EFFECT OF MODIFIED POLE SHAPES ON THE PERFORMANCE OF HYBRID SWITCHED RELUCTANCE MOTOR

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Abstract: *Hybrid Switched Reluctance Motor (HSRM) has the advantage of improved torque and efficiency than conventional Switched Reluctance Motor (SRM). The presence of permanent magnet and auxiliary winding in the stator yoke increases the torque density in HSRM when compared to SRM. However cogging torque and torque ripple is a major drawback in HSRM which causes acoustic noise and vibration. This work emphasis on minimization of torque ripple and cogging torque by altering the stator and rotor pole geometry. This paper deals with the influence of altered pole shapes such as pole tapering in stator, pole shoe attached to rotor and non-uniform air gap at stator pole face on the torque characteristics of the HSRM.. Based on the analysis an optimum design is arrived to enhance the performance of HSRM.*

Keywords: *Hybrid Switched Reluctance motor; Average torque; cogging torque; torque ripple; design modifications*.

1. Introduction

Switched reluctance motors (SRM) are doubly salient singly excited variable speed electric motors[1]. In SRM, torque is generated as a result of reluctance variation in the air gap. These motors comes with advantages such as robust construction, higher speed, higher starting torque and increased fault tolerance which makes the motor desirable in variable speed applications.

Hybrid switched reluctance motor (HSRM) has constructional features same as conventional switched reluctance motor (CSRM) with modifications in its stator core. A doubly salient permanent magnet (DSPM) motor with permanent magnet (PM) on its stator core is proposed in [2]. This DSPM motor has shown that addition of PM increases torque density and efficiency. SRM with DC assisted field excitation is discussed in [3]. This motor has better torque density than that of the conventional SRM. Hybrid SRM (HSRM) which has PM and auxiliary windings in the stator back iron is proposed in [4]. The authors have highlighted the merits of the HSRM by comparing its characteristics with conventional SRM.

In these hybrid SRM configurations the presence of permanent magnet influences the torque characteristics[5].In [6] the author have analysed the influence of magnet size on the torque ripple characteristics of DSPM. The dimension of permanent magnet and the choice of permanent magnet material is a major factor contributing to the cogging torque in these configurations[7].Hence from application perspective the drawbacks with respect to torque ripple and cogging torque needs to be addressed. In this perspective this work focuses on performance analysis of HSRM with respect to average torque, torque ripple and cogging torque.

In [8], stator pole tapering has been introduced to improve the torque characteristics of conventional SRM. The effect of pole shape modifications on improving the performance of SRM has been extensively explored by researchers[9-11]. In this work the effect of pole tapering in stator, pole shoe attached to rotor and non-uniform air gap at stator pole face on the torque characteristics of HSRM is analyzed using Finite Element Analysis (FEA) based computer aided design (CAD) package MagNet.

2. Study of HSRM with altered pole shapes

The structure of hybrid SRM is shown in Fig.7. The rotor structure is same as that of conventional SRM while permanent magnets and auxiliary windings are embedded in the stator yoke[4]. The dimension details of the HSRM are given in Appendix 1. The effect of each design parameter on average torque, torque ripple and cogging torque of HSRM has been examined by modeling and simulation using FEA based CAD package MagNet.

By using the following equations average torque is computed [15]

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

$$W_a = \int_0^I L_a i di \quad (2)$$

$$W_u = \frac{1}{2} I^2 L_u \quad (3)$$

where I stands for the rated phase current, L_a stands for fully aligned position inductance and L_u stands for fully unaligned position inductance.

Torque ripple is defined as [16]

$$.\%.T_{ripple} = \frac{T_{max} - T_{min}}{T_{max}}.100 \quad (4)$$

where T_{max} is the peak of static torque profile which is called the maximum torque and T_{min} is the torque at the intersection instants.

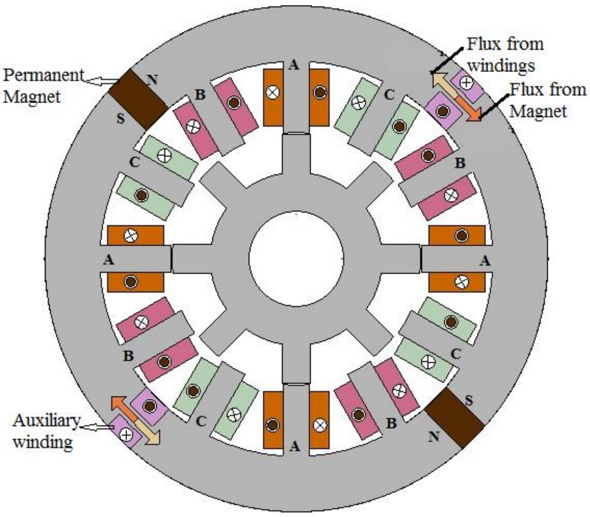

Fig. 1. Structure of HSRM

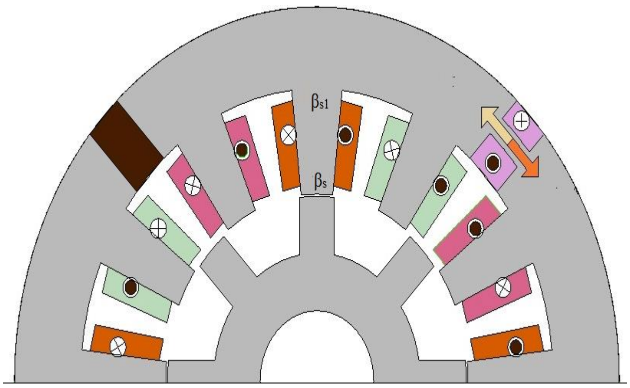

Fig. 2. Structure of HSRM with tapered stator pole

A. *HSRM with stator pole tapering*

The structure of HSRM with tapered stator pole is shown in Fig. 2. Let β_s and β_{s1} denote the stator pole arc at the tip and pole root. Stator pole taper ratio 'b' (β_{s1}/β_s) is varied from 1 to 2 keeping β_s constant at 15^0. By increasing the ratio 'b' the overall area of cross-section of stator pole is increased which results in improved inductance profile [8]. The effect of tapering stator is evident at the aligned position and it has essentially no effect near the unaligned position. There is a substantial gain in inductance near the aligned position thus leading to a rectangular torque profile as shown in Fig. 3. The cogging torque characteristics for various stator pole taper ratio of HSRM is shown in Fig.4. The average torque, torque ripple and cogging torque for different stator pole taper ratio is outlined in Table 1 from which it is evident that there is a improvement in average torque and reduction in torque ripple and cogging torque.

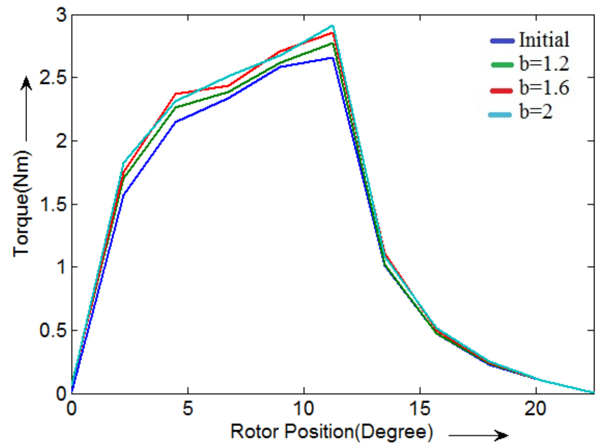

Fig. 3. Torque characteristics of HSRM with tapering in stator pole

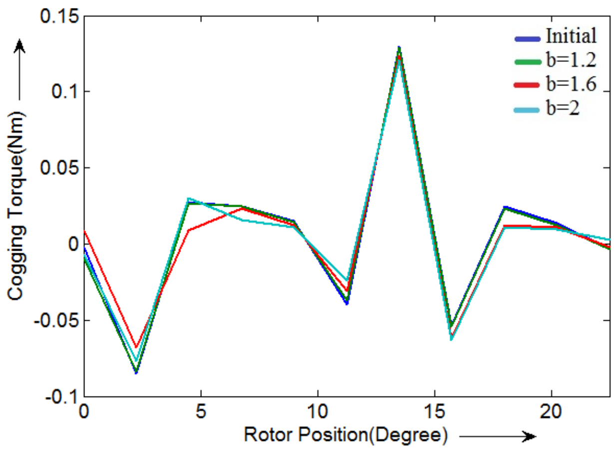

Fig. 4. Cogging torque profile of HSRM with tapering in stator pole

Table 1. Average torque, Cogging torque and Ripple torque for various pole taper ratio

ratio 'b'	T_{avg}(Nm)	T_{ripple}(%)	T_{cog}(Nm)
1.2	2.016	52.6	0.129
1.4	2.069	52.3	0.125
1.6	2.123	51.0	0.123
1.8	2.153	49.5	0.122
2.0	2.169	48.3	0.120
Initial design	1.9	52.4	0.129

B. *HSRM stator pole face with non uniform air gap profile*

The most important parameter to enhance the torque profile of HSRM is the length of air gap [13]. HSRM with modified air gap profile is shown in Fig 6.The design parameter 'θ' controls the air gap profile between the stator and rotor when the rotor is rotating in counter-clockwise direction. In this design, the parameter 'θ' is chosen such that the air gap becomes wider as the rotor pole rotates over a stator pole. For different values of 'θ' from 0 to 2 degrees the performance of HSRM is examined. Increasing 'θ' has the effect of reducing the inductance value which in turn results in torque characteristics almost flatter which has the advantage of reduction in torque ripple and cogging torque as shown in Fig.6 and Fig.7. The average torque, torque ripple and cogging torque for various values of 'θ' is summarized in the Table 2 from which it is obvious that by altering the air gap contour there is a substantial minimization in torque ripple and cogging torque. However the results are not encouraging with respect to average torque.

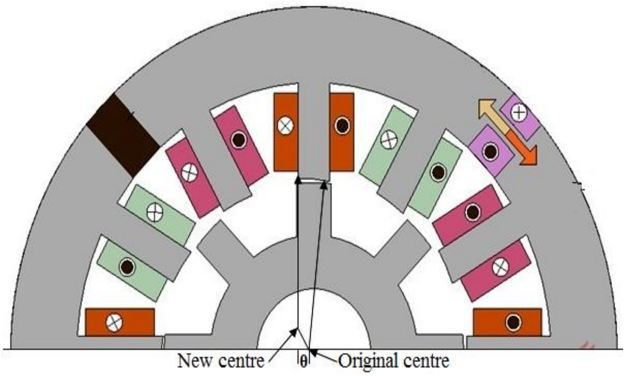

Fig. 5. HSRM with non uniform air gap

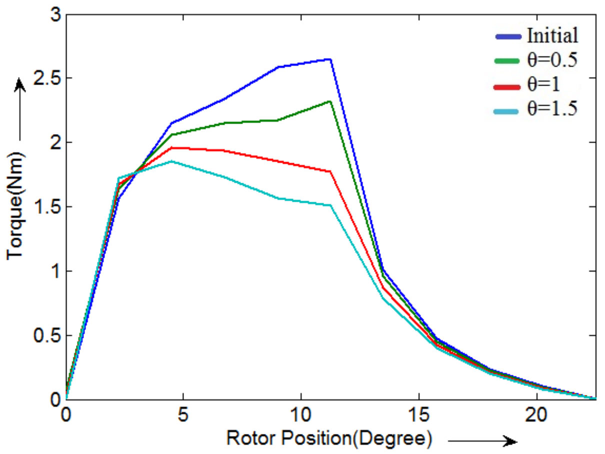

Fig. 6. Torque characteristics of HSRM with non uniform air gap

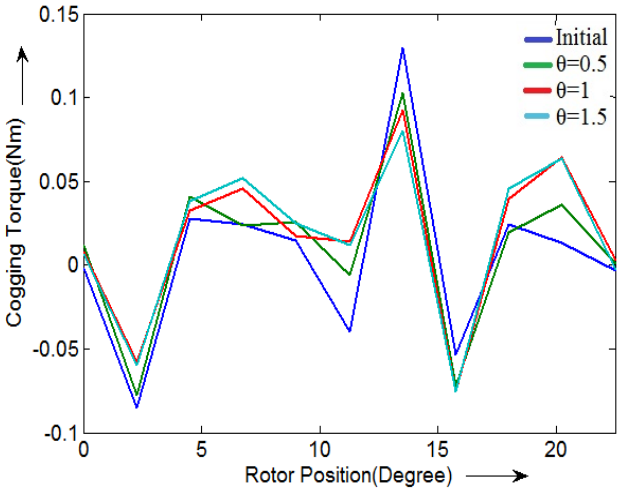

Fig. 7. Cogging torque characteristics of HSRM with non uniform air gap

Table 2. Average torque, Ripple torque and Cogging torque for various value of 'θ'

θ(degree)	T_{avg}(Nm)	T_{ripple}(%)	T_{cog}(Nm)
0.5	1.503	42.7	0.102
1	1.190	39.6	0.092
1.5	0.914	37.5	0.080
2	0.677	30.2	0.067
Initial design	1.9	52.4	0.129

C. *HSRM with pole shoe fixed to the rotor tip*

The structure of HSRM with pole shoe fixed to rotor pole is shown in Fig. 8. Introducing pole shoe has the effect of altering the inductance profile at the unaligned position which in turn controls the rising torque profile and reduces torque ripple [14]. The torque vs. rotor position characteristics and cogging torque characteristics for different pole shoe angle 'α' is shown in Fig. 9 and Fig.10. Table 3 summarizes the average torque, ripple torque and cogging torque for various values of 'α' from which it is evident that there is a considerable cut back in torque ripple with the introduction of rotor pole shoe. Cogging torque is very minimum for the design with α=1.5&2 degree.

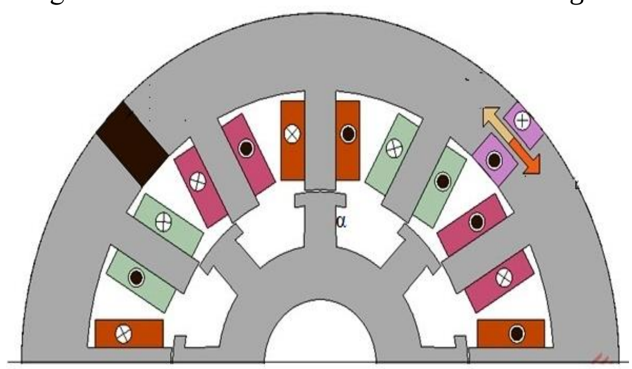

Fig. 8. HSRM with pole shoe fixed to rotor pole

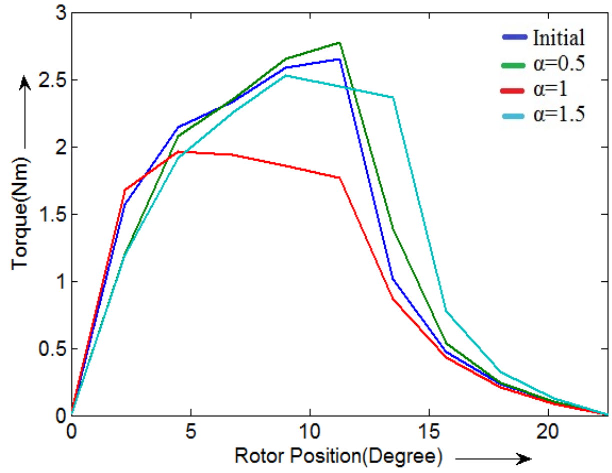

Fig. 9 Torque characteristics of HSRM with rotor pole shoe

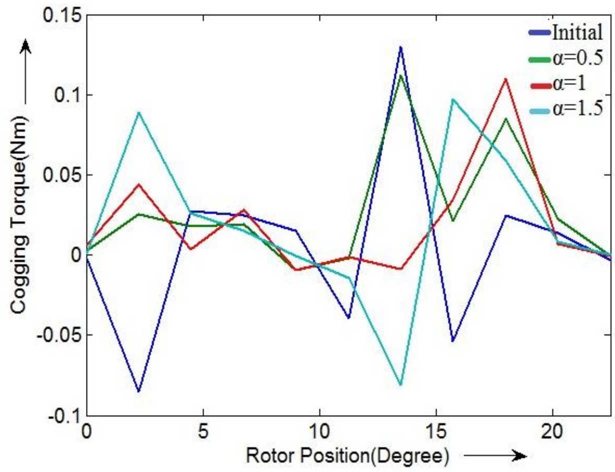

Fig. 10. Cogging torque characteristics of HSRM with rotor pole shoe

Table 3. Average torque, Ripple torque and Cogging torque for various values of 'α'

α (degree)	T_{avg}(Nm)	T_{ripple}(%)	T_{cog}(Nm)
0.5	1.909	53.1	0.111
1	1.916	44.3	0.109
1.5	1.931	36.6	0.097
2	1.939	34.5	0.073
Initial design	1.9	52.4	0.129

D. HSRM with stator pole tapering and non uniform air gap

From the above analysis it is clear that HSRM design with stator pole tapering results in greater average torque and HSRM design with altered air gap profile produces lesser torque ripple. Hence a design is considered based on stator pole taper with non uniform air gap as shown in Fig. 11. The static torque profile and cogging torque profile for the considered design shown in Fig.12 & Fig.13. Table 4 summarizes the average torque, ripple torque and cogging torque for various values of ratio 'b' and 'θ' value of 0.5 degree from which it is evident that there is a significant reduction in torque ripple and cogging torque for ratio 'b' value 1.4 and θ value 0.5.

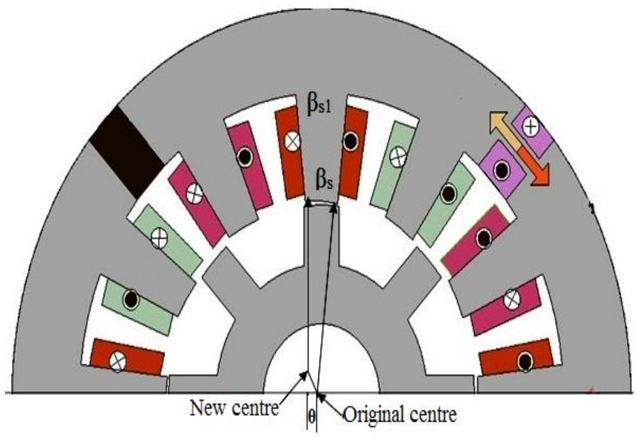

Fig.11. HSRM with stator pole tapering and non uniform air gap

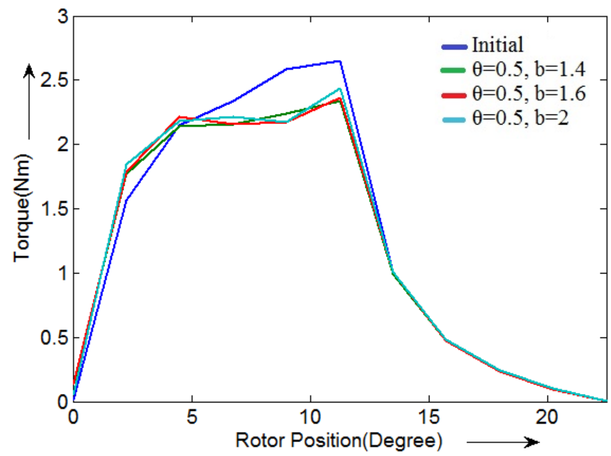

Fig.12. Torque characteristics of HSRM with stator tapering and non uniform air gap

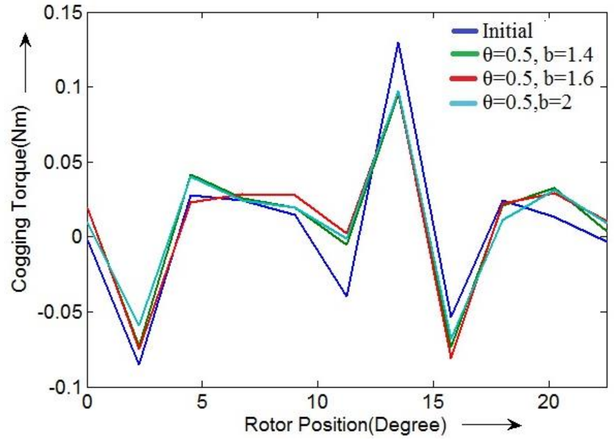

Fig. 13. Cogging torque characteristics of HSRM with stator tapering and non uniform air gap

Table 4. Average torque, Ripple torque and Cogging torque for various taper ratio and ‘θ’ of 0.5

ratio 'b'	θ(degree)	T_{avg}(Nm)	T_{ripple} (%)	T_{cog}(Nm)
1.4	0.5	1.626	40.2	0.095
1.6	0.5	1.648	40.7	0.096
2.0	0.5	1.710	42.4	0.097
Initial design	-	1.9	52.4	0.129

E. HSRM with stator pole tapering and pole shoe fixed to the rotor pole tip

From the previous analysis it is evident that HSRM design with pole shoe fixed to the rotor pole tip results in lower torque ripple while maintaining the same average torque .Hence a design is proposed based on stator pole tapering and with pole shoe attached to rotor pole tip as shown in Fig. 14. Fig.15 & Fig.16 shows the static torque profile and cogging torque profile for the proposed design. The average torque, ripple torque and cogging torque for ratio 'b' of 1.6 and various value of ‘α’ is summarized in Table 5. From table it is evident that there is considerable reduction in torque ripple, cogging torque and significant improvement in average torque for the proposed design.

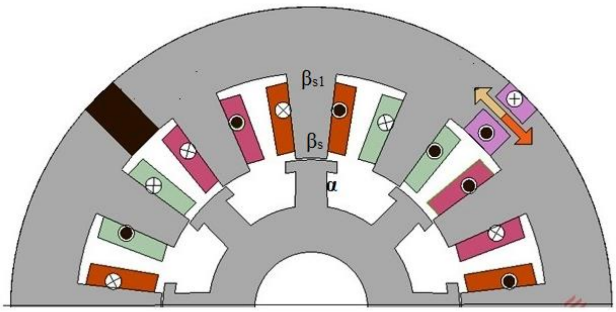

Fig. 14. HSRM with stator tapering and pole shoe at rotor

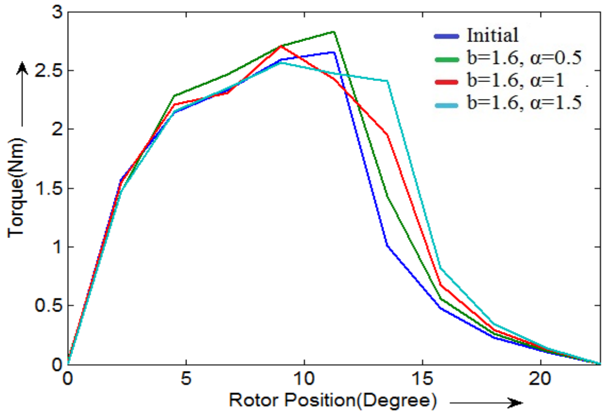

Fig. 15. Torque characteristics of HSRM with stator tapering and pole shoe fixed to rotor

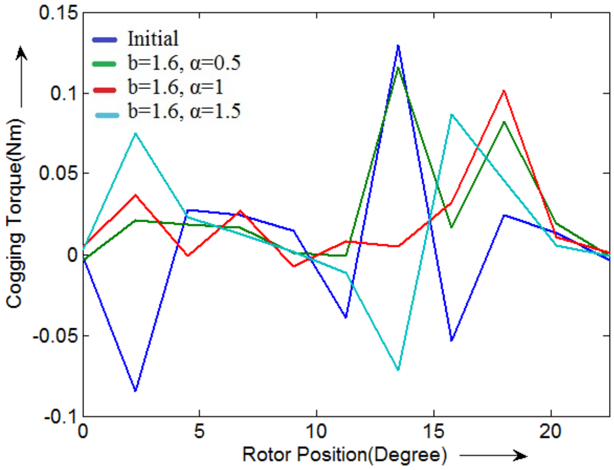

Fig. 16. Cogging torque characteristics of HSRM with stator tapering and pole shoe fixed to rotor

Table 5. Average torque, Ripple torque and Cogging torque for stator pole taper ratio of 1.6 & various value of ‘α’

ratio 'b'	α(degree)	T_{avg}(Nm)	T_{ripple} (%)	T_{cog}(Nm)
1.6	0.5	2.115	47.0	0.116
1.6	1	2.138	37.1	0.101
1.6	1.5	2.153	33.6	0.086
Initial design	-	1.9	52.4	0.129

3. Conclusions

This paper has examined the effect of geometrical parameters that modifies the pole face shape on the torque profile of HSRM. Considering torque ripple, cogging torque and average torque as optimizing factors, the following results relating to the geometrical parameters involved in the study could be useful

- There is a significant reduction in torque ripple and improvement in average torque for the model of HSRM with tapered stator pole. Increasing pole taper ratio has the consequence of increasing the average torque and reducing the torque ripple and cogging torque.
- Torque ripple and cogging torque is minimum for stator pole face with non-uniform air gap but the average toque of the design is reduced.
- By incorporating rotor pole shoe significant reduction in torque ripple is achieved while average torque is constant and cogging torque is minimum for pole shoe angle of 1.5&2 degree.
- Stator pole taper design with pole taper ratio 1.4 and air gap angle 0.5 degree produces

minimum torque ripple and cogging torque but average torque is reduced compared with initial design.

- Tapered stator pole design with rotor pole shoe shows significant reduction in torque ripple and cogging torque. The average torque produced by the design is also improved.

The analysis and the geometric modifications presented will enhance the application prospects of hybrid SRM.

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Appendix 1

Design Data of HSRM[12]

Design Specification	Value
Shaft diameter	20 mm
Rotor pole root diameter	36.4 mm
Rotor crown diameter	52.6 mm
Stator pole root diameter	83.2 mm
Stator outside diameter	113.2 mm
Air gap length	0.3 mm
Rotor pole angle	16 degrees
Stator pole angle	15 degrees
Permanent Magnet	NdFeB

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