Torque ripple minimization of direct drive switched reluctance motor

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Abstract—**Switched reluctance motors (SRM) are gaining importance in the variable speed market due to their simple and rugged construction. To design the motor for higher performance, the estimation of their performance is essential at the time of their geometric design. In this project, finite element analysis (FEA) is used to calculate their performance parameters from their geometry. The dynamic performance of SRM is predicted by MAGNET software using the calculated parameters. The circuit coupled finite element analysis is used to estimate the dynamic performance of the SRM. The torque ripple is the one of the major problems in the Switched Reluctance Motor. In this project, a detailed investigation is made to decrease the torque ripple by increasing the stator and rotor pole shoes.**

***Index Terms*—ANSYS, Swithed Reluctance Motor, Torque Ripple, MAGNET, Vibration.**

I. INTRODUCTION

IN Switched Reluctance Motors gained attention during the last few decades due to their simple and rugged construction, attractive alternative for the existing ac and dc motors for variable speed drive and fault tolerance performance. Then the motor usage of winding very less, efficient power conversion at all load condition and overall efficiency better when compare to conventional motor [2]. Although motors operating on the principle of torque production due to reluctance variation. Hence rotor position sensor used and sensor less operation also possible. This machine was not popular due to vibration, torque ripple which lead to acoustic noise [4], [5]. These acoustic noise are harmful to human being [8]. The torque ripple can be minimized by geometrical design modifications The recent developments in switched reluctance motor are due to the availability of fast switching power semiconductor devices and improved design using modern computer aided design and circuit simulation packages [1].

II. SPECIFICATION

The basic configuration of the prototype at the moment when A phase is aligned with one pair of rotor poles. The proposed SR motor has an outer rotor structure. It has eight inner stator poles and six outer rotor poles with single tooth per pole configuration.

Table 1: specification

Rated speed	200 rpm
Rated current	7.5 A
No of phase	4
No of turns per phase	236
Stack length	150 mm
Stator pole arc	22 degree
Rotor pole arc	24 degree

The Switched Reluctance Motor is a singly excited motor with salient poles on both the stator and the rotor. Only the stator poles carry windings and the rotor has no windings. Both stator and rotor are built up from stacks of steel laminations. The number of stator and rotor poles are chosen such that the motor can start and run in any direction. The given configuration of the Switched Reluctance motor shown in fig. 1

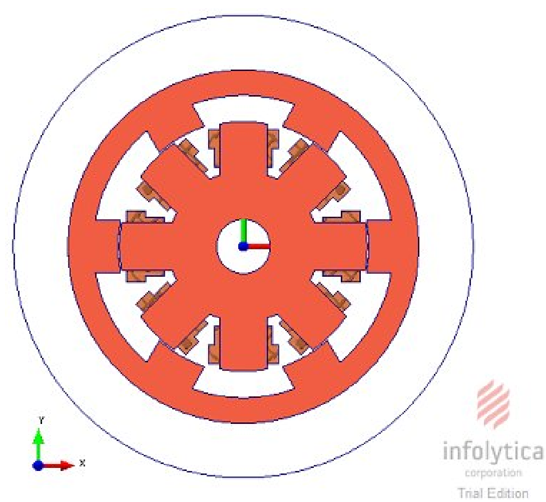

Fig. 1 Four phase direct drive 8/6 switched reluctance motor

One stator phase of the motor consists of two series connected windings wound on diametrically opposite poles. The air gap between stator and rotor is very less which makes The motor to operate in the saturated condition. The stator and rotor Unaligned pole flux plot shown in fig. 2

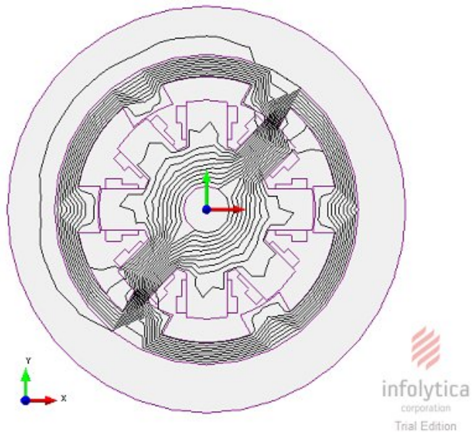

Fig. 2 Flux plot from the 2D FEA

Switched reluctance motor operates [3] on the basic principle that any excited magnetic device tends to occupy the minimum reluctance position. In switched reluctance motor, torque is produced on the rotor whenever the stator windings are excited. The rotor moves to a position where the reluctance of the excited winding is minimum [7], [10]. The stator and rotor unaligned pole magnetic field density shown in fig. 3

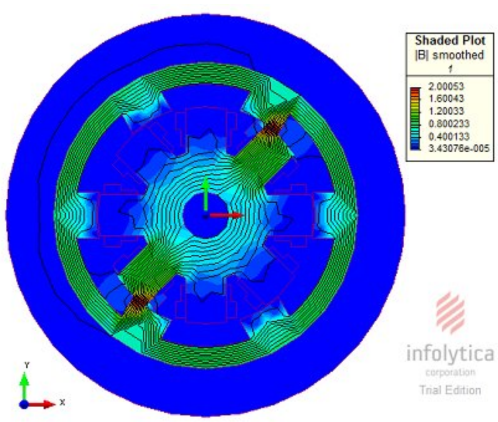

Fig. 3 Magnetic filed density plot from the 2D FEA

When the rotor pole axis is exactly aligned with the excited stator pole axis, the motor is said to be in aligned position; where the air gap between stator and rotor poles is minimum and inductance of the phase windings is maximum [1]. In this switched reluctance motor torque Vs rotor position curve shown in fig. 4

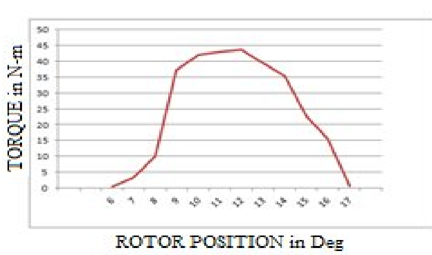

Fig. 4 Torque Vs Rotor Position Curve

Magnetic characteristics of curve shown in fig. 5 . the simulation result obtained for maximum, minimum, and average torque value tabulated in the table 2.

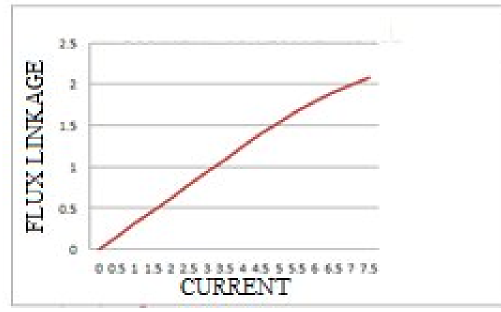

Fig. 5 Magnetic Characteristics of a 8/6 Switched Reluctance Motor

Table 2: Torque ripple during operation for stator and rotor pole shoe design

	Stator angle (deg.)	Rotor angle (deg.)	$T_{\max}$ $(N-m)$	$T_{\min}$ $(N-m)$	T_{avg} $(N-m)$	T_{ripple} $(N-m)$
Main	22	24	43.7366	0.5188	24.4499	1.7676

III. TORQUE RIPPLE REDUCTION USING POLE SHOES

In the normal design procedure of the switched reluctance motor, generally, the rotor and stator pole arcs are designed with the condition that the stator pole arc is less then rotor pole arc (Lawrenson 1980) [1], [3]. The torque produced on the SRM is given by

$$T = \frac{\Delta W_C}{\Delta \theta} \quad \text{...} \quad (1)$$

When the current is maintained constant, the torque is given by

$$T = \frac{\partial W_C(i,\theta)}{\partial \theta} = \frac{1}{2} i^2 \frac{dL(i,\theta)}{\partial \theta} \quad \text{..........} \quad (2)$$

The equation (2) explains that the torque produced depends on the inductance variation and the phase current. The torque ripple produced in the motor is expressed as

$$T_{ripple} = \frac{T_{\max} - T_{\min}}{T_{average}} \quad \text{............................} \quad (3)$$

In the general design of SRM, increasing the stator pole arc will reduce the area for the stator coil. The stator and rotor pole arcs can be increased without reducing the stator coil Space by providing the pole shoe arrangement. Using the pole shoes arrangement, three design Modifications are proposed on the stator and rotor poles. Increasing the stator pole shoes angle by keeping constant rotor angle, Increasing the rotor pole shoe angle by keeping constant stator angle, Simultaneously, Increasing the rotor and stator pole shoes angle [1].

IV. INCREASING THE STATOR POLE SHOES ANGLE

The stator pole shoes of the motor is increased from the designed value of 22 degree to new values of 24, 26, 28, and

30 degrees. New stator pole shapes with the proposed pole shoe arrangement are shown in the Fig. 6(a), 6(b), 6(c), 6(d). Using the electromagnetic FEA software the torque and inductance profile is obtained for the current values 7.5A shown in the fig. 7, 8.

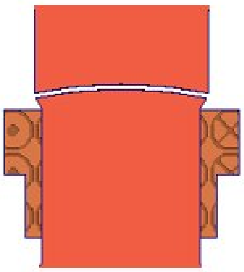

Fig. 6 (a) Stator pole shoe 24 deg.

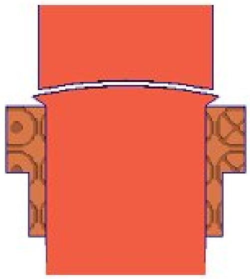

Fig. 6 (b) Stator pole shoe 26 deg.

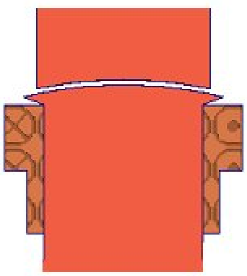

Fig. 6 (c) Stator pole shoe 28 deg.

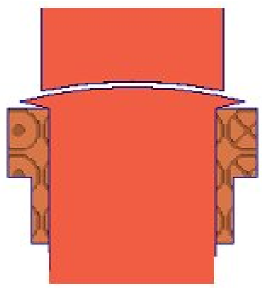

Fig. 6 (d) Stator pole shoe 30 deg.

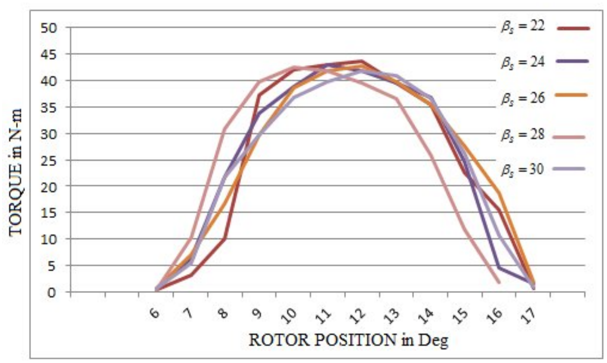

Fig. 7 Comparison of torque profile when stator pole shoe is increased

The torque profile obtained when the stator pole shoes are varied is shown in the Fig 7 that an increase in the stator pole shoe increases the region of torque production; the maximum value of the torque decreases with an increase of average torque. This increase in torque production region will allow SRM power control circuit to get good control on torque ripple minimization [1]. It is also observed that maximum torque is produced during partial overlap of stator and rotor poles. the respective inductance profile is shown in the Fig 8 that increases in the stator pole shoe result in the change of inductance profile at the start of overlap region. The rate of change of inductance with rotor position remains fairly

constant over the partial overlap regions of poles.

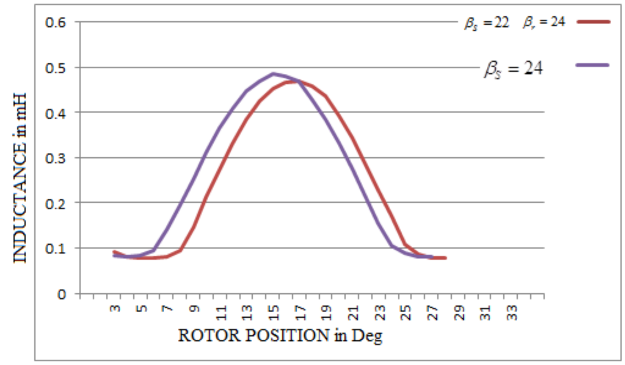

Fig. 8 Comparison of inductance profile when stator pole shoe is 24 deg.

Table 3 : Torque ripple during operation for different stator pole shoes design

	Stator angle (deg.)	Rotor angle (deg.)	T_{max} $(N-m)$	T_{min} $(N-m)$	T_{avg} $(N-m)$	T_{ripple} $(N-m)$
Main	22	24	43.7366	0.5188	24.4499	1.7676
	24	24	42.9757	1.5838	28.8690	1.4337
	26	24	42.6758	0.6538	25.0495	1.6775
	28	24	42.5889	0.3537	25.5531	1.6528
	30	24	41.7649	0.8356	26.4054	1.5500

It is observed from the simulation that the torque ripple decreases with increase of stator pole shoes. For the each stator pole shoes design configuration, the average torque and the minimum torque values are high when the torque ripple is minimum [9].

V.INCREASING THE ROTOR POLE SHOE ANGLE

In this method, the rotor pole shoes is increased from the designed value of 24 degree to new values of 26, 28, 30 and 32 degrees. The proposed rotor pole shapes with pole shoe arrangement are shown in the Figure 9(a), 9(b), 9(c), 9(d). Using the electromagnetic FEA software, the torque and inductance profile is obtained for the current values of 7.5A shown in fig. 10, 11. The torque profile obtained when the rotor pole shoe are varied is shown in the Fig 10 that an increase in the rotor pole shoe increases the region of torque production; the maximum value of the torque decreases with an increase of average torque [6]. the respective inductance profile is shown in the Fig 11

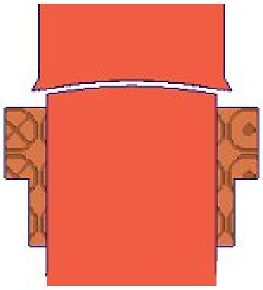

Fig. 9 (a) Rotor pole shoe 26 deg

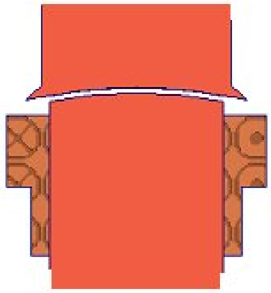

Fig. 9 (b) Rotor pole shoe 28 deg

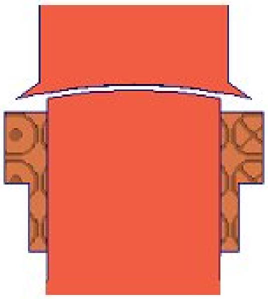

Fig. 9 (c) Rotor pole shoe 30 deg

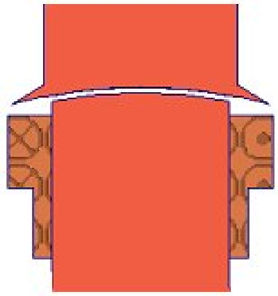

Fig. 9 (d) Rotor pole shoe 32 deg

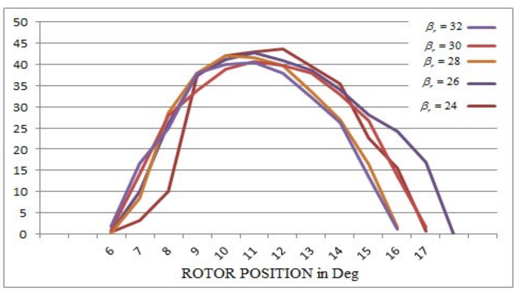

Fig. 10 Comparison of torque profile when rotor pole shoes is increased

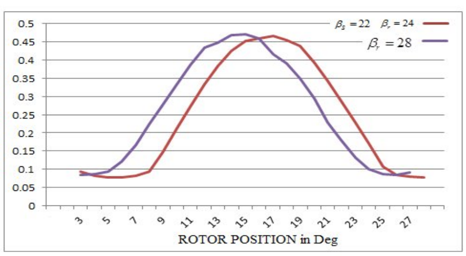

Fig. 11 Comparison of inductance profile when stator pole shoe is 28 deg.

Table 4 : Torque ripple during operation for different rotor pole shoes design

	Stator angle (deg.)	Rotor angle (deg.)	$T_{\max}$ $(N-m)$	$T_{\min}$ $(N-m)$	T_{avg} $(N-m)$	T_{ripple} $(N-m)$
Main	22	24	43.7366	0.5188	24.4499	1.7676
	22	26	42.7853	1.5149	26.2056	1.6326
	22	28	41.9966	1.6053	27.7043	1.4579
	22	30	40.7643	0.9273	25.7562	1.5466
	22	32	40.4952	1.0385	24.7727	1.5927

It is observed from the simulation that the torque ripple decreases with increase of rotor pole shoes. For the each rotor pole shoes design configuration, the average torque and the minimum torque values are high when the torque ripple is minimum [9].

VI. SIMULTANEOUS INCREASE OF THE ROTOR AND STATOR POLE SHOES ANGLE

The stator and rotor pole shoes of the motor is increased from the designed respected value of 22 and 24 degree to new values of 26, 28, 30, and 32 degrees. New stator and rotor pole shapes with the proposed pole shoe arrangement are shown in the Fig. 12(a), 12(b), 12(c), 12(d). Using the electromagnetic FEA software the torque and inductance profile is obtained for the current values 7.5A shown in the fig. 13, 14

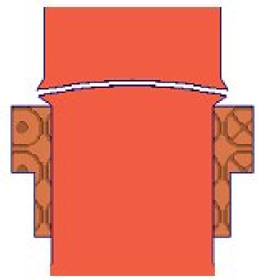

Fig. 12 (a) Stator pole shoe 26 deg.
Rotor pole shoe 26 deg.

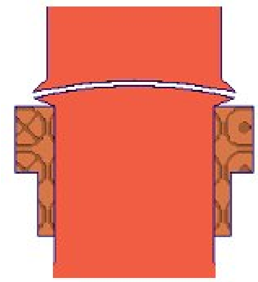

Fig. 12 (b) Stator pole shoe 28 deg.
Rotor pole shoe 28 deg.

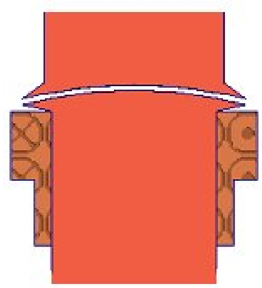

Fig. 12 (c) Stator pole shoe 30 deg.
Rotor pole shoe 30 deg.

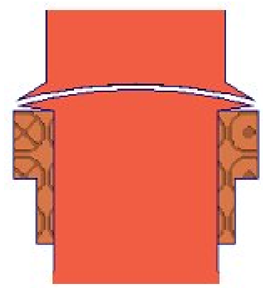

Fig. 12 (d) Stator pole shoe 32 deg.
Rotor pole shoe 32 deg.

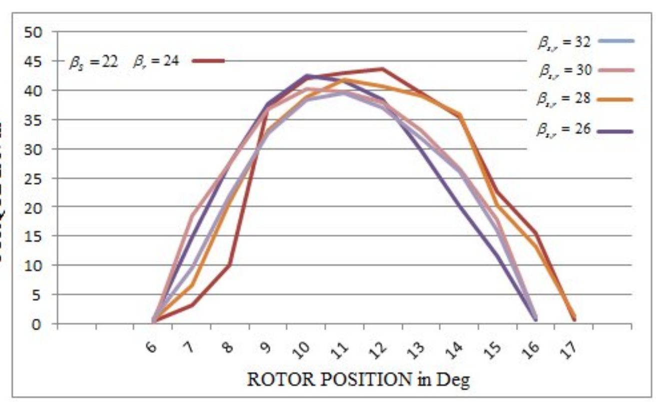

Fig. 13 Comparison of torque profile stator and rotor pole shoes is increased

The torque profile obtained when the stator and rotor pole shoes are varied is shown in the Fig 13 that an increase in the stator and rotor pole shoes increases the region of torque production; the maximum value of the torque decreases with an increase of average torque [1] [6]. the respective inductance profile is shown in the Fig 14

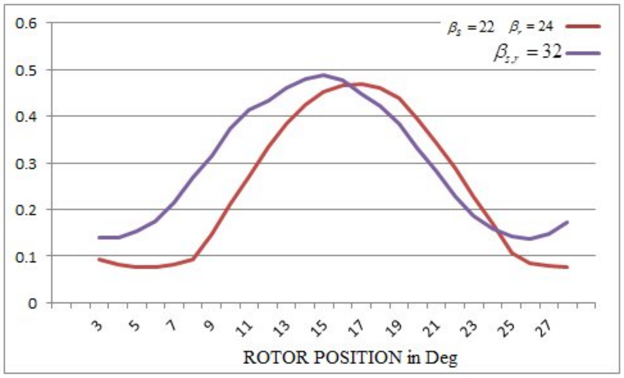

Fig. 14 Comparison of inductance profile, stator and rotor pole shoe 32 deg.

Table 5 : Torque ripple during operation for different stator and rotor pole Shoes design

	Stator angle (deg.)	Rotor angle (deg.)	T_{max} $(N-m)$	T_{min} $(N-m)$	T_{avg} $(N-m)$	T_{ripple} $(N-m)$
Main	22	24	43.7366	0.5188	24.4499	1.7676
	26	26	42.5686	0.6387	24.1286	1.7377
	28	28	41.7993	0.5767	24.3699	1.6915
	30	30	40.2203	0.2642	25.3696	1.5749
	32	32	39.5675	1.0968	25.4126	1.5138

It is observed from the simulation that the torque ripple decreases with increase of stator and rotor pole shoes. For the each rotor pole shoes design configuration, the average torque and the minimum torque values are high when the torque ripple is minimum [9].

VII. CONCLUSION

In this project, an investigation is made to find the torque ripple on the SRM for the different stator and rotor pole arc design using pole shoe arrangement. The torque ripple is calculated for the proposed design, and the results are compared. The maximum torque is higher when the stator pole shoe are 24 degree. For higher average torque the stator pole is 24 degree and the rotor pole shoe is 24 degree For the minimum torque ripple the stator and rotor pole shoe are 32 degrees From the comparison it is observed that the torque ripple is reduced when the stator pole shoes are increased suitably. The increase in pole shoes in SRM, also reduces maximum torque induced, Rotor Position, Average torque, Minimum torque moves the maximum torque production location accordingly and increases the average torque. It concludes that, a given design of stator and rotor pole arc of motor cannot give lower torque ripple or higher maximum or average torques at the same time. Torque ripple minimization can be achieved by changing the pole shoe configuration of the motor, but at the expense of reduced maximum or average torque. The future work is the reduction of vibration. Torque ripple is reduced vibration will also be reduced.

REFERENCES

[1] Balamurugan S., (May 2007), "Vibration and Thermal Analysis of 6/4 Pole Switched Reluctance Motor," Ph.D. thesis, Anna University, india

[2] K. N. Srinivas, *Member, IEEE* and R. Arumugam, member, IEEE, "Analysis and Characterization of Switched Reluctance Motors," 0-7803-7906-3/03/$17.00 ©2003 IEEE

[3] Kazuhiro Ohyama , Maged Naguib F. Nashed, Kenichi Aso , Hiroaki Fujii , and Hitoshi Uehara, "Design Using Finite Element Analysis of Switched Reluctance Motor for Electrical Vehical," 0-7803-9521-2/06/$/20.00 ©2006 IEEE

[4] K. N. Srinivas1, *Member, IEEE*, and R. Arumugam2, *Member, IEEE*, "Analysis and Characterization of Switched Reluctance Motors: Part II—Flow, Thermal, and Vibration Analyses," *IEEE TRANSACTIONS ON MAGNETICS, VOL. 41, NO. 4, APRIL 2005*

[5] Roy **S.** Colby, *Senior **Member,*** FranCois M. Mottier, and Timothy J. E. Miller, *Fellow,* "Vibration Modes and Acoustic Noise in Four-Phase Switched Reluctance Motor,*" IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 32, NO. 6, NOVEMBERDECEMBER 1996*

[6] Jung-Pyo Hong, *Member, IEEE*, Kyung-Ho Ha, and Ju Lee, "Stator Pole and Yoke Design for Vibration Reduction of Switched Reluctance Motor," *IEEE TRANSACTIONS ON MAGNETICS, VOL. 38, NO. 2, MARCH 2002*

[7] T. **S.** Low, H. Lin, **S.** X. Chen and K. T. Chang, "Design and Analysis of 4-Phase (In-hub) Mini-Switched Reluctance Motor for Spindle Motor in Hard Disk Drive," *IEEE Catalogue No. 95TH8025 0-7803-2423-4l95/$4.OOOl995IE EE*

[8] Jian Li and Yunhyun Cho, "Investigation into Reduction of Vibration and Acoustic Noise in Switched Reluctance Motors in Radial Force Excitation and Frame Transfer Function Aspects,"*IEEE TRANSACTIONS ON MAGNETICS, VOL. 45, NO. 10, OCTOBER 2009*

[9] K. Vijayakumar□, R. Karthikeyan_, S. Paramasivam_, R. Arumugam_, and K. N. Srinivas, "Switched Reluctance Motor Modeling, Design, Simulation, and Analysis: A Comprehensive Review," *IEEE TRANSACTIONS ON MAGNETICS, VOL. 44, NO. 12, DECEMBER 2008*

[10] N.C. Lenin1, R. Arumugam2 , "Analysis and Experimental Verification of a Linear Switched Reluctance Motor Having Special Pole Shape Majlesi," *Journal of Electrical Engineering Vol. 4, No. 2, June 2010*