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Sensitivity Analysis of Geometrical Parameters of a Switched Reluctance Motor with Modified Pole Shapes

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Abstract - A major problem in Switched Reluctance Motor (SRM) is torque ripple, which causes undesirable acoustic noise and vibration. This work focuses on reducing the undesirable torque ripple in SRM by modifying stator and rotor geometry. This paper presents a comparative study on torque ripple minimization in SRM with modified pole shapes such as stator pole taper, stator pole face with non-uniform air gap and pole shoe attached to rotor pole. Further this paper presents a detailed sensitivity analysis of the effect of different geometrical parameters that alter the pole face shapes on the performance of SRM. The analysis is performed using finite-element method considering average torque and torque ripple as performance parameters. Based on the analysis, a design combining stator pole taper with non-uniform air gap is proposed to improve the torque characteristics of SRM. The dynamic characteristics of the proposed design are simulated and the results show satisfactory reduction in torque ripple.

Keywords: Average torque, Torque ripple, Switched reluctance motor, Design modifications

1. Introduction

There has been growing research interest towards the design and development of SRM for variable speed applications [1-2]. The primary disadvantage of an SRM is the higher torque ripple compared with conventional machines, which contributes to acoustic noise and vibration. The origin of torque pulsations in an SRM is due to highly non-linear and discrete nature of torque production mechanism. Torque pulsations are most significant at commutation instants when torque production mechanism is being transformed from one active phase to another [3]. Two different approaches are considered for torque ripple minimization in SRM. One is to pursue a motor geometry which reduces torque ripple and the other is to manipulate motor current [4, 5] to improve the performance. It is to be noted that even if electronic torque ripple reduction techniques are used, it is desirable to look for an optimum geometry for inherent improvement [6]. SR motors normally have three operating modes; low speed mode, chopped current mode at medium speeds and high speed mode. The effect of torque ripple is most significant at low speeds where torque variations considerably affect instantaneous speed of the shaft. At higher speeds, inertia of the rotor helps to reduce these speed variations and hence vibration. At low speed, torque ripple is significant, and the overlap of the phase current may be assumed negligible. Further the phases are assumed to turned on and off at rotor position corresponding to the intersections of the torque characteristics [3]. The effect of different design parameters on torque ripple in SRM and the design approaches to minimize torque ripple have been discussed in detail by Iqbal Husain. The sensitivity of geometrical parameters on the performance of SRM has been described in the literature [7-11]. In [10], the sensitivity of the stator and rotor pole arcs is studied to determine optimum pole arc configuration to minimize torque ripple. From the literature it is evident that the torque output and torque ripple of SRM are sensitive to stator and rotor pole arcs and their selection is a vital part of SRM design process.

In recent years a lot of research has been directed towards reducing the undesirable torque ripple in SRM by modifying stator and rotor geometry. Several attempts have been made to study the effect of special pole shapes on the torque profile and torque ripple characteristics of SRM [12-16]. In these methods the basic idea for torque ripple minimization comes from the fact that the torque profile and the exciting current profile, is a function of the inductance profile when the exciting voltage profile and the switching time for each phase are fixed [16]. While studying the effect of modified geometry on the performance of SRM due consideration should be given to both average torque and torque ripple, since improvement in torque ripple may result in degradation of average torque. Hence a detailed sensitivity study of the design parameters that alter the pole shapes on average torque and torque ripple needs to be performed. This paper intends to address this by presenting a sensitivity analysis of geometrical parameters on the performance of SRM with modified pole

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shapes such as stator pole taper [15], stator pole face with non-uniform air gap, pole shoe attached to rotor pole [16].

2. Performance Analysis of SRM with Modified Pole Shapes

The structure of 8/6 SRM is shown in Fig. 1. The initial design details of the motor are given in Appendix 1. For each design modification average torque and torque ripple are calculated by modeling and simulation using Finite Element Analysis (FEA) based CAD package MagNet.

Average torque is computed by the following equations

$$T_{ave} = \frac{(W_a - W_u) N_s N_r}{4\pi} \tag{1}$$

$$W_a = \int_0^I L_a i di \tag{2}$$

$$W_u = \frac{1}{2} I^2 L_u \tag{3}$$

where I represents the rated phase current, L_a represents the inductance at the fully aligned position and L_u represents the inductance at the complete unaligned position.

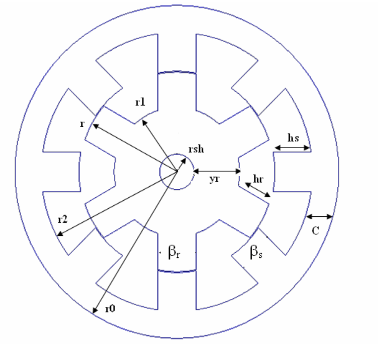

Fig. 1. Structure of SRM

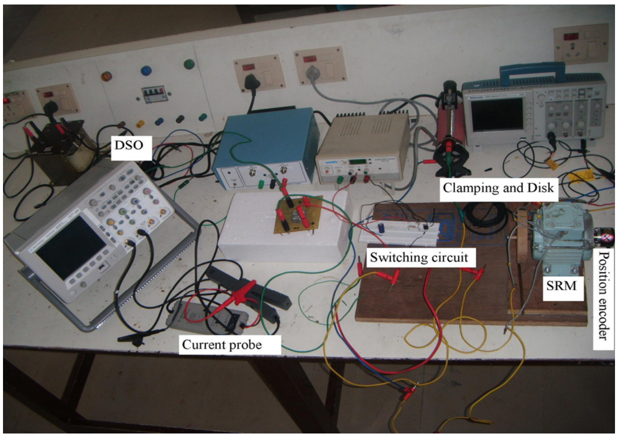

Fig. 2. Experimental setup to determine flux linkage vs. current characteristics

Torque ripple is evaluated from the torque dip present in the static torque characteristics [6] and is given by

$$T_{ripple} = T_{max} - T_{min} \tag{4}$$

where T_{max} is the maximum torque determined from the peak of the static torque characteristics and T_{min} is the torque at the intersection instants.

In order to validate FEA modeling, a prototype SRM was subjected to static measurements to determine the flux linkage current characteristics. For this purpose, an experimental setup comprising a motor, and position encoder was used. The components of the experimental setup are shown in Fig. 2. The experimental method [17, 18] makes use of the voltage equation as the basis for determining the magnetization characteristics of the machine. When a voltage pulse is applied to one of the phases of SRM with all other phases open, its voltage equation is given by

$$V = iR + \frac{d\psi}{dt} \tag{5}$$

where V is the instantaneous voltage across the phase winding, R is the resistance and i is the current. The flux linkage is given by

$$\psi = \int (V - iR) dt \tag{6}$$

The flux-linkage can be determined for different values of current by using the Eq. (6). The general practice is to apply a voltage pulse to the stator winding by clamping the rotor to a known position. The current rises up to a steady state level, and then the voltage is turned off, de-energizing the stator winding. Throughout this time, integration takes place to determine the instantaneous flux-linkage as a function of current and position. The current and voltage waveforms recorded while the rotor was locked at aligned

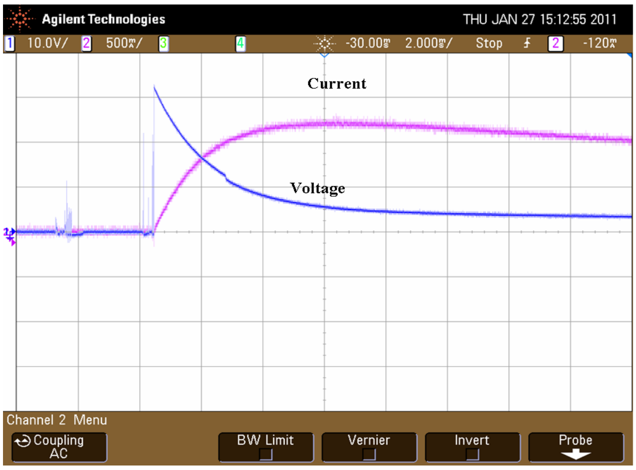

Fig. 3. Waveforms recorded at aligned position

position are shown in Fig. 3. Table 1 shows a comparison of the flux-linkage by measurement and FEA methods at discrete points to evaluate the correlation between the results. The flux linkages obtained by FEA show higher values than those of experimental values. However the difference is small. Inspite of the same physical dimensions of the motor, differences are inevitable due to measurement errors in the experiment and tolerances in the numerical computation. The closeness of the results have confirmed and validated the FEA model.

2. 1 SRM with tapered stator pole

The tapered stator pole model [15] is shown in Fig. 4. The ratio **'a'** between the enlarged stator pole arc at the base (β_{S1}) and the initial constant width stator pole arc at the base (β_S) is varied from 1 to 2 keeping β_S constant. Increasing **'a'** has the effect of increasing the overall area of the cross section, leading to a decrease in the reluctance of the stator pole sections. This in turn reduces the total reluctance of the machine and increases the flux for the given mmf resulting in higher inductances and average torques [2]. The effect of tapering is evident near aligned position. There is a considerable increase in the inductance and its slope near aligned position. This is evident from the phase inductance characteristics shown in Fig. 5. This results in a rectangular torque vs. rotor position characteristics as shown in Fig. 6. As a result of rectangular torque vs. rotor position characteristics there is considerable reduction in torque ripple.

Table 1. Comparison of Flux-linkage

Current (A)	Position (Degree)	Experimental (Wb-turns)	FEA (Wb-turns)
0. 75	0	0. 0054	0. 007
	30	0. 033	0. 036
1. 1	0	0. 012	0. 0107
	30	0. 0487	0. 055
2	0	0. 0152	0. 0184
	30	0. 0868	0. 094
3	0	0. 02567	0. 027
	30	0. 135	0. 138

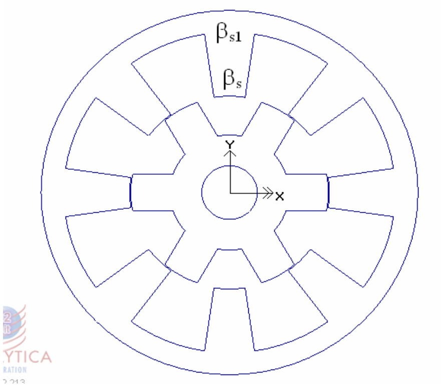

Fig. 4. SRM with tapered stator pole

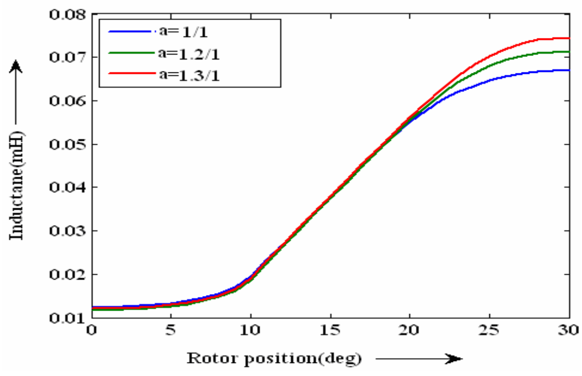

Fig. 5. Inductance profile with stator pole taper

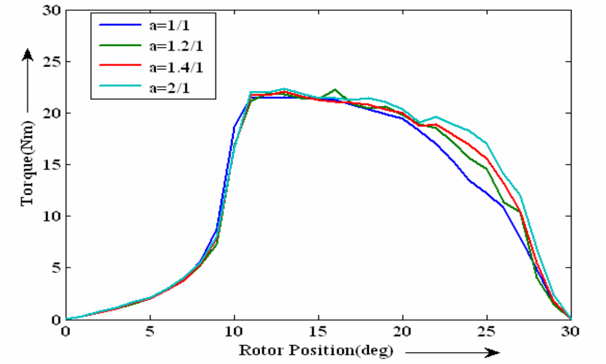

Fig. 6. Torque characteristics with stator pole taper

Table 2. Average torque and torque dip for various pole taper ratios

Pole taper ratio 'a'	Average Torque (Nm)	Torque dip (Nm)
1. 2	24. 68	7. 23
1. 4	25. 18	6. 29
1. 6	25. 45	5. 92
1. 8	25. 79	5. 57
2	26. 06	5. 35
Initial Design	23. 43	8. 56

The average torque and torque dip for different pole taper angles are summarized in Table 2. From the table it is clear that there is improvement in the average torque and reduction in torque ripple with tapered stator pole configuration.

2. 2 Stator pole face with non-uniform airgap

For optimizing the torque profile of SRM by changing the inductance profile, the most significant parameter is the air gap profile between the stator and rotor poles. SRM with a modified air gap profile [16] is shown in Fig. 7. The design parameter θ varies the air gap profile when the rotating direction of the rotor is clockwise. In this design the air gap becomes narrower as the rotor pole overlaps with the stator pole. This results in a flatter inductance profile near aligned position which results in reduced torque dip. The performance of the machine is analyzed by

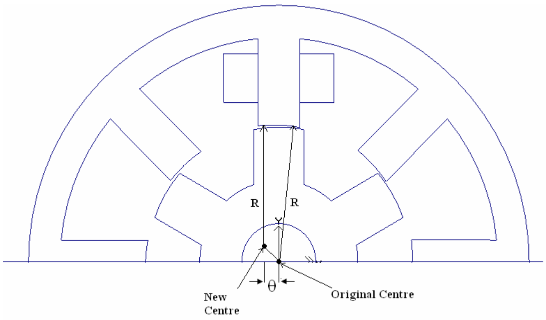

Fig. 7. SRM with non-uniform air gap profile

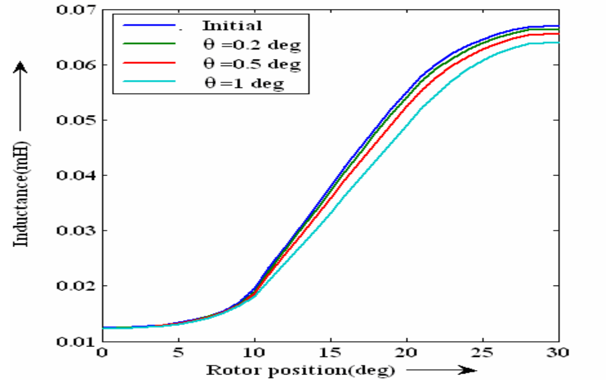

Fig. 8. Inductance profile of stator pole face with non-uniform air gap

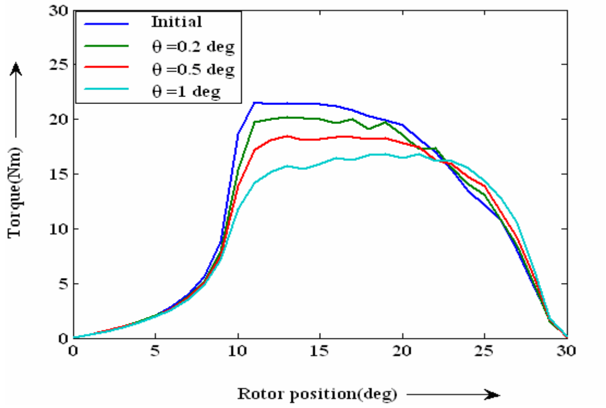

Fig. 9. Torque characteristics of stator pole face with non-uniform air gap

varying the design parameter θ from 0 to 2 degrees.

The inductance profile and torque vs rotor position characteristic is shown in Figs. 8 and 9 respectively. From the figures it is evident that inductance value is reduced with increase in θ which in turn results in reduced torque. However the shape of the torque vs. rotor position characteristics is almost rectangular, which has the advantage of reducing torque ripple.

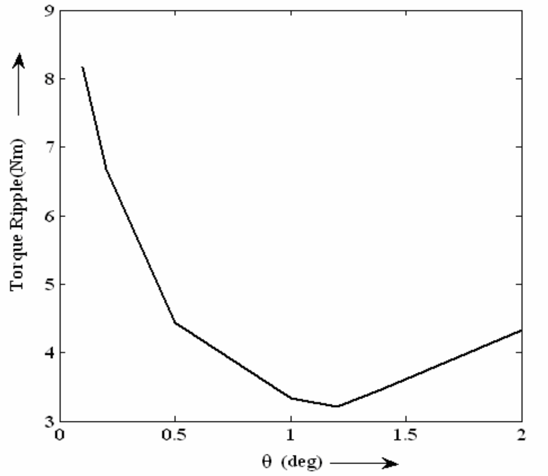

Fig. 10. Torque dip variations with design parameter θ

Table 3. Average torque and torque dip for various values of θ

Teta	Average Torque(Nm)	Torque Dip(Nm)
0. 1	23. 06	8. 16
0. 2	22. 74	6. 67
0. 5	21. 72	4. 43
1	20. 23	3. 34
1. 2	19. 69	3. 20
1. 4	19. 18	3. 47
2	17. 73	4. 32
Initial	23. 43	8. 56

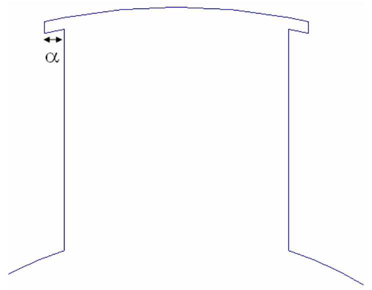

Fig. 11. SRM with Rotor pole shoe

The torque dip variation for different values of θ is shown in Fig. 10. The torque dip is minimum for the design with θ=1. 2deg. The average torque and torque dip for different angles are summarized in Table 3. It is evident that by modifying the air gap profile there is considerable reduction in torque ripple. But due consideration should be given to the fact that the average torque of the machine with modified air gap profile is reduced when compared to the initial design.

2. 3 SRM with pole shoe attached to rotor pole

SRM model with pole shoe attached to the lateral side of the rotor pole [16] is shown in Fig. 11. As the rotor moves from unaligned to aligned position the introduction of pole shoe changes the inductance profile at the unaligned positions which in turn controls the rising torque profiles and reduces torque ripple. The inductance profile of SRM with different pole shoe angle α is shown in Fig. 12.

The electromagnetic torque vs rotor position characteristic is shown in Fig. 13. The average torque and torque dip for different pole shoes are summarized in Table 4. From the table it is clear that the introduction of rotor pole shoe reduces torque ripple with less variation in average torque.

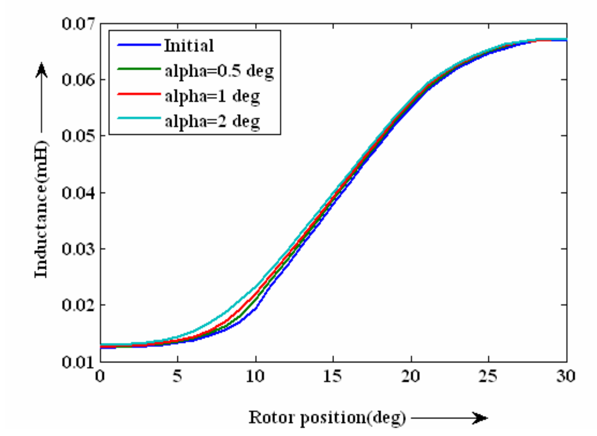

Fig. 12. Inductance profile of SRM with rotor pole shoe

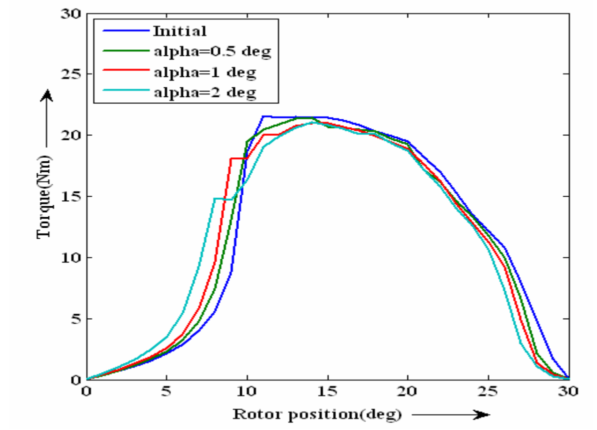

Fig. 13. Torque characteristics of SRM with rotor pole shoe

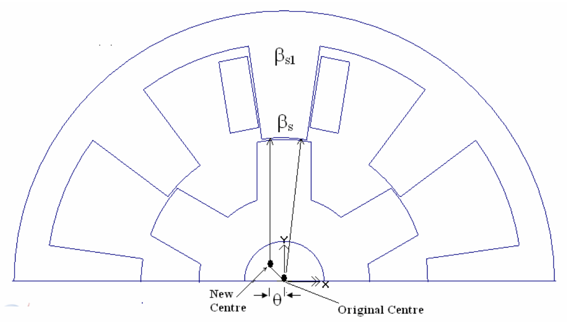

Fig. 14. SRM with stator pole taper and non-uniform air gap

Table 4. Average torque and torque dip for various values of α

Alpha(deg)	Average Torque(Nm)	Torque Dip(Nm)
0. 5	23. 57	8. 17
1	23. 54	7. 27
2	23. 42	6. 78

2. 4 SRM with stator pole taper and Non-uniform air gap

SRM structure with tapered stator and non-uniform air gap is shown in Fig. 14. From the above analysis it is evident that the SRM design with modified air gap profile produces less torque ripple when compared with other configurations. However there is considerable reduction in average torque. SRM design with a tapered stator pole results in higher average torque when compared with other configurations. Hence a design based on stator pole taper with non-uniform air gap is proposed.

This results in a flatter torque vs. rotor position characteristics near aligned position as shown in Fig. 15. The average torque and torque dip for different pole taper angles are summarized in Table 5. From the table it is clear that there is improvement in the average torque and reduction in torque ripple with the proposed design configuration.

The dynamic torque characteristics of the machine is analysed using a drive circuitry [19] as shown in Fig. 16. The characteristics with a taper angle 1. 4 and θ=0. 5deg

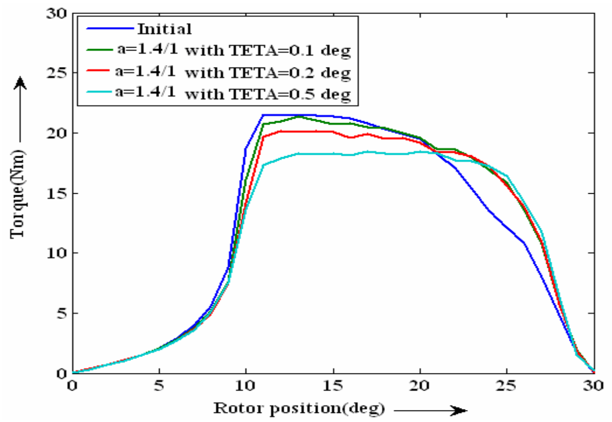

Fig. 15. Torque characteristics of tapered stator model with non-uniform air gap

Table 5. Average torque and torque dip for various values of pole taper angle and θ

Pole taper ratio 'a'	Teta (deg)	Average Torque (Nm)	Torque Dip (Nm)
1.8	0.2	24.84	4.23
2	0.2	24.76	4.15
1.2	0.5	22.73	4
1.4	0.5	23.08	2.71
1.6	0.5	23.38	3.55
1.8	0.5	23.38	3.48
2	0.5	23.46	3.05

Table 6. Performance characteristics of initial and proposed design

Performance parameter	Initial design	Pole taper with air gap
Maximum instantaneous torque (Nm)	1. 49	1. 287
Minimum instantaneous torque (Nm)	0. 58	0. 462
Mean torque (Nm)	1. 022	0. 9918
T_{max}- T_{min}	0. 91	0. 825

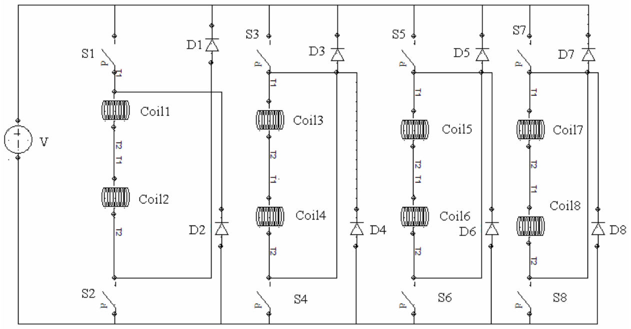

Fig. 16. Drive circuitry for dynamic analysis

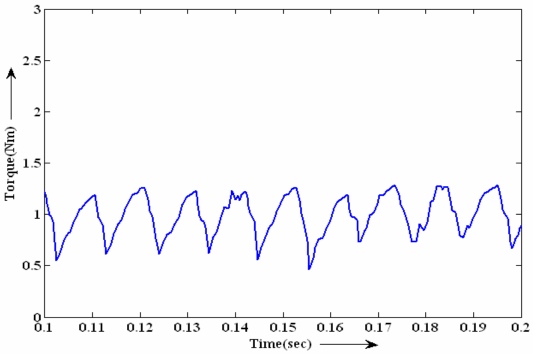

Fig. 17. Dynamic torque characteristics of tapered stator model with non-uniform air gap

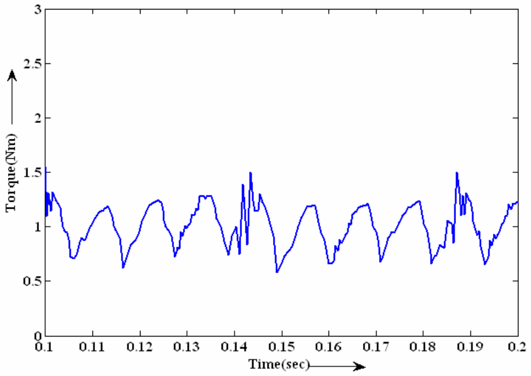

Fig. 18. Dynamic torque characteristics of initial design

with load torque 1Nm is shown in Fig. 17. The characteristics of the initial design is shown in Fig. 18. The results are summarized in Table 6. From the table it is evident that torque ripple is reduced in the proposed design.

3. Conclusion

This paper has investigated the influence of geometrical parameters that alter the pole face shape on the torque profile of SRM. Considering average torque and torque ripple to be optimizing factors, the following results pertaining to the geometrical parameters involved in the study could be useful

a) There is considerable improvement in average torque and reduction in torque ripple for the structure with stator pole taper. An increase in pole taper angle increases the average torque and reduces torque ripple.

b) Considerable reduction in torque ripple is achieved with SRM design incorporating rotor pole shoe while the average torque produced is almost the same for different pole shoe angle.

c) Stator pole face with non-uniform air gap produces minimum torque ripple. There is an optimum angle for which the torque ripple is minimum. However average torque produced by the design is reduced.

d) Stator pole taper design with non-uniform air gap shows significant improvement in average torque with considerable reduction in torque ripple. For the 8/6 SRM configuration considered in this work the pole shape design with pole taper angle 1. 4 deg and air-gap angle 0. 5 deg produces minimum torque ripple without compromising the average torque.

The analysis reported will aid the designer in choosing the bounds of design variables to determine optimum design by applying multi-objective optimization.

APPENDIX-1

Design Data of Machine

Design Parameter	Value
Stator pole arc β_s	18 degrees
Rotor pole arc β_r	22 degrees
Air gap length g	0. 5 mm
Stator diameter D_0	190 mm
Bore diameter D	100. 6 mm
Stack length L_{stk}	200mm
Shaft diameter D_{sh}	28mm
Back iron thickness C	12 mm
Height of stator pole h_s	32. 7 mm
Height of rotor pole h_r	19. 8 mm
Turns per phase	154
Rated current	13 A
Lamination Material	M43

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