Method of Cogging Torque Reduction for Built-in Permanent Magnet Synchronous Motor

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Abstract: Cogging torque is one of the main factors that deteriorate the performance of permanent magnet motor. In order to reduce the cogging torque of built-in permanent magnet motor, a method of optimizing Rib and DminMag to reduce groove torque of built-in permanent magnet motor was proposed. Firstly, the relationship between Rib and DminMag and groove torque is analyzed through the expression of groove torque. Secondly, the optimal Rib and DminMag were found by finite element parametric calculation, and compared with the pre-optimization groove torque, the groove torque was significantly reduced. Finally, the main performance of motor before and after optimization is not significantly reduced.

1. Introduction

In recent years, with the continuous improvement of the performance of permanent magnet materials, permanent magnet motors have gradually occupied various applications, such as electric vehicle industry, high-precision machine tool processing industry and aerospace field, with the advantages of simple structure, high control accuracy and large acceleration. However, due to the existence of the groove torque, the performance of the motor will deteriorate, so that the motor in the process of movement of vibration and noise, especially in low-speed applications more serious. With the rapid maturation of control technology and high performance permanent magnet materials, the advent of permanent magnet motor combined with drive control system is widely used in New energy vehicle market. The permanent magnetic field interacts with the stator grooves, the control accuracy of the system will be caused by generating the cogging torque. Vibration and noise sweep. Groove torque is a high performance permanent magnet motor cannot be ignored in the important issue, reduce or even eliminate the groove turn. Moments will have a profound impact on the industry. In order to reduce the cogging torque, how to reduce the groove torque of permanent magnet motor has always been one of the hot issues studied by scholars at home and abroad. In general, the reduction of cogging torque can be carried out from the optimization of stator side structure and rotor side structure. the literature [1] with a slot number cooperate to reduce the cogging torque the cogging torque, literature [2] by optimizing the pole edge shape to reduce the cogging torque, harmonic cancel Each other out in literature [3] methods to reduce the cogging torque, literature [4] placement Angleby changing the magnet and magnet grouping method to reduce the cogging torque. In this paper, based on the structure of built-in permanent magnet motor, the finite element parameterization of Rib and DminMag parameters was carried out to find a set of data that could reduce the most groove torque, and the comparison analysis with the pre-optimization groove torque showed that the effect of groove torque reduction was obvious. Finally, the comparison of the main motor performance before and after optimization shows that the main motor performance basically remains unchanged.
2. Analytical expression
The groove torque is the circumferential torque generated by the interaction between the magnetic field generated by the permanent magnet and the slotted armature core when the armature windings are not energized. Specifically, the center line of the magnetic pole of the permanent magnet coincides with the center line of the stator slot, the gravity generated by the magnetic flux on both sides of the stator teeth cancel each other, and the torque of the slot is zero. When the permanent magnet rotates, the tangential component force generated at this time cannot completely cancel out. There is a groove torque that tries to bring the permanent magnet back to the aligned position. The groove torque will generate vibration and noise, which deteriorates the motor performance. The groove torque expression can be obtained according to the energy method.

Before studying the cogs torque, the following assumptions are made: (a) the permeability of the armature core is infinite. (b) The permanent magnets have the same shape and size, the same performance and uniform distribution. (c) A permanent magnet has the same permeability as air. (d) Core overlap coefficient is 1. The groove torque expression can be obtained according to the energy method, i.e.$$
T_{cog} = \frac{\pi L_0}{4\mu_0} (R_2^2 - R_1^2) \sum_{n=1}^{Z} nG_n B_n \frac{\sin n\alpha}{2P} \sin n\alpha \alpha
$$

Where Z is the number of stator slots, $L_0$ is the length of stator core, $R_1$ is the outer diameter of rotor, $R_2$ is the inner diameter of stator, P is the polar logarithm, and n is the integer that makes $NZ / 2P$ an integer.

According to Equation (1), the groove torque can be reduced by reducing the $NZ / 2P$ sub-Fourier decomposition coefficient $BnZ/2P$. Groove torque and 6k (k= 1,2,3...) For the built-in permanent magnet motor, the polar arc coefficient can be expressed by the central Angle corresponding to the two arcs.$$
\alpha_p = \frac{\alpha_1}{\alpha_2}
$$

In the formula, $\alpha_1$ and $\alpha_2$ are the central angles of the two arcs. From the polar arc coefficient definition, it can be seen that changing Rib and DminMag is equivalent to indirectly changing the polar arc coefficient, thus reducing the groove torque. By arc, coefficient of definition, can be change by changing the parameters of the rotor pole arc coefficients. For built-in V type permanent magnet motor, the biggest influence parameters for every two adjacent permanent magnets and magnetic bridge, the minimum distance, in this paper, by changing the Rib and the value to change arc coefficient of Dm, resulting in the rotor block under the condition of inclined extremely optimal Rib and Dai, to weaken the cogging torque.

3. Simulated analysis
In this paper, a 48-slot 8-pole built-in permanent magnet motor is taken as an example, and 1/8 model of the motor is selected for simulation analysis. FIG. 1 shows the 1/8 motor model, and the main parameters are shown in Table 1. The simulation method of tooth groove torque is excitation source zero, the speed is set to 1deg_per_sec, the solution time is set to 7.5s and the time step is set to 0.1s. FIG.2 shows the groove torque when Rib=10mm and DminMag=2mm, with peak-to-peak value of 6.1n.m and amplitude of 3.05N.m.

| Parameter Name                  | Value |
|-------------------------------|-------|
| Rated Power /kW               | 40    |
| Stator internal diameter Dos/mm | 144   |
| Outer diameter of rotor Dir/mm | 142   |
| Minimum distance between adjacent permanent magnets Rib/mm | 10    |
3.1 Rib and DminMag parametric analysis
During the parameterization analysis of Rib and DminMag, the value should not be too large or too small. If the value is too large or too small, the motor stiffness and weak magnetic properties will be affected\(^7\), so that the motor cannot run. Rib and DminMag selection range is shown in Table 2.

| Optimize parameters                                      | Start | Stop | Step |
|-----------------------------------------------------------|-------|------|------|
| Minimum distance between adjacent permanent magnets Rib/mm| 9     | 12   | 0.5  |
| Minimum distance between adjacent permanent magnets DminMag/mm | 1     | 3    | 0.5  |

Rib and DminMag were analyzed, and several obvious curves were selected as shown in FIG. 3. It was known that proper Rib and DminMag values would significantly reduce the groove torque, that is, Rib=9mm, DminMag=3mm would significantly reduce the groove torque, improper Rib and DminMag values would increase the groove torque, That is, when Rib=12mm and DminMag=2mm, the groove torque is significantly increased.
Figure 3. Parametric analysis

FIG. 4 shows the comparison of the groove torque before and after optimization. The peak-to-peak value of the groove torque after optimization is 0.84N.m, and the amplitude is 1.68N.m, which is 73.5% lower than that before optimization, and the optimization effect is very obvious.

FIG. 4 comparison before and after optimization

4. Motor performance comparison before and after optimization

Changing Rib and DminMag values may affect other performance of the motor and cause it to decrease, thus the motor will not work properly. Therefore, when we study the groove torque, we must study whether the other parameters of the motor are in the normal range, such as output torque, no-load air gap flux density and no-load back potential. The main performance of the motor includes no-load air gap flux density and no-load back potential. The performance of the motor can be reflected by comparing and optimizing the harmonic distortion rate, which is expressed as\(^{(8)}\):

\[
THD = \sqrt{\sum_{n=2}^{\infty} \left(\frac{B_n}{B_1}\right)^2}
\]

In Formula (3), \(B_n\) is the amplitude of the NTH harmonic wave, and \(B_1\) is the amplitude of the fundamental wave.

The no-load back potential \(E_0\) of the motor is induced by the no-load air gap magneto-dense fundamental wave flux generated by the permanent magnet in the armature winding. The size of the back potential will directly affect the weak magnetic properties of the motor. Rib and DminMag values before and after optimization are shown in Table 3.

Table 3. Rib and DminMag values

| Parameters   | Parameter value before optimization | Parameter value after optimization |
|--------------|-------------------------------------|------------------------------------|
| Rib/mm       | 10                                  | 9                                  |
| DminMag/mm   | 2                                   | 3                                  |
It is generally considered that the higher the sinusoidal of no-load backpotential, the better the motor performance. FIG. 5 shows the no-load back potential of the motor before and after optimization. It can be seen from the figure that the no-load back potential of the motor before and after optimization has a small difference and basically remains unchanged. THD remained largely unchanged.

FIG. 5 Back electromotive force before and after optimization

Air gap is the place where the motor exchanges magnetic field energy. The waveform and amplitude of air gap flux density will affect the control precision and exchange efficiency of the motor. Therefore, air-gap flux density has always been the focus of researchers. Good air-gap flux density waveform and amplitude can improve motor performance and increase motor generation cost. Bad air gap flux density waveform and amplitude will reduce motor efficiency and shorten motor service time. FIG.6 shows the air gap flux density in 1/2 pole distance before and after optimization. It can be seen from the figure that the no-load air gap flux density also remains basically unchanged. THD remained largely unchanged.

FIG. 6 magnetic density comparison of no-load air gap before and after optimization

5. Conclusion
In this paper, Rib and DminMag are optimized to reduce the groove torque of a built-in permanent magnet motor. Through simulation analysis, it is found that when Rib=9mm and DminMag=3mm, the amplitude of groove torque decreases most obviously by 0.84N.m, which is 72.5% lower than 3.05N.m before optimization. Finally, the no-load back potential and no-load air gap flux density of the motor were analyzed before and after optimization, which did not significantly decrease, indicating that Rib and DminMag optimization had little influence on the main performance of the motor.

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