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

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Article Info	ABSTRACT
Article history:	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
Received Aug 5, 2014	family is the presence of high force ripple leads to vibration and acoustic
Revised Nov 3, 2014	noise. The proposed structure provides a smooth force profile with reduced
Accepted Nov 20, 2014	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
Keyword:	experimental results of this paper prove that LSRMs are one of the strong

candidates for linear propulsion drives.

FFT Finite element analysis Force ripple Switched reluctance motor Skewed pole

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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

Fabla 1	Specific	ationa	of Drototyma	LODM
i able i.	specific	ations	of Prototype	LSKIVI

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	Maximum force=3.21N	
Statol pole skewed ungle 1 to 10 degrees	degrees	Maximum force 9.211	

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:

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

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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

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Figure 7. Propulsion force for base motor



Figure 9. Propulsion force for proposed motor



Figure 8. Inductance Profile for base 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						
Туре	Peak propulsion M force (N) for	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

FAST FOURIER TRANSFORM APPLICATION TO LSRM 5.

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.

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

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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
 Amplitude (dB)

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.



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





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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.

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