Minimization of Cogging Torque for V-Type IPMSM by the Asymmetric Auxiliary Slots on the Rotor

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ABSTRACT The interaction between the permanent magnets and the armature teeth of the PMSM generates cogging torque. It causes vibration and noise. Therefore, this paper establishes the analytical formula of the cogging torque of the motor with auxiliary slots on the surface of the rotor. It shows that reasonable slots can weaken the cogging torque. But it’s essential to determine whether the air-gap flux density harmonics will increase appreciably by slotting. A V-type IPMSM with 8-pole, 48-slot is modeled to analyze the cogging torque. Two new rotor slot shapes—inwardly biased slots and outwardly biased slots—are proposed and researched to reduce the cogging torque of the V-type IPMSM. And they are compared with the traditional symmetrical auxiliary slots. Research shows that the inwardly biased slots and the symmetric auxiliary slots can obtain a better effect on the cogging torque than the outwardly biased slots. By the symmetrical auxiliary slots, the cogging torque is weakened by 75.88%, but the torque ripple increases from 22.36% to 29.60%. By the inwardly biased slots, the cogging torque is weakened by 75.64%, and the torque ripple drops from 22.36% to 12.95%. The inwardly biased slots could successfully suppress the torque ripple.

INDEX TERMS Cogging torque, interior V-type permanent magnet synchronous motor, auxiliary slots.

I. INTRODUCTION

Compared with the induction motor, the interior permanent magnet synchronous motor (IPMSM) has several advantages in terms of efficiency, power density, and weak magnetic property. Compared with the surface permanent magnet synchronous motor (SPMSM), the IPMSM has a slightly higher torque density per unit volume due to the reluctance torque. Thus, the IPMSM has wide applications in electric vehicles [1], [2]. However, the interaction between the permanent magnets and the stator teeth generates the cogging torque. Therefore, reducing the cogging torque that may cause vibration and acoustic noise becomes an increasingly critical issue in the IPMSM [3], [4].

Currently, there are many studies on reducing cogging torque. These methods can be divided into the stator’s and rotor’s optimization [5]. M. Zhou investigated the impact of the pole shape on the cogging torque of the SPMSM [6]. G. Kang put the symmetrical auxiliary slots on the surface of the pole shoe to reduce the cogging torque [7]. T. Nur reduced cogging torque by combining auxiliary slots with magnet edge shaping [8]. C. Peng divided the interior V-type permanent magnet synchronous motor (V-type IPMSM) into two sections from the middle of the axial direction. The angle between the two permanent magnets of a certain V-shaped magnetic pole in each section is different from other magnetic poles in the section. Then the two sections are assembled 180° interleaved. This method results in a different pole arc to pole segment ratio, eliminating cogging torque [9]. Z. Li minimized the cogging torque of the spherical motor by
auxiliary slots [10]. A. Bie’n optimized the cogging torque of the Direct Current Excited Flux Switching Machine by changing the shape of the rotor teeth [11].

In addition, few studies have proposed to optimize the cogging torque of the PMSM by putting slots on the surface of the rotor [12], [13], [14], [15], [16], [17], [18]. However, few studies have been done on the expression of the cogging torque of the IPMSM with auxiliary slots on the surface of the rotor. The literature did not report the reason that rotor slotted can weaken the cogging torque.

In this paper, the analytical formula of the cogging torque of the IPMSM with auxiliary slots on the surface of the rotor is deduced. Considering that the magnetic pole structure of V-type IPMSM is "V" and half of it is embedded in the rotor obliquely, this paper tries to minimize the cogging torque of the V-type IPMSM by asymmetric auxiliary slots.

II. THE GENERATION MECHANISM AND ANALYTICAL FORMULA OF THE COGGING TORQUE
A. THE GENERATION MECHANISM OF THE COGGING TORQUE

The cogging torque is due to the circumferential component of the interaction force between the permanent magnet and the stator teeth. In this paper, a PMSM with 2-pole, 2-slot is used to interpret the mechanism of cogging torque generation.

Figure 1 shows the diagram of the 2-pole, 2-slot permanent magnet motor.

As shown in Figure 1(a), position \(a\), the two stator teeth produce the same but contrary forces on the permanent magnet, so the joint force on the rotor is zero. However, according to the principle of minimum reluctance, the rotor attempts to rotate to the location with minimal reluctance (i.e., position \(c\)). Thus, position \(a\) is unstable.

During the rotor rotation from the position \(a\) to the \(c\), the circumferential component of the force on the permanent magnet is not zero, i.e., there is torque. The direction of this torque is the same as the rotor rotation.

As shown in Figure 1(b), when the middle axis of the permanent magnet is aligned with the edge of the stator teeth (i.e., position \(b\)), the rotor is subjected to the maximum torque.

As shown in Figure 1(c), while the rotor rotates to position \(c\), the circumferential component of the force on the permanent magnet is zero. At this point, the rotor will remain stationary if no external force is applied. However, if there is an external force forcing the rotor to maintain rotating. Because of the principle of minimum reluctance, the stator teeth will prevent the permanent magnet from leaving the minimum reluctance position (i.e., position \(c\)). The direction of torque generated is opposite to the direction of the rotor rotation.

When the rotor keeps rotating to position \(d\), one cycle of the cogging torque curve is complete. A typical cogging torque waveform is shown in Figure 2.
B. THE ANALYTICAL FORMULA OF THE COGGING TORQUE

The cogging torque is the magnetostatic effect due to the interaction between the stator teeth and the permanent magnets. If the magnetostatic energy is $W$, the cogging torque is defined as the negative derivative of $W$ to $\alpha$, the cogging torque $T_{\text{cog}}$ can be expressed as [19]

$$T_{\text{cog}}(\alpha) = -\frac{\partial W}{\partial \alpha}$$  \hspace{1cm} (1)$$

where $\alpha$ denotes the angle between a specific pole shoe center and the corresponding stator tooth center.

The total energy stored in IPMSM can be expressed as

$$W = \int_{V} \left[ \frac{B_{r}(\theta)}{h_{m}(\theta)+\delta(\theta, \alpha)} \right]^2 dV$$  \hspace{1cm} (2)$$

where

- $\mu_0$ is the permeability of air,
- $B_r(\theta)$ is the remanence of the permanent magnet,
- $\delta(\theta, \alpha)$ is the length of the air gap,
- $h_{m}(\theta)$ is the length of magnets in the magnetization direction,
- $\theta$ is the angle along the rotor rotation direction.

2) The Fourier expansion of $B_r^2(\theta)$ is as follows

$$B_r^2(\theta) = B_{r0} + \sum_{m=1}^{\infty} B_{m \alpha} \cos 2m \phi \theta$$  \hspace{1cm} (3)$$

3) The Fourier expansion of $\{h_{m}(\theta)/[h_{m}(\theta)+\delta(\theta, \alpha)]\}^2$ can be expanded as follows [20]

$$\left[ \frac{h_{m}(\theta)}{h_{m}(\theta)+\delta(\theta, \alpha)} \right]^2 \approx 1 - 1.646 \frac{\delta_{\phi}(\theta, \alpha) + \delta_{s}(\theta, \alpha)}{h_{m}}$$  \hspace{1cm} (4)$$

$$+ \left[ \frac{\delta_{\phi}(\theta, \alpha) + \delta_{s}(\theta, \alpha)}{h_{m}} \right]^2$$  \hspace{1cm} (5)$$

3) The expression of the cogging torque

Substituting equations (2), (3), (4), (5), and (6) into (1), the expression of the cogging torque of the motor with slots on the surface of the rotor is as follows

$$T_{\text{cog}} = \frac{Z_1 L_{Fe} \pi (R_s^2 - R_l^2)}{4\mu_0}$$

where $L_{Fe}$ is the length of the stator; $R_i$ is the inner radius of the stator; $R_e$ means the outer radius of the rotor.

From Eq. (7), there are five components of the cogging torque. They can be classified into three categories by the mechanism of generation.

Define the 1st, 2nd, and 3rd components of Eq. (7) as the first type of cogging torque. This kind of cogging torque is generated by the harmonic of $B_r^2(\theta)$ and permeance harmonics caused by the stator slots. The number of periods is determined by the number of stator slots and the number of poles. The constant part $\delta_{\phi}(\theta, \alpha)$ of the permeance harmonics caused by the stator slots and constant part $\delta_{s}(\theta, \alpha)$ of the permeance harmonics caused by the rotor auxiliary slots only affect its amplitude, not its period.

Define the 4th component of Eq. (7) as the second type of cogging torque. This kind of cogging torque is produced by the harmonic of $B_r^2(\theta)$ and permeance harmonics caused by the rotor auxiliary slots. The number of periods is determined by the number of stator slots and the number of rotor auxiliary slots. The constant part $B_{m \alpha}$ of $B_r^2(\theta)$ affects its amplitude, not its period.

Define the 5th component of Eq. (7) as the third type of cogging torque. This kind of cogging torque is produced by the harmonic of $B_r^2(\theta)$, the harmonics of magnetic conductance caused by the stator slots, and harmonics of magnetic conductance caused by the rotor auxiliary slots. The number of periods is determined by the number of rotor poles, the number of stator slots, and the number of rotor auxiliary slots.

4) The influence of the rotor’s auxiliary slots on cogging torque

Eq. (7) indicates that the rotor slotting changes the amplitude and the period of the cogging torque. There is a possibility that the cogging torque is increased by putting the slots on the surface of the rotor. Therefore, the cogging torque can only be optimized by the appropriate parameters.

Minimizing the cogging torque by auxiliary slots on the surface of the rotor changes the harmonic of $B_r^2(\theta)$ and the harmonic of permeance. Therefore, there is a possibility.
that the permeance harmonics are optimized, but the harmonic content of the air-gap flux density is increased. In this case, although auxiliary slots will reduce the cogging torque, the output torque ripple will be aggravated by increasing the harmonic content of the air-gap flux density. Therefore, it’s essential to determine whether the air-gap flux density harmonics will increase appreciably by slotting. Thus, the flowchart for optimizing the cogging torque should be shown in Figure 3.

### III. MOTOR MODELING

The V-type IPMSM of the Prius hybrid vehicle is modeled for analyzing the cogging torque. The mechanical structure parameters of the motor are shown in Table 1. The material of the stator and the rotor is M19_29G. The material of the permanent magnet is N36Z_20. The rated speed of the motor is 3000 r/min. The frequency is 200 Hz.

The literature [21] illustrated that the number of periods of the prototype motor’s cogging torque within a tooth pitch could be expressed as

$$N_P = \frac{2p}{\text{GCD}(Z_1, 2p)}$$  

where $N_P$ is the number of periods of the cogging torque within a tooth pitch. $\text{GCD}(Z_1, 2p)$ is the greatest common divisor between slot number and pole number.

Thus, when the rotor has rotated $360^\circ$, the number of periods of the prototype motor’s cogging torque is 48.

![Flowchart for the optimization of the cogging torque](image)

**Figure 3.** The flowchart for the optimization of the cogging torque.

**Table 1.** Mechanical structure parameters.

| Parameter                                      | Value  |
|------------------------------------------------|--------|
| The number of poles                            | 8      |
| The number of stator slots                     | 48     |
| The number of winding layers                   | 1      |
| The number of conductors per slot              | 9      |
| The number of parallel branches                | 1      |
| The outside diameter of the stator (mm)        | 269.24 |
| The inner diameter of the stator (mm)          | 161.90 |
| The outside diameter of the rotor (mm)         | 160.40 |
| The inner diameter of the rotor (mm)           | 110.64 |
| The axial length of the armature core (mm)     | 83.00  |

![Cogging torque curve](image)

**Figure 4.** The cogging torque of the motor.

![Output torque curve](image)

**Figure 5.** The output torque of the motor.

Figure 4 shows the cogging torque curve of the prototype motor. In order to obtain the instantaneous changes of the magnetic field precisely, the rotor speed is set to 1°/s. Thus, the period of the cogging torque is 7.5 s. Figure 4 illustrates that the peak of the cogging torque is $T_{cog\_peak} = 1.7349$ Nm.

Figure 5 shows the output torque curve of the prototype motor. The rotor speed is 3000 r/min. Figure 5 illustrates that the peak-to-peak value of the output torque is $T_{peak\_peak} = 51.3719$ Nm.
TABLE 2. The optimal cogging torque at different slot positions.

| Slot position angle(°) | Optimum cogging torque (Nm) | Slot depth (mm) | Slot width (mm) |
|------------------------|-----------------------------|-----------------|-----------------|
| 9.25°                  | 0.5656                      | 1.2             | 4.2             |
| 11.25°                 | 0.4426                      | 0.9             | 6.0             |
| 13.25°                 | 0.9952                      | 3.0             | 0.9             |
| 15.25°                 | 1.0914                      | 3.0             | 6.0             |
| 17.25°                 | 1.7294                      | 0.6             | 0.9             |
| 19.25°                 | 1.1898                      | 0.3             | 4.8             |
| 21.25°                 | 1.6807                      | 2.7             | 0.3             |

IV. THE OPTIMIZATION OF THE COGGING TORQUE

The different slot shapes result in different permeance harmonics. Thus, the impact on the cogging torque is different.

In this study, the number of auxiliary slots on the one-pole rotor surface is taken as 2, and the effects of the three slots shown in Figure 6 on the cogging torque are compared.

Figure 6(a) is called inwardly biased slots. Two slots are symmetrical along the $q$-axis axis. And a single slot has no axis of symmetry and therefore exhibits an asymmetric shape.

Figure 6(b) is called outwardly biased slots. Two slots are symmetrical along the $q$-axis axis. And a single slot has no axis of symmetry and therefore exhibits an asymmetric shape.

Figure 6(c) shows the traditional symmetrical auxiliary slots. Two slots are symmetrical along the $q$-axis. A single slot has an axis of symmetry.

The slot positions of the three slots are shown in Figure 6. Select the slot positions as $\Phi=9.25°$, $\Phi=11.25°$, $\Phi=13.25°$, $\Phi=15.25°$, $\Phi=17.25°$, $\Phi=19.25°$, $\Phi=21.25°$ in turn.

The slot depth and the slot width are parametrized. The value range of the slot depth is 0.3~3.0 mm, and the step length is 0.3 mm. The value range of the slot width is 0.3~6.0 mm, and the step length is 0.3 mm.

A. THE EFFECT OF INWARDLY BIASED SLOTS ON THE COGGING TORQUE

At different slot positions, the optimal cogging torque obtained by optimizing the slot depth and the slot width of the inwardly biased slots is shown in Table 2.

It is illustrated in Table 2 that for the inwardly biased slots, the optimal slot position is $\Phi=11.25°$, the optimal slot depth is 0.9 mm, and the optimal slot width is 6.0 mm.

The corresponding peak value of the cogging torque is 0.4226 Nm, 75.64% lower than the motor without slotting.

Figure 7 is the nephogram of the cogging torque of the inwardly biased slots with the slot depth and the slot width when the slot position is $\Phi=11.25°$.

B. THE EFFECT OF THE OUTWARDLY BIASED SLOTS ON THE COGGING TORQUE

At different slot positions, the optimal cogging torque obtained by the slot depth and the slot width of the outwardly biased slots is shown in Table 3.

It is illustrated in Table 3 that for the outwardly biased slots, the optimal slot position is $\Phi=11.25°$, the optimal slot depth is 0.9 mm, and the optimal slot width is 4.8 mm.

The corresponding peak value of cogging torque is 0.7368 Nm, 57.53% lower than the motor without slotting.

Figure 8 is the nephogram of the cogging torque of the outwardly biased slots with the slot depth and the slot width when the slot position is $\Phi=11.25°$. 
C. THE EFFECT OF THE SYMMETRIC AUXILIARY SLOTS ON THE COGGING TORQUE

At different slot positions, the optimal cogging torque obtained by optimizing the slot depth and the slot width of the symmetric auxiliary slots is shown in Table 4.

It is illustrated in Table 4 that for the “symmetric auxiliary slots”, the optimal slot position is $\Phi = 17.25^\circ$, the optimal slot depth is 0.9 mm, and the optimal slot width is 6.0 mm.

The corresponding peak value of the cogging torque is 0.4184 Nm, 75.88% lower than the motor without slotting.

Figure 9 is the nephogram of the cogging torque of the symmetric auxiliary slots with the slot depth and the slot width when the slot position is $\Phi = 17.25^\circ$.

Figures 7, 8, and 9 show that the cogging torque can only be optimized by appropriate slot depth and slot width. But if the slot depth and the slot width are incorrect, the cogging torque will be deteriorated. It verifies the conclusion in Section II that the cogging torque can only be optimize by using appropriate parameters.

Further compare the optimal cogging torque of the three slot shapes with the prototype motor’s cogging torque. It is depicted in Figure 10 that three auxiliary slots could decrease the cogging torque. Moreover, the effect of the inwardly biased slots and the symmetric auxiliary slots on the cogging torque is more prominent. Therefore, the inwardly biased slots and the symmetric auxiliary slots can obtain better cogging torque than the outwardly biased slots.

V. THE PERFORMANCE COMPARISON

Based on the research in Section IV, the auxiliary slots are selected as the inwardly biased slots and the symmetric auxiliary slots. The optimal slot position, slot depth, and slot width of them are used to optimize the cogging torque of the V-type IPMSM.
Table 2 presents that for the inwardly biased slots, the optimal slot position angle is $\Phi = 11.25^\circ$, the optimal slot depth is 0.9 mm, and the optimal slot width is 6.0 mm.

Table 4 presents that for the symmetric auxiliary slots, the optimal slot position angle is $\Phi = 17.25^\circ$, the optimal slot depth is 0.9 mm, and the optimal slot width is 6.0 mm.

Based on the above, the air-gap flux density and the output torque ripple of the motor with the different slots on the surface of the rotor are compared.

A. THE COMPARISON OF THE AIR-GAP FLUX DENSITY

If the air-gap flux density contains a lot of harmonics, it will cause noise and vibration in the motor [22]. Therefore, it is necessary to compare the air-gap magnetic density of three motors.

In the literature [23], the harmonic content in the air-gap flux density can be measured by the air-gap flux density waveform distortion rate $R_{\text{THD}}$. If $R_{\text{THD}}$ is smaller, the harmonic content is smaller, and the air-gap flux density waveform is more similar to the sinusoidal waveform.

$$R_{\text{THD}} = \sqrt{\sum_{n=2}^{\infty} \left( \frac{B_n}{B_1} \right)^2} \quad (9)$$

where $B_n$ is the $n$-th harmonic amplitude of the air-gap flux density, and $B_1$ is the fundamental wave amplitude of the air-gap flux density.

Figure 11 indicates that,

1) The amplitude of the fundamental wave of the air-gap flux density of the unslotted motor is 0.73328 T, and the air-gap flux density waveform distortion rate is 24.49%.

2) The amplitude of the fundamental wave of the air-gap flux density of the motor with the inwardly biased slots on the surface of the rotor is 0.7318 T, and the air-gap flux density waveform distortion rate is 22.36%.

3) The amplitude of the fundamental wave of the air-gap flux density of the motor with the symmetrical auxiliary slots on the rotor is 0.71703 T, and the air-gap flux density waveform distortion rate is 50.60%.

Therefore, the inwardly biased slots weaken both the cogging torque and the harmonics of $B_r(\theta)$. However, although the cogging torque is weakened by the symmetrical auxiliary slots, the harmonics of $B_r(\theta)$ are significantly increased.

Further analysis shows that minimizing of the cogging torque by slotting on the rotor would change the harmonics of $B_r^2(\theta)$.

B. THE COMPARISON OF THE OUTPUT TORQUE

Figure 12 compares the output torque curves of the three motors when the motor’s speed is 3000 r/min.

The torque ripple is defined as the percentage of the difference between the maximum torque $T_{\text{max}}$ and the minimum torque $T_{\text{min}}$ compared to the average torque $T_{\text{avg}}$ [24],

$$T_{\text{ripp}} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{avg}}} \times 100\% \quad (10)$$

As shown in Figure 12 and Table 5,

1) The auxiliary slots on the rotor have a negligible effect on the average value of the output torque.

2) The torque ripple of the motor is reduced to 12.95% by the inwardly biased slots.

3) However, the torque ripple of the motor increases to 29.6% by symmetric auxiliary slots.

Further analysis shows that if the method of minimizing cogging torque by putting slots on the surface of the rotor, there is a possibility that the cogging torque is optimized, but the output torque ripple increases.
The analytical formula of cogging torque and the finite element simulation shows that if putting the slots on the surface of the rotor, there is a possibility that the permeance harmonics are optimized, but the harmonic content of the air-gap flux density increases. In this case, although cogging torque is reduced by the auxiliary slots, the output torque ripple is aggravated by increasing the harmonic content of the air-gap flux density.

REFERENCES

[1] Y. Yang and X. Wang, “Method of cogging torque reduction for brushless permanent magnet synchronous motor,” J. Phys., Conf. Ser., vol. 2170, no. 1, pp. 1–5, Feb. 2022, doi: 10.1088/1742-6596/2170/012046.

[2] Y. Zhang, W. Cao, and J. Morrow, “Design of an interior permanent magnet synchronous motor (PMSM) for EV traction,” Diangong Xuebao, vol. 30, no. 14, pp. 108–115, Jul. 2015, doi: 10.3969/j.issn.1000-6753.2015.14.015.

[3] W. Fei and Z. Q. Zhu, “Comparison of cogging torque reduction in permanent magnet brushless machines by conventional and herringbone skewing techniques,” IEEE Trans. Energy Convers., vol. 28, no. 3, pp. 664–674, Mar. 2013, doi: 10.1109/TEC.2013.2270871.

[4] Z. Q. Zhu and D. Howe, “Influence of design parameters on cogging torque in permanent magnet machines,” IEEE Trans. Energy Convers., vol. 15, no. 4, pp. 407–412, Dec. 2000, doi: 10.1109/60.900501.

[5] A. E. Sayed and E. Erturk, “Minimizing cogging torque in permanent magnet synchronous generators for small wind turbine applications,” Int. J. Renew. Energy Res., vol. 11, no. 2, pp. 691–700, Jun. 2021, doi: 10.23919/CIJCIE.2019.000600.

[6] M. Zhou, X. Zhang, W. Zhao, J. Ji, and J. Hu, “Influence of magnet shape on the cogging torque of a surface-mounted permanent magnet motor,” Chin. J. Electr. Eng., vol. 5, no. 4, pp. 40–50, Dec. 2019, doi: 10.1109/TIE.2021.3063869.

[7] Z. Li, X. Yu, X. Wang, and X. Xing, “Optimization and analysis of cogging torque of permanent magnet spherical motor,” IEEE Trans. Appl. Supercond., vol. 31, no. 8, pp. 1–5, Nov. 2021, doi: 10.1109/TASC.2021.3094445.

[8] A. Bień, T. Drabek, D. Kara, and T. Kolacz, “Reduction of the cogging torques in the DCEFMSM motor by changing the geometry of the rotor teeth,” Energies, vol. 15, no. 7, pp. 1–17, 2022, doi: 10.3390/EN15072455.

[9] C. Bianchini, F. Immovilli, E. Lorenzani, A. Bellini, and M. Davoli, “Review of design solutions for internal permanent-magnet machines cogging torque reduction,” IEEE Trans. Magn., vol. 48, no. 10, pp. 2685–2693, Oct. 2012, doi: 10.1109/TMAG.2012.2199509.

[10] L. Hao, M. Lin, D. Xu, N. Li, and W. Zhang, “Cogging torque reduction of axial-field flux-switching permanent magnet machine by rotor tooth notching,” IEEE Trans. Magn., vol. 51, no. 11, pp. 1–4, Nov. 2015, doi: 10.1109/TMAG.2015.2453340.

[11] M. Hwang, H. Lee, and H. Cha, “Analysis of torque ripple and cogging torque reduction in electric vehicle traction platform applying rotor notched design,” Energies, vol. 11, no. 11, pp. 30–53, Nov. 2018, doi: 10.3390/en11113053.

[12] G.-H. Kang, J. Hur, W.-B. Kim, and B.-K. Lee, “The shape design of interior type permanent magnet BLDC motor for minimization of mechanical vibration,” in Proc. IEEE Energy Convers. Congr. Expo., San Jose, CA, USA, Sep. 2009, pp. 2409–2414.

VI. CONCLUSION

According to the energy method, this paper deduces the expression of the cogging torque of the IPMSM with slots on the surface of the rotor.

Based on the analytical formula of the cogging torque, two new rotor slot shapes—inwardly biased slots and outwardly biased slots—are proposed and researched to reduce the cogging torque of the V-type IPMSM. And they are compared with the traditional symmetrical auxiliary slots.

Research shows,

1) The slots are optimized by the finite element analysis method. The results show that the cogging torque can be reduced by 75.64%, 57.53%, and 75.88% by using the inwardly biased slots, the outwardly biased slots, and the symmetrical auxiliary slots, respectively.

2) Comparing the optimal cogging torque curves of the three auxiliary slots, it is known that the inwardly biased slots and the symmetrical auxiliary slots can obtain a better cogging torque than the outwardly biased slots. Thus, the inwardly biased slots and the symmetric auxiliary slots are used to optimize the cogging torque of the motor.

The performance comparison suggests that,

1) The optimum slot position of the inwardly biased slots is 11.25°; the optimum slot depth is 0.9 mm; the optimum slot width is 6.0 mm. After putting it on the rotor’s surface, the cogging torque’s peak value decreased from 1.73485 Nm to 0.4226 Nm; the air-gap flux density waveform distortion rate decreased from 22.80% to 12.95%.

2) The optimum slot position of the symmetric auxiliary slot is 17.25°; the optimum slot depth is 0.9 mm; the optimum slot width is 6.0 mm. After putting it on the rotor’s surface, the peak value of cogging torque decreased from 1.73485 Nm to 0.4184 Nm; the air-gap flux density waveform distortion rate increased from 24.49% to 51.3719%; the torque ripple of output torque rose from 22.80% to 29.6%.
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