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Research Article

Investigation of the Effect of Notches Opened on the Stator Shoe on the Cogging Torque by Parametric Analysis in Inner Rotor Single-Phase BLDC Motors

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ABSTRACT

An asymmetric air gap is required for the self-starting capability of BLDC motors; however, this condition causes an increase in cogging torque, which negatively affects motor performance. In this study, a parametric analysis of notches opened on the stator legs was conducted to reduce cogging torque in inner rotor single-phase brushless DC (BLDC) motors. In the finite element analyses performed using Ansys Maxwell 2D software, notches with different positions and geometries were modeled on the stator legs in the air gap region. Within the scope of the parametric studies, the effects of the notches were examined in regions where the air gap is both at its minimum and maximum, and the optimum position was determined to be the region with the minimum air gap. During the production phase, a notched stator was manufactured, and the impact of these notches on the production processes and manufacturability was evaluated. According to the simulation results, the newly created notched stator model achieved approximately a 28.5% reduction in cogging torque.

Introduction

Increasing sensitivity to energy efficiency has led to the preference of high-performance three-phase BLDC motors instead of low-efficiency induction motors. In this context, research and development activities in single-phase BLDC motors have also come to the forefront due to cost advantages [1]. Single-phase BLDC motors are widely used in low-power applications thanks to their simple structures, low production costs, and easy manufacturing processes. They have lower efficiency and response time compared to three-phase BLDC motors. However, due to their lower costs, they are preferred in low-power applications such as computer fans, boiler fans, the automotive industry, and household appliances. Especially, the number of transistors and position sensors used in single-phase BLDC motors is significantly less compared to three-phase motors; this ratio is generally around one-third. This situation, along with the reduction in the number of components, significantly reduces costs and makes single-phase BLDC motors a strong alternative to multiphase motors in applications where economic efficiency is prioritized over performance [2-6]. Additionally, their compact size, reliable structures, low maintenance requirements, precise speed control, and potentially high efficiency are other advantages that make these motors attractive [7].

One of the most significant disadvantages of single-phase BLDC motors is the risk of the rotor stopping at dead spots where no torque is produced. To prevent this situation, the air gap between the stator poles must be asymmetric. Otherwise, if the rotor is positioned at a dead spot, the motor may not be able to start. To enable the motor to start on its own, an asymmetric air gap design is preferred to shift the torque position from zero to a non-zero point. However, this asymmetric structure causes the motor to operate in only one direction. While this provides an advantage in applications such as fans that operate unidirectionally, it can lead to torque fluctuations and a decrease in overall efficiency [8-11].

Asymmetric air gap causes the formation of cogging torque within the motor; this situation leads to undesirable effects such as vibration, noise, and torque fluctuations. Various methods have been proposed in the literature to reduce cogging torque. These methods include changing the size of the air gap, applying skew to the rotor or stator structure, redesigning the stator tooth geometry, and opening notches on the stator teeth [12-13].

In this study, the analysis of the inner rotor single-phase brushless direct current (BLDC) motor, whose technical specifications are given in Table 1, was carried out using Ansys Maxwell 2D software. Notches were opened on the stator teeth to reduce the cogging torque, and parametric analyses were conducted on this structure. As a result of the literature review, it was determined that similar studies have largely focused on outer rotor single-phase BLDC motors; no studies aiming to reduce cogging torque in inner rotor single-phase BLDC motors were found. Additionally, existing studies show that notches have been placed in both minimum and maximum air gap regions. In this study, an inner rotor motor model was considered, and the effect of applying notches to both positions as well as placing them only in the minimum air gap region on reducing cogging torque was investigated, and the parametric analysis process carried out in the Ansys Maxwell environment was explained.

Table 1. Specifications of the Single-Phase BLDC Motor.

Parameters	Value	Unit
Input Voltage	300	V_{DC}
Rated Speed	7200	rpm
Rated Current	0.8	A
Stator outer diameter	71	mm
Rotor outer diameter	36.5	mm
Stack length	12	mm
Slot depth	8.5	mm
Minimum air gap	0.5	mm
Maximum air gap	1	mm
Number of magnet poles	4	
Number of stator poles	4	

Cogging Torque

Cogging torque originates from the variations in magnetic permeability and reluctance between the slots and tooth tips of the rotor and stator during the rotor's rotational motion. An increase in the magnitude of this torque raises the amount of torque required for motor startup, which negatively affects the motor's operational performance and efficiency [14].

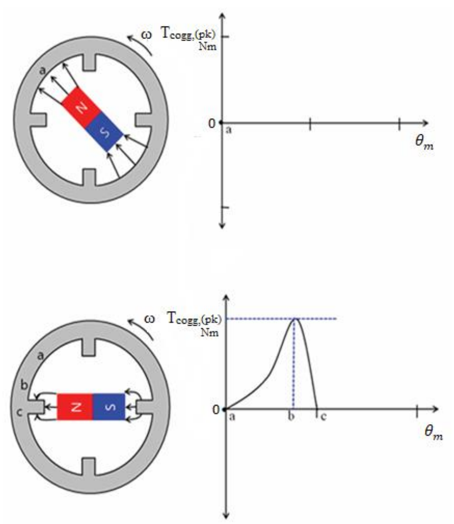


Figure 1. First half cycle of cogging torque

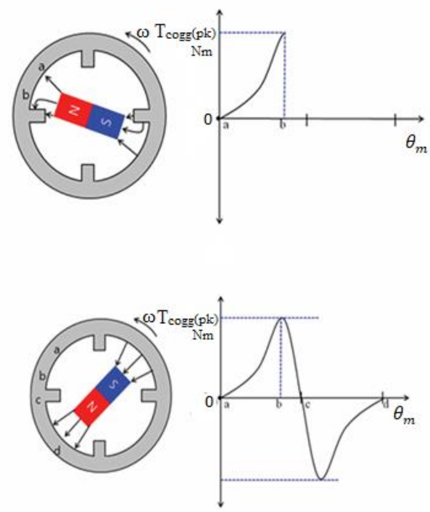


Figure 2. Last half cycle of cogging torque

Figure 1 and 2 shows the distribution of cogging torque at different angular positions of the rotor. Cogging torque is a periodic torque component in permanent magnet synchronous motors, especially brushless direct current (BLDC) motors, caused by variations in magnetic permeability occurring in the air gap between the rotor and stator. This torque arises from the imbalance of magnetic attraction forces resulting from the alignment of the rotor with the stator teeth at certain angles and has direct negative effects on the motor's operational stability at low speeds, noise levels, and efficiency.

The formation of cogging torque can be explained by the change in the system's magnetic energy during the rotor's movement. Even if the motor is not operating, when the rotor is moved, an energy fluctuation occurs in the system due to its relative position with the stator. This energy fluctuation produces a torque that varies depending on the rotor's position. Theoretically, cogging torque is expressed as the derivative of the motor's magnetic energy with respect to the rotor's angular position. This relationship is expressed in Equation 1.

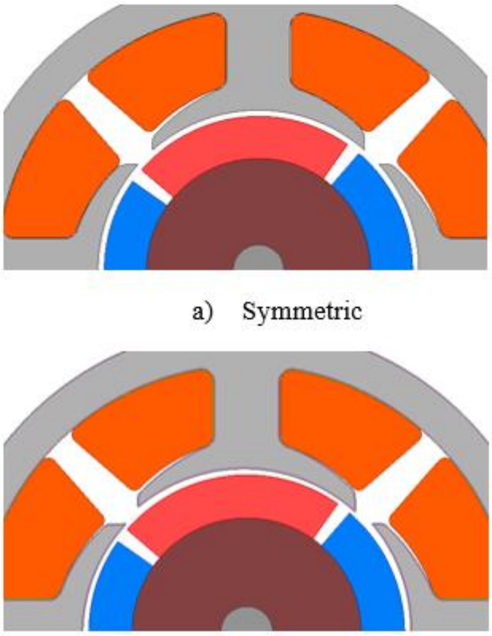
$$T_{cogg}(\alpha) = \frac{\partial W(\alpha)}{\partial \alpha} \quad (1)$$

In this equation, $T_{cogg}(\alpha)$ represents the cogging torque that arises depending on the rotor's angular position; $W(\alpha)$ denotes the amount of magnetic energy possessed by the motor at the given rotor position; and α represents the rotor's mechanical angular position [15].

This equation reveals that cogging torque is entirely of electromagnetic origin. Specifically, parameters such as tooth structure, slot geometry, and air gap distribution affect the position-dependent variation of this energy, determining the magnitude of the cogging torque. Therefore, approaches to reduce cogging torque in motor design, including air gap optimization, changing the tooth angle, or applying notches, aim to regulate this energy variation.

Asymmetric Air Gap in Single-Phase BLDC Motor

Three-phase BLDC motors inherently have a characteristic where torque production is continuous, and therefore, no dead-point problem occurs during startup. In contrast, single-phase BLDC motors experience a dead point when the rotor aligns with the stator at a certain position, resulting in no torque generation. This situation especially causes the rotor to remain stationary at the initial startup moment and prevents the motor from starting on its own.



a) Symmetric

b) Asymmetric

Figure 3. Symmetric and asymmetric geometries of the stator shape

Figure 3(a) shows the structure with a symmetric air gap. In this configuration, when the rotor aligns at an unexpected position, the phases in which the back electromotive force (EMF) and cogging torque both cross zero may coincide. In such a case, since the current flowing through the motor windings approaches zero, electromagnetic torque cannot be generated, which may lead to startup failure. As seen in Figure 4, due to the symmetric design of the air gap in a four-pole single-phase BLDC motor, the torque drops to zero every 90 degrees [16]. Any delay in current during switching may also result in the generation of negative torque.

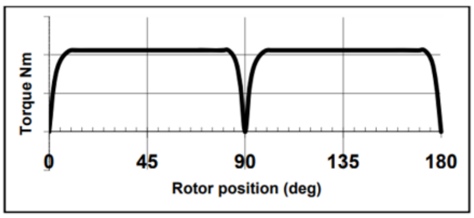


Figure 4. Excitation torque of a symmetric 4-pole single-phase BLDC motor

One of the methods proposed in the literature to solve the startup problem of the motor is to create structural asymmetry by introducing varying air gaps between the stator teeth and the rotor, as shown in Figure 3b. With this method, the possibility of the rotor aligning at a dead point is eliminated, and an initial torque can be generated under all conditions. In designs with an asymmetric air gap, the points at which the back EMF and cogging torque become zero can be separated to prevent their overlap. In this way, the rotor is always aligned in a position where torque generation is possible. This approach enables the generation of initial torque in single-phase BLDC motors, thereby improving startup performance. However, although such asymmetric air gap designs eliminate the dead-point problem, they may lead to an increase in cogging torque and a decrease in average torque, resulting in undesirable effects on motor performance.

Notch Creation and Parametric Analysis in Ansys Maxwell

The amount of variation in magnetic reluctance is a parameter that directly affects the cogging torque. In single-phase brushless direct current (BLDC) motors, the use of an asymmetric air gap increases the reluctance, which in turn leads to an increase in cogging torque. Therefore, reducing the cogging torque is of great importance for the performance of such motors. Another expression related to cogging torque is given in Equation (2). As can be seen, in order to minimize cogging torque, the rate of variation in magnetic reluctance must be minimized [17].

$$T_{cogg} = -\frac{1}{2}\phi_g{}^2\frac{dR}{d\theta} \tag{2}$$

Thanks to the accurate association of variables with geometry in the Ansys Maxwell software, optimization, parametric analysis, and many other engineering applications can be effectively performed. In this study, with an approach not previously found in the literature, an approximate parabolic function was first defined to fit the geometry of the stator shoe. The parabola was expressed as a second-degree polynomial and is given in Equation (3).

$$y = ax^2 + bx + c \tag{3}$$

In Equation (3), the coefficients a, b, and c are parameters that determine the slope, position, and shape of the parabola. If the given curve passes through three known points on a plane, these coefficients can be determined by relating them to the coordinates of the corresponding points. Three different points on the arc of the stator shoe shown in Figure 2 have been selected. These points are defined as follows:

$$(x_1, y_1), (x_2, y_2), (x_3, y_3)$$

If these points lie on the parabola, three equations that satisfy the parabolic expression for each point are given in Equation (4).

$$\begin{cases} y_1 = ax_1{}^2 + bx_1 + c \\ y_2 = ax_2{}^2 + bx_2 + c \\ y_3 = ax_3{}^2 + bx_3 + c \end{cases} \tag{4}$$

Equation (4) forms a system of linear equations containing the coefficients a, b, and c. By solving this system, the coefficients in question are determined, and thus the equation of the parabolic function is obtained.

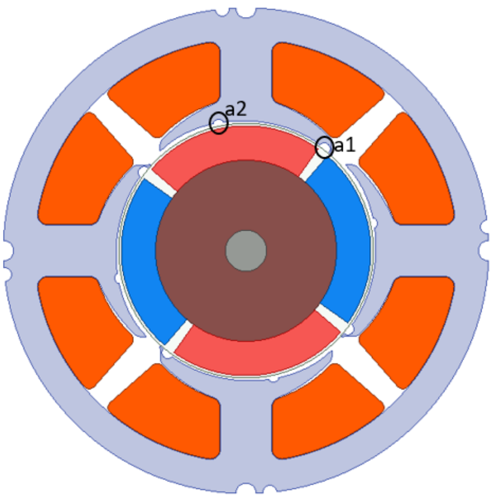


Figure 5. Opening of Two Notches on the Stator Shoe

The number of notches to be placed on the stator shoe is determined based on the suitability of the available area and can be optimized according to system requirements and the results of the analyses conducted. In the Ansys Maxwell environment, the positions of the notches created were parameterized using the derived parabolic equation. The diameters of these notches were defined as variables and used as control parameters during the analysis process.

The diameters of the notches shown in Figure 4 are denoted as a1 and a2, respectively; and two different position parameters, X1 and X2, were defined to determine the locations of these notches on the stator. Here, the parameter X1 is used for the position of notch a1, while X2 is used for the position of notch a2. Specific ranges were defined for these four variables, and a parametric analysis was conducted based on multiple combinations. The analysis parameters were determined as follows:

- X1 and X2: in the range of 2 mm to 12 mm, with a step size of 0.5 mm,
- a1 and a2: in the range of 0.5 mm to 2 mm, with a step size of 0.3 mm.

In line with these definitions, a total of 15876 different combinations were analyzed. As a result of the analyses conducted, the findings related to some combinations with the lowest values in terms of cogging torque are presented in Table 2.

Table 2. Parameter Combinations with the Lowest Cogging Torque

a1 (mm)	**a2** (mm)	**X1**	**X2**	**Cogging Torque** (mNm)
1.7	1.1	11.5	11.5	7.7456
1.7	1.7	11.5	9	7.7669
1.7	1.4	11.5	10	7.7674
1.7	1.1	11.5	12	7.7692
1.7	1.7	11.5	8.5	7.7696
1.7	2	11.5	7.5	7.7839
1.7	1.4	11.5	9.5	7.7844
1.7	1.4	11.5	10.5	7.7904
1.7	1.7	11.5	9.5	7.7918

When the manufacturability and positions of the notches were evaluated, it was observed that opening notches in regions with a wide air gap was not necessary. This is due to the limited effect of the notch in areas with low magnetic flux density. Therefore, it was deemed sufficient to open only one notch in the region where the air gap is narrow. A parametric analysis was conducted for the newly opened notch using only the parameters a1 and X1.

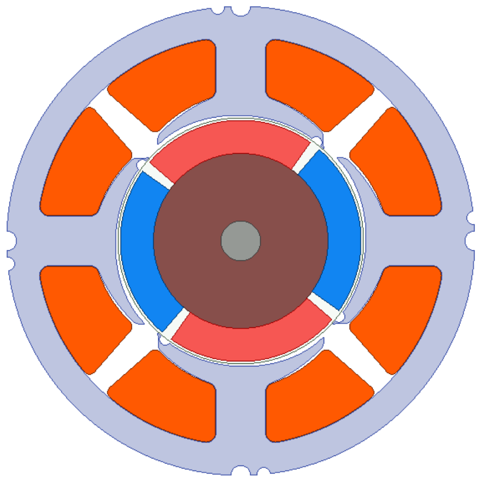


Figure 6. Opening of a Single Notch on the Stator Shoe

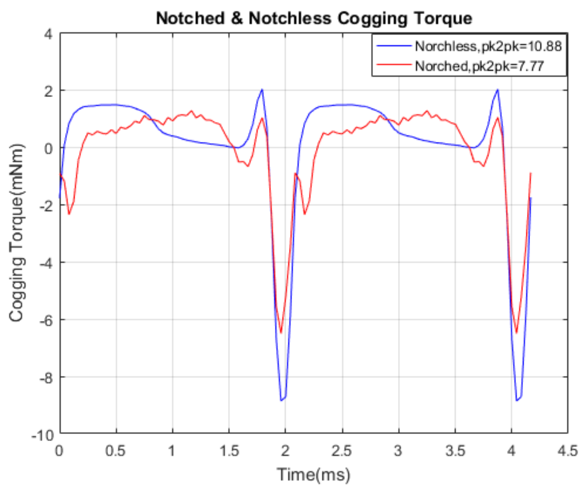


Figure 7. Cogging torque obtained before and after introducing notchesin the stator shoe

As a result of the conducted parametric analyses, the notched stator structure shown in Figure 6 was obtained. This structure was achieved with the notch parameters a1 = 1.7 mm and X1 = 11.4. In Figure 7, the cogging torque values obtained from this notched structure and the unnotched structure are presented comparatively. Upon examining the graph, it can be seen that the peak-to-peak cogging torque in the unnotched structure was 10.88 mNm, while it was reduced to 7.77 mNm in the notched structure.

Examination of the Manufacturability of the Notched Stator Structure

In order to evaluate the possible effects of the notches on the stator sheet shown in the Ansys 2D drawing in Figure 6 such as distance, fracture, bending, or slipping during the manufacturing process the stator sheet was manufactured using the laser cutting method, as seen in Figure 8. Subsequently, the sheet underwent the stacking process, was placed in the winding plastic, and wound. As a result of these applications, it was determined that the opened notches did not cause any mechanical issues or manufacturability obstacles during the production process.

Figure 7. Notched stator in its stacked and wound state

Conclusion

In this paper, the stator geometry of an inner rotor single-phase brushless direct current (BLDC) motor was examined, and a method to reduce cogging torque was developed. As a result of analyses conducted in the Ansys Maxwell 2D environment, an approximate reduction of 3.11 mNm in cogging torque was achieved compared to the initial model, corresponding to an improvement of 28.5%. It was observed that the designed notch structure did not cause any structural issues during the manufacturing process, and its manufacturability was successfully evaluated. The presented method is considered an applicable and effective alternative for reducing cogging torque in single-phase BLDC motors.

Ethics committee approval and conflict of interest statement

There is no conflict of interest with any person / institution in the article prepared.

Authors' Contributions

Both authors contributed equally to the research and manuscript preparation.

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