SETSCI Conference Proceedings
14 ,66-70, 2022

6th International Symposium on Innovative Approaches in Smart Technologies
December 8-10, 2022, Turkey

https://doi.org/10.36287/setsci.5.2.015

Skewed Rotor Design to Reduce Torque Ripple in SRM

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Abstract – Synchronous Reluctance Motors (SRMs) are defined as reliable electric motors. Although the history of this type of motor dates back a very long time, their usage areas have started to increase with the developments in power electronics in recent years. While they have advantages such as their simple structure and their ability to operate at high speeds, the biggest disadvantages of these motors are the torque ripple (torque pulses) that occur at low speeds and the acoustic noise caused by this disturbance. One of the methods used to overcome this problem is the formation of a skew in the rotor structure. In this study, in addition to the traditional skewing method, a different degree of skew is created by creating a unique skew shape and compared with the normal motor topology. The analyses are carried out using Finite Element Method (FEM). The results obtained are given in detail.

Keywords – SRM, tork ripple, skew, FEM

I. Introduction

Synchronous reluctance motors (SRMs) are simple electric machines with salient poles on the stator and rotor. SRMs have windings only in the stator. There are no additional materials or structures such as windings, magnets, or flux barriers in the rotor. Since there is no winding or magnet in the rotor, they can operate at high speeds. In addition, since the stator windings of SRM are independent of each other (physically, magnetically, and electrically), they are more reliable machines than other motor types[1], [2].

SRMs use the reluctance force to transform electrical energy into mechanical energy. The torque produced by this force causes the rotating movement. A sinusoidal current occurs through the coil when an alternating current is applied to the stator winding, changing the magnetic flux. A large magnetic resistance is obtained when the air gap is high and a lower magnetic resistance is faced where the air gap is low for the lines of force from the N pole in the stator to the S pole. As a result, the less resistive region of the pole surfaces is where the magnetic fluxes of the poles shift. Within a half-period, the direction is reversed. The movement of this magnetic flux on the pole surface causes the rotor to rotate. The rotor rotates in this direction because the magnetic flux moves from the unit with the large air gap to the component with the small air gap [3]–[5].

In order for SRM motors to operate, the motor must produce torque continuously. This is only possible by determining the stator pole according to the rotor position and excitation appropriately[6], [7]. The major disadvantage of these motors is the torque ripple. In SRM, torque ripple is mainly influenced by two parameters: the natural structure of the machine and the control method[8]. For SRMs to operate, the pole combinations must be correctly determined. The current applied to the motor is not continuous but discrete time. The fact that the current is not continuous causes oscillations in torque. Another factor of torque ripple is the structure of the machine [9]–[11].

Many studies have been carried out to reduce torque ripple in SRM. The machine design process is important to minimize the torque ripple value caused by structural factors. Because torque ripple causes acoustic problems in machines. The optimum value of the machine design should be determined by defining the factors that will affect the torque ripple value such as stator and rotor structure. For this reason, the magnetic behavior of the designed motor is examined with the Finite Element Method (FEM) method and necessary improvements are made for torque optimization [12]–[14]. The other parameter that causes torque ripple in SRM is the triggering process in the current while driving the motor. The noncontinuance of the current causes interruptions in the torque produced. Different driving methods are used to eliminate this error [15]–[18].

The skewing method was applied on both sides, unlike traditional skewing methods. For 3 different rotor structures, 3D FEM analyses of the SRM are performed. The results obtained show that the proposed skew structure is effective up to a certain degree, and after this degree, the increase in the skew degree does not improve the motor parameters.

II. Materials and Method

Although SRMs are simple structure, the main disadvantage of this type of motor is that they require rotor position information and the use of a driver circuit. SRMs have salient pole designs in different stator and rotor combinations. The number of rotor and stator poles can be even less, more or equal to each other in number. Often the number of stator poles is greater than the number of rotor poles. According to the application areas, stator/rotor combinations vary from 6/4, 8/6, 12/8, etc.[4]. In applications requiring high torque, the number of rotor poles is selected very close to the number of stator poles, while in high-speed applications, the number of rotor poles is selected smaller than the number of stator poles[19]. In this study, a 6/4 stator/rotor combination was preferred.

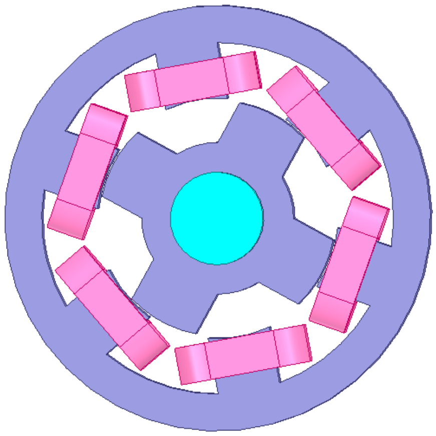

Figure 1 Reference SRM 3D model

A. Torque Production at SRM

The position of the rotor and the phase current have a big impact on the torque generated in each SRM phase winding. The T_k value in each phase is generated by the active phase current. This torque value is calculated by finding the partial derivative of the magnetic coenergy W_C of the rotor position and the phase current at arbitrary values of k [6].

$$T_k(\theta, i_k) = \frac{\partial W_c(\theta, i_k)}{\partial \theta}, \quad k = 1,2,3,\dots,n \tag{1}$$

where n is the motor's phase number. The definition of the magnetic co-energy is,

$$W_c(\theta, i_k) = \int_0^{i_k} \lambda_k(\theta, i_k) di_k \tag{2}$$

The flux linkage per phase, denoted by λ_k, is defined as:

$$\lambda_k(\theta, i_k) = L_k(\theta, i_k) i_k \tag{3}$$

The phase inductance, L_k, is affected by both phase current and rotor position. When the saturation field effects in SRM are disregarded, the inductance, L_k, becomes independent of the current, i_k. Using (1)-(3) as an example, one can then calculate the torque per phase, T_k.

$$T_k(\theta, i_k) = \frac{1}{2} \frac{dL_k(\theta)}{\partial \theta} i_k^2 \tag{4}$$

The torque generated each phase is defined in equation (4). The following definition describes the total torque produced:

$$T_{total}(\theta, i) = \sum_0^k T_k(\theta, i_k) \tag{5}$$

According to equation 4, when the inductance slope is positive, the torque produced will always be positive even though the current value is large. The torque being produced is mostly influenced by current. In order to minimize torque ripple, it is crucial to be aware of how the form and commutation of current effect the torque generated by the SRM.

B. 3D model of SRM and Skewed Rotor

Electromagnetic analysis of the SRM should be performed to investigate the effect of the proposed skew shape. For this reason, 3D models of the reference motor, the SRM with traditional skewed rotor and the SRM with the rotor of the proposed skewed structure were created. The 3D model of the reference motor is given in Fig. 1, while the rotor structures analysed in this study are given in Fig. 2.

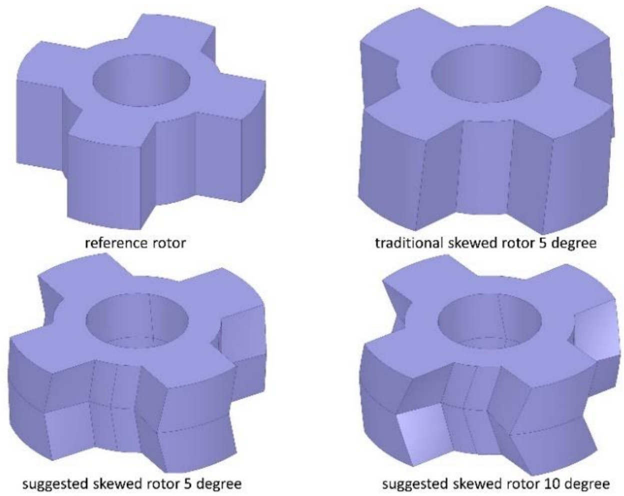

Figure 2 Rotor topologies

The necessary definitions were made for the reference motor and skewed rotor structures and transient analysis was performed. In this study, mechanical design method is preferred to reduce torque ripple. Traditional skew methods create a single directional skew on the rotor, but in this study, a double-sided skew method is proposed as an alternative to the traditional skew method and the torque behavior of the motor is investigated. For this study, while the traditional skew method is applied as 5 degree, skew ratios of 5 and 10 degrees are given to analyze the effect of the proposed structure. Images of these structures are given in Fig 2. The mesh structure created in the motor parameters directly affects the accuracy of 3D FEM results. The increase in the number of meshes increases the accuracy of the results to the same extent. The mesh structure created in these solutions is given in Fig 3.

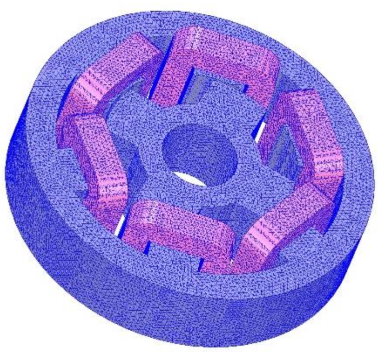

Figure 3 Mesh structure

As a result of the mesh process structure, 170009 meshes were formed in the stator, 61696 meshes in the rotor and 516756 meshes in other motor parts and regions.

III. RESULT

With the solid models created, transient analysis of SRMs was performed with 3D FEM. As a result of the analyses, phase currents, phase voltages, back-emf values, torque graphs, losses, power values and magnetic properties of the motors were obtained. In the 3D FEM analysis results, the effect of the skew on the current was first analysed. Fig. 4 - Fig. 7 shows the current curves of rotor motors with different rotor skewed.

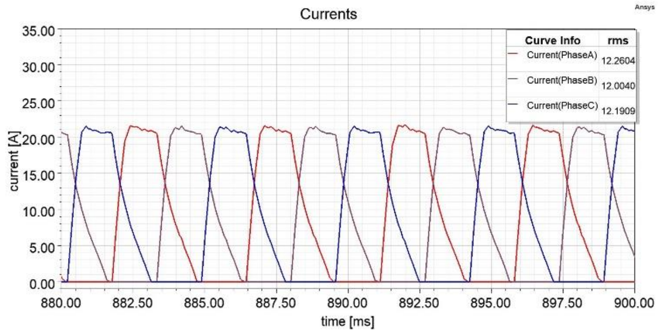

Figure 4 Reference SRM currents graphs

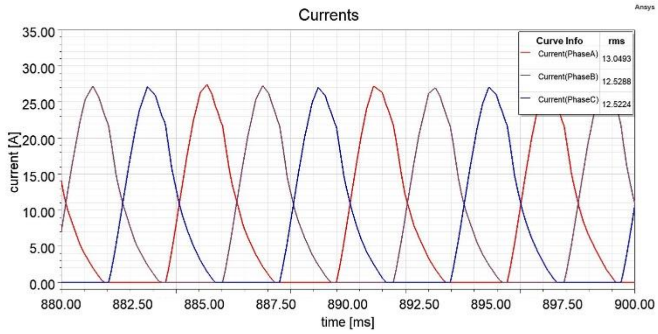

Figure 5 Traditional skewed (5^0) rotor SRM currents graphs

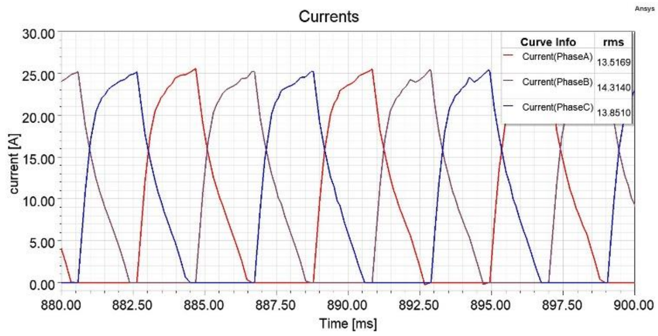

Figure 6 Suggested skewed (5^0) rotor SRM currents graphs

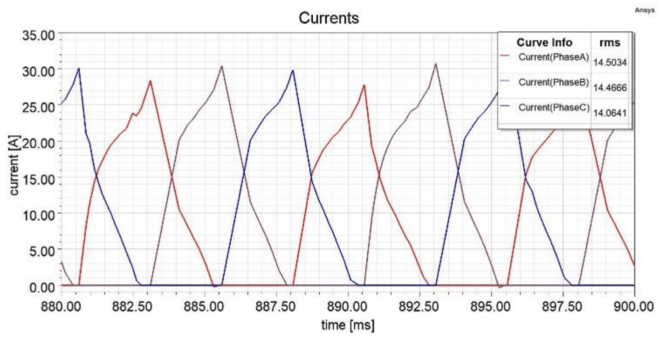

Figure 7 Suggested skewed (10^0) rotor SRM currents graphs

The main purpose of the skewing process in SRMs is to minimize the oscillations occurring in the signals of the motor. When the current graphs are analyzed, it is seen that the skew is affecting the current signals. High frequency harmonics occur at the peaks of the current signal of the reference motor. These harmonics in the current waveforms were minimized with different skew types and ratios. Despite the increase in the rms values of the current at the end of the skew process, the ripples in the signals also improved. In this study, 5 and 10 degrees of skew were applied in the proposed skew structure. For the current graphs in the proposed skew structures, both the value of the current drawn and the proximity of the current waveform to sinusoidal was best obtained in the traditional skewing method. While the rms value of the current by the motor increases in the skewing process, the harmonics occurring at the peak are reduced and a curve close to sinusoidal was obtained.

The main purpose of this study is to minimize the torque ripple in the SRM. Different degrees of rotor skew are investigated and the torque curves obtained in these structures are given in Fig 8 and Fig 11.

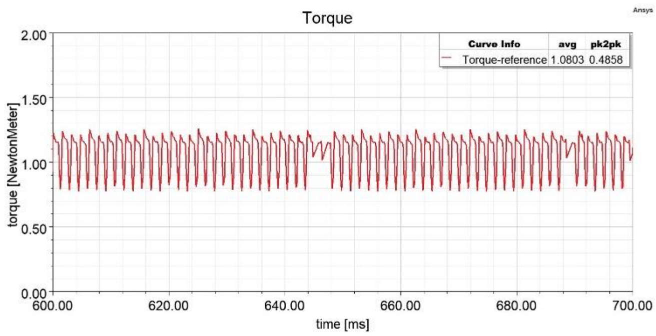

Figure 8 Reference SRM torque graph

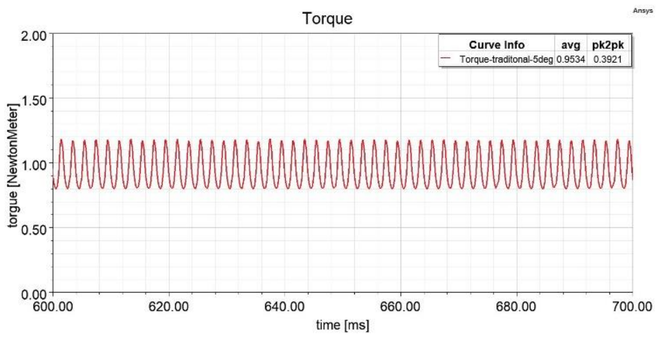

Figure 9 Traditional rotor Skew (5^0) torque graphs

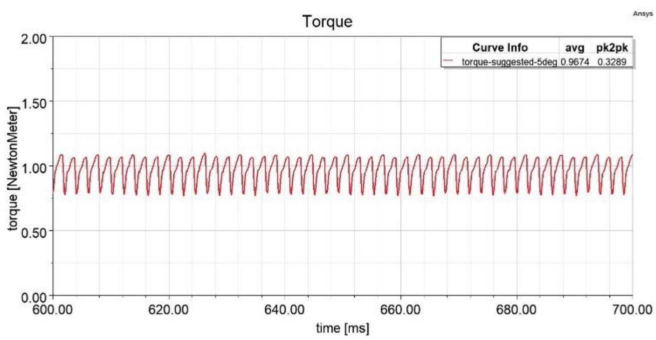

Figure 10 Suggested rotor Skew (5^0) torque graphs

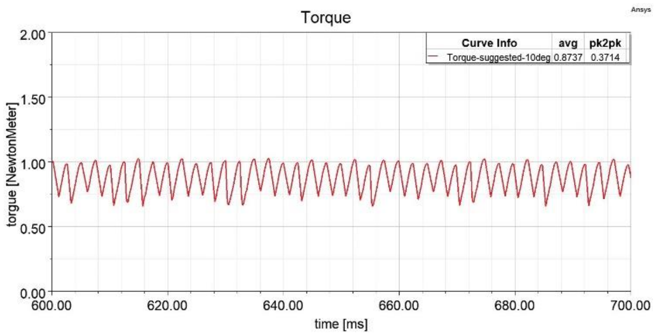

Figure 11 Suggested rotor Skew (10^0) torque graphs

When the torque graphs are analyzed, it is seen that the skew has a positive effect. In the Reference motor, the percent torque ripple values of the traditional, proposed, 5- and 10-degree belts were obtained as 44.97%, 41.13%, 33.99% and 42.51%, respectively. In general, it is observed that the skew reduces the average torque value while improving the ripple rates. Although there is not much decrease in the average torque level in the traditional skew, the improvement in the peak-to-peak value of the torque signal is lower than the other structures. Among the proposed skew methods, the rotor structure with 5 degrees of double skew gives the best result in the average value of the output torque and the oscillations in the output torque.

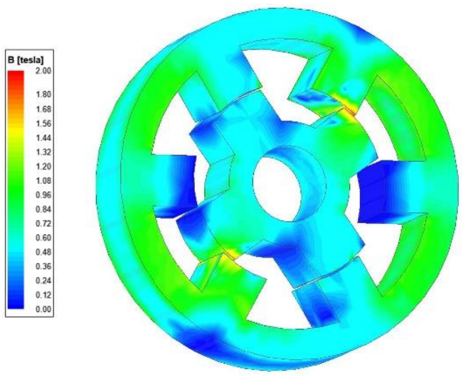

Figure 12 Reference SRM magnetic flux distribution

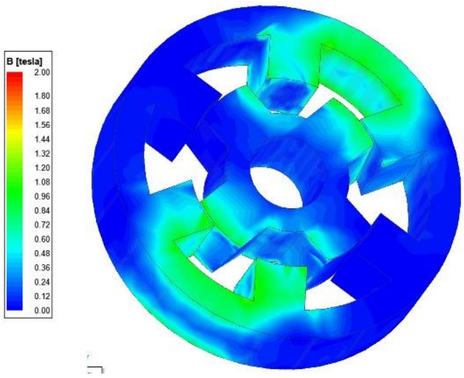

Figure 13 Traditional rotor Skew (5^0) magnetic flux distribution

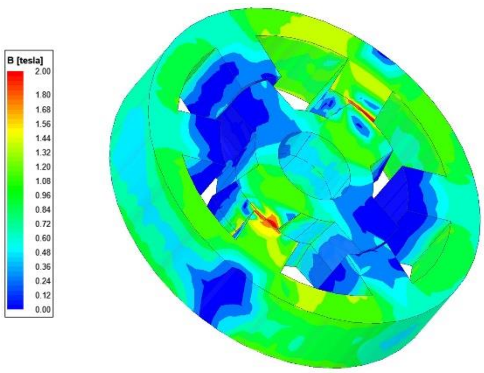

Figure 14 Suggested rotor Skew (5^0) magnetic flux distribution

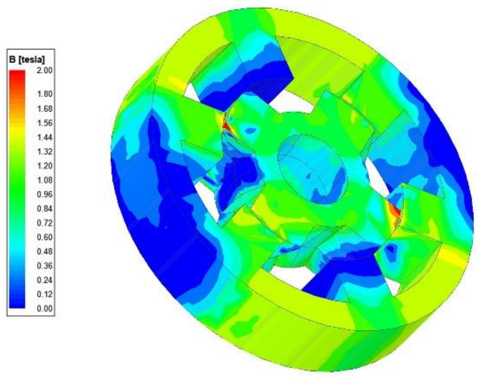

Figure 15 Suggested rotor Skew (10^0) magnetic flux distribution

Fig. 6 -Fig. 9 shows the flux distributions of motors with different rotor structures. According to the results obtained, the average value of the magnetic flux distribution in the stator and rotor cores of the reference model is around 1.5 T (at the excited poles), while the flux values of the motor with the traditional skew motor are lower than the normal level. In the motors with the suggested rotor structure, the flux density of the 10 degree skewed motor is higher than the other motors. According to the flux distributions, the flux density is close to each other in the reference motor and the double-sided 5 degree skew motor and both are around 1.7 T, which is the saturation region. As a result, no oversaturation was observed in any structure. However, in the traditional skew motor, the materials are observed to operate in the unsaturated region.

Table. 1 Motor parameters

	reference srm	**rotor skew (5^0)**	**suggested rotor skew (5^0)**	**suggested rotor skew (10^0)**
outer diameter/package length (mm)	115 / 25			
stator material	JFE 50JN400, 0.50 mm			
number of turns (pieces) / wire diameter (mm	36 / 0,85			
current (A)	12.15	12.70	13.89	14.34
motor voltage (V DC)	24			
speed(rpm)/shaft torque(Nm)	2645 /1.0803	3005 / 0.9534	2955 / 0.9674	3272 / 0.8737
input power (W)	369.48	371.62	373.23	389.77
output power (W)	299.28	300.38	299.40	299.35
total loss (W)	70.20	71.24	73.83	90.42
efficiency (%)	81.00	80.83	80.21	76.80

Table 1 shows the motor parameters of motors with different skewed rotors. In the results, it is observed that the skewing process influences the motor output parameters. Although there are no significant changes in motor efficiency, motor output power decreases when the motor supply is kept constant. Motor speeds also vary depending on the output power. While an acceptable decrease in efficiency is achieved, there is an improvement in torque ripple.

IV. CONCLUSION

The main noise source in SRMs is defined as the radial force between the rotor and the stator. To reduce this noise, different studies are carried out in the literature. Geometric design methods include creating skews in stator and/or rotor structures. While the skew causes some decrease in the average power value, when the output signal shapes are examined, it is seen that there is a decrease in the torque ripple. Failure to determine the skew degree appropriately causes negative results in the motor as it can affect the resultant torque. For this reason, it is important to determine the degree of skew in SRMs.

In this study, a special skew structure is proposed in the rotor structure different from the traditional skew method. The difference of the proposed method from the other structures is that double-sided skew is applied to the rotor. For this purpose, a reference motor with a stator/rotor pole ratio of 6/4 is preferred. The rotor structure of this motor is analyzed using FEM by creating a 3D solid model of the traditional skew method and the sliding shapes proposed for this study. In the traditional skew method, the rotor is given 5 degrees of skew, while 5 and 10 degrees of skew are used in the proposed structure.

In the FEM analysis results, it is seen that the skew structure slightly decreases the average value of the output torque but improves the torque signal. The best result is obtained when the proposed method has a rotor structure with 5 degrees of skew. In this case, although there is an 11% decrease in the average torque, an improvement of 32.3% in the torque ripple value is obtained. In the proposed method, after the rotor with 5 degrees of skew, the rotor structure with traditional skew gave the best result.

As a result, the torque ripple value in SRMs can be improved with the skew method. Although not all skew ratio gives successful results, it may cause different failures in the motor. For this reason, the value that gives the best result in improving the torque ripple value can be obtained by optimization studies.

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