Performance Improvement of a Switched Reluctance Motor

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Abstract— In this paper, impacts of different operating factors of switched reluctance motors (SRM) upon vibrations and noise in the motor are reviewed. The noise in the motor may be reduced by applying a suitable control strategy or modifying design technique. Attempt is made to minimize the noise by creating a hole in the rotor poles of the motor. It is shown that a circular shape hole is preferred to rectangular one. A proper rotor and stator pole arcs are adjusted and optimal hole radius is determined.

1. INTRODUCTION

Switched reluctance motor (SRM) operates based on magnetic reluctance variations and its application is economical due to its high efficiency and low maintenance. However, acoustic noise and high torque ripples reduce its wide application and its noise reduction is essential. In [1], impact of stator yoke shape and in [2] effect of pole number of SRM on the noise has been investigated. Using different materials in the motor leads to different level of noise and rotor pole shape affect the noise level [3].

The origins of the noise in SRM are due to magnetic, mechanical, aero-dynamic and electrical characteristics of the motor. Magnetic noise crossing the air gap almost radially leads to radial forces on the teeth and motor vibrations. Dominant noise generating factor is radial deformation of the stator due to magnetic variation of radial magnetic attraction by rotor [4]. Shape, dimensions, materials and winding type are among the factors influencing these forces. If natural frequency of SRM stator interferes one of the excitation winding switching frequencies the resonance occurs which generates the noise. Dominant vibrating mode frequency as a function of sheet dimensions and materials has been given in [5]. Movement of air and other fluids are aero-dynamic origin of noise generating in the motor. Interaction between SRM, power electronics converters and its control system are electrical origin of the noise. Torque ripple is the major factor in noise generation which can be mitigated by controller and its switching pattern. Optimal design of magnetic structure [1, 6] can reduce resonance effect during motor operation. Holes inside rotor pole may decrease the radial forces and noise; however this may lead to a lower efficiency [7].

Generally radial forces, torque ripples and switching pattern play dominant roles in the noise generation in SRM. In the case of radial forces and torque ripples, there are two major procedures for noise reduction: 1) control strategy and 2) design technique. Control strategies are active techniques and they propose the windings supply type and shaping input current waveform. Design techniques as passive methods concentrate on the motor structural design. This paper deals with the noise reduction based on the structural design techniques.

2. DESIGN-BASED TECHNIQUES FOR NOISE REDUCTION

The radial force in 6/4 SRM is almost twice that of 12/8 SRM while deformation of 12/8 SRM is 1.26 times that of 6/4 SRM [2]. Modal analysis shows that the noise and vibration in 12/8 SRM is very smaller than that of 6/4 SRM. A very robust dielectric or non-magnetic material of slot wedge, called spacer, can mitigate the noise level in SRM [8]. Trapezoidal poles on a yoke with external hexagonal shape and internal circular shape can lead to a low noise SRM [6]. To damp vibration and oscillation in SRM, Piezoelectric material has been recommended [9]. The optimum location for the piezoelectric material placement has been determined by Genetic algorithm [10], Deformation of rotor pole tips and asymmetry of stator pole (non-uniform air gap) are optimized to reduce the torque ripples [3]. Simultaneous optimization of stator and rotor poles arc and switching patterns of converter may decrease the noise level in SRM [11]. Stator slots internal spans have been optimized to minimize the vibration of SRM [12]. A multi-objective optimization technique has been presented for a 4/2 SRM [13] using rotor and stator dimensions as optimization variables and the noise of the proposed SRM has been mainly reduced by optimal rotor configuration.

A rectangular hole inside rotor teeth can reduce the noise. FE analysis shows that the width of the hole has impact on the noise reduction compared to that of the height of the hole [7]. Trapezoidal fins with wide upper part and narrow lower part have influence on the noise reduction with no negative impact on the heat transfer [14]. Multi-layer design can reduce noise and increase the starting torque [15]. Some modifications of the rotor and stator pole head shape may be applied and then dimensions optimized in order to reduce the torque ripple [16].

3. ESTIMATION OF RADIAL FORCES, TORQUE RIPPLE, VIBRATION AND ACOUSTIC NOISE

Prior to the manufacturing SRM, it is essential to estimate radial forces and torque ripples. Analytical method is appropriate when optimizing large number of parameters. Coupled mechanical-electromagnetic FEM is first applied to estimate electromagnetic forces exerted on the motor and then forces data is transferred for mechanical and modal analysis [1, 14]. Combination of Matlab-Simulink and FEM can be used to model noise and vibration in SRM [17]. A microscopic-based method has been employed in [18] to analyze the force in SRM. First FE analysis with pulse waveform excitation is carried out and the response is analyzed by Fourier series, then all excitations are modeled by Canvolution. This method provides proper excitation for reduction of radial forces.

Using Maxwell stress method, the radial forces and tangential flux densities in any node are calculated and then force density is estimated as follows [5]:

$$F_n = (B_n^2 - B_t^2)/2\mu_0 \tag{1}$$
$$F_t = B_n B_t/\mu_0 \tag{2}$$

where B_t, B_n, F_t and F_n are the tangential, radial flux densities, and force densities respectively. Thus tangential force is as follows:

$$F_t = \int_0^{2\pi} \frac{1}{2\mu_0}(B_n^2 - B_t^2) r_{gap} d\varphi \tag{3}$$

An external voltage source is applied to each phase of the motor and transient analysis is used in which the back emf is calculated. For simulation purpose, the slipping surface between the rotor and stator is employed and each stage following motor move and placing it on arbitrary location, the Lagrenge equations on the nodes between rotor and stator nodes applied by CE command in Ansys. Fig. 1 shows phase connection in the software. Inductance of the winding is calculated by the 2D-FEM. If the 3D or end-winding inductance was known, it can be put in series with supply. Every phase of SRM consists of two coils (in series or parallel) and each coil has two levels. One coil element is defined in Ansys. for each level.

Parameters	Value
No. of stator/rotor poles	8/6
Stator outer diameter (mm)	125
Stator slot bottom diameter (mm)	100
Rotor outer diameter (mm)	63
Rotor slot bottom diameter (mm)	41
Air gap length (mm)	0.35
Shaft Diameter (mm)	21
Stack length (mm)	90
Stator and rotor pole arc (°)	21
Turn per coil	124
Rotor resistance (Ω)	0.69

Table 1. Specifications of proposed SRM.

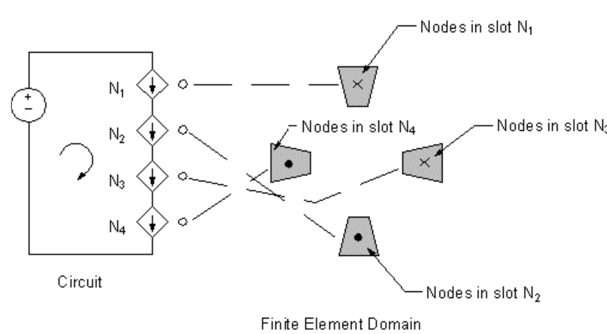


Figure 1. Procedure for applying phase voltage in software.

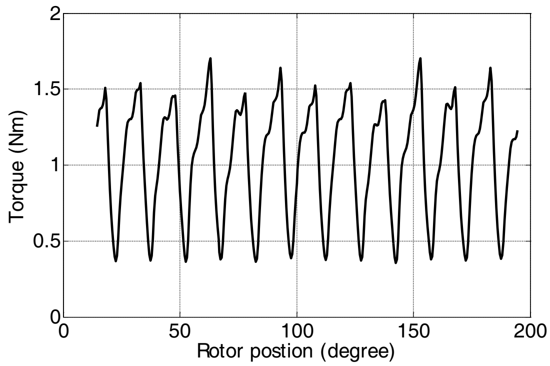


Figure 2. Developed torque of SRM phase versus rotor angular position.

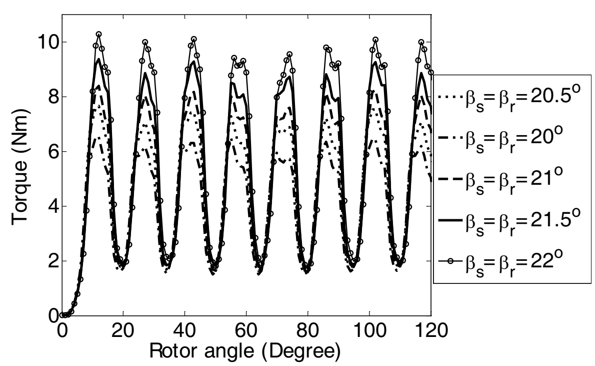


Figure 3. Torque of SRM versus rotor angle for different pole arcs.

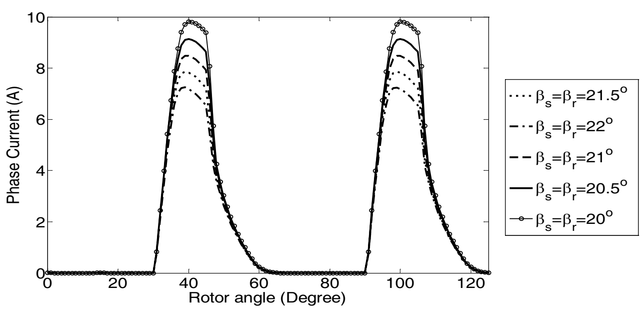


Figure 4. Current of SRM versus rotor angle for different pole arcs.

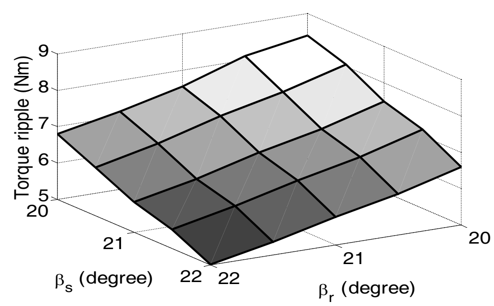


Figure 5. Torque ripples variations versus rotor and stator poles arcs.

Specifications of the proposed SRM have been summarized in Table 1. The motor is simulated for rated speed of 1500 rpm with 0.5 step and half rotation. The developed torque of the SRM with considerable ripples has been shown in Fig. 2.

4. IMPACT OF POLES ARCS ON TORQUE AND CURRENT WAVEFORMS

The poles arc of rotor and stator of the proposed SRM is 21 degrees. To investigate the impact of the poles arc on the performance of the motor, poles arc of 20, 20.5, 21.5 and 22 degrees are also considered and the torque versus rotor angular position has been presented in Fig. 3. The corresponding current waveforms have been shown in Fig. 4. As seen in Fig. 3, smaller pole arc increases the torque ripples, however in this case the average torque rises which is an advantage. Fig. 4 indicates that for smaller pole arc, current is higher and this the reason for larger average torque. If the pole arc is reduced further the current may increase beyond its permissible value. In such a case a hysteresis controller is needed. Therefore, the minimum pole arc is determined by the maximum phase current and its maximum pole arc by minimum average torque. Fig. 5 exhibits the torque ripple variations versus rotor and stator poles arc. Considering contradictory effects of pole arc on the performance indexes of the SRM a 22 degrees arc has been recommended as optimum value.

5. IMPACT OF CIRCULAR HOLE ON RADIAL FORCES REDUCTION

Figure 6 shows the total radial forces exerted on the SRM over different rotor positions which is almost the same for pole arcs 21 and 22 degree. Radial forces in SRM with optimum pole arcs are estimated. The impact of a rectangular hole inside the rotor teeth in radial force reduction has been demonstrated [7]. However, the circular hole has some advantages such as simplicity of manufacturing, structural stability and preventing from the local saturation in sharp corners.

The circular hole is inserted in the rotor teeth as such that the distance between the hole center and shaft center is chosen to have enough mechanical robust, far enough from the pole tip, as shown in Fig. 7. The holes radius, r_h, is optimized based on FEM. This distance would be 1 mm and hole radius 2 mm. Figs. 8 to 9 show the magnetic flux lines and forces exerted on the pole with peak radial forces. Fig. 10(a) presents the radial forces due to excitation of one phase for

70 degrees rotation of SRM and different radius. As seen the radial force decreases by increasing radius of the hole and tend to 71% at 4 mm radius. Fig. 10(b) shows the developed torque for one excited phase with different hole radius which has the largest drop at radius 4 mm. If unidirectional SRM is considered the impact of the circular hole displacement from center to the left of teeth (in rotation direction) can be studied. For radiuses 1.5, 2 and 2.5 mm the radial forces approach 70%, 64% and 57% that of the initial value. There is no considerable reduction of the force for larger radius. However, the mean torque also decreases and this reduction is considerable for 4 mm radius. This reduction is about 10% up to radius 2.5 mm which is negligible against 43% reduction of their forces. So the hole with radius 2.5 mm is the optimal one.

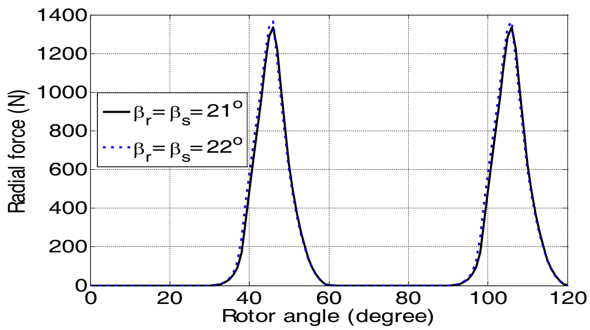


Figure 6. Radial force exerted on SRM with optimum poles arc.

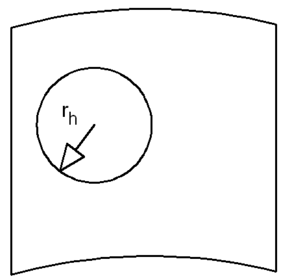


Figure 7. Pole with circular hole.

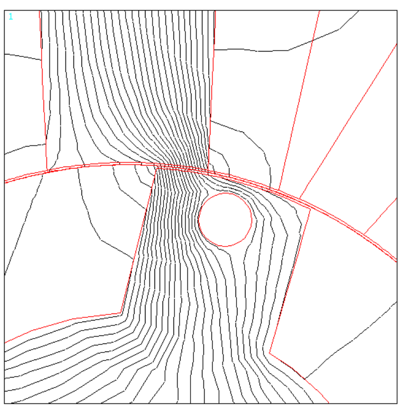


Figure 8. Flux distribution at angle with peak radial forces.

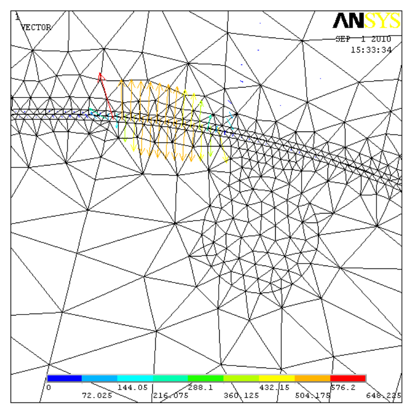
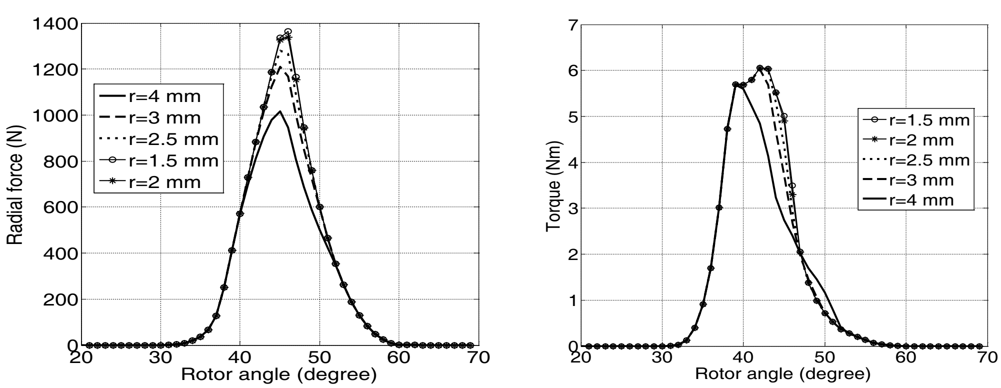


Figure 9. Forces exerted on SRM at angle with peak radial forces.



(a) (b)

Figure 10. Radial forces (a) and developed torque (b) of SRM with radius of hole 1.5 mm to 4 mm.

6. CONCLUSION

Acoustic noise reduction based of design technique of the SRM was discussed and implemented in this paper. Radial force as a dominant factor on the acoustic noise generation is reduced by circular holes inside of the rotor teeth. The holes with radius 1.5, 2, 2.5, 3 and 4 mm were examined and it was found that a 2.5 mm radius hole is the optimal one reducing the force by 43%. Combination of the optimal rotor poles arc and the circular holes reduce both radial forces and torque ripples. Advantages of the circular hole compared to rectangular hole include higher average torque and better reduction of the radial force. Two-dimensional FEM was applied to estimate precisely the magnetic flux distribution, current waveforms, forces and developed torques within the motor.

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