

ACCURACY ASSESSMENT OF THE LINEAR INDUCTION MOTOR PERFORMANCE USING ADAPTIVE FEM

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Abstract- The majority of electrical machines are designed to produce the rotary motion, there by exploiting the blessing of circularity which man has enjoyed since the discovery of the wheel. Electromagnetic forces may also be employed to produce the linear motion resulting in linear motion electrical machines. The Linear Induction Motor (LIM), first conceived in the 19th century, could present a viable solution to the problem of quick and efficient transportation. However, the performance of a high speed LIM is severely degraded by 'End Effects'. The paper provides an overview of the modern field simulation techniques available to assist in the design and performance efficiency comparison of linear induction motor in terms Goodness factor (G) widely depends on the factor such as pole pitch, total air gap, input frequency & surface resistivity etc. The COMSOL multiphysics software used here is based on finite element techniques in very advanced and provides reliable and accurate results.

I. INTRODUCTION

Linear Induction Motors are electrical machines which unlike normal machines do not have rotors in the traditional sense, but elements which move in a straight line when the machine is excited. In a normal three phase induction motor, the stator produces a rotating magnetic field which induces the rotor to rotate along with it. One may consider the Linear Induction Motor (LIM) to be constructed out of its rotary counterpart where the stator and the rotor have been cut and unrolled. Now, the stator produces a traveling magnetic field instead of a rotating one. The rotor is induced to move along it. The exciting element of the LIM (like the stator in the normal rotary machine) is called

the primary and the element in which currents are induced (like the rotor in the normal rotary machine) is called the secondary of the LIM. Usually either of the primary or the secondary is stationary and extends over the entire range of motion of the other element. Thus, LIMs may be classified as either short- primary (also called short-stator in literature) or short-secondary (called short-rotor) LIMs. LIMs may also be classified based on its construction as Single Sided LIM (SLIM) in which there is one primary and one secondary placed one on top of the other, Double Sided LIM (DLIM) in which there are two primaries on the two sides of a secondary, Tubular LIM (TLIM) in which the primary and secondary are placed co-axially etc. They are also classified as high-speed and low-speed LIMs.

The basic difference in the analysis of the rotary induction motor and the SLIM lies in the open air gap of the LIM due to the finite length and width of the elements of the LIM. These cause pronounced 'distortions' called longitudinal and transverse end effects (due to the finite length and width respectively). It has been observed from studies that the longitudinal end effect degrades the performance and bring to question the very feasibility of the use of SLIMs. [5] Also, the air gaps in LIMs are usually of higher magnitude than those in normal induction motors. The product of efficiency and power factor ($\cos \phi$) in a LIM usually does not exceed 0.5, whereas rotary induction motors with $\cos \phi = 0.8$ have been designed. In addition to that in induction motors, electromagnetic noise is sometimes the predominant acoustic noise. Electromagnetic vibration and noise are mainly generated by electromagnetic forces resulting from the combination of harmonic fluxes in the air gap. [7].

II. SLIM MODEL FORMULATION

The two dimensional finite element analysis model of SLIM has been designed with following specifications [6]

Number of phases: 3, number of poles: 3

Length of primary stack: 240 mm

Width of magnet: 14 mm

Length of mover: 170 mm

Height of mover 45 mm,

Height of permanent magnet teeth: 4 mm

Thickness of back-iron: 10 mm

Air gap length: varied from 0.5 mm to 5 mm

The analysis of an LIM is carried out in terms of electromagnetic field equations. As we are well aware that the slotted primary structure with its winding is by no means an ideal boundary conditions, or even a sufficiently simple one, where the solution to the governing field equations can be obtained. To reduce the boundary value problem the actual slotted structure is replaced with smooth surface and the current carrying windings are replaced by fictitious, infinitely thin current elements called current sheets, having linear current densities (A/m). The current density distribution of the current sheet is the same as that of the slot-embedded conductor configurations, such that the field in the air gap remains unchanged.

The relationship between the primary current sheet and the resulting air gap field is given by the air gap field equations as given:

$$H_y' = \frac{\partial H_y}{\partial x} \Delta x + H_y \quad (1)$$

And

$$E_z' = \frac{\partial E_z}{\partial x} \Delta x + E_z \quad (2)$$

Ampere's law

$$\oint H \cdot dl = \int_S J \cdot dS$$

We get

$$g \frac{\partial H_y}{\partial x} = J^s + J^r \quad (3)$$

$$\frac{\partial E_z}{\partial x} = \mu_o \frac{\partial H_y}{\partial t}$$

$$J^r = \sigma E_z$$

$$g \frac{\partial^2 H_y}{\partial x^2} = \mu_o \sigma \frac{\partial H_y}{\partial x} + \frac{\partial J^s}{\partial x} \quad (4)$$

In terms of B_y

$$\frac{\partial^2 B_y}{\partial x^2} - \frac{\mu_o \sigma}{g} \frac{\partial B_y}{\partial t} = \frac{\mu_o}{g} \frac{\partial J^s}{\partial x}$$

The governing equation which describes the magnetic vector potential in a single sided linear induction motor is given by

$$\text{rot} \frac{1}{\mu} \text{rot} \vec{A} = \vec{J}_o - \sigma \left(\frac{\partial \vec{A}}{\partial t} - \vec{v} \times \vec{B} \right) \quad (5)$$

Where σ is an equivalent conductivity of mover's material taking account of transverse edge effect [2] and v is the velocity of mover. The current density of the sheet at the primary surfaces is denoted by \vec{J}_o . The current sheet distribution is given by

$$\vec{J}_o = J_o \exp(j(\omega t - kx)) \quad (6)$$

J_o is related to primary current which is given by

$$J_o = \frac{3\sqrt{2} \omega_1 k_{\omega_1} I_1}{P\tau} \quad (7)$$

Where ω_1 is the number of turns, k_{ω_1} is the primary winding factor, τ is the pole pitch and P is the number of poles.

And from above relations the Goodness factor could achieve as

$$G = \frac{\omega \sigma \mu_o}{g \beta^2} \quad (8)$$

From the equation-5 further computation of force acting on machine could be derived [1]

$$F_x = \int_l \frac{\omega}{2\mu_o} \{ (B_x^2 - B_y^2) n_x + 2n_y B_x B_y \} dl \quad (9)$$

$$F_n = \int_l \frac{\omega}{2\mu_o} \{ (B_y^2 - B_x^2) n_y + 2n_x B_x B_y \} dl \quad (10)$$

where n_x and n_y are the unit normal direction vectors, ω is the primary stack width. In order to improve accuracy, the SLIM has been computed at different air gaps and it was observed that entry-end-effect could be reduced to high extent with change in the air-gap by keeping the speed of SLIM at constant value of 30 m/s.

III ADAPTIVE MESH GENERATION

After defining the distinguish boundary conditions, meshing is performed with following statics for the different air gaps varies from 0.5 mm to 2.0 mm. after applying the Adaptive Mesh refinement technique the degree of freedom could be increased to 9.6 times and number of boundary element increased to 1.45 times of the slandered meshing statics shown in Table 1. Mesh refinement has been done by Adaptive Mesh technique shown in Figure.1 after the calculation of Magnetic Potential vector and current density vector done by post processing in Comsol multiphysics ver 3.5.[8]

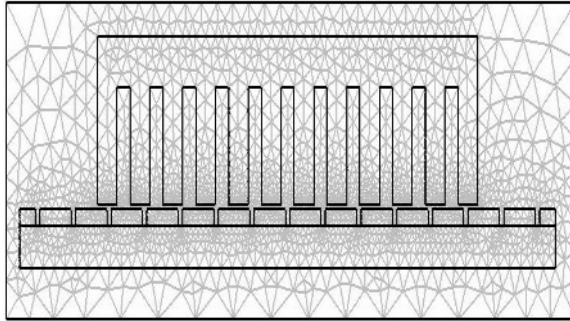


Figure1 Meshing of SLIM model

Table 1 Adaptive Meshing Refinement Statics

Items	Standard Meshing	Adaptive Mesh Refinement
Number of degree of	4813	46680
Number of mesh points	4813	9363
Number of elements	9559	18592
Triangular	9559	18592
Number of boundry	1085	1576
Number of vertex	140	140
Minimum element	0.391	0.6373
Element area ratio	0.001	0.0030

It is necessary to clarify the objectives of refinement and specify 'permissible error magnitudes' and here the engineer or user must have very clear aims. For instance the naive requirement that all displacements or all stresses should be given within a specified tolerance is not acceptable. The reasons for this are obvious as at singularities. Various procedures exist for

the refinement of finite element solutions. Broadly these fall into two categories:

1. The h -refinement in which the same class of elements continue to be used but are changed in size, in some locations made larger and in others made smaller, to provide maximum economy in reaching the desired solution.
2. The p -refinement in which we continue to use the same element size and simply increase, generally hierarchically, the order of the polynomial used in their definition.

Degrees of freedom (DOFs) give connection between local and global finite element functions. It is required to have several finite element spaces and corresponding sets of degrees of freedom at the same time. One set of degrees of freedom may be shared between different finite element spaces, when appropriate.

During adaptive refinement and coarsening of a triangulation, not only elements of the mesh are created and deleted, but also degrees of freedom. The geometry is handled dynamically in a hierarchical binary tree structure, using pointers from parent elements to their children. For data corresponding to degrees of freedom, which are usually involved with matrix-vector operations, simpler storage and access methods are more efficient. For that reason every degrees of freedom is realized just as an integer index, which can easily be used to access data from a vector or to build matrices that operate on vectors of degrees of freedom data.

During coarsening of the mesh, degrees of freedom are deleted. In general, the deleted degree of freedom is not the one which corresponds to the largest integer index. "Holes" with unused indices appear in the total range of used indices. One of the main aspects of the degrees of freedom administration is to keep track of all used and unused indices. One possibility to remove holes from vectors is the compression of degrees of freedom, i.e. the renumbering of all degrees of freedom such that all unused indices are shifted to the end of the index range, thus removing holes of unused indices. While the global index corresponding to degrees of freedom may change, the relative order of degrees of freedom indices remains unchanged during compression.

III. RESULTS AND DISSUSIONS

The predicted of end effects in the linear motion machine is shown in the figure 2. A set of balanced voltages applied to the terminals of the three phase LIM does not result in a set of balanced currents, and vice-versa. This causes a reduction in the LIM output and its efficiency.

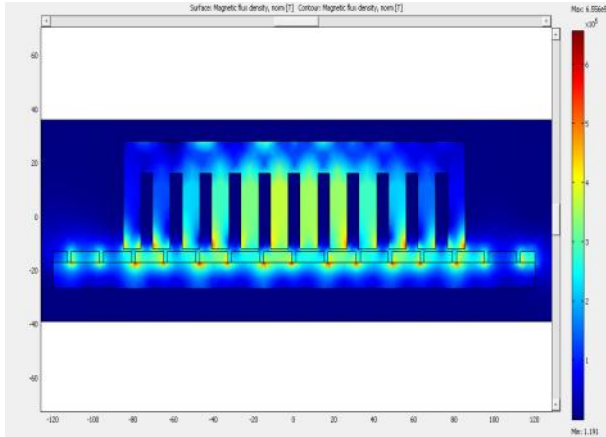


Figure 2 Surface Plot created with COMSOL

These effects are more pronounced at high speeds. The electromagnetic field travelling in the air gap is not a purely forward travelling field. The net field has three components (forward, backward and pulsating) because of these end effects. This results in the core flux density relatively higher than is found when end effects are neglected. The induced currents, resulting in surface current density, are reduced as the air-gap length in the linear induction motor progressively increases from 0.5 mm to 2.0 mm. Hence 2mm air-gap length should have the lowest induced current in the middle slots, which is desirable to eliminate the losses. But this large air-gap is responsible for introducing the fringing effect, fringing flux and also larger air gap requires the large magnetization current and result in the smaller power factor.

The exit end zone losses air gap increases with a larger air gap. Resulting, in the decrease of output force and efficiency. So the air gap should be optimised so, that up to certain extent the larger goodness factor with proper mechanical clearance. Magnetic field distribution of SLIM after getting it simulated with Comsol Multiphysics is shown in figure.2. The surface current density at the end poles of SLIM with variable air gap(from 0.5mm to 2mm) has been shown in Figures 3.1- 3.4.

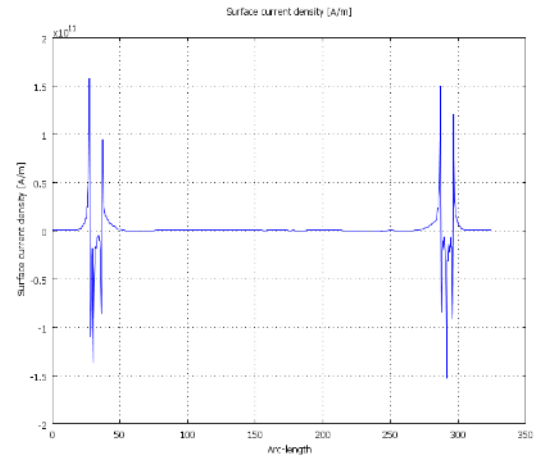


Figure 3.1 Current density plot with 0.5mm air gap

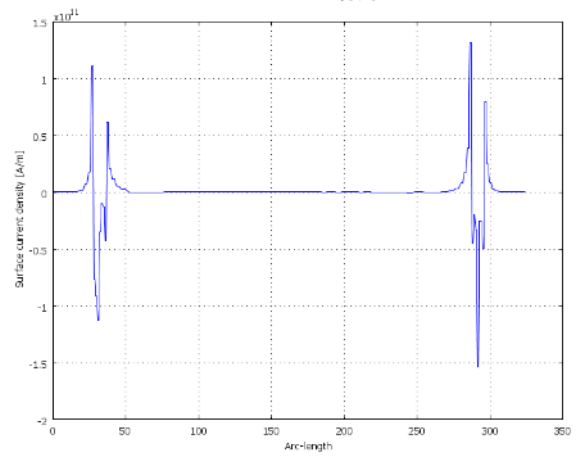


Figure 3.2 Current density plot with 1mm air gap

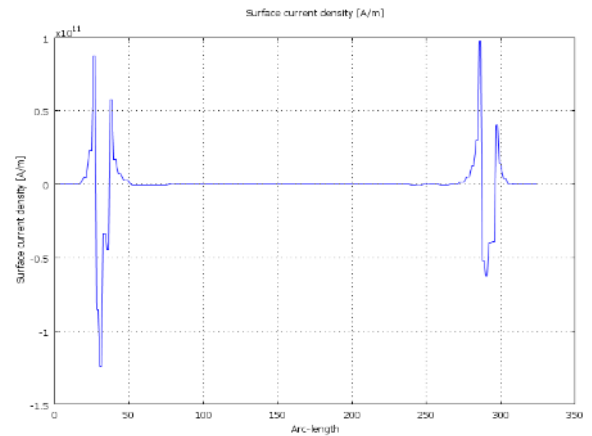


Figure 3.3 Current density plot with 1.5mm air gap

It is evident; the magnetic field in the air gap can be divided into three parts. The two parts represent the end effect in which one part is as 'entry-end-effect-wave' and the other one is as 'exit-end-effect-wave'. The Magnetic field distribution in the LIM is effected by air gap

between the stator and mover. So by varying the air gap the optimum performance can be achieved.

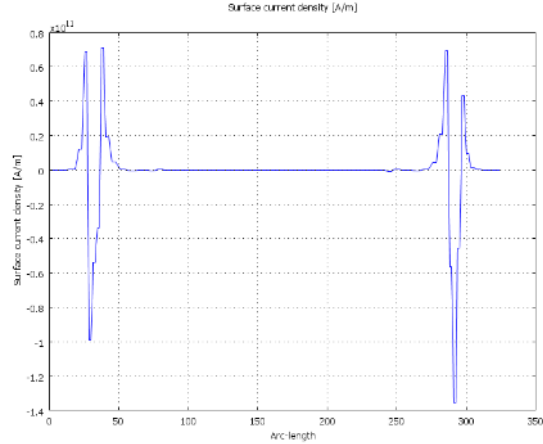


Figure 3.4 Current density plot with 2 mm air gap

The current distribution in the secondary sheet is not uniform. It would be governed by skin effect. This is the another factor which contributing to non-ideality.[2]

The induced currents, resulting in surface current density, are reduced as the air-gap length in the linear induction motor progressively increases from 0.5 mm to 2.0 mm. Hence 2mm air-gap length should have the lowest induced current, which is desirable to eliminate the losses. But this large air-gap is responsible for introducing the fringing effect and fringing flux. This fringing flux leads to following two undesirable consequences: [7].

- I. The inductance is increased due to an effective increase in the air-gap cross-sectional area, thereby reducing the reluctance of the gap.
- II. Fringing flux induces eddy currents in the surrounding surface of the neighbouring coil conductors that cause the total power losses to increase. In addition, a temperature rise takes place in conductor, which leads to further increase in the ohmic losses.

The rise of fringing effect due to the number of poles in the mover member magnets which are of the same material i.e. silicon steel. The number of poles hence reflect in the plot of surface current density, in the form of number of peaks / surges / spikes in the plot which are 12 (corresponding to the 12 poles of the mover).

IV. CONCLUSIONS

COMSOL Multi physics can be used as a viable tool for assessment of various critical parameters which affects the performance of LIM. Use of such application software can offer improved performance by fine coarsening of mesh. Surface current density plots with the variable air gap is analysed in this paper. The selection of actual air gap in the critical region i.e. in between primary and stationary is pointed out.

The Magnetic field distribution in the LIM is affected by air gap between the stator and mover. The air gap (and also the surface resistivity) affects length of penetration differently at low speed and high speeds.

V. REFERENCES

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