A harmonic injection method for improving NVH performance of permanent magnet synchronous motor

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Abstract. A harmonic injection method is proposed for reduce permanent magnet synchronous motor torque ripple and noise, which is based on harmonic model of PMSM. The effectiveness of the method is verified by simulation and experiment. It is proved that this method can significantly improve NVH performance of the motor.

1. Introduction
Permanent magnet synchronous motor (PMSM) is widely used in electric-vehicle, because of its high energy density [1]. Torque fluctuation is the main factor for motor NVH performance, so it is great significance to research it.

Scholars do a lot of research on torque ripple of PMSM. On the one hand, the sinusoidal of air gap is improved by slotting stator and optimizing skew pole. Changing stator’s structure influence the loss and efficiency. On the other hand, dead-time compensation and current suppression are used to reduce torque ripple [2]. Due to highly cost and long period for changing the motor body, harmonic injection become the main method.

Based on the mathematical model of PMSM, this paper proposed a harmonic injection method to suppress torque ripple. The effectiveness of the method is verified by simulation and experiment, and the NVH performance of the motor significantly improved.

2. Theoretical basis of the method

2.1. Harmonic model of PMSM
As the main excitation of motor vibration, minimizing torque ripple is an efficient measure. This article adopts Id=0 control strategy, the formula of electromagnetic torque and dq-axis current of PMSM can be written as [3]

\[ T_e = \frac{3}{2} n_p \phi_q I_q \]

When Id=0, the relationship between Te and Iq as follows.

\[ T_e = \frac{3}{2} n_p \phi_q I_q \]

Expand its Fourier series separately, shown as

\[ T_e = T_{e0} + \sum_k T_{ek} = T_{e0} + \sum_k T_{ek} \cos(k\theta - \phi_k) \]

\[ I_q = I_{q0} + \sum_k I_{qk} = I_{q0} + \sum_k I_{qk} \cos(k\theta - \phi_k) \]
The electromagnetic torque includes the average torque and the kth harmonic torque. And the q-axis current same as electromagnetic torque. Making the torque generated by the kth current harmonic offset the existing torque ripple, its amplitude should be equal and the phase is opposite. The formula is as follows.

\[ T_{ek} \cos(k\theta - \phi_k) = \frac{3}{2} n \varphi_i I_q \cos(k\theta - \phi_i) \]  
\[ T_{ek} = \frac{3}{2} \varphi_i I_{qk} \]  
\[ \phi_k = \phi_i + \pi \]  
(5)  
(6)  
(7)

Then, dq-axis voltage can get by next equation.

\[ u_d = -w_e L_d I_q + R I_d \]  
\[ u_q = -w_e L_q I_d + w_e \varphi_f + R I_q \]  
(8)  
(9)

When \( I_d = 0 \), the equation is simplified as follows.

\[ u_d = -w_e L_d I_q \]  
\[ u_q = w_e \varphi_f + R I_q \]  
(10)  
(11)

According above theoretical derivation, the control strategy model is shown as Fig1. Firstly, torque harmonic component is obtained by the filter module. Then compared with the target value, the Iq target value is obtained by PI regulation. Final, using forluma10 and 11 get the dq-axis voltage.

![Figure 1. Harmonic injection system](image)

3. Simulation and experiment

3.1. simulation analysis

In order to verify the effectiveness of the harmonic injection algorithm, this paper compares the simulation analysis for harmonic injection before and after. The three-phase current form motor control software is used as the excitation source. This simulation considers the control strategy and stator slot, which is closer to the actual condition [4]. The specific parameters of PMSM are shown in the table1.

![Table 1. Electromagnetic parameters of permanent magnet synchronous motor.](image)

| Parameter                | Value    | Parameter                | Value    |
|--------------------------|----------|--------------------------|----------|
| Motor moment of inertia  | 0.008/ (kg m²) | Phase resistance         | 0.008    |
| Polar logarithm          | 4        | d-axis inductance         | 4/mH     |
| carrier frequency        | 10KHz    | q-axis inductance         | 5/mH     |

The simulation conditions are 120Nm and 2000rpm.
The harmonic amplitude and phase of harmonic injection before and after are shown in table 2. The amplitude of fundamental current increased from 322.48A to 322.57A, which increased by 0.03%. According to the fig 2, it can be seen that the torque period does not change. And the fundamental frequency amplitude of the motor torque increases from 117Nm to 118.45Nm, which indicates that it has no effect on the efficiency and power performance of the motor.

Because the 5th and 7th current harmonics only affect the 6th torque ripple [5], the 6th torque harmonic is reduced from 1.83Nm to 0.87Nm, which is reduced by 52.5%. The results show that the torque ripple can be significantly improved by matching current harmonics. It can not only maintain the dynamic performance, but also significantly reduce the torque ripple.

### Table 2. Comparison of current and torque before and after harmonic injection

| Current order | 1\(^\text{st}\) | 5\(^\text{th}\) | 7\(^\text{th}\) |
|---------------|----------------|----------------|----------------|
| Current amplitude and phase (Original Plan) | 322.48A/27.2deg | 1.51A/219.4deg | 2.29A/200.3deg |
| Current amplitude and phase (Harmonic Injection) | 322.57A/216deg | 0.27A/239deg | 5.2A/-43.5deg |
| Torque order | 6\(^\text{th}\) | 0\(^\text{th}\) | 12\(^\text{th}\) |
| Torque(Original Plan) / Nm | 117.08 | 1.83 | 0.64 |
| Torque(Harmonic injection) / Nm | 118.45 | 0.87 | 0.72 |

3.2. Experimental research and result analysis

The vibration and noise of the motor are carried on the experimental platform. Test and simulation conditions is same. The current test data is shown in the figure 3.

The 5th current harmonic amplitude is suppressed at 1000-2500rpm, and increased to 5A-6A from 2500rpm to 5000rpm. However, the amplitude of the 7th harmonic current rises to 2A-5A at 1000rpm-
5000rpm. The current harmonic injection value is real-time adjusted to minimize the 6th harmonic of torque.

![Figure 3. Compare current harmonic amplitude between original plan and harmonic injection](image1)

![Figure 4. Current 24th Vibration and noise between original plan and harmonic injection](image2)

From the fig4. it can be seen that the vibration of motor shell decreases at full speed, especially at 3000rpm-4500rpm. For example, at 3700 rpm, the vibration of the motor shell decreased from 0.45g to 0.2g, which decreased by 56%. The 24th noise was improved at full speed, the maximum motor noise decreased from 81db to 68db, which was reduced by 16%.
The results of experiment and simulation are consistent, which prove the effectiveness of the proposed harmonic injection method. Besides, it is shown that the NVH performance can be significantly improved by this method.

4. Conclusion
This paper presents a harmonic inject method for reducing PMSM torque ripple. Through theoretical analysis, simulation and experimental verification, the following conclusions are obtained:

1) Torque ripple is the main excitation source of motor vibration and noise. Reducing the corresponding torque amplitude can significantly improve its vibration and noise.

2) This paper show that the appropriate amplitude and phase of current harmonic can significantly reduce the torque ripple, which provides valuable optimization direction for the subsequent engineering application.

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