A Novel Method of Reducing the Cogging Torque in SPM Machine with Segmented Stator

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Abstract – The method of stator segmentation is generally taken to enhance the electromagnetic performance of surface-mounted permanent magnet (SPM) machine and reduce its production cost. Based on the model with single slot, the expressions of cogging torque in machine with uniform or non-uniform segmentations are deduced and the optimal combination is given. Moreover, this paper discusses a structured skewing method and put forward a novel stator structure model to reduce the cogging torque in segmented permanent magnet machine. The model can reduce the cogging torque amplitude by shifting a proper angle of slot-opening. The shifting angle formula for analysis can also be suitable for other permanent machine with segmented stator. Finally the results of finite element simulation are given to prove that the method is effective and feasible.

Keywords: SPM machine, Segmented stator, Cogging torque, Slot-opening shift, Finite element analysis

1. Introduction

With the increasing of the NdFeB material's high cost performance, BLDC machine with one-piece stator core structure has been widely used in industrial drive and servo control due to its small size, high efficiency and good dynamic response [1-3]. However, it needs a large area of raw materials during lamination punching, resulting in more leftover materials with lower material utilization and higher manufacturing cost. Besides, the complicated stator winding process and low copper fill factor also reduce the efficiency of the machines [4-6]. In the process of machine design, only when the slot opening is wide enough, can the stator winding be easily winded. So that the air gap field will contribute to high harmonic component and lead to torque ripple. Stator segmentation may cause an obviously high copper fill factor and power density, especially in the process of simplifying stator winding [7-8]. But the additional air gap may appear when the stator is segmented. It has been confirmed that the additional cogging torque components have a strong relationship with the least common multiple of additional gaps and pole numbers.

An analytical prediction of the cogging torque is derived based on the single slot model. As a matter of fact, the influences of the manufacturing tolerances, errors and defects on the machine performance, especially the

cogging torque, are not negligible [11-13]. Due to the manufacturing limits, the additional air gap, even the non-uniform air gap will exists in the process of segmentation, which may have a significant impact on the cogging torque. Literatures [14-15] have a detailed introduction about that, so this article is no longer to repeat.

A large number of scholars at home and abroad have researched on the methods of weakening the cogging torque of machines with one-piece stator core. However, it is rarely mentioned about weakening the cogging torque of machines with segmented stator core structure. Based on the model with single slot, the expressions of cogging torque in machine with uniform or non-uniform segmentation are deduced. Then a novel integrally skewing method and a new stator structure are proposed which can effectively reduce the cogging torque of PM machine with the segmented stator core by proving according to the finite element stimulation.

2. The Influences of Uniform Segmentation on Cogging Torque

Since the cogging torque results from the interaction between permanent magnets and iron core when the machine is energized, and caused by the tangential component of interaction force between permanent magnets and armature, the cogging torque can be synthesized from the single slot model [16], which can be expressed by Fourier series:

$$T_{sc} = \sum_{i=1,2,3,\dots}^{\infty} T_{sci} \sin 2pi\theta \quad (1)$$

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where T_{sc} is the cogging torque caused by the single slot, T_{sci} is the amplitude of the i th harmonic, $2p$ is the pole numbers and θ is the angle between stator and rotor. When the additional air gaps appear due to the segmented stator, the amplitude of cogging torque for the single slot model may change. The cogging torque caused by additional air gaps can be expressed as:

$$T'_{sc} = \sum_{i=1,2,3,\dots}^{\infty} T'_{sci} \sin 2\pi i \left[\theta + \frac{2\pi}{N_s} (k-1) \right] \quad (2)$$

where T'_{sci} is the amplitude of the i th harmonic caused by additional gaps, and N_s is the slot number.

Therefore the cogging torque caused by stator slot can be expressed as:

$$T_{cog} = \sum_{j=1,2,3,\dots}^m \sum_{k=2,3,\dots}^n \sum_{i=1,2,3,\dots}^{\infty} \left\{ T'_{sci} \sin 2\pi i \left[\theta + \frac{2\pi}{N_s} (j-1)n + \frac{2\pi}{N_s} [(j-1)n + (k-1)] \right] \right\} \quad (3)$$

where m is uniform segments and $n=N_s/m$ is the slot numbers per segment.

According to appendix, the synthetic cogging torque can be expressed as:

$$T_{cog} = \sum_{i=1,2,3,\dots}^{\infty} \left\{ \frac{\sin 2\pi p i}{\sin \frac{2\pi p}{N_s} i} [(T'_{sci} - T_{sci}) \sin(2\pi i \theta - \pi \frac{2p}{m} i)] + T_{sci} \frac{\sin \frac{2\pi p}{N_s} i}{\sin \frac{2\pi p}{N_s} i} \sin(2\pi i \theta - \pi \frac{2p}{N_s} i) \right\} \quad (4)$$

Since $\sin(2\pi p i)$ is always zero, the corresponding cogging torque will exist only when $\sin(2\pi p i/m)$ is also zero. That is to say, $2\pi p i/m = k\pi$, where i and k are integers, so:

$$i = \frac{m}{2p} k = \frac{LCM(2p, m)}{2p} k'; k' = 1, 2, 3, \dots \quad (5)$$

In the second part of formula (4), the cogging torque will exist only when $\sin(2\pi p i/N_s)$ is zero.

$$i = \frac{LCM(2p, N_s)}{2p} k''; k'' = 1, 2, 3, \dots \quad (6)$$

Thus, the cogging torque in the SPM machines with segmentation can be expressed as:

$$T_{cog} = \sum_{k'=1,2,3,\dots}^{\infty} m(T'_{sci} - T_{sci}) \sin[LCM(2p, m)k'\theta] + \sum_{k''=1,2,3,\dots}^{\infty} N_s T_{sci} \sin[LCM(2p, N_s)k''\theta] \quad (7)$$

The variation of the cogging torque with uniformly segmented stators can be concluded from formula (7):

Segmenting the stator into m sections may cause the low-order harmonic, which can significantly increase the amplitude of cogging torque.

When $LCM(2p, m)$ is not equal with $LCM(2p, N_s)$, the main component of cogging torque is the additional harmonic order, which is mainly influenced by the segment number.

By using a smaller value of m , the $LCM(2p, m)$ will be kept as same as the original period and the cogging torque will not increase significantly due to the segmented stator.

The fundamental harmonic order depends on the $LCM(2p, m)$.

To verify the analytical prediction, the paper chooses the 10 pole-12 slot SPM machine as the model. Table 1 is the main parameters of machine.

As mentioned, the additional air gaps may occur after segmenting the stator core. According to the study, the additional air gap will have great influence on cogging torque even though the impact on electromagnetic property can be neglected. The additional air gaps still exist although great achievements have been made in stator manufacture as the minimum length of 0.05mm. The stator structures referred in this section are all with uniform segmentation and have the length of 0.05mm. The Fig. 1 shows the 10 pole-12 slot stator core is uniformly segmented into 6 segments.

Table 1. Major parameters of machine

Parameters	Values
Permanent magnet Inner diameter/ mm	63
Permanent magnet outer diameter/ mm	75
Stator inner diameter/ mm	77
Stator outer diameter/mm	140
Air gap/mm	1
Core axial length /mm	65
Pole-pairs p	5
Slot number N	12
Remanence B_r /T	1.2
Additional air gap/mm	0.05
Rotation rate n/rpm	1000

Fig. 1. Section map of machine with the uniformly segmented stator

Fig. 2. Comparison figure of cogging torques

Fig. 4. Harmonic analysis of cogging torque

(a) Stator with 6 segments

(b) Stator with 3 segments

Fig. 3. Flux lines of 10p-12s machines with uniform stator segments

Fig. 2 compares the cogging torques of machines with the uniformly segmented stators and the additional air gap with 0.05mm thick. It can be seen from the cogging torque waveforms that the stator segmentations cause additional air gaps which significantly change the period of cogging torque. As predicted, each electrical period is $LCM(2p, m)/2p$ and each mechanical period is $LCM(2p, m)$. When

$LCM(2p, m)$ decreases, the low-order harmonics are introduced and the corresponding amplitude of cogging torque increases.

It can also be seen that when the $LCM(2p, m)$ is not equal with the $LCM(2p, N_s)$, and the periodicity $LCM(2p, m)$ is equal, the more segments have, the additional air gaps are more and corresponding cogging torque will be larger. Because the main components of cogging torque are caused by additional air gaps. When additional air gaps increase, the stator reluctance will increase more flux linkage will be produced between slot opening and tooth tip, which increase the tangential flux density and has a seriously impact on the cogging torque. Fig. 3 separately shows the flux lines with 3 segments and 6 segments in 10 pole-12slot machines and the influence of lines caused by additional air gaps can be clearly seen.

From the analysis of harmonic spectrum about the cogging torque in Fig. 4, it can be easily seen that the cogging torque contains not only the component produced by original air gaps, but the additional air gap, and the period of which respectively are $LCM(2p, N_s)$ and $LCM(2p, m)$. Thus, the original measures to reduce the cogging torque in the one-piece stator core machines are still effective since they could suppress the component produced by the original air gaps. Besides, for the machine with stator core segments, more attention should be paid to decrease the low harmonic order which is produced by the additional air gaps. To sum up, the segment number is the main factor for the stator with uniform segmentation. Meanwhile, the amplitude of cogging torque is also straightly influenced by the additional air gap number. The optimal choice of the number of uniform segments should be determined according to the largest $LCM(2p, m)$ and the least segments number.

3. The Influence of Non-uniform Segmentation on Cogging Torque

The stator with non-uniform segmentation and the

additional air gaps may cause a more complex situation. We take the condition that the stator is divided into 2 segments to synthesize cogging torque in which the stator segmentation is non-uniform but the air gap is still 0.05mm. If the additional air gaps are set corresponding to the 1st and k_n th slot, the cogging torque can be expressed as:

$$T_{cog} = \sum_{k=2,3,\dots,k \neq k_n} \sum_{i=1,2,3,\dots} \{T'_{sci} \sin 2\pi i \theta + T'_{sci} 2\pi i [\theta + \frac{2\pi}{N_s}(k_n - 1)] + T_{sci} \sin 2\pi i [\theta + \frac{2\pi}{N_s}(k - 1)]\} \\ = \sum_{i=1,2,3,\dots} \{(T'_{sci} - T_{sci})[\sin 2\pi i \theta + \sin(2\pi i \theta + 2(k_n - 1)i\alpha)] + T_{sci} \frac{\sin 2\pi pi}{\sin \frac{2\pi pi}{N_s}} \sin(2\pi i \theta - \pi \frac{2p}{N_s} i)\} \quad (8)$$

where α is the electrical angel of slot pitch.

From the formula of cogging torque with non-uniform segmentation, the following rules can be concluded:

- 1) The component of cogging torque includes the component of air gaps and additional gaps component, and the period respectively are LCM ($2p$, N_s) and $2p$.
- 2) The non-uniform segmentations break the symmetry of stator, and introduce the low harmonic order and signifnificantly increase the cogging torque.
- 3) When the electrical angel between two additional air gaps is 90° , that is $(k_n - 1)\alpha = 90^\circ$, the odd numbers of harmonic order produced by the additional air gaps are eliminated and the cogging torque can be obviously reduced.
- 4) When the electrical angel between the two additional air gaps is 0° or 180° , that is $(k_n - 1)\alpha = 0^\circ$ or 180° , all numbers of harmonic order produced by the additional air gaps are duplicated and the cogging torque has been increased significantly.

In this section, it mainly focuses on the stator with non-uniform segmentation. For example, the 10 pole-12 slot SPM machine's stator is divided into two individual segments and separately has 3 teeth and 9 teeth, which is simplified as 3-9 structure in the following content. Similarly, we also have the 1-11, 2-10, 4-8, 5-7 and 6-6 structures for the stators with non-uniform segmentation.

By comparing the cogging torques of the 10pole-12slot machines in Fig. 6, it can be seen that when the stator is segmented into 3-9 structure, the electrical degree is 90° and the amplitude of cogging torque is the minimum; when the stator is segmented into 6-6 structure, the electrical degree is 180° and the amplitude of cogging torque is maximum, which are as same as the analytical prediction. That can be explained from the flux density. For the 3-9 structure, the amplitude of cogging torque is small because

Fig. 5. Section map of machine with the uniformly segmented stator

Fig. 6. Amplitude comparison of cogging torque between different matches

cogging torque is superposed by a maximum value and a minimum value. However, when the electrical degree between two additional air gaps is 0° or 180° , the cogging torques produced by the two additional air gaps gets to the maximum simultaneously, and therefore the synthesized cogging torque is relatively high. When the stator core is divided into 2 individual segments, most of the problems have been settled since the stator material utilization has been improved and the winding process has become easier. Besides, the assembling of 2 individual stator segments is much easier than the large number of individual stator core segments. However, attention should be paid that although the cogging torque is relatively low when the electrical degree between the two additional air gaps is 90° , the cogging torque with non-uniform segments is still larger than that with the optimal condition of uniform segments, since the 90° electrical degree condition only removes the odd harmonic orders but not the even low harmonic orders.

4. The Stator Connection Position

Fig. 7(a) shows the 10 pole-12 slot machine is divided

into 12 uniform segments and this kind of machine has been analyzed above. Fig. 7(b) shift 5° (mechanical degree) of the stator connection position, as shown in the picture. To find out the influence on PM machine caused by stator connection, Fig. 8 shows the comparison between the machine before shifting and after shifting.

It can be seen clearly that cogging torque does not change with the variation of stators' connection positions. Because connection positions only determines the position of additional air gaps on the back-iron and has little

Fig. 7(a). Connection position is in the center

Fig. 7(b). Connection position has skewed 5°

Fig. 8. Comparison figure of cogging torques

influence on the reluctance. Therefore, as long as the additional air gaps are above on the back-iron, the flux of the machine will not be affected and the cogging torque will not change.

5. Weaken Cogging Torque

The most detrimental effect on the cogging torque by stator segmentation is increasing the period of cogging torque. For the sake of clarity and simplicity of the general solutions in the motor, we usually don't take into account saturated. It makes the well-known skewing method lose the expected strong capability of cogging torque reduction. Because the normal skewing method can only suppress high order harmonic and has a little impact on the main components of machines. However the stator segmentation may introduce low-order harmonic. So no matter how the rotors skew, the cogging torque is unchanged. Based on the common skewing method, this section presents a new stator structure: the whole stator is divided into two parts, and the slot opening has been shifted into a certain degree, as shown in Fig. 9. Like the traditional machines, the slot opening shift only change the phase degree and will not influence the amplitude of cogging torque.

According to the literature [17], without considering the magnetic saturation, the cogging torque in the machines with no segmentation can be expressed as:

$$T_{cog} = \sum_{n=1,2,3,\dots}^{\infty} T_{c,n} \sin(nN_c\alpha) \quad (9)$$

where, $T_{c,n}$ is the cogging torque amplitude of the n th harmonic; N_c is the smallest common multiple between the slot number Q_s and the pole number $2p$; α is the mechanical angle between the stator and the rotor. However, the stator's symmetry has been changed for the machines with stator segmentation. Take a 10 pole-12 slot machine with no segmentation as the example. The stator repeats 12 times within one period. But for the stator with 6 segments (Fig. 1), it repeats only 6 times in one period. Thus, the N_c is not 60 but 30. Due to that, the cogging torque of the machine with segmented stator can be expressed as:

Fig. 9. New stator structure model

$$T_{\text{cog-segment}} = \sum_{n=1,2,3,\dots}^{\infty} T_{N_{cm},n} \sin(N_{cm}n\theta) \quad (10)$$

where N_{cm} is $LCM(2p, m)$. Similar to the ordinary PM machines with no segmentation, the frequency of cogging torque depends on the value of the N_{cm} . And the amplitude of cogging torque depends on the width of the slot opening and gaps. Based on literature [17], higher the value of N_{cm} is, higher the frequency of the cogging torque is, and lower the corresponding amplitude of cogging torque is. So the weakening method is suitable for the proper combination of pole number $2p$ and segment number m . For example, for the 16 pole-18 slot machines with segmented stators, if uniformly divide the stator into 9 segments, the N_{cm} will be 144 and the peak value of resulting cogging torque will be very small. Thus this kind of machine is not discussed in this paper.

This section still takes the 10 pole-12 slot PM machine (the stator is segmented into 6 parts) as the model machine. The upper half of stator slot openings is shifted to the right with β , and the lower half is shifted to the left with β . For this situation, the resulting cogging torque can be expressed as:

$$T_{\text{cog1}} = \sum_{n=1,2,3,\dots}^{\infty} T_{cm,n} [\sin nN_{cm}(\alpha - \beta)] \quad (11)$$

$$T_{\text{cog2}} = \sum_{n=1,2,3,\dots}^{\infty} T_{cm,n} [\sin nN_{cm}(\alpha + \beta)] \quad (12)$$

It can be seen from the formula (11) and (12) that the final cogging torque can be shifted in phase for a certain degree by using the new stator core. Therefore, by combining the two ways of slot shifting (to left and to right) in one stator core, the resulting cogging torque components compensate each other, and the cogging torque can be completely canceled for an optimal shifting angle. Formula (13) shows the expression for resulting cogging torque when two stator structures are combined in one core.

$$\begin{aligned} T_{\text{cog}} &= \frac{1}{2} \sum_{n=1,2,3,\dots}^{\infty} T_{cm,n} \{ \sin[nN_{cm}(\theta - \beta)] + \\ &\quad \sin nN_{cm}(\theta + \beta) \} \\ &= \sum_{n=1,2,3,\dots}^{\infty} T_{cm,n} \sin(nN_{cm}\theta) \cdot \cos(nN_{cm}\beta) \end{aligned} \quad (13)$$

Formula (13), the generated cogging torque of the T_{cm} harmonic is zero, then

$$\cos(nN_{cm} \cdot \beta) = 0 \Rightarrow \beta = \frac{\pi}{2nN_{cm}} \quad (14)$$

According to the formula (14), when the stator is divided into 6 segments and n is 1, the best value of shifting angle is 3° (mechanical degree). Fig. 10 is the comparison figure

Fig. 10. Comparison figure of cogging torques

between the shifting slot opening and unshifting slot opening of cogging torque.

As shown in Fig. 10, the cogging torque amplitude is reduced by 62.4% after the stator shifting.

6. Conclusion

This paper respectively studies the influences on the SPM machines by stator with uniform segmentation and non-uniform based on the model with single slot and the optimal combination is given. The segments number depends on the large $LCM(2p, m)$ and the smaller m when the stator is uniformly segmented; when the stator is non-uniformly segmented, the component of cogging torque produced by additional air gaps should not be the maximum value. The stator with uniform segmentation is more suitable for the practical production application in production cost, procedure and machine performance. Moreover, in order to weaken the cogging torque of SPM machine with the uniformly segmented stator, this paper presents a novel stator core structure and the result of finite element simulation shows that the structure can effectively reduce the cogging torque.

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