| Before optimization                  | After optimization                  |
|--------------------------------------|-------------------------------------|
| Heavy line: 100-8000rpm 35kW 60s    | Heavy line: 100-8000rpm 35kW 60s    |
| Thin line: 100-8000rpm 70kW 60s     | Thin line: 100-8000rpm 70kW 60s     |

![Figure 9](image)

6. Conclusion

In this paper, it can be seen from the electromagnetic field analysis and calculation that the slotting on the rotor surface can reduce the motor torque fluctuation, weaken the electromagnetic amplitude and achieve the effect of reducing the noise. It is concluded that due to the high torque/power density and the wide speed operation design of EV motors, it is difficult to analyze the vibration/noise suppression. Since vibration/noise are a comprehensive problem, including motor structure, process assembly, electromagnetic design, and installation and fixation mode, when solving the problem, we must think from multiple perspectives, first determine which direction it belongs to, and then conduct screening and analysis the problem.

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