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Page 64 - 74

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Reducing Cogging Torque in V-Shape BLDC Motors: A FEA Simulation Study on the Impact of Skew Angle

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Abstract

This study thoroughly investigated the impact of stator skew angles on cogging torque in V-shape Brushless Direct Current (BLDC) motors, focusing on electric vehicle applications. Using Finite Element Analysis (FEA) with ANSYS Maxwell, the research assessed how variations in stator core skewness affect torque performance, prioritizing the reduction of cogging torque known for inducing undesirable fluctuations during rotor movement, impacting motor smoothness and noise levels. FEA calculations reveal a significant reduction in cogging torque with the introduction of skew angles to the stator core, enhancing motor efficiency. The study introduces novelty by analyzing the magnetic flux distribution resulting from skew angle variations. Simulation results, particularly on no-load characteristics based on D-axis flux linkage data, offer a comprehensive overview of the motor's response under no mechanical load. Observations showed that D-axis flux linkage values decreased with increasing stator skew angle, indicating a shift in winding angle. This decline in D-axis flux linkage under no-load conditions demonstrates how variations in stator core skew angles impacted magnetic flux distribution, resulting in different values and promoting a more uniform flux linkage waveform. Increased stator core skew angles correlated with reduced flux linkage values, contributing to decreased cogging torque fluctuations and smoother BLDC motor operation.

1 Introduction

The Brushless Direct Current (BLDC) motor, widely used in electric vehicle traction applications, utilizes permanent magnets on the rotor and electronic commutation on the stator. BLDC motors offer several advantages for traction applications, including high starting torque, enabling the motor to overcome initial inertia and friction of the vehicle; high efficiency, reducing energy consumption and extending the vehicle's battery life; and high rpm capabilities, allowing the motor to operate at high speeds for better acceleration and performance. Additionally, BLDC motors require low maintenance as they do not have brushes or commutators that wear out and need replacement. They produce low noise and vibration due to the absence of mechanical contacts that generate sparks and noise [1].

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Two predominant variants of BLDC motors with permanent magnets are utilized in electric vehicle propulsion, specifically Interior Permanent Magnet (IPM) motors and Surface Permanent Magnet (SPM) motors. A comparative analysis between these two types reveals distinct operational differences and advantages. IPM motors are characterized by their high-power density, superior efficiency, and enhanced torque capabilities compared to their SPM counterparts. The permanent magnet is attributed mainly to the IPM motor's rotor design, which integrates embedded or buried magnets. Such an arrangement maximizes magnet utilization, leading to a heightened power output relative to the motor's volume, as documented in recent studies [2]. The strategic distribution of magnetic flux and the optimized placement of magnets in IPM motors significantly bolster their efficiency, a trait that becomes increasingly pronounced at higher operational speeds.

Furthermore, IPM motors are typically associated with reduced torque ripple compared to SPM motors. This advantage is primarily due to the strategic arrangement of magnets within the IPM motor structure. Choosing between different magnet configurations, such as flat-type and V-shape, is pivotal in diminishing cogging torque, contributing to a smoother motor operation. This attribute is particularly beneficial at higher speeds where torque consistency is crucial for optimal performance [3].

BLDC motors characteristically generate three distinct types of torque: mutual, reluctance, and cogging. The cogging torque, an essential aspect of BLDC motors, especially those with an IPM V-shape configuration, arises from the interaction between the permanent magnets (PM) embedded in the rotor and the stator slots [4]. In slot motors, variations in the air gap's permeance, stemming from the interplay between the stator teeth, slots, and rotor, cause flux density fluctuations across the air gap. These fluctuations affect the fundamental air gap flux density and lead to the generation of harmonic components, thereby contributing to torque ripple. Cogging torque is particularly pronounced under high-load, low-speed conditions, where the system's inertia is insufficient to smooth out the motor's output torque effectively. This phenomenon results in a notable torque ripple, which can generate acoustic noise and result in rough motor operation [5].

Extensive research has been undertaken to mitigate cogging torque in BLDC motors, particularly those used in electric vehicle applications. Two primary methods have emerged as effective solutions among the various strategies explored. The first method involves the optimization of the skew angle, which is applied to the stator or the rotor core. The second method entails increasing the air gap between the rotor and stator. Studies focusing on BLDC IPM motors with a V-shape configuration have validated the efficacy of these approaches in reducing cogging torque.

The findings from these investigations reveal that strategic modifications in the BLDC IPM motor design, primarily through skew angle optimization and air gap enlargement, can significantly alleviate cogging torque. Implementing a skew angle on the stator core is particularly effective, potentially reducing the cogging torque [6].

Skewing, defined as the helical twisting of the rotor or stator in electric machines [7], significantly optimizes motor performance, particularly in reducing cogging torque and torque ripple. In theory, fabricating a skew angle on the stator core of a motor is a straightforward process involving twisting thin steel laminations before their stacking and bonding. However, practically implementing the desired skew angle presents particular challenges. One notable challenge is the "cosine effect" of the skew angle on the stator. This effect reduces the cross-sectional area of the stator slots, subsequently necessitating an elongation of the winding wire within these slots. This elongation contributes to increased copper losses within the motor [7]. Such losses are a critical factor to consider, as they directly influence the efficiency and operational costs of the motor. Furthermore, determining the optimal skew angle is crucial. While skewing the stator slots can effectively minimize torque ripple, it also has the potential to reduce the average torque produced by the motor, impacting its dynamic performance [8].

The principal objective of this research is to explore the effects of varying the skew angle on diminishing cogging torque in electric motors. The study aims to provide a detailed analysis of the relationship between skew angle adjustments and cogging torque reduction, based on FEA utilizing Ansys Maxwell towards cogging torque curve, operational torque curve, harmonic analysis, and flux linkage analysis, offering insights into optimal motor design practices for traction applications. Saied et al. employed the skew method in the stator slot opening, utilizing three stator layers with distinct slot designs to mitigate cogging torque[9]. However, this approach entails a more intricate manufacturing process, leading to increased production costs. An alternative method for reducing cogging torque involves skewing the rotor, particularly by segmenting the permanent magnet [10–14].

Nevertheless, rotor skewing may escalate manufacturing costs due to the complexity of magnet shapes, which are not widely available in the market. Therefore, the most effective means of cogging torque reduction appears to be skewing the stator slot. Levin et al. conducted skewing in the stator slot with the condition that the slot opening width equals the interpolar distance, reducing cogging torque [15]. Investigations by Jagiela et al. and Donmezer et al. also delved into the effects of stator skew on motor performance [4] and [6]. Compared to previous research on reducing cogging torque using skew angles on the stator, this paper analyses magnetic flux distribution in the motor resulting from variations in skew angles.

2 Simulation Methods

This work presents the model of a BLDC motor with a skew angle on the stator. The skew angle motor design model is a challenge for the industry in terms of manufacturability. The design of the motor model is shown in **Figure 1**.

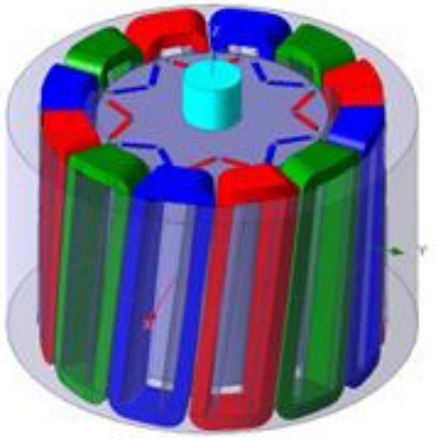

Figure 1. BLDC motor design with stator skew angle

In this research, FEA, utilizing ANSYS Maxwell software, analyzed electric motors. FEA is an exceptionally effective methodology for modelling and simulating the intricate components of electric motors. It facilitates a precise representation of the motor's geometry, enabling a comprehensive understanding of the complex interactions among various elements, including magnetic fields, coils, and additional components. This approach is precious for delving into the detailed aspects of motor performance, explicitly focusing on electromagnetic characteristics. Using FEA allows a thorough exploration of how different design parameters, such as skew angle, influence the motor's performance.

In analyzing the cogging torque in electric machines (T_{cog}), the energy method serves as a fundamental approach. This method involves the utilization of the magnetic co-energy (W) equation, which is intricately related to the movable displacement component (ϑ_r), to derive torque in Equation 1 accurately [16]. The co-energy equation plays a pivotal role in quantifying the interaction between the magnetic fields and the machine's mechanical components, providing a clear understanding of how variations in displacement affect torque generation.

$$T_{cog}(\vartheta_r) = -\frac{\partial W}{\partial \vartheta_r} \tag{1}$$

In addressing cogging torque, the design of stator slots in electric motors encompasses various strategies, including eliminating slots, implementing skewed or uniquely shaped slots, and carefully selecting both slot and pole numbers [17]. Skewing stator slots, a method known for its simplicity and effectiveness, are typically executed during the motor's construction phase. This process involves angling the stator laminations before they are stacked and bonded. In the context of this research, intentional skewing of the stator was adopted as a means to mitigate cogging torque.

This strategy is underpinned by the principle that the uniform distribution of magnetic energy across the air gap significantly influences cogging torque. Consequently, the relationship between the skew angle and the resulting torque can be elucidated in Equation 2, which leverages the concept of periodicity in the motor's operational dynamics [18].

$$T_{skew}(\theta) = \sum_{i=1}^{\infty} K_{sk} T_i \sin\left(iC_p\theta_m + \theta_i\right) \tag{2}$$

In the analysis of motor design, particularly in reducing cogging torque, the skew factor, denoted as K_{sk}, plays a crucial role. It quantifies the degree of skewing applied to the motor's stator or rotor. Additionally, T_i represents the absolute value of the harmonic content, which is critical in evaluating the motor's electromagnetic behaviour. C_p, on the other hand, is defined as the lowest common multiple of the number of stator slots and poles, a factor that significantly influences the motor's magnetic interactions.

During the motor's operation, θ_m represents the mechanical angle between the stator and rotor axes, providing insight into the relative positioning of these components. The phase angle of K_{sk}, denoted as θ_i, is another pivotal parameter in determining the skew factor's influence on motor performance.

In instances where the motor laminations are not skewed, the value of K_{sk} is equal to 1, indicating no skewing. However, in designs where skewing is implemented, K_{sk} deviates from 1, reflecting the extent of the skew applied. The specifics of how K_{sk} is calculated [18], and its impact on motor performance is detailed in Equation 3.

$$K_{sk} = \frac{\sin(i\,C_p\pi\alpha_{sk}/N_s)}{i\,\dfrac{C_p\pi\alpha_{sk}}{N_s}} \quad i = 1,2,3,\ldots \tag{3}$$

The stator skew angle, denoted as α_{sk}, and the number of stator slots represented by N_s [18]. The stator skew angle can be determined using Equation 4.

$$\alpha_{sk} = \frac{360^{\circ}}{N_s N_{period}} \tag{4}$$

N_{period} denotes the cogging torque period in a single-slot pitch. The interaction between the number of slots and poles is critical in electric motor design, particularly in spatial harmonics. These harmonics, which occur at high frequencies, generate rotating magnetic fields with varying speeds and directions. This phenomenon produces undesirable effects, notably iron loss, eddy currents, vibrations, and noise. Each of these issues poses a significant challenge to the efficiency and operational smoothness of the motor. Iron losses and eddy currents, for instance, directly impact the motor's efficiency by increasing energy wastage, while vibrations and noise can affect the motor's performance and user experience.

One effective strategy to address the challenges involves skewing the stator windings. This method reduces the intensity of the harmonic fields without requiring alterations to the stator slots' geometry. By adjusting the orientation of the windings, the interaction of magnetic fields within the motor is modified, consequently diminishing the high-frequency harmonics that lead to the above side effects. An illustrative approach to understanding this concept is studying a full-pitch concentrated winding system characterized by a specific number of turns per coil, denoted as N_k [18]. This setup allows for an in-depth examination of how varying the winding configuration and stator skew angle can influence the motor's electromagnetic characteristics, as detailed in Equation 5.

$$N_k = N_t K_{pk} K_{dk} K_{sk} \tag{5}$$

Where $N_t, K_{dk}, K_{pk}, and\ K_{sk}$ denote the total number of turns within each coil, factors of harmonic distribution, harmonic pitch, and harmonic skew. Torque harmonics analysis examines the influence of harmonic frequencies on the torque produced by the motor. The interaction between the stator's magnetic field and the rotor generates torque ripples due to the presence of harmonics. By adjusting the stator winding's skew K_{sk}, the harmonics' impact on torque production can be mitigated, leading to a reduction in torque ripple and improved motor performance.

In this research, the stator skew angle values varied to observe their impact on a V-shape BLDC IPM motor. The outcomes of the FEA simulations, conducted using ANSYS Maxwell, were analyzed across various aspects, including cogging torque and its harmonics and their effects on the operational torque of the BLDC motor. The results from each skew angle simulation were compared to discern the changes and understand the optimal skew angle that yields the best performance in reducing cogging torque and improving overall motor efficiency. The parameters for the motor design are presented in Table 1, the meshing of the BLDC motor model is shown in Figure 2, and the boundary conditions are in Table 2.

Table 1. Motor design parameter

Parameter	Value
Motor type	BLDC IPM V-Shape
Input voltage (VDC)	72
Number of phases	3
Number of slots	12
Number of poles	8
Stator outer diameter (mm)	175
Rotor outer diameter (mm)	98.8
Lamination length (mm)	105
Magnet thickness (mm)	3
Magnet width (mm)	14.3

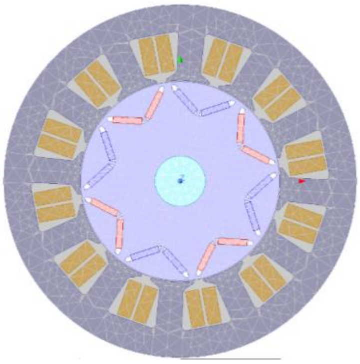

Figure 2. The meshing of the BLDC motor model

Table 2. The boundary FEA simulation

Parameter	Value
Input voltage (VDC)	72
Rated speed (rpm)	5000
Rated torque (Nm)	15

3 Results and Discussion

Applying a skew angle to the stator core in BLDC motors can effectively reduce cogging torque, which is known to cause high levels of vibration and noise [7]. Even a tiny skew angle had been shown to reduce cogging torque, decreasing vibration and noise levels compared to motors without skewing. The FEA simulation results, employing the parameters outlined in Table 1, encompassed the cogging torque curve, operational torque curve, harmonic analysis, and flux linkage analysis.

3.1 Cogging torque analysis

In this research, various stator skew angles, specifically 0°, 5°, 10°, and 15°, were used for design optimization. With the increase in the skew angle, a continual reduction in cogging torque was observed. Ultimately, the aim was to achieve a cogging torque of less than 10% of the nominal torque. Although some residual cogging torque remained, it was within the predetermined limits. Each stator skew angle was simulated using FEA, and the resulting cogging torque was analyzed to select the best angle for comprehensive motor performance analysis, aiding in prototype development considerations. Cogging torque data was obtained from the FEA simulations with varied stator skew angles, as shown in Table 3.

Table 3. FEA simulation results

Parameter	Stator Skew Angle			
	0°	5°	10°	15°
Torque Ripple (Nm)	6.144	4.322	2.126	0.006
Cogging Torque (Nm)	4.888	3.251	1.353	0.000
Average Torque (Nm)	16.366	16.338	16.284	16.252
Shaft Torque (Nm)	15	15	15	15
Output Power (kW)	7.931,3	7.933,2	7.932,8	7.930,4

Table 3 provides simulation results of a BLDC motor’s performance across different stator skew angles. These angles ranged from 0° to 15°, and their effects on various parameters such as torque ripple, cogging torque, average torque, shaft torque, output power, and efficiency were detailed. The data showed that as the skew angle increased from 0° to 15°, there was a substantial decrease in both torque ripple and cogging torque. The torque ripple reduced dramatically from 6.144 Nm at 0° to a negligible 0.006 Nm at 15°. Similarly, cogging torque decreased from 4.888 Nm at 0° to effectively zero at 15°. The curve of cogging torque with stator skew angle variations is shown in Figure 3. These results highlight the effectiveness of skewing the stator to mitigate torque irregularities and vibrations affecting motor smoothness and noise levels.

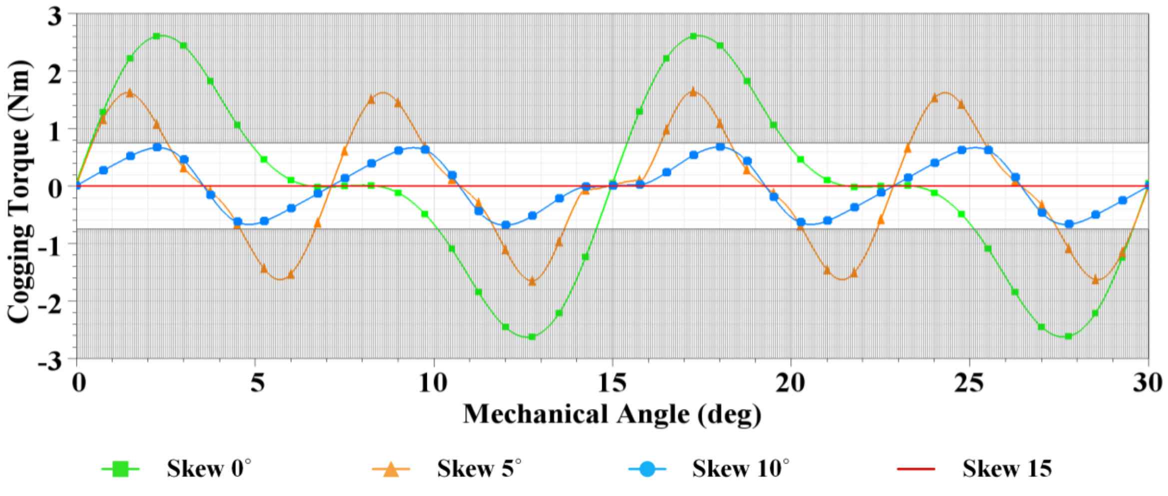

Figure 3. Cogging torque curve with stator skew angle variations

The average torque remained relatively stable across all skew angles, indicating that the skewing process did not significantly affect the motor's ability to produce consistent torque. The shaft torque stayed constant at 15 Nm, which implied that the motor's capacity to deliver torque to the load was unaffected by the stator skew angle. The output power showed a marginal decline as the skew angle increased, but the changes were slight, suggesting that the impact on the motor's power output was minimal.

The simulation results revealed that at a 15° skew angle, cogging torque in a BLDC motor with an 8-pole and 12-slot configuration can be effectively eliminated, as demonstrated by the simulation data and aligned with Equation 4. Cogging torque occurs when the magnet positions on the rotor align with the teeth or stator poles, independent of current flow. The maximum value of cogging torque is achieved when the interpolar axis is parallel to the stator end, causing the most significant change in magnetic energy. The 15° skew angle introduces a spatial displacement of the rotor magnets concerning the stator slots, mitigating the cogging effect. This angular skew disrupts the alignment between the rotor magnets and the stator teeth, resulting in a more continuous and smooth motor rotation.

The simulation data supports using stator skewing to reduce cogging torque and torque ripple in BLDC motors without adversely impacting average torque, shaft torque, or overall efficiency. This analysis would be crucial for optimizing motor design for specific applications, especially where noise and vibration are critical considerations.

The implementation of skewing in the stator core of a BLDC motor can effectively reduce cogging torque, which in turn influences torque fluctuations during operation [7]. The reduction in cogging torque lessens the torque ripple as the motor functions. This effect is observable in the torque curve derived from FEA simulations, as shown in Figure 4.

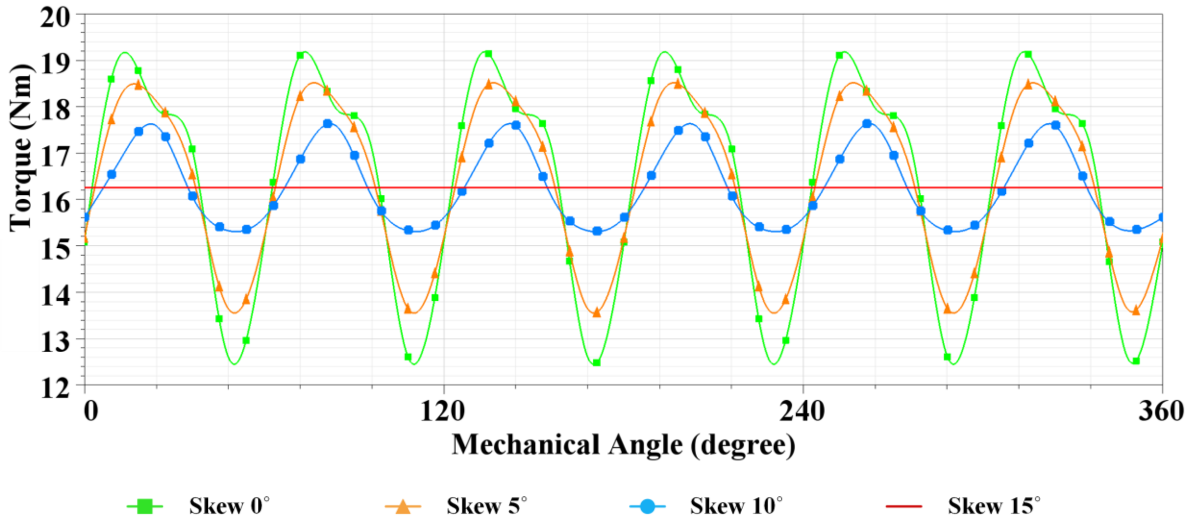

Figure 4. Torque curve with stator skew angle variations

Figure 4 shows that the motor's torque curve became smoother and more stable as the skew angle increased from 0° to 15°. A significant torque fluctuation at a skew angle of 0° indicated a high cogging torque level. As the skew angle increased to 5° and 10°, the torque curve fluctuations diminished, showing a decrease in cogging torque, as shown in Figure 4. The torque fluctuations were nearly imperceptible at a skew angle of 15°, as shown in Figure 5, suggesting that cogging torque can be minimized to near zero. This reduction in cogging torque has a beneficial impact on motor operation, leading to smoother performance, reduced vibration and noise, and potentially increasing the motor's lifespan and user comfort in traction applications such as electric vehicles.

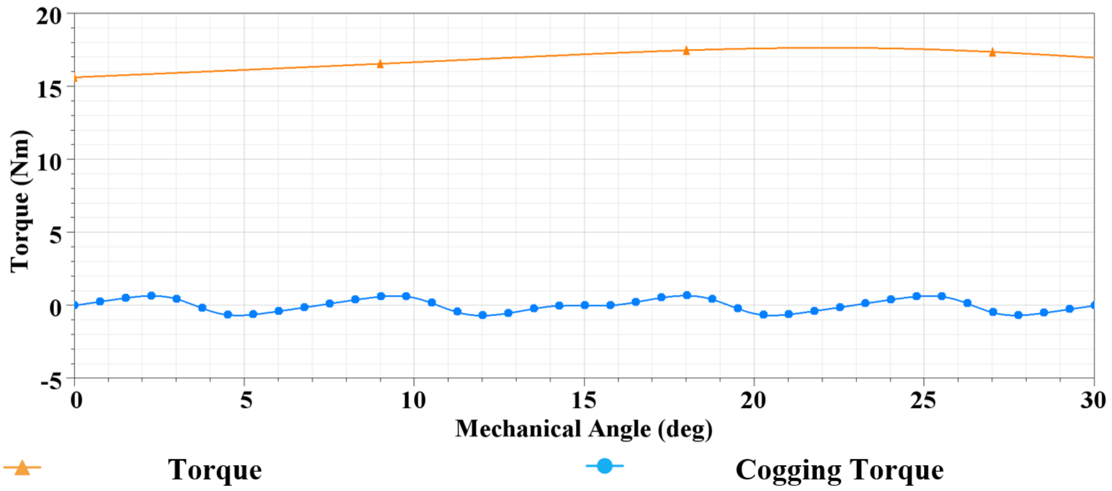

Figure 5. Torque and cogging torque curve in 10˚ stator skew angle

3.2 Harmonics analysis

In the analysis of harmonic torque distribution in BLDC motors, as shown in Figure 6, the employment of stator skew angles played a pivotal role in minimizing torque ripple, which directly translated to reduced vibration and acoustic noise during motor operation. The bar graph under examination delineated the harmonic torque amplitudes across various harmonic orders, stratified by skew angles of 0°, 5°, 10°, and 15°. The torque amplitude at each harmonic order is visually encoded with distinct colour representations, facilitating a clear comparative assessment.

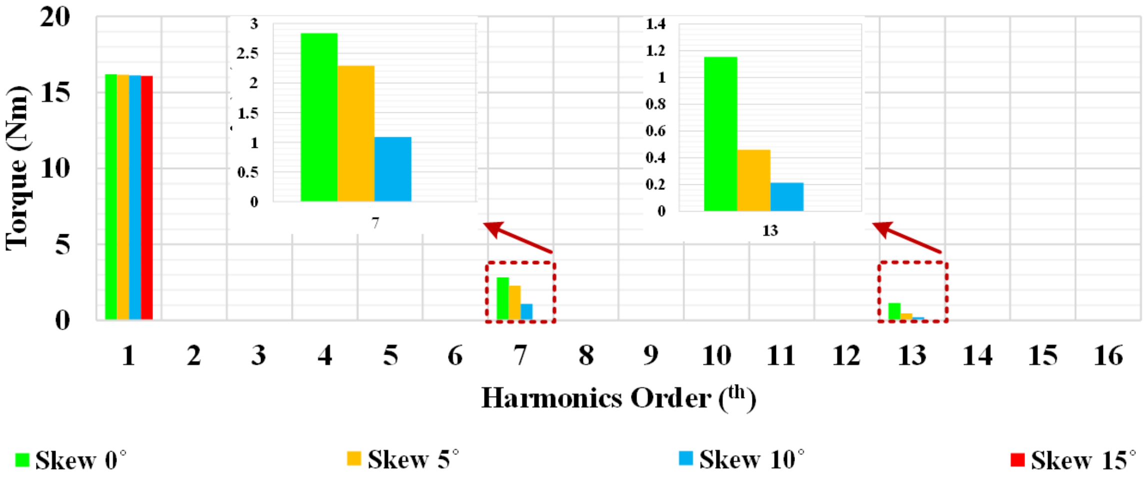

Figure 6. Torque harmonics bar curve with stator skew angle variations

Based on the simulation results of a 10° skew angle on the stator core in ANSYS Maxwell, it was observed that the torsional wave harmonics at the 7th order amounted to 1.1 Nm. In comparison, simulations with a 5° skew angle on the stator core resulted in a higher value of 2.29 Nm in the same order. Similarly, for the 13th order, a 10° stator core skew angle yielded a harmonic torsional wave of 0.21 Nm, while the 5° skew angle simulation produced a higher value of 0.46 Nm. The increase in the stator core skew angle from 5° to 10° led to more than 50% reduction in torsional wave harmonics at the 7th and 13th orders. Moreover, introducing a 15° skew angle in the stator core successfully eliminated the harmonics at the 7th and 13th orders in the torsional wave. This demonstrates the substantial effect of increasing the stator core skew angle on reducing harmonics in the torsional wave. The decrease in torsional wave harmonics can be directly associated with the attenuation of torque fluctuations occurring in the BLDC motor.

The simulation results indicated that altering the stator core skew angle minimizes torsional wave harmonics. The reduction in harmonics, especially at critical orders like the 7th and 13th, corresponds to a notable decrease in torque fluctuations within the BLDC motor, emphasizing the importance of carefully selecting and optimizing the stator core skew angle for improved motor performance.

3.3 Flux linkage analysis

The emergence of cogging torque is attributed to imperfections in the magnetic flux distribution within a motor's stator and rotor windings, particularly under no-load conditions. Therefore, analyzing flux linkage characteristics under no-load becomes crucial to comprehend cogging torque, as it describes the magnetic flux characteristics penetrating the motor windings without mechanical load.

Implementing skew angles to reduce cogging torque significantly impacts the magnetic flux distribution in the motor. Skew angle implementation causes a shift in the angle between the windings and the rotor axis, affecting the magnetic flux distribution. Thus, variations in skew angles provide insight into changes in magnetic distribution that can minimize cogging torque.

Under no-load conditions, the current flowing in the synchronous motor rotor is zero, allowing the flux linkage of the Q-axis (Ψq) to be zero or close to zero. Therefore, in the analysis of no-load flux linkage characteristics, the simulation focuses on the flux linkage of the D-axis. Simulation results of FEA flux linkage of the D-axis with varying skew angles can be seen in Figure 7.

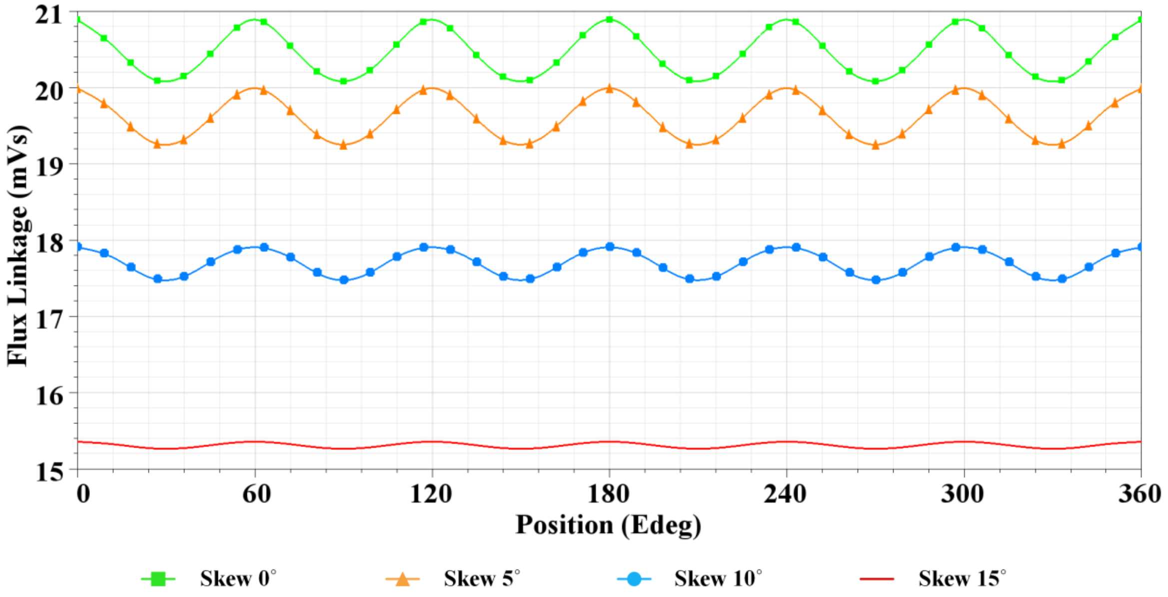

Figure 7. Graph of flux linkage D-axis with variation of skew angles on the stator core

Simulation results of no-load characteristics based on D-axis flux linkage data provide an overview of the motor's response under no mechanical load. In this simulation, it was observed that the D-axis flux linkage values decreased with an increase in stator skew angle, implying a shift in the winding angle in the motor. At a 0° skew angle, the D-axis flux linkage reached the highest value of 20.455 mVs, but decreased at skew angles of 5°, 10°, and 15° to 19.605 mVs, 17.700 mVs, and 15.315 mVs, respectively.

The decrease in D-axis flux linkage under no-load conditions explains that variations in stator core skew angles impact the magnetic flux distribution within the motor, resulting in different values of D-axis flux linkage. Figure 7 illustrates that an increase in the stator core's skew angle correlated with a reduction in flux linkage value and a more uniform flux linkage waveform. Such an increase in the skew angle enhances the uniformity of magnetic flux distribution across the windings, contributing to decreased cogging torque fluctuations and promoting the smoother operation of the BLDC motor.

4 Conclusions

The study demonstrated that implementing stator skew angles in BLDC motors significantly impacted torque behaviour, cogging torque, and harmonic distortion. FEA established that introducing a 15° skew angle eliminated cogging torque, substantially improving the overall torque profile. Comparative FEA simulations showed a progressive reduction in cogging torque with increasing skew angles, reaching a noteworthy decrease of approximately 72% at 10° and achieving near elimination at 15°. Notably, the 15° skew angle proves highly effective in minimizing torque irregularities. The study highlights the significant influence of skew angles on harmonic distortion, particularly at the 7th and 13th orders, as evidenced by a consistent reduction in harmonic amplitudes with increased skew angles. Furthermore, examining no-load characteristics based on D-axis flux linkage data reinforces these findings, providing valuable insights into the motor's response without mechanical load. The observed decrease in D-axis flux linkage values with an increase in stator skew angle indicates a corresponding shift in winding angle within the motor. This decrease under no-load conditions elucidates the impact of stator core skew angles on magnetic flux distribution, promoting a more uniform flux linkage waveform. The study concludes that the 15° skew angle minimizes cogging torque and substantially reduces harmonic amplitudes, leading to a smoother operation of the BLDC motor. This result is particularly advantageous in applications where noise and vibration are critical factors.

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