Analyzing the Impact of Skewing Techniques for Cogging Torque Reduction in PM Synchronous Motor Design for Electric Vehicles

Mahesh A. Patel[1] and Mohmmad Basit Kazmi[2]

Abstract—**The paper aims to explore and analyze various skewing techniques used for reducing cogging torque and torque ripple in the design of permanent magnet synchronous motors (PMSMs) for electric vehicles. Cogging torque, a phenomenon resulting from the interaction between permanent magnets on the rotor and teeth on the stator, causes higher torque ripple and affects the overall performance and efficiency of PMSMs. This paper evaluates the effectiveness of different skewing techniques, including linear and V-skewing, in mitigating cogging torque and reducing torque ripple. The proposed methods are investigated through static and time-stepping finite element analysis (FEA) simulations. The results show a significant reduction in cogging torque and torque ripple, leading to improved performance of the PMSM motor. This study highlights the effectiveness of the linear skewing technique in comparison with the V-skew technique for cogging torque reduction in PMSMs, leading to better motor efficiency and performance.**

Index Terms—**Cogging torque; electric vehicle; finite element analysis; PM synchronous motor; skewing techniques.**

I. INTRODUCTION

Various strategies are researched to mitigate cogging torque in PMSMs, such as optimizing the design of the stator and rotor, using skewed stator slots, and implementing advanced control algorithms. These methods aim to minimize the effects of cogging torque, thereby enhancing the smoothness and efficiency of the motor. In summary, while EVs and PMSMs offer significant advantages in terms of efficiency and performance, addressing challenges like cogging torque is crucial for further improving their viability and user experience.

Electric vehicles (EVs) have gained significant popularity due to their advanced battery and motor configurations, which enhance fuel efficiency and reduce emissions [1]. These vehicles are seen as key to decarbonizing the transportation sector, which is a major source of carbon dioxide emissions. EVs offer numerous benefits over traditional internal combustion engine vehicles, including zero tailpipe emissions, lower maintenance costs, and improved reliability due to fewer moving parts. The development of battery technologies, particularly lithium-ion batteries, has been crucial in making EVs more viable by increasing energy density and reducing costs. Permanent Magnet Synchronous Motors (PMSMs) are widely used in EVs due to their high efficiency, excellent torque control, and compact design. However, one significant challenge with PMSMs is cogging torque [2], which is the pulsating torque caused by the interaction between the permanent magnets and the stator teeth. This cogging torque can lead to torque ripples, noise, and vibration, adversely affecting the motor's performance and the vehicle's overall driving experience [3], [4], and [5].

To address the issue of cogging torque, researchers and engineers have explored various techniques, among which skewing has emerged as a promising approach [6]. Skewing involves the deliberate angular displacement of stator or rotor laminations to break the symmetry and alter the magnetic field distribution, thereby reducing the cogging torque. One typical method for lowering torque ripple and cogging torque is rotor/stator skew design [7]. Skewing can be applied to either magnets or slots, with the main goal being to modify the interaction between the rotor magnet and stator space. By introducing a specific skew angle, the interaction between the permanent magnets and stator teeth is modified, resulting in a smoother rotation and decreased cogging torque [8]. Several hybrid techniques of skewing that combine both radial and tangential skewing have been proposed [9]. Their experimental results demonstrated a significant reduction in cogging torque and improved motor performance. To reduce the cogging torque with a least negative effect on the output torque of the machine using a multi-objective optimization approach has also been adopted [10]. Furthermore, [11] investigated the influence of skewing techniques on the electromagnetic characteristics of interior permanent magnet synchronous motors. Their analysis revealed that an optimal skew angle can not only reduce cogging torque but also enhance the motor's torque density and efficiency. In this paper, finite element analysis are performed [12], [13], [14] to analyze the cogging torque characteristics of a 80 kW PMSM design for an electric vehicle application. The simulations are repeated for various skew angles and two different skew patterns to assess the reduction in cogging torque.

This paper presents various approaches for cogging torque reduction in PMSMs through skewing techniques. The proposed approach aims to achieve an optimal skew angle that minimizes the cogging torque while preserving the motor's overall performance. Through extensive scrutiny

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and experimentation, a comparative analysis is conducted to evaluate the performance of different skewing techniques regarding cogging torque reduction, torque ripple reduction, and effect on average and maximum torque.

In the proposed paper, section 1 introduces an overview of the cogging torque phenomenon and its detrimental effects on PMSM performance, modeling, and analysis of the PMSM in section 2. The skewing patterns and simulations with different skew angles are discussed in section 3. The results and analysis of the experimental findings are compared in section 4. The summary of key findings while discussing implications and suggesting the potential outcome for future prospective of the research in Section 5.

II. DESIGN AND ANALYSIS OF PMSM

A. *Determination of Design Dimensions*

Considering electric vehicle applications, an interior V-web PMSM(IVW-PMSM) which can deliver a maximum output power of 80 kW has been used. Fig. 1 shows the radial configuration of Interior V web PMSM. The main dimensions of the motor along with other important parameters are shown in Table 1.

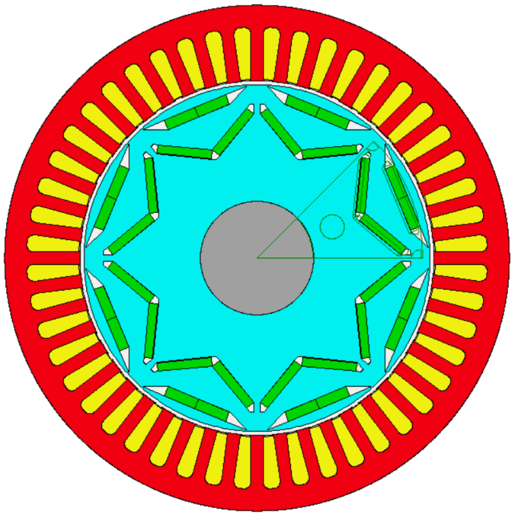

Fig. 1. Radial configuration of a PMSM

TABLE I
SPECIFICATIONS AND MAIN DIMENSIONS OF THE MOTOR

Parameter	Value	Parameter	Value
Base speed	4000 rpm	Number of Slots	48
Rated Torque	191 Nm	Number of poles	8
Stator Outer Diameter	198 mm	Shaft Diameter	45 mm
Axial Length	160 mm	RMS Current	271.4 Amps
Stator Bore Diameter	138.6 mm	Air Gap length	0.7 mm

NdFeB(N42UH) permanent magnet is used as it exhibits high magnetic energy product and good magnetic flux density [15]. Overall, NdFeB offers a good balance between the cost and performance of the motor. Lamination of stator and rotor tooth and back iron M350-50A is used to minimize eddy current losses [16]. A Double layer of magnets is used to get better control over torque and to get enhanced magnetic flux density in the air-gap [17].

The electromagnetic torque (T_{em}) of a PMSM can be calculated using the following equation [18],

$$T_{em} = \frac{L_s}{\mu_o} \oint_l r B_n B_t dl \tag{1}$$

In the given equation, L_s represents the length of the stack, l denotes the contour used for integration, B_n signifies the normal magnetic flux density, B_t indicates the tangential magnetic flux density, and r corresponds to the radius of the circumference located within the air gap. Torque ripple (T_r), in a PMSM refers to the slight fluctuations or variations in the generated torque during its operation. It can be calculated using,

$$T_r = \frac{T_{p2p}}{T_{av}} \times 100 \tag{2}$$

where, T_{p2p}, T_{av} are the peak to peak torque and average torque respectively.

Cogging torque is a phenomenon that occurs in Permanent Magnet Synchronous Motors (PMSMs) and is characterized by a pulsating torque that resists the motor's rotation at certain positions. This pulsating torque is caused by the interaction between the permanent magnets on the rotor and the stator teeth. It can be calculated by [19].

$$T_{cogg} = -\frac{1}{2}\phi^2 \frac{\delta R_g}{\delta x}[Nm] \tag{3}$$

where T_{cog} is the cogging torque, ϕ is the magnetic flux present in the air gap and R_g is the amount of reluctance through which the flux passes.

In practical applications, θ_{skew} is the skew angle of magnets in a permanent magnet synchronous motor (PMSM) which is defined using angular measurements in degrees or radians. It signifies the angular shift of the magnets from their original or nominal position.Equation is [6].

$$\theta_{skew} = \frac{360}{LCM(N_P, N_S)} \tag{4}$$

where, N_P is the number of rotor poles and N_S is the number of stator slots.

III. IMPLEMENTATION OF SKEWING TECHNIQUES IN PMSM

A. *Magnet geometry with skewing Techniques:*

Skewing in PMSMs has a significant impact on reducing cogging torque, which leads to smoother operation and improved torque ripple characteristics. Skewing modifies the spatial alignment of the stator and rotor magnetic fields, resulting in a reduction in the cogging torque amplitude [20].

In Fig. 2(a) magnet is being sliced into four pieces or steps as shown in Fig. 2(b). Typically, the skew angle and arrangement of slices are established through optimization studies [21].

In Fig. 3, the magnet geometry is shown for various configuration. Fig. 3(a) shows the step skew configuration as well as Linear skew in Fig. 3(b) and V-Skew configuration in Fig. 3(c).

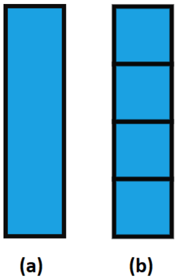

Fig. 2. Skewing of permanent magnet (a) No Skew (b) Step Skew

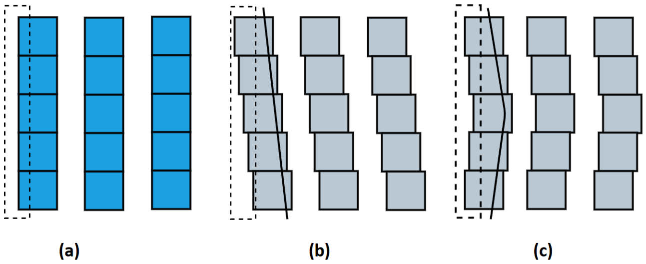

Fig. 3. Skewing techniques (a) Step Skew (b) Linear Skew (c) V-Skew

1) Step Skew: In this type of skewing as shown in Fig. 3(a), a magnet is divided into equal slices known as steps and the determination of the precise angle and a number of magnet slices for the step skew technique relies on the motor's design and the intended reduction in cogging torque [22].

2) Linear Skew: The linear skew technique involves shifting the magnet position uniformly in the axial direction as shown in Fig. 3(b). This change in magnet position reduces cogging torque [23]. By using a linear skew, the motor runs smoother and more efficiently. The amount of skew depends on how much we want to reduce cogging torque and the motor's design [24]. Overall, linear skew helps improve the motor's performance by reducing torque fluctuations.

3) V-Skew: The V-skew technique involves a specific rotor construction with V-shaped magnet arrangements as shown in Fig. 3(c). The magnets are placed in a double-layered configuration, forming a V-shaped pattern. V-Skew is applied to reduce the z-axial force instead of the Linear skew [25]. Also, the optimal skew angle can be found by equation (5) for the reduction of cogging torque [26] according to the skew angle when V-skew is applied. By keeping the values of number of stator slots (N_S) and rotor poles (N_P) in equation, the optimal skew angle θ_{skew} is 7.5°. This is the angle up to which one can skew the position of the magnet otherwise it leads to a high ripple torque.

IV. FEA Simulation Results and Discussion

Static and time-stepping FE analyses have been carried out for the proposed PMSM motor. Fig. 4 shows the linear skewed PM on the rotor of the proposed PMSM. The simulations were performed by introducing different skew angles.

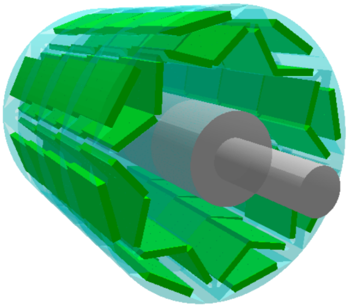

Fig. 4. Skewed rotor of the proposed PMSM

The skewing implementation technique have been implemented using the Fig. 5.

The flux density distribution of the proposed machine is shown in Fig. 6 under loading conditions. The obtained simulation results were analyzed to evaluate the impact of different skew angles on motor performance. Key parameters,

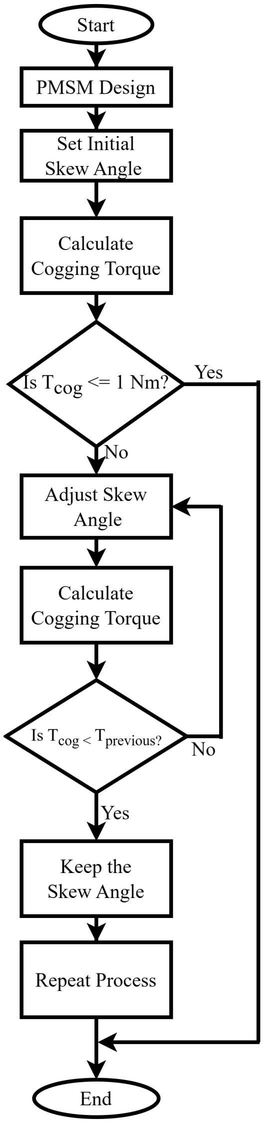

Fig. 5. Flow chart of skewing technique implementation

such as cogging torque and torque ripple reduction, efficiency improvement, and maximum and average torque were quantitatively assessed.

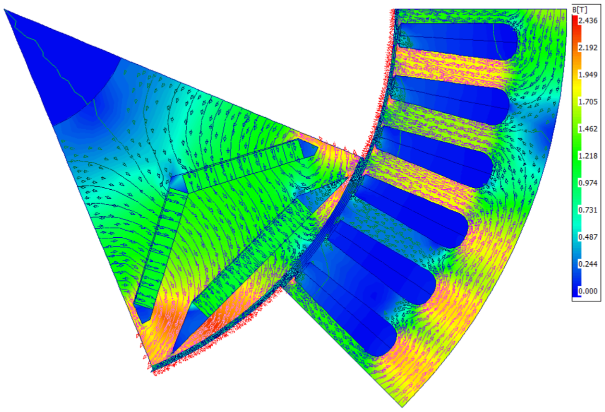

Fig. 6. Flux density plot at no-load condition of PMSM

A. *Linear Skew Results*

Table 2 shows the effect on output parameters of PMSM with the increase in skewing angle.Cogging torque has been reduced from 5.792 Nm to 0.038 Nm and subsequently the torque ripple has reduced from 50.01 to 15.07 Nm.

TABLE II
RESULT PARAMETERS FOR LINEAR SKEWING

Skew Angle [Degree]	Maximum Torque[Nm]	Average Torque[Nm]	Torque Ripple	Cogging Torque[Nm]
0	236.3	183.84	50.01	5.792
1.5	226.19	183.76	48.06	5.0093
2.5	225.98	183.73	44.964	4.1137
3.5	225.61	183.69	40.349	3.48
4.5	225.14	183.55	34.757	2.7185
5.5	224.54	183.26	28.265	1.7643
6.5	223.82	182.99	20.987	0.93823
7.5	223.04	182.72	16.25	0.038809
8.5	222.18	182.46	15.067	0.803

Fig. 7 shows the cogging torque waveform at different linear skewing angles and Fig. 8 shows the torque profile at different linear skewing angles. Fig. 9 shows Average torque wave forms at different linear skewing angles.

It can be observed that even the cogging torque and torque ripple have been reduced to the desired value but along with that, the maximum and average torque have been decreasing degrading the motor's performance.

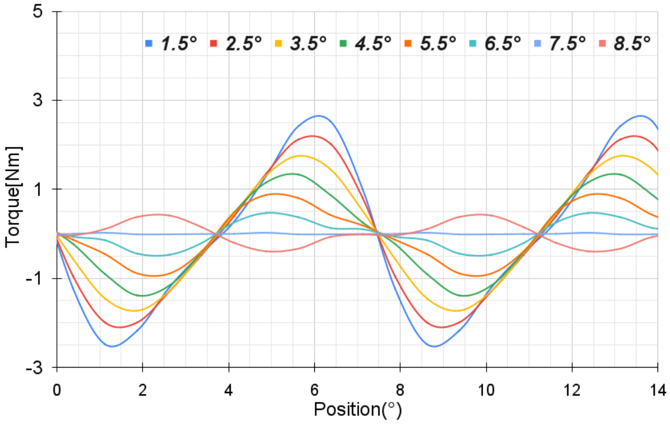

Fig. 7. Cogging torque at various θ_{skew} at linear skewing

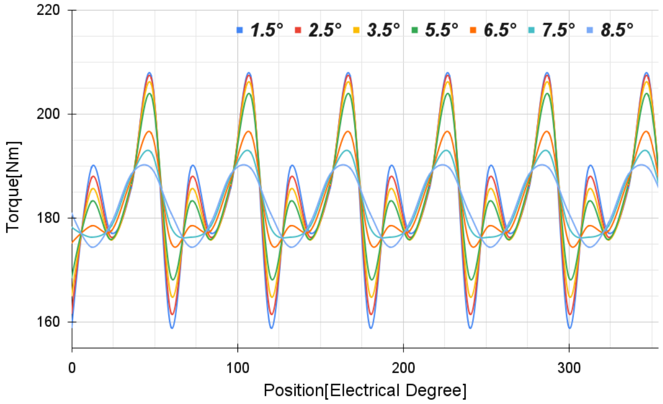

Fig. 8. Torque profile at various θ_{skew} at linear skewing

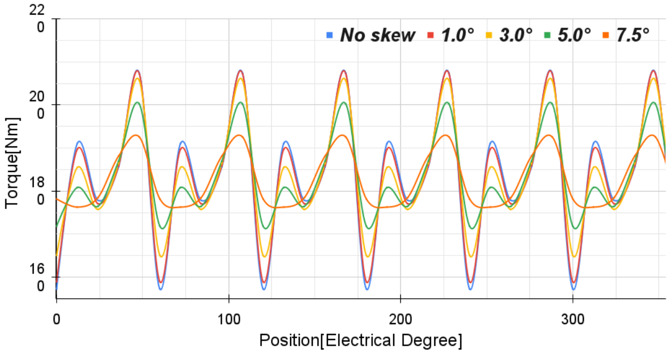

Fig. 9. Torque comparison at no-skew and various θ_{skew} at linear skewing

B. *V-Skew Results*

Table 3 shows the effect on output parameters of PMSM with the increase in skewing angle. Maximum torque, average torque, torque ripple, and cogging torque have been obtained for various skew angles for V-skew configuration. Cogging torque has been reduced from 5.792 Nm to 1.9486 Nm and subsequently, the torque ripple has reduced from 50.01 to 23.359 Nm. Fig. 10 shows the cogging torque waveform at different V skewing angles.

Fig. 11 shows the Torque profile at different V skewing angles as calculated using the equation. Beyond the calculated angle of skewing, it has been observed that the cogging torque has increase drastically. Fig. 12 shows comparison of average torque waveform at no skew and different V skewing angles. Fig. 13 and Fig. 14 shows a comparison of Linear and V-skew in terms of torque ripple reduction. It can be observed that

TABLE III
RESULT PARAMETERS FOR V-SKEW

Skew Angle [Degree]	Maximum Torque[Nm]	Average Torque[Nm]	Torque Ripple	Cogging Torque[Nm]
0	236.3	183.84	50.01	5.792
1.5	225.66	182.91	47.246	5.1104
2.5	225.09	182.3	43.639	4.4334
3.5	224.36	181.68	38.55	3.6088
4.5	223.53	180.94	32.54	2.7064
5.5	222.56	180.08	25.709	2.4591
6.5	221.5	179.21	22.02	2.1799
7.5	220.37	178.36	23.359	1.9486
8.5	219.17	177.5	24.312	2.3621

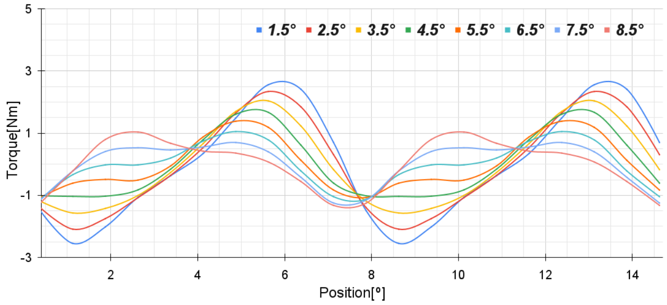

Fig. 10. Cogging torque at various θ_{skew} at V-skewing

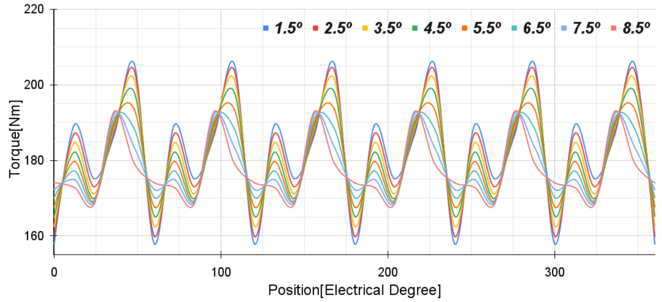

Fig. 11. Torque profile at various θ_{skew} for V-skew

even the cogging torque and torque ripple has been reduced to the desired value but along with that the maximum and average torque has been decreasing at higher rate than that of the Linear Skew, degrading the motor's performance.

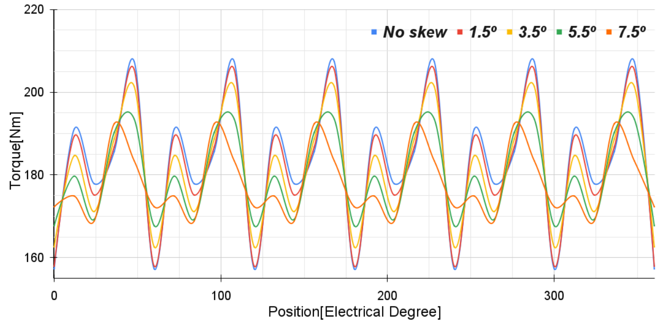

Fig. 12. Torque comparison at no-skew and various θ_{skew}(for V-skew)

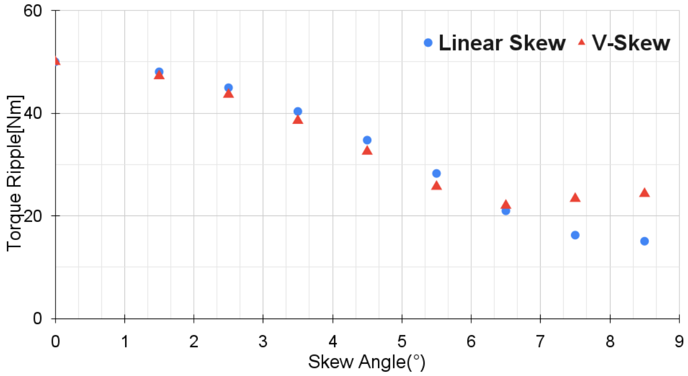

Fig. 13. Comparison of torque ripple at various θ_{skew}

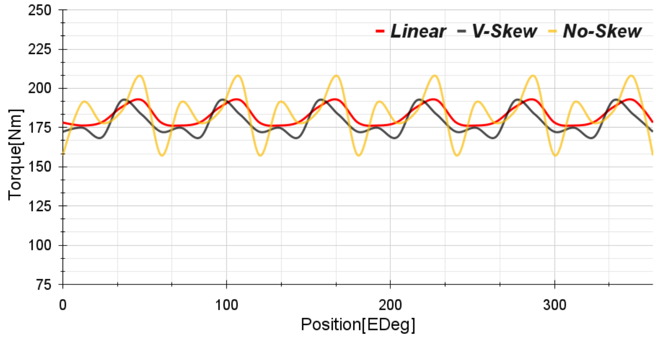

Fig. 14. Torque ripple at various θ_{skew}

V. CONCLUSION

This study on PMSMs has highlighted the importance of careful design and optimization of motor parameters, such as skewing angle for achieving optimal motor performance and reduction of cogging torque. Skewing is a popular technique however, there are some drawbacks to both skewing techniques, such as implementing V-skew may introduce additional complexity in the manufacturing process compared to linear skew. From the result parameters, it was observed that both techniques have reduced cogging torque to a desirable value. The torque profile becomes smoother but the value of average torque has decreased. Therefore, the optimal magnet skewing strategy for a given PMSM design and application should carefully consider the trade-offs between reduced cogging torque and other performance criteria.

Further studies can explore the development of advanced optimization algorithms and models for identifying the optimal skewing angles for the Zigzag pattern of skewing.

VI. DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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