

Design and Development of Permanent Magnet Linear Synchronous Motor (PMLSM)

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Abstract

Background/Objectives: A steady increase in industrial applications has secured an important place for linear electric motors. This paper deals with the design, development and electromagnetic analysis of PMLSM for conveyor and transit applications. **Methods/Statistical Analysis:** PMLSM for the stated application has been designed and modelled. Electromagnetic analysis of the model has been done using 2D Finite Element Method (2D-FEM) to predict the performance of PMLSM. **Findings:** Electromagnetic characteristics of PMLSM have been investigated and results have been presented. Results show the upper hand of PMLSM over Linear Induction Motor (LIM) in terms of normal force to propulsion force ratio which is one of the primary concerns while choosing a linear drive for transit and conveyor applications after manufacturing costs. **Applications:** Some typical industrial applications of linear motors like PMLSM include electronic assembly, baggage handling, machine tools, PCB assembly/drilling, robotics, conveyors, elevators etc.

Keywords: Cogging Force, Finite Element Analysis (FEA), Linear Motor, Permanent Magnet Linear Synchronous Motor (PMLSM)

1. Introduction

A PMLSM is similar to a typical permanent magnet synchronous motor, but unwound and laid lengthwise along the guide way¹. PMLSMs generate propulsive force by running current through a creating a travelling electromagnetic field that interacts with a set of Permanent Magnets (PMs) on a translator to create thrust. These motors are characterized by high force density, faster response and small electrical time constant². Some of the drawbacks of PMLSMs are its high manufacturing cost and stray magnetic fields because of the presence of PMs³. PMLSMs have better performance compared to other linear motors like LIMs because of their higher $\eta \cos \phi (< 0.6 - 0.7)$ value than for LIMs (0.4 – 0.45)⁴. In this paper, design, development and electromagnetic analysis of PMLSM have been presented for conveyor and transit applications.

2. Analytical Design

There is a myriad of topologies proposed so far for

PMLSMs⁵. In this paper, electromagnetic design and development of a 3 phase single sided longitudinal flux PMLSM with primary stator and permanent magnet translator for industrial applications have been described. The PMLSM primary has a full-pitched 3-phase winding in a laminated steel core with 6 slots per pole, and the secondary comprises of permanent magnet material (NdFeB N30H) embedded in a steel backing. The PMs can be placed either in tangential direction, radial direction or in Halbach array as shown in Figure 1(a), Figure 1(b) and Figure 1(c).

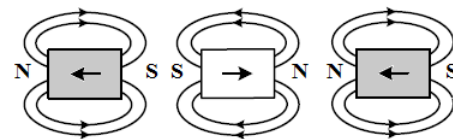


Figure 1(a). PMs in tangential direction.

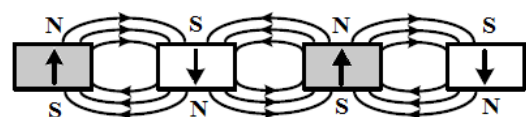


Figure 1(b). PMs in radial direction.

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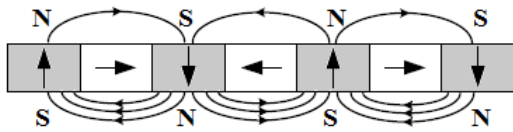


Figure 1(c). PMs in Halbach array.

The specifications of the designed motor are tabulated in Table 1. For a linear electric machine, the width of the air gap and active length of the machine determine four key performance factors namely motor force ripple, back EMF, resistance of primary winding and motor force constant. The thickness of PMs affects the PMLSM performance significantly⁵. PM thickness of 5mm is chosen based on peak no-load EMF waveform versus the PM thickness to achieve a maximum peak no-load EMF⁶. The PM thickness has to be chosen such that, it is thick enough to avoid accidental irreversible demagnetization in case of applications like large scale electromagnetic launch where high values of armature flux exists because of substantial values of stator current loading⁷. Also by using a thick PM, smaller main inductance and better power factor can be achieved. Increase in the number of winding turns increases the amount of magnetic flux cut by the coils which will increase the induced EMF.

Table 1. Specifications of LPMSM

Rated power	100 W
Rated current	5 Amps
Rated speed	12 m/s
Pole pitch	120 mm
Length of PM	100 mm
PM residual flux density	1.117 T

The cogging force in a slotted PMLSM is caused by slotting and end effects. Slotting effect is due to the interaction between PMs and the armature slotted core with the wavelength of one slot pitch. End effect arises from the interaction between PMs and the finite length of armature core with the wavelength of one pole pitch. Cogging force or detent force in PMLSM increases the thrust ripple and may introduce a disturbance in positioning precision. Since the cogging force occurs due to the interaction of primary iron core and PMs, it can be reduced by increasing the distance between the primary and secondary. But an increase in the air gap is a compromise on the maximum thrust and efficiency. An open slot leads to a higher resultant cogging force than a

semi-closed slot. To mitigate the open slot effect, proper selection of slot number (N_s) and magnet pole number (N_p) combination is a common technique. To illustrate this factor (k_{cog}), consider the number of cogging periods for one pole translation, as given in Equation⁸.

$$k_{cog} = \frac{\text{LCM}(N_p, N_s)}{N_p} \quad (1)$$

Smaller the factor, larger the cogging force. The LCM is larger for tooth wound windings than for distributed windings. Cogging force can be minimized and average thrust force can be maximized by applying techniques like magnets or slots skewing, semi-closed slot design, two-step optimization using Taguchi parameter method, along with 2-D and 3-D FEA, PM length adjustment etc⁸. The air gap should be about the size of the slot openings (or less) for small EMF harmonics and low cogging force. The PMLSM has been designed with a primary stator and PM translator. This topology would be typical for MAGLEVs and conveyors (air gap from 6 to 10 mm). The speed of the PM translator of designed PMLSM can be given as Equation 2.

$$v = 2f\tau \quad (2)$$

The electromagnetic power (P_{em}) can be given as Equation 3.

$$P_{em} = m \left[\frac{VE}{X_{sq}} \sin \delta + \frac{V^2}{2} \left(\frac{1}{X_{sq}} - \frac{1}{X_{sd}} \right) \sin 2\delta \right] \quad (3)$$

The electromagnetic thrust (F_x) can be give as Equation 4.

$$F_x = \frac{m}{v} \frac{VE}{X_{sd}} \sin \delta \quad (4)$$

Where f is the source frequency, τ is the primary pole pitch, m is no. of phases, V is source voltage, E is no-load rms voltage induced (EMF) in one phase by the PM excitation flux. δ is the load angle; X_{sq} and X_{sd} are q-axis and d-axis synchronous reactance respectively.

3. Modelling and FEA

Finite element analysis is a numerical tool for calculating electromagnetic field distribution in the machine based on its geometry and material. In finite element method of analysis, the model is divided into a mesh of elements. The

field inside each element is represented by a polynomial with unknown coefficients. FEA is the resultant solution of the set of equations for the unknown coefficients. In 2D FEA, the mesh elements are shaped like triangles. The accuracy of the FEA solution depends on the nature of the field and the size of mesh elements. In regions where the direction or magnitude of the field is changing rapidly, like the air gap region in PMLSM, it is preferred to have elements of smaller size or higher polynomial order, for better accuracy.

A two-dimensional Finite Element Analysis (FEA) is carried out to predict the performance of the designed PMLSM. Figure 2 shows a portion of designed PMLSM. It represents two pole pitches of an infinitely long machine. The field pattern in the designed PMLSM repeats for every two pole pitches. Periodicity of poles of PMLSM is used to repeat primary and PM secondary on both sides of Figure 2 to achieve better results in less computational time.

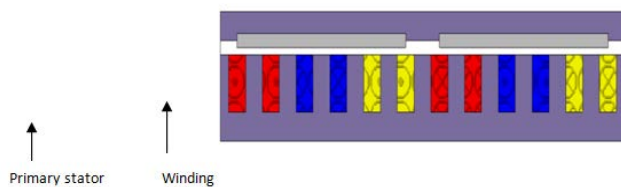


Figure 2. 2D model of PMLSM.

The primary of the PMLSM is stationary and magnetic track is designed to move. Figure 3 shows the flux linkage of a phase (phase angle=0°) when the load angle is varied from 0° to 180°.

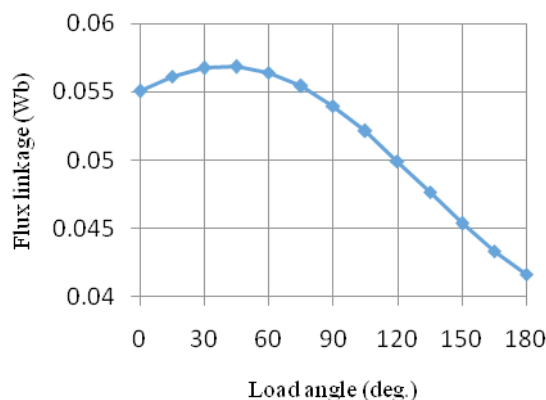


Figure 3. Flux linkage vs. load angle.

Figure 4 shows the propulsion force of the translator when the load angle is varied from 0° to 180°. The peak propulsion force obtained is 5.42 N as inferred from Figure 4.

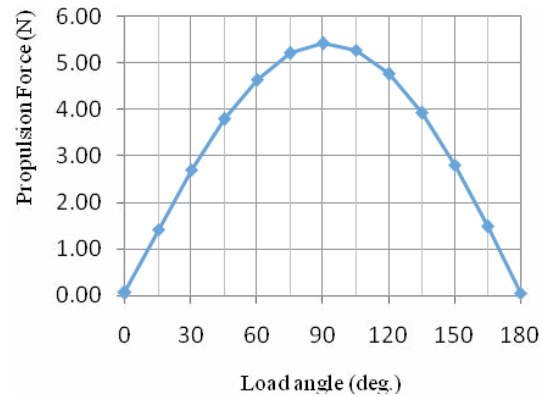


Figure 4. Propulsion force vs. load angle.

Figure 5 shows the propulsion force of the translator when it is moving at synchronous speed.

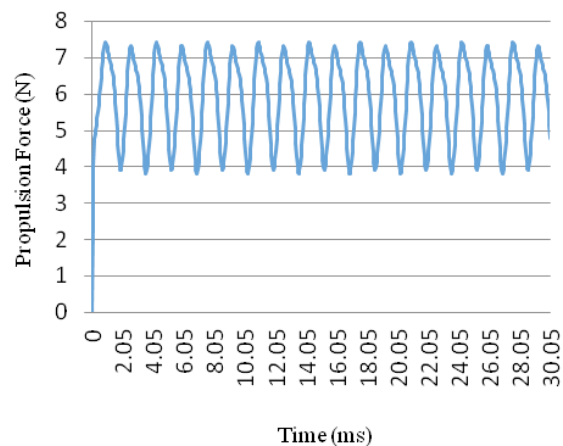


Figure 5. Propulsion force vs. time.

Figure 6 shows the normal force on the translator when the load angle is varied from -180° to 180°. The peak normal force obtained is 147 N as inferred from Figure 6. The ratio of normal force to propulsion force is 27 ($F_n/F_x=27$).

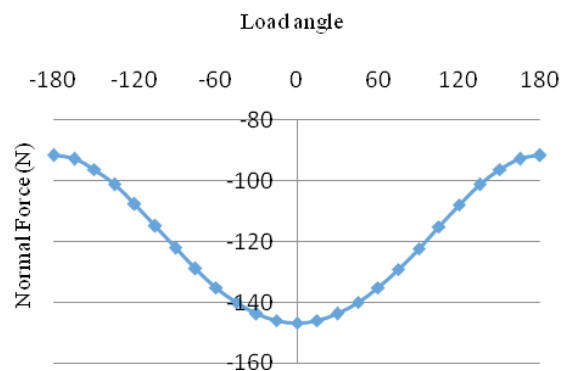


Figure 6. Normal force (N) vs. load angle.

The cogging force of PMLSM can be computed by the change of the magnetic co-energy in the air gap, while the translator is in motion.

4. Conclusion

A 3 phase single sided PMLSM has been designed and modelled. 2D FEA simulations have been carried out for predicting the performance of the designed PMLSM. Electromagnetic characteristics have been investigated and results are shown. A maximum propulsion force of 5.42N and a maximum normal force of 147N were obtained for the designed PMLSM. Because of the high normal force to propulsion force ratio of PMLSM ($F_n/F_x=27$) than that of Linear Induction Motor (LIM) ($F_n/F_x=3$)⁹ as obtained from the results, PMLSM can be considered as a strong candidate than other linear motors for conveyor and transit applications.

5. References

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