Reducing the Output Torque Ripple in Brushless Permanent Magnet Motor by Proper Slot Shaping in Stator Teeth

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Abstract

Brushless permanent magnet motors have considerable advantages and have found many applications nowadays. Despite the acceptable efficiency and high-power density, the output torque ripple is the main drawback of motor performance. Creating slots in stator teeth reduces the cogging torque of brushless PM motor. It is shown how the slots shape and dimensions affects the generated cogging torque. Cogging torque is calculated by finite-element analysis.

Keywords: PM motor, slot creation in teeth, cogging torque, Finite Element Method.

1. Introduction

Nowadays permanent magnet motors have many applications. The ability to achieve a wide range of constant torque per medium and high speeds, acceptable efficiency at high speeds and the ability to control with the electrical commutation are the effective advantages of this motor [9-6]. High energy density, proper torque density and high torque to inertia ratio are other important features of this motor [4]. Brushless permanent magnet motors are using in wide range of industrial applications. The ability to create additional torque, achieve constant torque over a wide range of speeds during performance in the field weakening mode are other features of permanent magnet motors [3]. Despite the advantages of this motor, some drawbacks are affecting on its performance and one of the important drawbacks of brushless motors is cogging torque. Cogging torque is due to the difference between mechanical and magnetic air gap. It is the main factor of torque ripple and referred to motors structure. Cogging torque is an oscillating torque creating due to variable magnetic permeance between the stator and rotor [8]. Using different pole arc to pole pitch ratio [10-5], using different magnets which have different remanence values [1] and using optimization methods of permanent magnet pole shape [7] are among the strategies that have been examined for cogging torque reduction.

2. The main strategies to reduce the extent variation of cogging torque

Cogging torque is calculated in Equation 1. In this equation, is cogging torque, is air-gap flux, is magnetic path reluctance and is mechanical rotor position. In electromagnetic motors, the magnetic permeability of the core is much greater than the air gap permeability. Therefore, air gap reluctance compare with reluctance of the core magnetic path is ignored and the order of magnetic path reluctance is air-gap flux reluctance.
\[ T_{cog} = -\frac{1}{2} \phi_g^2 \frac{dR}{d\theta} \]  

According to the above equation, reducing the changes of the reluctance flux in air-gap during rotation of the rotor is effective in the cogging torque reduction directly. Main cause of variable magnetic reluctance in the permanent magnet motor structure is the path length difference within the air-gap between fluxes passing through the stator slot opening and through the bottom of the stator tooth. Thus when slot opening's width be less, fluxes number which entered into the slot would be reduced. In addition, by decreasing the width of slot opening, the length discrepancy between the entering fluxes into the bottom tooth and the fluxes passing through slot direction is reduced. Thereby reducing the width of slot opening diminishes the flux’s range of the variation in the air-gap significantly. But on the other hand, the prices of winding and hank inside the slots are dependent on the width of the slot opening directly.

Also excessive reduction in width of the slot opening increases inductance leakage of the winding. The minimum width of the slot span is determined by the permitted range of slot’s inductance leakage increasing and the prices of motor winding. Rotor pole or stator tooth skewing in motor axis direction divides length difference of the existing air-gap from view rotor between the slot and the bottom of the stator tooth on the motor axis. In this way, changes of air-gap’s flux reduce during rotation of the rotor. But doing so, addition to increasing the difficulty of motor construction, cause a drop in the amplitude of torque by changing the inductive voltage variations mode from trapezoidal shape to sinusoidal one partially. Creating the slot in the stator tooth without reducing the width of the slot opening or using the skewing method can decrease the flux variations in the air-gap and consequently changing in the cogging torque. To use this approach some points should take into account, because grooving the stator tooth regardless of how it effects on the air-gap flux changes can increase the amplitude of cogging torque.

3. Examination of creating slot strategy on stator tooth

3.1. Cogging torque variations in the basic structure

For decreasing reluctance changes during rotor rotation, creating some slots on the bottom of motor tooth could reduce average discrepancy of path length of the air-gap magnetic flux in entering into the main slot and into the stator tooth. As it can be observed in fig.1 fluxes that enter into stator tooth from slot path, pass longer length compared to which are entering directly into the tooth in the air-gap. Also number of fluxes which enter into the tooth directly are much further of fluxes which passing through the slot path. But with creating the slots inside the tooth of the stator, the portion of input fluxes into this area must pass the path with same size of the entering fluxes into the main slot and with shrinking of the difference between the numbers of fluxes passing through the tooth and the slot’s opening, the average changes of reluctance versus rotation of the rotor is reduced. Figure 2 shows the variation of the cogging torque in an internal permanent magnet motor with 4-poles and 18-slots with arrangement of the surface magnet and a nominal power of 400 watts. As can be seen in this figure the maximum value of cogging torque is 87 (m N. M).

3.2. Determination of number of slots in stator teeth

During creating slots on stator tooth it should be noted that this action doesn’t increase the symmetry of the motor structure. Symmetry of motor structure has significant impact in changes of magnetic flux path versus any change in rotor position.
A symmetric structure is the structure which the stator tooth is a multiple of the rotor pole numbers. In this structure, redirection of produced flux of each of the poles is in accordance with changes in the generated flux path of other pole. In other words, redirection of flux poles relative to each other is in phase. Therefore, extent of the reluctance variation of air gap flux in this structure is more than the other structures. For example, in a motor with 4 poles and 12 slots, total amplitude of flux variation is four times of amplitude flux changes in each of the poles and the cogging torque in this structure has considerable amount.

A structure with 4-poles and 18-slots is not a complete symmetrical structure because Number of stator slots in this structure is not a multiple of the pole numbers of the permanent magnet rotor. But with create a slot in each stator tooth this structure will be very closer to the 4 poles and a 36 slots that is a perfectly symmetrical structure. On the other hand, cogging torque’s amplitude with a slot on each tooth will increase remarkable in stated structure. Fig. 3 shows cogging torque in 18-slots structure with a slot in each tooth. As in this figure is clear, create a slot in the tooth increase maximum extent of the variation of cogging torque to 209 (m N.M).
Creating two slots in each stator tooth make the motor similar to a 4-pole and 54-slot motor which is identical with symmetry of a 4-pole and 18-slot structure. Using this structure the difference between the fluxes passing through the main slots path and fluxes passing through the teeth path decreases, and variation of air gap reluctance versus rotation of the rotor is reduced. Therefore without increasing motor symmetry amplitude of cogging torque is reduced. Making 3 slots in each tooth has similar effect to single slot. But creating more slots reduces the tooth area and leads to tooth saturation. Therefore, considering the tooth width and the initial slots in this case study the most appropriate strategy is making two slots in each stator tooth.

### 3.3. Determination the dimensions of created slots in stator teeth

To determine the appropriate dimensions for creating two slots in each tooth, the depth and width of the slots in the basic structure has been altered. To do this, first width of the slots equivalent to the main slots is used. Then depth of the created slots compared to tooth’s shoe area is increased and decreased. Also, cogging torque variations is investigated using the tooth depth equivalent to the main tooth’s shoe area, increasing and decreasing the width of slots compared to main slots opening width of the stator. In exchange for the width of slots opening of 2 mm and depth of the bottom area of 2 mm as the dimensions of motor slots, Fig. 4 shows flux’s path inside created slots and beside it cogging torque changes in this structure. Table. 1 gives the dimensions of created slots in each structure and the maximum amplitude of cogging torque versus creating two slots in the stator tooth. Using two slots with the same dimensions as the main stator slots has the greatest effect in reducing cogging torque. Also the maximum amplitude of cogging torque is reduced from 87 mN.M in the basic structure to 3.6 mN.M.

With increasing depth of created slot compared to depth of main slot, part of fluxes which is entered from the bottom of tooth into the stator’s core, pass from upper corner of created slots and increase irregularity in the flux crossing path. So increasing depth of the slot is not effective than using the main slot dimensions in reducing cogging torque. Creating a slot with less depth compared to the main slot depth increase the area of upper section of slot with respect its sides. For this dimension number of flux lines passing through the upper section of slot is higher. Difference between flux paths in main slot and in created slot with lower depth is higher than the difference between flux paths in main slot and in created slot with the same size of main and created slots.
**Figure 4:** Cogging torque variation versus various dimensions of the created slot for each tooth.

**Table 1:** Maximum cogging torque amplitude versus changing dimensions of the created slot for each tooth.

<table>
<thead>
<tr>
<th>Slot dimension</th>
<th>W=2</th>
<th>W=2</th>
<th>W=2.5</th>
<th>W=1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot width: W(mm)</td>
<td>b=2.6</td>
<td>b=1.6</td>
<td>b=2</td>
<td>b=2</td>
</tr>
<tr>
<td>Slot depth: b(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum cogging torque amplitude: (N.M)</td>
<td>6.8</td>
<td>3.8</td>
<td>3.6</td>
<td>70</td>
</tr>
</tbody>
</table>
So the effect of using these dimensions is less than the effect of using main slot dimensions in reducing cogging torque. Also increasing and decreasing the width of created slot cause to decrease and increase the number fluxes passing through the created slot opening in comparison with fluxes passing through the main slot opening. The difference between flux paths through the main slot and created slots becomes more as the slot opening increases. According to the above discussion, If the dimensions of tooth slot are similar to the dimensions of the stator main slot, flux path in both slots are more similar that leads to lower cogging torque.

3.4. Modified slots shape in stator teeth

Magnetic fluxes which passing through the main slot opening, finally cross from the stator tooth. Ideally to keep an invariable distance from each other, these fluxes exit perpendicular to the surface of the rotor. After passing through the air gap and slot opening enter perpendicularly to the bottom area of tooth. To meet the above conditions the path of flux through the main slot can be modeled with circular arches [2]. Fig. 5 shows the path of the fluxes from slots among tooth of the stator. As can be seen in this Figure fluxes in parallel by passing the length with size of the air gap arrive to slot’s opening and from there each one of them proportional to their distance from the edge of slot pass quarter-circle path until they reach the tooth in the created air gap of the slot. The passed length in the air gap by fluxes which are entering into tooth directly is equal to the length of the air gap called \( g \). Using the circular arc approximation for the fluxes passing through the slot, passed length by these fluxes in the air gap is calculated in eq. 2. In this equation \( x \) as shown in Fig. 5 is the distance of flux to the edge of the tooth. If the width of slot’s opening be considered \( w \), the maximum length of the flux in the air gap within slot occurs from the middle of slot’s opening which has been calculated in eq. 3.

Fig. 5 shows the path of the magnetic flux in the created slots of the tooth. As can be seen the basic difference of the flux path in main slots and created slots is in the top section of slots. Unlike the main stator slots, top section material of created slots in the tooth as the lateral section is ferromagnetic material which is used in core. This feature causes fluxes passing through the middle of slots opening distribute uniformly in the top section of slot instead of deviation to its edge. Therefore path of magnetic fluxes in these two slots is different. Fig. 7. shows passed length of fluxes crossing from the slots between the tooth and created slots inside the tooth with considering the slot’s width, \( w \) and slot’s depth of bottom area, \( b \). Fluxes which passing through the main slots of motor, proportional to their distance to the slot sides pass more length in the air gap that maximum length belongs to crossing.
fluxes from middle of the slot. But the air gap length for fluxes passing through the created slots is increasing when entering the bottom of the slot to its top corner and is decreasing when entering the core from top corner of slot to the middle of slot’s top section.

Figure 6: The path of the flux in the created slot on tooth.

Figure 7: Path’s length of flux in the air-gap for fluxes passing from two slots.

Left: slots between the tooth Right: created slots in the tooth

Difference observed in distortion of the passed air gap length between two mentioned slots have caused by crossing fluxes through the two top corner of created slots in the tooth. Reducing this differences with closing the trend of flux length variation in these two types of slots makes further reductions in magnetic fluxes changes in the air gap and the subsequent will led to further reductions in change of air gap reluctance and cogging torque per rotation of the rotor. To do this should reduce length of fluxes passing through the top edges of slot. Half-ellipse is a smooth geometrical shape which without a significant reduction in the volume of slot area could help to less cogging torque changes by filling edges of slot and reducing the air gap for fluxes passing through this. Fig. 8 shows two created slot in tooth with half-ellipse shape and next to it the variation of cogging torque in these structure. As can be observed in this figure by creating two elliptical slot in each tooth ( half-ellipse small diameter equivalent to width of the main slot and half-ellipse large diameter equivalent to depth of the main slot) amplitude of cogging torque has been reduced to 2.49 (m N.M). Comparison of maximum torque amplitude in this structure with the values of Table. 1 show that creating two elliptical slots in each tooth of a 4 poles -18 slots permanent magnet motor has the greatest impact in reducing cogging torque compared to other strategies.
CONCLUSION

Creating slots in the stator tooth can be used as one of the strategies to reduce the cogging torque. If these slots increase the symmetry of motor structure, this approach will raise the amount of cogging torque. Therefore number of created slots in each stator tooth depends on the number of stator teeth and main slot dimensions. Using the same dimensions of the main slot for the tooth slot leads to more reduction of the cogging torque. In this paper discussion of creating new slots in the stator tooth, proper dimensions, and number of new slots are presented for a 4-poles and 18-slots brushless permanent motor. It is shown that shape of new slots affects the flux path through the slots and leads to less cogging torque. Finally, using the elliptical-bottom slot in each stator tooth the maximum amplitude of cogging torque is reduced from 87.6 mN.m in primary structure to 2.4 mN.m in modified structure.

References


