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Design, Development and Electromagnetic Analysis of a Linear Switched Reluctance Motor for Automatic Door Systems of Railway Carriages

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ABSTRACT:

Day in, day out millions of people all around the world use public transportation systems. Within a metropolis, local rail transport is usually the only cheap and efficient way to get from one place to another. This is making new demands on the rail-bound mass transit. The door system needs to be robust, reliable, maintainable, safe and unaffected by the environment in order to guarantee an efficient train service. Because of round the clock operation of these trains, it is difficult to maintain the door systems regularly. They also get exposed to harsh environment like rain, sunlight and rough handling which may lead to malfunction. Safety is a very important constraint in any mass transit system and any malfunction in the door system can lead to severe mishap. Considering all the above constraints, we are proposing Linear Switched Reluctance Motor (LSRM) based door systems for railway carriages. The phase independent nature of LSRM makes it the best choice for door systems application as it can be made to operate even if any phase fails to work. This paper presents a clear design guide for a longitudinal flux single sided LSRM. The design parameters have been verified using two dimensional finite element analysis (2D-FEA). Finally a prototype has been built and tested. Test results imply the features of LSRM that make it a strong candidate for door systems of railway carriages.

KEYWORDS:

Linear motors; Linear switched reluctance motor; Finite element analysis; Automatic door systems

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ACRONYMS AND NOMENCLATURE:

LSR	Linear switched reluctance motor
FEA	Finite element analysis
PCB	Printed circuit board
P	Power rating
k_e	Efficiency
k_d	Duty cycle
B	Stator pole flux density at aligned position
A_s	Specific electric loading
D	Bore diameter (mm)
v_s	Rated speed
F_x	Propulsion force
B_g	Air gap flux density
L_w	Stack length
g	Air gap
w_{sp}	Primary tooth width
μ_0	Permeability of free space
F_{ripple}	Force ripple
F_{max}	Maximum force
F_{min}	Minimum force
F_{avg}	Average force
L	Inductance
T_{ph}	Turns per phase
φ_k	Flux at k^{th} magnetic flux path in the air gap

1. Introduction

Nowadays, linear electric motors have gained special interest in industrial applications like electronic assembly, baggage handling, machine tools, PCB assembly/drilling, robotics, conveyors, elevators, rapid transportation, baggage handling, crane drives, flexible manufacturing systems, etc where there is a need for direct linear or oscillatory motion. Mechanical systems like ball-screw, rack and pinion, lead screw and timing belt drives which are used in the above applications for linear motion have been drastically surpassed by linear motors because of various disadvantages of mechanical systems like backlash, belt stretching, mechanical windup, which would all contribute to in accuracies and instabilities in the system. LSRMs are the counterparts of rotating switched reluctance machines obtained by cutting them along the shaft over its radius and rolling them out. LSRMs can be used as an alternative to linear induction motors and linear synchronous motors because of various advantages stated in [1-3].

2. Analytical design

There is a myriad of LSRM topologies proposed so far. They have been clearly explained in [4]. Longitudinal flux topology has lower eddy current losses than transverse flux LSRM as the flux is along the direction of motion in the former case. LSRMs are easy to construct and need very less maintenance. The LSRM is a doubly salient machine. LSRMs are suffering to compete in industry applications because of high force ripple and vibration. Novel LSRM topologies have been proposed to reduce the force ripple and vibration by changing the stator geometry in [5] [6]. Multi phase excitation to reduce the force ripple has been explained in [7]. In this paper, electromagnetic design and development of a 4 phase single sided longitudinal flux LSRM with primary translator have been described. As the LSRM is being designed for the application of automated door systems, it is necessary to design the linear motor meeting the door system standards as available in [8]. These standards are tabulated in Table 1. Fig. 1 shows the two dimensional (2D) model of the designed LSRM. The LSRM primary has a 4 phase concentric winding with 8 poles. Table 2 shows the specifications and dimensions of the LSRM prototype.

Table 1: Standards for automated door systems

Parameter	Value
Size of each door	1.06 m
Average weight of each door	95 Kg
Speed of door at the time of opening and closing	0.3 m/sec
Average power rating	130 W
Minimum door closing time	3.5 sec

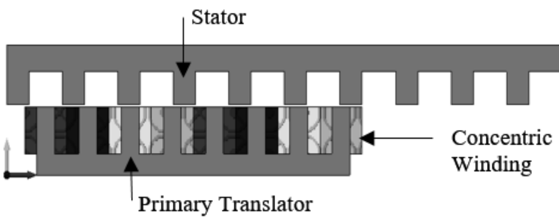

Fig. 1: 2D model of designed LSRM

Table 2: Specifications of LSRM prototype

Parameter	Value
Rated power	20 W
Rated current	5 Amps
Maximum force	70 N
Translator pole pitch	38 mm
Stator slot pitchxlength	50 mm x 80 mm
Air gap	2 mm

Contrary to the active stator and passive translator structure, there is no reversal of flux at the instant of phase current commutation. Regardless of switching of the phase winding current, the back irons of stator and translator experience the magnetic flux in same direction. The design of LSRM utilizes the design procedure of rotary SRM. The machine is first designed in rotary domain and then transformed into linear domain. The design procedure of LSRM is described in[4]. The output power can be given as Eqn. (1):

$$P = k_e k_d k_1 k_2 k B A_s D^2 \vartheta_s 60/\pi \qquad (1)$$

The total propulsion force can be given as Eqn. (2):

$$F_x = B_g{}^2 L_w g / \mu_0 \qquad (2)$$

The total normal force (F_n)can be given as Eqn. (3):

$$F_n = -B_g{}^2 w_{sp} L_w / \mu_0 \qquad (3)$$

When the frequency of the exciting force is close or equal to any of the natural frequencies of the machine, resonance occurs and results in substantial increase of vibrations and noise [9]. The Force ripple (Fripple) can be given as Eqn. (4):

$$\%F_{ripple} = 100 \times (F_{\max} - F_{\min}) / F_{avg} \qquad (4)$$

The inductance of LSRM is related to the machine dimensions such as excitation currents, translator and stator pole and slot widths, and translator position. The inductance L (i, x) for a phase with all magnetic flux paths (k) can calculated as Eqn. (5):

$$L(i,x) = \frac{T_{ph}}{i} \sum_k \phi_k(i,x) \qquad (5)$$

where, k_e is the efficiency, k_d is the duty cycle which is determined by the current conduction angle for each rising inductance profile, k_1 is constant (0.08224), k_2 depends on the operating point and is determined by using aligned saturated and unaligned inductance. k is 0.8. B is stator pole flux density at aligned position. As is the specific electric loading. D is the bore diameter of SRM. τ is the primary slot pitch. w_{sp} is the primary tooth width. L_w is the stack length. μ_0 is the permittivity of free space. T_{ph} is the number of turns per phase. i is the rated phase current. φ_k is the flux at k^{th} magnetic flux path in the air gap.

3. Modeling and Finite Element Analysis

Finite element analysis (FEA) is a numerical tool in which simulations are carried out to validate the constructed model and to observe the characteristics of machine. Here, the machine is partitioned into a mesh of elements where the field in each element is represented by a polynomial of unknown coefficients. FEA is the resultant solution of the set of equations for the unknown coefficients. A 2D FEA has been carried out to predict the performance of the designed LSRM. The secondary of the LSRM is stationary and the primary is designed to move. The asymmetrical bridge converter used to drive the LSRM is shown in Fig. 2. The propulsion force of LSRM when a pole is moving from one unaligned position to another unaligned position when the corresponding phase is excited is shown in Fig. 3. The peak force obtained is 67 N. The inductance profile of the corresponding phase from one unaligned position to another unaligned position is shown in Fig. 4.

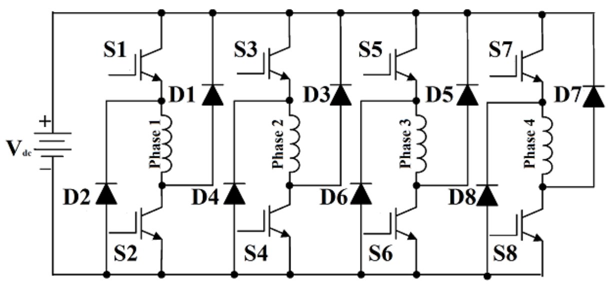

Fig. 2: 4 Phase asymmetric bridge converter.

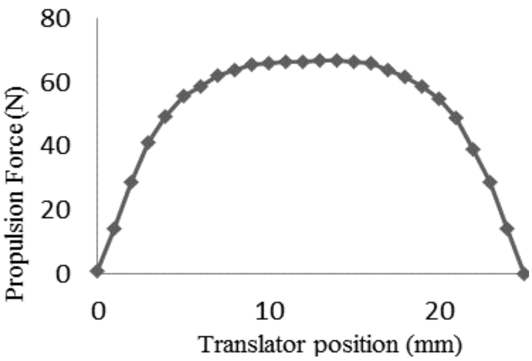

Fig. 3: Propulsion force vs. Translator position

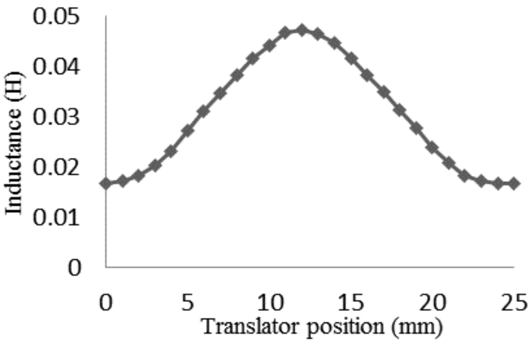

Fig. 4: Inductance vs. Translator position

4. Experimental results

A 4 phase single sided longitudinal flux LSRM has been fabricated based on the designed model. Fig. 5 shows the experimental setup and current waveform of a single phase from asymmetric bridge converter for the designed LSRM. The experimental track is designed to be 2 meters long. Propulsion force and inductance values at each position were measured using S-type load cells. The measured values are plotted in Figs. 6 and 7 respectively. The falling current profile is computed by applying a constant current of 5 Amps to a phase and turning it off. The time constant is measured from the profile and hence the inductance is calculated.

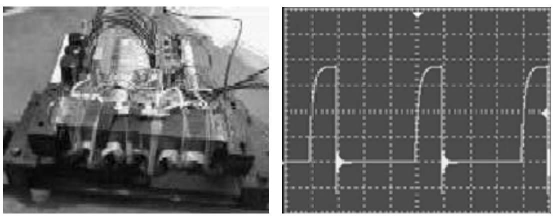

Fig. 5: Expermintal setup and current waveform of a single phase

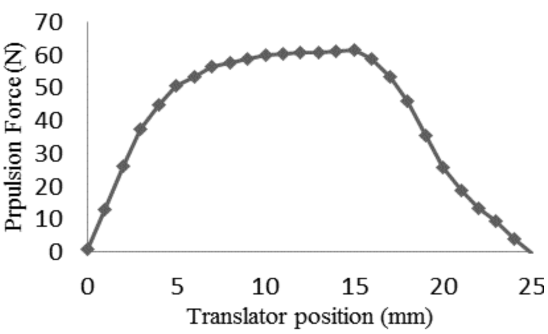

Fig. 6: Propulsion force vs. Translator position

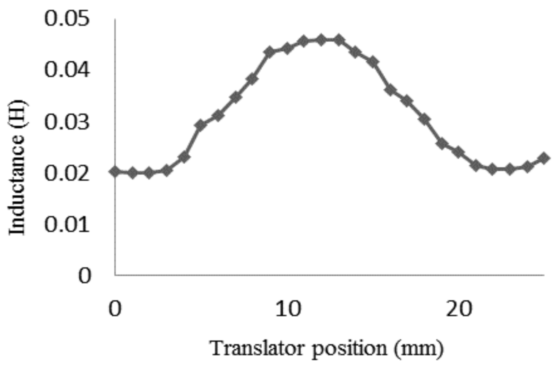

Fig. 7: Inductance vs. Translator position

5. Conclusion

A 4 phase single sided longitudinal flux LSRM has been designed. 2D FEA simulations has been carried out for predicting the performance of the designed LSRM. Electromagnetic characteristics have been investigated and results were shown. A laboratory prototype of the proposed model has been fabricated and its performance results were compared with FEA results. The experimental results are in close correlation with the FEA results. The power rating of the designed LSRM is 20W which is much lesser than the average rating of the current automated door systems for the same load. Hence, it can be concluded that LSRM is a strong candidate for automated door systems of railway carriages.

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