ELECTROMAGNETIC ANALYSIS OF THE SKEWED IPM MOTOR USING MULTI-SLICED 2D FINITE ELEMENT METHOD

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ABSTRACT: This research paper investigates the adoptability of the multi-sliced 2D finite element method (FEM) on the skewed interior permanent magnet (IPM) motor. Conventional IPM motors are without skewing, and analyzed by using the 2D FEM, however, skewed IPM motors require 3D FEM, thus huge computation time and memory are needed. The multi-sliced 2D FEM consumes less computational time compared to a traditional 3D FEM. Therefore, a multi-sliced 2D FEM is presented and adopted to analyze the skewed-stator IPM motor for the hybrid electric vehicle (HEV) application. To realize the computational accuracy of the multi-sliced 2D FEM, the back EMF of a conventional un-skewed IPM motor computed by a conventional 2D FEM is compared with the back EMF results of the multi-sliced 2D FEM. The electromagnetic characteristics, such as cogging torque, torque ripples, back EMF and electromagnetic torque of the skewed-stator IPM motor are computed using the multi-sliced 2D FEM, and results are discussed.

Keywords: Finite element method (FEM), hybrid electric vehicle (HEV), interior permanent magnet (IPM) motor, multi-sliced 2D FEM, permanent magnet machines, skewing effect.

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INTRODUCTION

The V-shaped IPM motor is widely used in electric vehicles (EVs) or hybrid electric vehicles (HEVs) [1]. The single-layered permanent magnet (PM) arrangement in the V-shaped IPM motor is used commercially in HEVs, such as, BMW 225xe, Audi A3 e-tron, Chevy Volt and Toyota Prius III [2]. Among different HEVs, the motor structures are either un-skewed or skewed at stator or rotor side [1]-[3]. The embedded V-shaped PM design is strategically employed to achieve several critical objectives of reducing the required amount of PM material, exploiting the reluctance torque to a greater extent, and enabling the broad constant power-speed range during the field weakening operation [3]-[4].

Unwanted reluctance torque at no-load conditions is the cogging torque, that occurs in an electrical motor because of the interaction between stator and rotor teeth causing the teeth locking [5]. It causes rotor vibration thus noise, increases the power losses thus reduces the efficiency, and causes difficulty in starting the motor [6]. Similarly, harmonic content in the back EMF causes difficulty in motor control [6]-[7]. Therefore, reducing the cogging torque, torque ripples and harmonics is crucial for enhancing the performance and efficiency of the V-shaped IPM motors for the HEVs [8].

Skewing is a primary technique widely used to address this parasitic effect and involves tilting the stator or the rotor to disrupt the alignment of magnetic fields, thereby significantly reducing the cogging torque [9]. While skewing is an effective method, there are few other methods, such as notching, auxiliary slots, pole pairing, tapering, rotor pole axial pairing, variable rotor arcs and optimization contribute to cogging torque reduction [10]. Skewing the stator of the IPM motors for the HEVs, such as, BMW 225xe, is a widely adopted technique to enhance the motor performance and overall efficiency by minimizing the cogging torque [2], [10].

Electromagnetic finite element method (FEM) is conventionally used for modeling and analyzing electrical machines [11]. Conventionally, IPM motors can easily be analyzed by a simple 2D FEM, however, skewing the stator or rotor of the IPM motor increases the geometrical complexity and the magnetic flux distribution along the axial and radial direction, thus difficult to be accurately represented by the 2D FEM [8], [12]. Thus, 3D FEM is indispensable for the precise and accurate electromagnetic analysis and design of the skewed-stator IPM motor, providing insights that are critical for reducing losses, noise and vibrations, and for enhancing the overall efficiency and reliability of the V-shaped IPM motor for the HEV application [10]-[12].

As the 3D FEM consumes heavy computational time, therefore, multi-sliced 2D FEM is adopted here, to include the skewing effects providing rapid and precise electromagnetic analysis of the IPM motor [10]- [11]. A 2D FEM model of a conventional IPM motor is built, and multiple layers or slices are extruded to simulate the skewed-stator IPM motor without resorting to a full 3D modeling, thus saving computational time and memory [11]. To realize the results of the multi-sliced 2D FEM, the back EMF of a conventional IPM motor is computed by the multi-sliced 2D FEM as well, and compared with each other.

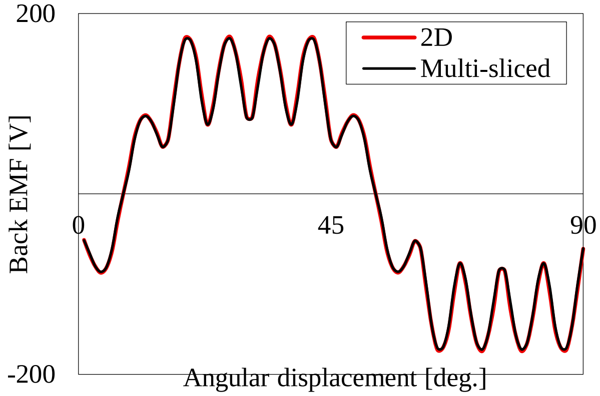

Fig. 1. Back EMF of a conventional un-skewed IPM motor, computed using the 2D FEM and multi-sliced 2D FEM.

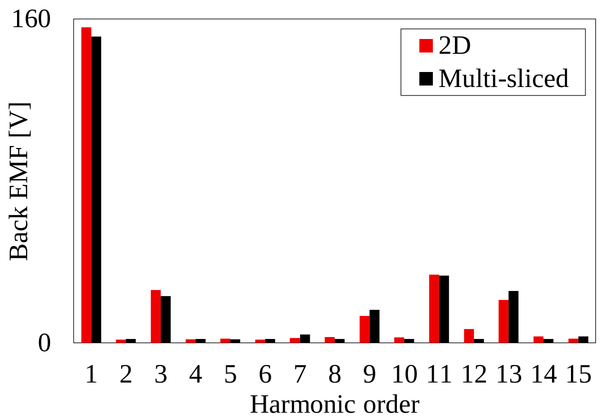

Fig. 2. Harmonic spectrum of the back EMF of a conventional un-skewed IPM motor, computed using the 2D FEM and multi-sliced 2D FEM.

The root mean square (rms) value of the back EMF of a conventional un-skewed IPM motor, using the 2D FEM and multi-sliced 2D FEM is 116.2 V and 114 V, respectively, as shown in Fig. 1. Similarly, harmonic spectrum analysis of the back EMF of a conventional un-skewed IPM motor computed using the 2D FEM and multi-sliced 2D FEM, is provided in Fig. 2. Working harmonic of the back EMF computed using the 2D FEM is slightly higher than the multi-sliced 2D FEM, however, trending values are similar and coherent. Thus, multi-sliced 2D FEM is adopted to investigate the influence of skewing the stator of the V-shaped IPM motor, on its electromagnetic characteristics. By skewing the stator, the cogging torque, back EMF and its harmonics, and torque ripples in the electromagnetic torque of the V-shaped IPM motor for the HEV applications can be reduced.

This research paper is organized into five sections: Section I provides the introduction to the IPM motor, skewing method, and validity of the multi-sliced 2D FEM. Section II discusses in detail the multi-sliced 2D FEM utilized for the numerical analysis of the skewed-stator IPM motor. Section III provides the structure and geometrical design specifications of the skewed stator V-shaped single layer IPM motor for the HEV application. Section IV presents the results and discusses the electromagnetic characteristics of the skewed-stator IPM motor. Finally, Section V concludes the carried-out research work.

Table I: Design specifications of the IPM motor.

Item	Value
Outer radius	121 mm
Average airgap radius	92.3 mm
Shaft outer radius	56 mm
Active axial length	75 mm
Stator's winding slots	48
Rotor pole pairs	4

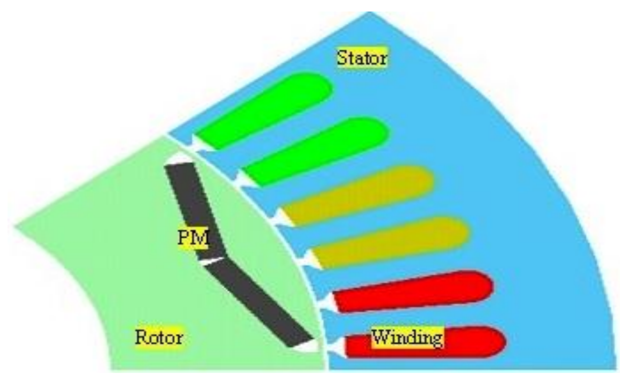

Fig. 3. Base geometry of the IPM motor.

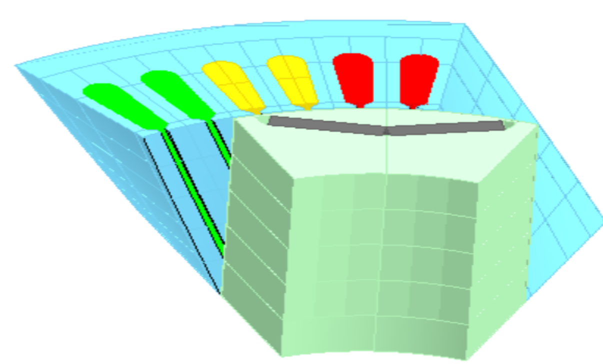

Fig. 4. Continuous skewing in 5 homogeneous layers of the stator of the IPM motor.

METHODOLOGY

The electromagnetic analysis of the skewed-stator V-shaped IPM motor for the HEV application is performed using the multi-sliced 2D FEM. This numerical method involves several steps from the creation of the V-shaped IPM motor's 2D geometrical model to the extraction of the results [8], [11]-[12].

Step 1: To reduce the computation time, the periodicity and symmetry of the IPM motor is determined by the number of stator and rotor poles. Thus, by applying the appropriate boundary conditions, the computational time and system memory for the multi-sliced 2D FEM simulation is significantly minimized. The considered 3-phase V-shaped IPM motor has 48 stator slots and 8 rotor poles, as shown in Table I, therefore, it has the periodicity of 8.

Step 2: The base geometry of the IPM motor is created by considering its repetitive components. Thus, the base geometry of the V-shaped IPM motor has 6 stator slots for 3-phase winding and 1 rotor pole, and the stator, rotor, and airgap of the IPM motor are created, as shown in Fig. 3. However, the airgap is divided into two parts, one stationary and one rotatory for incorporating the accurate and precise electromagnetic interacting influences between the stator and rotor of the IPM motor. This step provides the simple 2D model of a conventional un-skewed structure of the V-shaped IPM motor.

Step 3: The meshing of the IPM motor is a key step that heavily influences the accuracy of results and their computation time. After creating the IPM motor's geometry, the mesh density parameters are specified. A finer mesh is applied to regions with high magnetic flux interaction, such as the PM, and rotor and stator iron facing the airgap, and airgap itself to accurately capture the variations in the magnetic and the electric fields. The mesh density is adjusted between 0.5 and 1.0 to strike a balance between achieving high accuracy by maintaining computational efficiency.

Step 4: The transient magnetic (skewed model) application is selected for computing the electromagnetic characteristics of the stator-skewed IPM motor. This allows the investigation of the skewing effect on the IPM motor's electromagnetic output characteristics, using the multi-sliced 2D FEM. Here, only the continuous skewing type with simple homogenous layers is adopted for skewing the stator. Stator of the IPM motor is skewed with a skewing angle of two stator slot pitches, i.e. 15°, and the continuous five slices from the basic 2D model of the IPM motor are extruded, as shown in Fig. 4.

Step 5: Physical properties, such as the material characteristics, are defined and assigned to the specific regions of the IPM motor, including the PMs, and stator and rotor core, and mechanical properties, such as the friction and viscosity. These materials and mechanical properties are essential for accurate FEM results.

Step 6: The physics involves the incorporation of the mechanical and electrical sets, and the procedure defines the rotor's speed as well as the number of the conductor and current passing through coil turns in the stator's winding scheme of the IPM motor. Thus, the assigned components are fundamental for the IPM motor's movement and the proper interaction of the rotor's magnetic field with the stator's conductors.

Step 7: Once all the regions of the skewed-stator IPM motor are defined and concerned materials are assigned, the multi-sliced 2D FEM simulation proceeds. After completion of each step, the results are analyzed to determine the skewed-stator IPM motor's performance, including parameters like the cogging torque, the back EMF and its harmonic content, and electromagnetic torque and its ripple.

Skewed-stator IPM motor: The skewed-stator IPM motor type under investigation is used in a BMW 225xe HEV traction application. The single-layered V-shaped IPM motor highlights its suitability for the high-performance HEV traction applications, where efficiency, power density and extended speed range are required. The brushless IPM motor features a stationary stator comprises of the yoke, slots and windings, a movable rotor with embedded PMs in a V-shape structure, and an air gap between stator and rotor, as shown in Fig. 3. The stator of the IPM motor has 48 slots for a 3-phase Y-connection winding, and the rotor of the IPM motor is slotted to accommodate four pole pairs of V-shaped PMs.

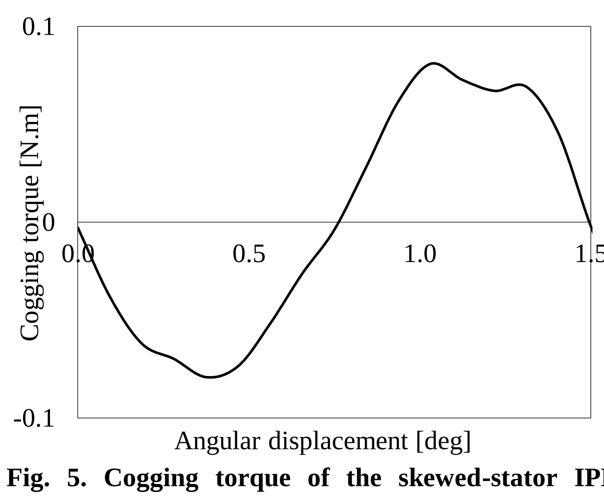

Fig. 5. Cogging torque of the skewed-stator IPM motor using multi-sliced 2D FEM.

The embedded V-shaped PMs are rare-earth NdFeB magnets, possessing a remanence of 1.2 T, for a strong magnetic field. The core material for the back iron of stator and rotor of the IPM motor is M270-35A electrical steel. The iron core is laminated to reduce the eddy current losses and improve the overall IPM motor's efficiency. The skewed-stator IPM motor's design is for the HEV traction applications, with specific geometrical parameters, as given in Table 1. The skewed-stator IPM motor's outer diameter is 242 mm, and the rotor's outer diameter is 184 mm, and an axial stack length of 75 mm. The embedded PMs have a thickness of 5 mm, and the stator's slot opening width is 2.0 mm and its depth is 1 mm. A crucial design aspect is the airgap of 0.6 mm between the stator and rotor. The airgap must be mechanically and electromagnetically stable and uniform, without eccentricity, ensuring the smooth operation of the IPM motor for a reliable and quiet operation of the HEV application.

RESULTS AND DISCUSSIONS

The cogging torque of the skewed-stator IPM motor is determined without stator current supply, using the multi-sliced 2D FEM. The cogging torque of the skewed-stator IPM motor from peak-to-peak value is 0.16 Nm, as shown in Fig. 5. Generally, the cogging torque period for a conventional IPM motor is determined by dividing the 360° by the least common multiple (LCM) of the stator slots and rotor poles. However, for the skewed-stator IPM motor, this conventional approach provides five periods of cogging torque, rather than one. Therefore, the resultant cogging torque period of the skewed-stator IPM motor is 1.5°, compared to conventionally calculated 7.5°, as shown in Fig. 5.

The back EMF of the IPM motor without skewing was not smooth and had more oscillations, as already presented in Fig. 1. However, the stator-skewed IPM motor has almost smooth sinusoidal back EMF without major oscillations, as shown in Fig. 6. The rms value of the skewed-stator IPM motor is 102.87 V. The harmonic spectrum of back EMF of the skewed-stator IPM motor is provided in Fig. 7. The working harmonic of the skewed-stator IPM motor is 144.8 V. However, the higher harmonics in the induced back EMF of the conventional IPM motor without stator skewing as shown in Fig. 2 are more than the skewed-stator model of the IPM motor. Although, there is a lesser 3rd harmonic in the skewed-stator IPM motor than a conventional un-skewed IPM motor, it is still considerable and needs to be reduced for a pure sine waveform.

The electromagnetic torque of the skewed-stator IPM motor is determined by using the multi-sliced 2D FEM, when stator winding is supplied with the rms current value of 132 A. The average electromagnetic torque of the skewed-stator IPM is 174.81 N.m, whereas the torque ripple is 5.7 N.m, as shown in Fig. 8.

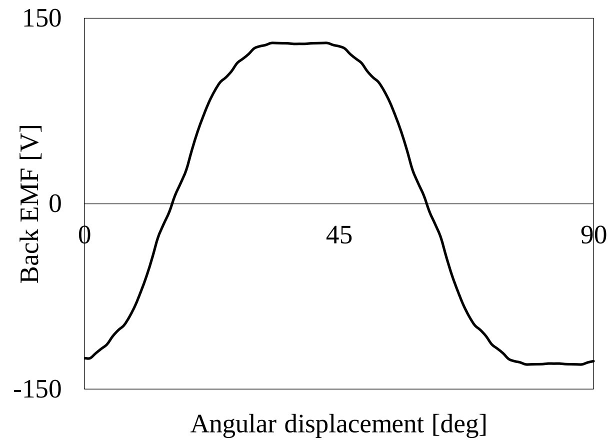

Fig. 6. Back EMF of the skewed-stator IPM motor using the multi-sliced 2D FEM.

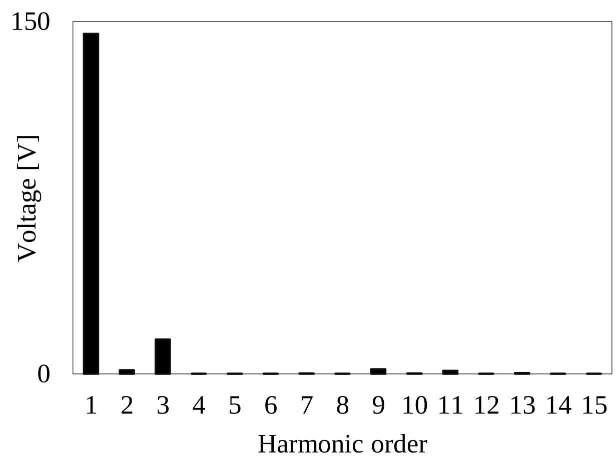

Fig. 7. Harmonic spectrum of the induced back EMF of the skewed-stator IPM motor, using multi-sliced 2D FEM.

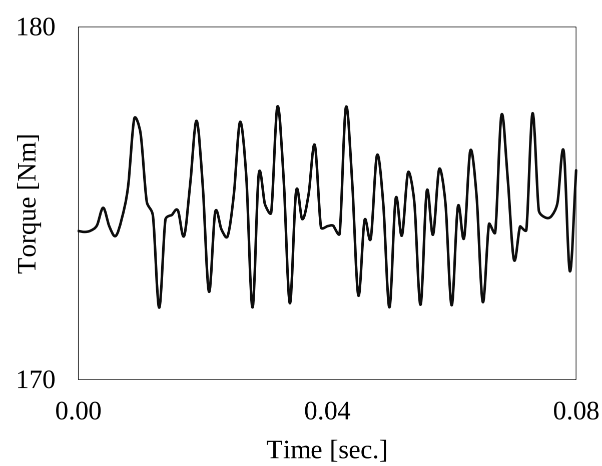

Fig. 8. Electromagnetic torque of the skewed-stator IPM motor using the multi-sliced 2D FEM.

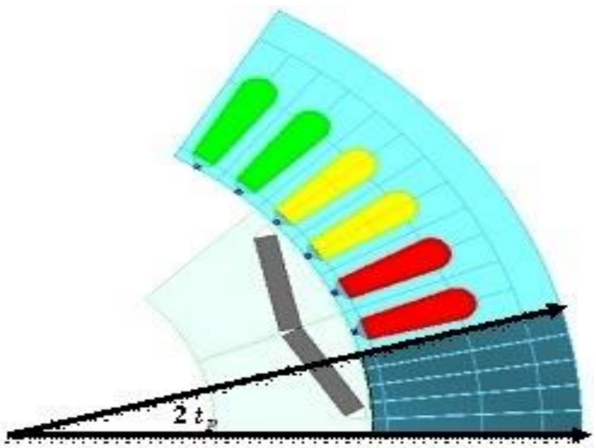

Fig. 9. Skewed-stator IPM motor with skew angle of 2 stator slot pitch.

The skewed-stator IPM motor with the skewing angle of two stator slot pitches (τ_p) of 15°, as shown in Fig. 9, shows promising electromagnetic characteristics to be employed for the HEV application. The stator is continuously skewed and segregated into continues five slices are computed using the multi-sliced 2D FEM, whereas, neither the V-shaped PMs nor the rotor core of the IPM motor is skewed.

Due to the skewing effect, the magnetic flux linkages as well as the magnetic flux distribution varies to reduce the cogging torque as well as harmonic content of the induced back EMF at no load conditions, similarly torque ripples are reduced at the load conditions.

Conclusion: The multi-sliced 2D FEM is adopted to electromagnetically analyze the output characteristics of the skewed-stator IPM motor. Although it consumes more computation time than a conventional 2D FEM, it consumes less computation time than the inherently required 3D FEM to incorporate the skewing influences. The multi-sliced 2D FEM methodology is adopted by using the Altair Flux® manual [11]. The adopted multi-sliced 2D FEM is compared with the conventional 2D FEM on the un-skewed IPM motor under no load conditions, and the results are in good agreement.

The peak-to-peak cogging torque of the stator-skewed IPM motor is reasonably low. The torque ripples are also less, however, these can be further reduced for reducing the vibrational noise, motor's eccentricity and losses. The back EMF of the skewed-stator V-shaped IPM motor is smooth and almost sinusoidal compared to a conventional un-skewed IPM motor. Although, the main harmonic component of the skewed-stator IPM motor is reduced, the harmonic contents are significantly reduced compared to a conventional un-skewed IPM motor. Therefore, reduced iron losses, better efficiency, smooth operation, less torque ripples and vibrational noise are expected for the HEV traction application.

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