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Design and Experimental Verification of Linear Switched Reluctance Motor with Skewed Poles

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ABSTRACT

This paper presents the realization and design of a linear switched reluctance motor (LSRM) with a new stator structure. One of the setbacks in the LSRM family is the presence of high force ripple leads to vibration and acoustic noise. The proposed structure provides a smooth force profile with reduced force ripple. Finite element analysis (FEA) is used to predict the force and other relevant parameters.A frequency spectrum analysis of the force profile using the fast Fourier transform (FFT) is presented.The FEA and experimental results of this paper prove that LSRMs are one of the strong candidates for linear propulsion drives.

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1. INTRODUCTION

Linear switched reluctance motors (LSRMs) with different machine configurations have been explored past in the literature [1]–[12]. They are an attractive alternative to linear induction and linear synchronous machines due to lack of windings on either the stator or translator structure. However LSRM has some disadvantages such as high force ripple, vibration, and acoustic noise because of doubly salient structure. Moreover power electronic converters are required for their continuous operation. Efforts to reduce or eliminate the torque ripple of the rotary switched reluctance motors (SRMs) are presented in literature [13]-[17]. Multi phase excitation to reduce the force ripple in the LSRM has been explained in [18]. However the previous method considerably increases the copper losses. LSRM with pole shoes and inter poles are presented in [19]-[20]. In this paper a new stator structure [21] is proposed to reduce the force ripple.

Most of the limitations of analytical techniques can be overcome by using the numerical methods such as finite element analysis (FEA). These tools provide accurate results but require significant computational effort and numerical procedures [22]-[24]. The FEA tools are used in this study to predict the force and inductance profile.

When the frequency of the exciting force is close or equal to any of the natural frequencies of the machine, then resonance occur, which results in dangerous deformations and vibrations and a substantial increase in noise [25]. FFT steps to analyze ripple in the force profile of aLSRM is presented. This methodology is comparatively simpler than the most widely used finite-element vibration analysis procedure for mode frequency identification.

The organization of the paper is as follows: Section 2 and 3 presents new stator geometry for LSRMs that improves the force profile. In the new geometry, poles are skewed. Section 4 presents FEA results for conventional and proposed structures. Frequency spectrum analysis of force profile using the fast Fourier transforms (FFT) is highlighted in section 5. Experimental results from the prototype machine and their correlation with FEA results are presented in Section 6. Conclusions are summarized in Section 7.

2. LSRM TOPOLOGY

Figure 1 shows the two dimensional (2D) cross sectional view for the conventional machine structure of a three phase LSRM. The LSRM has an active translator and a passive stator. It consists of six translator poles and 120 stator poles. Figure 2 shows the stator pole alone for the conventional structure whereas, Figure 3 shows the stator pole for the proposed structure used for this study. The poles are skewed by an angle 1 degree to 10 degrees in steps of 1 degree for the purpose of optimization. Table 1 shows the physical dimensions of the LSRM prototype.

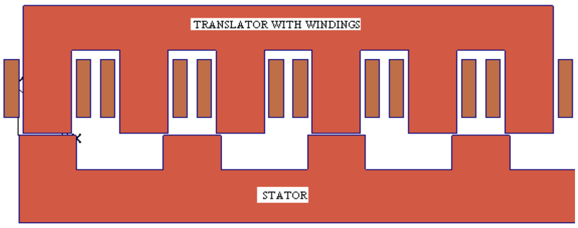


Figure 1. 2D cross sectional model of conventional LSRM

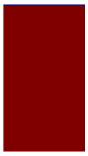


Figure 2. Conventional stator pole

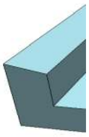


Figure 3. Proposed stator pole

Table 1. Specifications of Prototype LSRM

Translator pole width=20mm	Translator slot width=20mm	Translator pole height=27mm
Translator back iron thickness=20 mm	No. of turns/phase = 86	Translator stack length=30 mm
Stator pole width=20mm	Stator slot width=26mm	Stator pole height=15 mm
Stator back iron thickness=20mm	Air gap length=2mm	Stator stack length=30 mm
Rated voltage=36 V	Rated current=4amps	Velocity=1m/s
Stator pole skewed angle = 1 to 10 degrees	Stator pole skew angle = 1 to 10 degrees	Maximum force=3.21N

3. INTRODUCTION TO FORCE RIPPLE IN LINEAR SWITCHED RELUCTANCE MOTOR

One of the inherent problems in LSRM is the force ripple due to switched nature of the force production. Force ripple may be determined from the variations in the output force. In order to predict the amount of force ripple, static force characteristics should be considered. The force dip is the distance between the peak value and the common point of overlap in the force angle characteristics of two consecutive LSRM phases as illustrated in Figure 4. Assuming that the maximum value of the static force F_{max} (peak static force) and the minimum value that occurs at the intersection point of two consecutive phases as $F_{min,}$ the percentage force ripple may be defined as:

$$\%\text{Force Ripple} = \frac{F_{max} - F_{min}}{F_{avg}} \times 100 \qquad (1)$$

The force dip is an indirect indicator of force ripple in the machine; the lesser the value of the force dip, the lesser will be the force ripple. The force dip of both the machines has been computed by FEA.

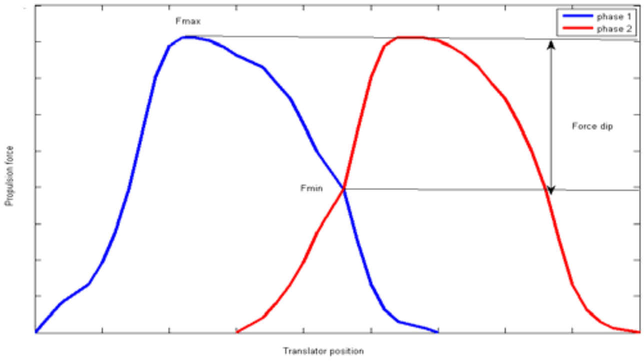


Figure 4. Force vs Translator position showing force dip

4. TWO – DIMENSIONAL FINITE ELEMENT ANALYSIS

Three asymmetric bridge metal oxide semiconductor field effect transistor (MOSFET) inverters are used to drive the LSRM shown in Figure 5. The translator position with respect to the stator position is sensed by three highly sensitive optical sensors. The active translator of the LSRM is moved from the unaligned position with respect to the stator to the aligned position for the excitation current of 4 amps. Therefore, static force and inductance profiles are obtained as a function of position and current.

Figure 6 shows the flux distribution taken from FEA for the conventional machine at the aligned position. The force and inductance profiles for the conventional and proposed LSRMs are depicted in Figure 7-10 respectively.

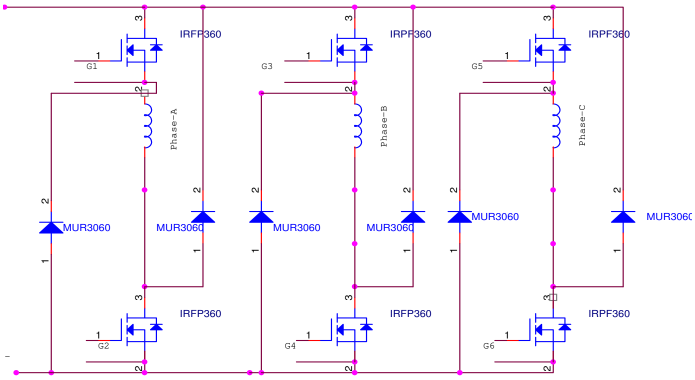


Figure 5. Three phase power converter for LSRM

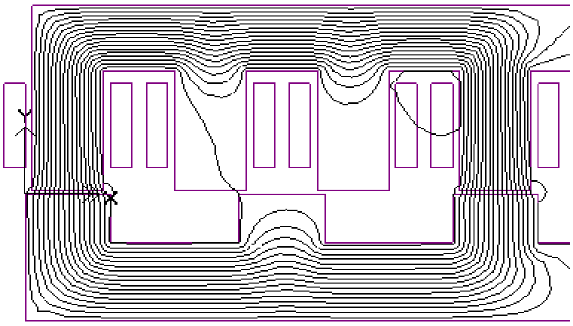


Figure 6. Flux distribution of conventional LSRM at the aligned position

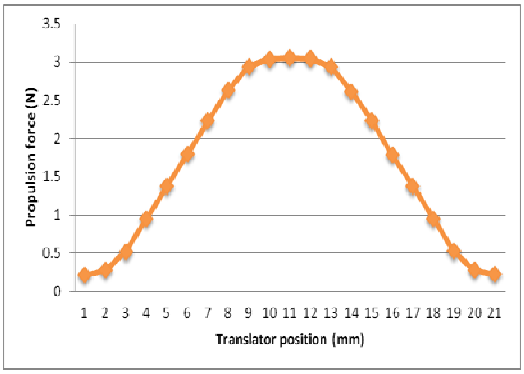


Figure 7. Propulsion force for base motor

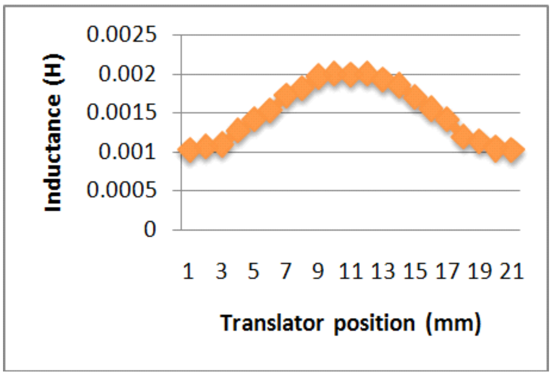


Figure 8. Inductance Profile for base motor

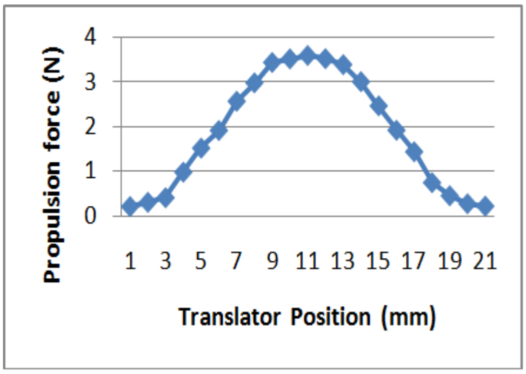


Figure 9. Propulsion force for proposed motor

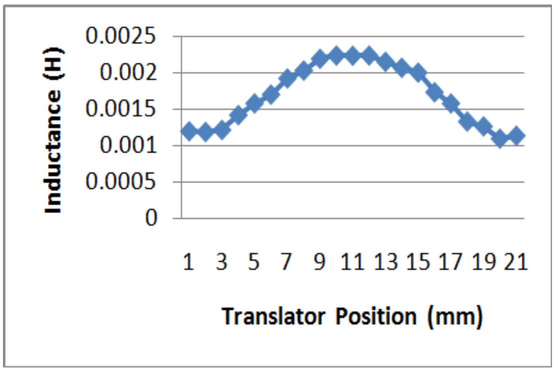


Figure 10. Inductance Profile for proposed motor

The force in a given direction is obtained by differentiating the magnetic co-energy of the system with respect to a virtual displacement of the translator. Based on this approach, the propulsion force with respect to various translator positions is calculated. The peak force obtained is 3.05N and the force ripple is 44.85% for the conventional LSRM whereas the peak force obtained in proposed LSRM is 3.32 N with the force ripple of 32.79%. The entire comparisons of the two structures are tabulated in Table 2.

Table 2. Summary of Comparison of the Two Structures

Type	Peak propulsion force (N)	Minimum propulsion force (N)	Average propulsion force (N)	Force ripple (%)	Inductance (H)	
					Aligned	Unaligned
Conventional Stator	3.05	1.83	2.72	44.85	0.0020	0.001
Stator with skewed pole(6 degrees)	3.52	2.5	3.11	32.79	0.0023	0.0012

5. FAST FOURIER TRANSFORM APPLICATION TO LSRM

From the results of 2-D finite-element field analysis performed earlier, force (N) versus translator position (mm) will be known (Figure 6-10). A program is written in MATLAB environment which contains a sequence of instructions to store the force parameter array of the three phases. FFT is applied to the net force profile after the elimination of dc offset [26]. Since FFT transforms the available data in time domain into frequency domain, the available force versus translator position profile must be converted to force versus time profile. In MATLAB, the command fft(x,p), where ‘x’ is the force array and ‘p’ is 512, denoting 512 point fft, will solve the Equation (2) to produce a complex discrete fourier transform (DFT) of force. The absolute value of the obtained complex DFT will form the magnitude axis.

$$f(t) = \frac{1}{2\pi}\int_{\frac{-T}{2}}^{\frac{T}{2}} F(j\omega_0)\, e^{j\omega_0 t}\,dt \qquad (2)$$

The magnitude plot is obtained by plotting the magnitude versus frequency. Figure 11 shows the results of the frequency spectrum analysis for the conventional structure of the stator. The frequency corresponding to the decibel (dB) peaks can be identified from the plot. Table 3 shows the dominant frequencies in hertz and its amplitude in dB.

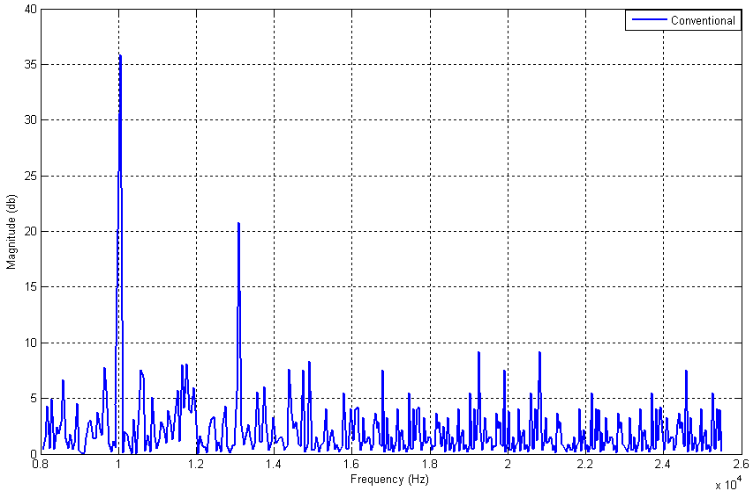


Figure 11. FFT output: dB versus frequency, for the LSRM

Table 3. Dominant Ripple Frequencies and its Amplitude for the Stator

Predominant ripple frequencies (Hz)	Amplitude (dB)
10,050	36
13,100	21
14,910	8
19,260	9.2

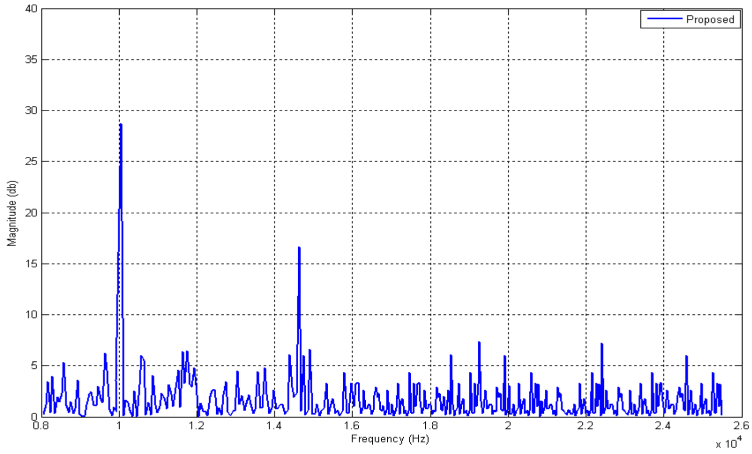


Figure 12. FFT output: dB versus frequency, for the LSRM with skewed poles

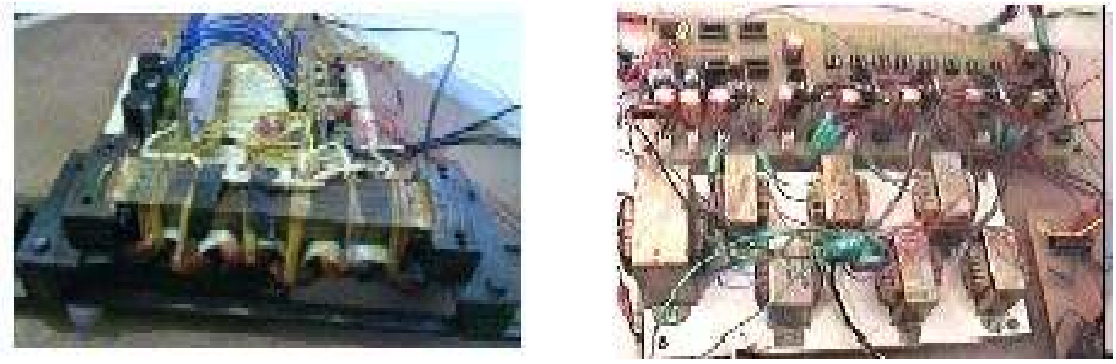
The result of FFT for the LSRM with skewed poles is depicted in Figure 12. It is observed that the magnitude dB peaks occurs at the same frequencies in both cases. However the magnitude of the dB peaks is reduced by a considerable margin, encouraging the design case of skewed stator poles (Table 4).

Table 4. Dominant Ripple Frequencies and its Amplitude for Stator with Skewed Poles

Predominant ripple frequencies (Hz)	Amplitude (dB)
10,050	29
14,620	17
19,260	7.4
22,420	7

6. EXPERIMENTAL RESULTS

Figure 13 shows the experimental setup for the prototype LSRM used as a material carrying vehicle in the laboratory. The experimental road is 0.5 m long and translator weight is 2.7kg. It should be noted that the present setup is intended for development purposes only.



(a) (b)

Figure 13. Experimental setup of (a) LSRM and converter (b) Driver circuit

The inductance for the different positions at rated current is measured by locking the translator at each position. A constant current is applied to a phase and is turned off and the falling current profile is computed. The time constant is measured from the profile and hence the inductance is calculated. The measured values of inductance and propulsion force are plotted alongside the FEA results in Figure 14 and Figure 15 respectively. Figure 16 shows phase current and pulse waveforms of the LSRM.

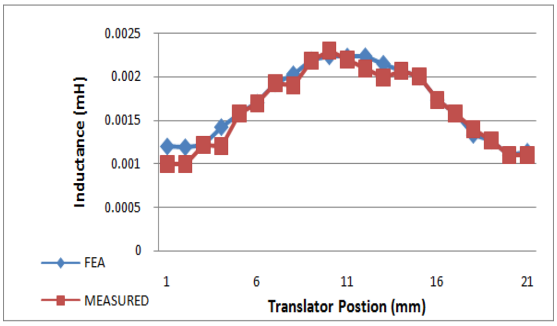


Figure 14. Comparison of FEA and measured inductance values at rated current

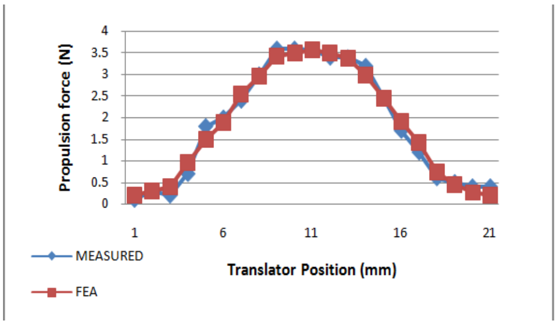
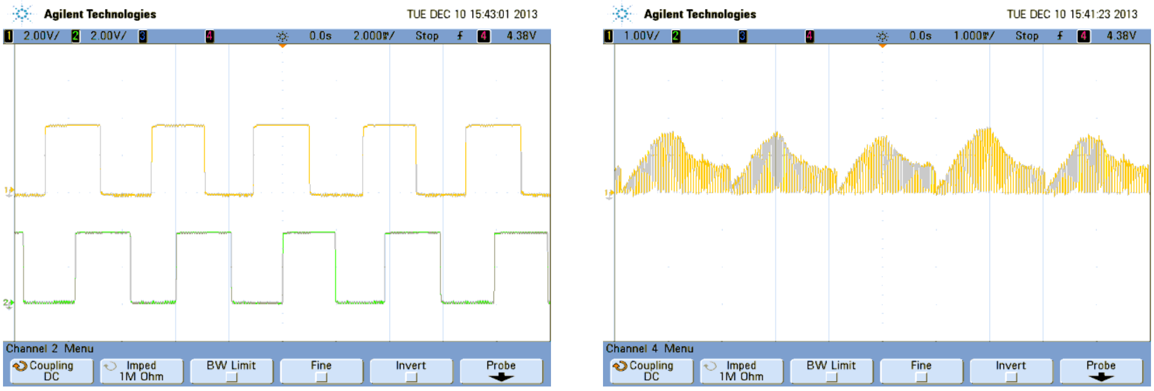


Figure 15. comparison of FEA and measured propulsion force at rated current



(a) (b)

Figure 16. Experimental waveforms (a) Pulses of LSRM (b) Phase current of LSRM

7. CONCLUSION

Modification of the stator geometry by the provision of skewed poles has been presented in this paper. A 2m long LSRM prototype has been constructed. Force and inductance profile has been obtained by using FEA. There is a good agreement between measurement results and FEA values of inductance profile of the motor. The proposed structure reduces the force ripple by approximately 27% compared to the conventional machine. FFT methodology is comparatively simpler than the most widely used finite-element vibration analysis procedure for mode frequency identification.

REFERENCES

[1] J Corda, E Skopljak, *Linear switched reluctance actuator*, IEEE Proceedings, 1987; 125(4): 535-539.
[2] D Matt, R Goyet, J Lucidarme, C Rioux, Longitudinal-field multi-air gap linear reluctance actuator, *Elect. Mach. Power Syst.*, 1987; 13(5): 299–313.
[3] K Takayama, Y Takasaki, A new type switched reluctance motor, *IEEE Transactions on Industry Applications*, 1988; 23(5): 71-78.
[4] Mimpei Morishita, A new maglev system for magnetically levitated carrier system, *IEEE Transactions on Vehicular Technology*, 1989; 38(4): 230-236.
[5] PM Cusack, GE Dawson, TR Eastham, *Design, control and operation of a linear switched reluctance motor*, Proc. Canadian Conf. Electrical and Computer Engineering, Quebec, PQ, Canada, 1991; 19.
[6] J Corda, E Skopljak, *Linear switched reluctance actuator*, Proc. Sixth Int. Conf. Electrical Machines and Drives, Oxford, U.K, 1993; 535–539.
[7] J Lucidarme, A Amouri, M Poloujadoff, Optimum design of longitudinal field variable reluctance motors-application to a high performance actuator, *IEEE Trans. Energy Conversion*, 1993; 8: 357–361.
[8] US Deshpande, JJ Cathey, E Richter, A high force density linear switched reluctance machine, *IEEE Transactions on Industry Applications*, 1995; 31(2): 345-52.
[9] CT Liu, YN Chen, *On the feasible polygon classifications of linear switched reluctance machines*, Conf. Rec. 1997 IEEE Int. Electric Machines and Drives Conf., Milwaukee, WI, 1997; 11.
[10] BS Lee, HK Bae, P Vijayraghavan, R Krishnan, Design of a linear switched reluctance machine, *IEEE Transactions on Industry Application*, 2000; 36: 1571-1580.
[11] Ferhat Daldaban, Nurettin Ustkoyuncu, A new double sided linear switched reluctance motor with low cost, *Energy Conversion and Management*, 2006; 47: 2983–2990.
[12] Hong Sun Lim, Ramu Krishnan, Ropeless Elevator with linear switched reluctance motor drive actuation systems, *IEEE Transactions on Industrial Electronics*, 2007; 54(4): 2209 - 2218.
[13] DS Schramm, BW Williams, TC Green, *Torque ripple reduction of switched reluctance motors by phase current optimal profiling*, Proc. IEEE PESC'92, 1992; 857–860.
[14] M. Moallem, C. M. Ong, and L. E. Unnewehr, Effect of rotor profiles on the torque of a switched reluctance motor, *IEEE Trans. on Ind. Applicat.*, 1992; 28(2): 364-369.
[15] Iqbal Hussain, and M. Ehsani, Torque Ripple Minimization in Switched Reluctance Motor Drives by PWM Current Control, *IEEE Trans., on Power Electronics*, 1996; 11(1): 83-88.
[16] R. Rabinovici, Torque ripple, vibrations, and acoustic noise in switched reluctance motors, *HAIT Journal of Science and Engineering B*, 2005; 2(5-6): 776-786.
[17] C Neagoe, A Foggia, R Krishnan, *Impact of pole tapering on the electromagnetic force of the switched reluctance motor*, Conf. Rec IEEE Electric Machines and Drives Conference, 1997: WA1/2.1- WA1/2.3.
[18] P Silvester, MVK Chari, Finite element solution of saturable magnetic field problems, *IEEE Trans. On Power Apparatus and Systems (PAS),* 1970; 89: 1642-1651.

[19] NC Lenin, R Arumugam, Analysis and characterisation of longitudinal flux single sided linear switched reluctance machines, *Turkish Journal of Electrical Engineering and Computer Sciences*, 2012; 20(1): 1220-1227.
[20] NC Lenin, R Arumugam, Vibration analysis and control in linear switched reluctance motor, *Journal of Vibroengineering*, 2011; 13(4): 662-675.
[21] NC Lenin, R Elavarasan, R Arumugam, *Investigation of Linear Switched Reluctance Motor with Skewed Poles*, International Conference on Advances in Electrical Engineering, 2014.
[22] JF Lindsay, R Arumugam, R Krishnan, *Magnetic field analysis of a switched reluctance motor with multitooth per stator pole*, Proc. Inst Elect Eng, 1986: 347–353.
[23] NN Fulton, *The application of CAD to switched reluctance drives*, Electrical Machines Drives Conf, 1987: 275–279.
[24] AM Omekanda, C Broche, M Renglet, Calculation of the electromagnetic parameters of a switched reluctance motor using an improved FEM–BIEM application to different models for the torque calculation, *IEEE Transactions on Industry Applications*, 1997: 914–918.
[25] DE Cameron, Jeffrey H Lang, SD Umans, The origin and reduction of acoustic noise in doubly salient variable-reluctance motors, *IEEE Transactions on Industry Applications*, 1992; 28(6): 1250–1255.
[26] KN Srinivas, R Arumugam, *Spectrum analysis of torque ripple in a switched reluctance motor*, Proc. Nat. Conf. Elect, Chennai, India, 2004; 88–93.

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