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Realistic Equivalent Circuit Analysis of Single-Sided Linear Induction Motor

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Abstract

The concept of equivalent circuit representation including end and edge effects of Linear induction motor (LIM) is mandatory to use in analyzing the performance of the machine. In this paper, conventional round rotor theory are extended to the analysis of LIM. The longitudinal end effect and transverse edge effect a coefficient is derived which are included in the parameters that are mainly affecting secondary resistance and magnetizing reactance. The total primary is sectionalized to show intensity of the effects at each section with respect to the position/movement of secondary and developed a new equivalent circuit model. The effect of input frequency and secondary sheet thickness on the thrust produced by LIM are analyzed. The physical interpretation for the performance degradation due to end, edge and saturation effects are made. Results have been formulated and validated with the existing literature.

Keywords: equivalent circuit parameters, linear induction motor (LIM), longitudinal end effect, transverse edge effect, thrust

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INTRODUCTION

Linear Motion is gaining momentum in present day automation industry. For the machines utilizing linear motion has proven that conversion efficiency is less. So linear machines is again focused for further investigation.

Linear machines are known for their high thrust for shorter stoke play. Because of the higher efficiency and shorter stoke play, Linear machines have typical applications like launchers .The principle of the Linear machines is classified as Linear Synchronous Machines (LSM), Linear Induction Machines (LIM), Linear Reluctance Machines(LRM). LIM mainly has high initial thrust when is compared with other linear motors.

The focus of this article is on design and analysis of LIM. Linear induction machine (LIM) is more realizable because of its simple structure and its low cost. LIM's are being actively investigated for use as a variety of consumer applications having contributed to an upsurge in interest in the linear machines. LIM works on the principle of moving magnetic field i.e., the force are produced by linearly moving magnetic field acting on conductors in the field.

Any conductor, be it a loop, a coil or simply a piece of plate metal, that are placed in this field will have eddy currents induced in it thus creating an opposing magnetic field, in accordance with the Lenz's law. The two opposing fields will repel each other, thus creating motion as magnetic field sweeps through the metal. Figure 1 shows the model of linear motor derived from a conventional rotary motor.[1-2]

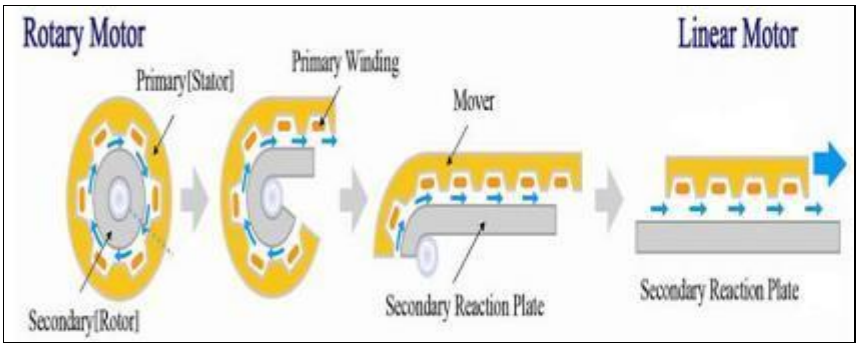

Fig. 1. *Development of LIM from Conventional Rotary Machine.*

However, the other classification of LIM is according to the length of the primary and the secondary, namely the long primary LIM and the short-primary LIM, as shown in Figure 2.

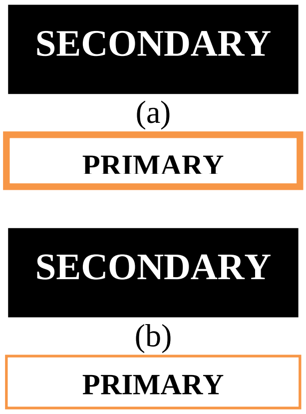

Fig. 2. *Two-dimensional Model of Two Types of LIM. (a) Short-Primary LIM.*

(b) Long-Primary LIM.

There are numerous papers published on LIM. Because of simple structure it gained the concentration of various researchers for further developments. Several different methods have been presented for analysis of the LIMs, such as equivalent circuit model (ECM), 1-D and 2-D electromagnetic field analysis, and the numerical methods including finite-element and finite-difference methods.[1-3] Unfortunately, analysis of the LIM is complicated because of the Longitudinal End Effect and Transverse Edge Effect.

The basic works of many researchers has been oriented towards the design and modeling of LIM. Their studies have yielded valuable information regarding the behavior of linear machines. But these models has number of limitations, which are to be included practically.[1-3]

Two dimensional solution of electrodynamics equations have been developed in.[4,5] The end effects are investigated as the function of design parameters but the edge effects are ignored.

R.M.Pai et.al.[6] has derived the equivalent circuit of LIM from fields analysis, but considering field diffusion and back iron saturation into account.

The LIM was designed with variable parameters in.[7] Effects are neglected and losses obtained are very high as the laminated sheet was not considered.

The transient model which allows fast and accurate simulations without including the effects in LIM was developed in.[8]. A review of design part of LIM and DLIM and proposed a control technique neglecting the effect of losses in.[9]

An analytical procedure for preliminary design of Multistage LIM operating as heavy mass electromagnetic catapult was given in.[10] .This article is strictly limited to catapult application and in[11] a T-Model equivalent circuit which is based on 1-D magnetic equations of air-gap and also two –axis equivalent circuit are obtained. The equivalent circuits are strictly limited to sinusoidal conditions.

This paper sets forth a new coupled circuit theory for the analysis of LIM .The approach is there by unique that it permits the use of conventional theory in the calculation of all parameters required in the model. A new approach for the formulation of equivalent circuit is proposed considering step-by–step approach to get the overall performance of the machine considering the longitudinal end effect, transverse edge effects, saturation effects and skin effect. There by resulting the analysis to be realistic.

EQUIVALENT CIRCUIT OF LIM

The performance analysis of SLIM is obtained by deriving the approximate per phase equivalent circuit model. The SLIM model used for the analysis has four distinct regions: primary, air-gap, reaction rail and back iron. The equivalent circuit parameters are analyzed by considering main dimensions of the core. The basic conventional per phase equivalent circuit is shown in the Fig. 3.

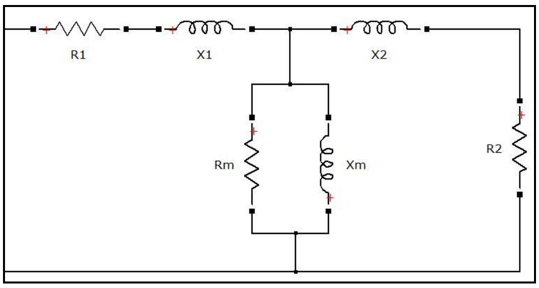

Fig. 3. *Basic Equivalent Circuit of LIM*

The primary resistance of each phase of the LIM stator windings will depend on the number of turns, length and the resistivity of the conductor and is expressed as;

$$R_1 = \frac{l_{av}\ N}{\sigma_{cu}\ A_{cu}} \qquad \text{Eq. (1)}$$

$$X_1 = \frac{2\mu_o \pi f\left[\left(\lambda_s\left(1+\frac{3}{p}\right)+\lambda_d\right)\frac{W_s}{q_1}+\lambda_e l_{wl}\right]N^2}{p} \qquad \text{Eq. (2)}$$

where μo is the permeability of the vacuum, p is the number of pole pairs, q1 is the number of the slots per pole per phase, f is the primary frequency, and λs , λe and λd are permeances of slot, the end connection and the differential, respectively.

The per-phase magnetizing reactance mainly depends on the number of poles, pole pitch, frequency, winding factors etc. and is calculated as

$$X_m = \frac{12.8 f\ (N_p\ \ k_w)^2\ \tau W_{se} 10^{-6}}{p\ g_e} \qquad \text{Eq. (3)}$$

where kw is the winding factor, ge is the equivalent air gap given by and Wse = (Ws + gm) is the equivalent stator width.

The per-phase rotor resistance R2 can be calculated from the goodness factor G and the per-phase magnetizing reactance Xm as

$$R_2 = \frac{X_m}{G} \qquad \text{Eq. (4)}$$

where G is the goodness factor of the motor given by

$$G = \frac{2\mu_o\ f \tau^2\ \sigma_e\, d}{\pi\, g_m\, k_l\ \ k_c\ (1+k_s)} \qquad \text{Eq. (5)}$$

Where gm is the magnetic air-gap, kl is the air-gap leakage factor, kc is the Carter's Coefficient, and ks is the secondary iron saturation factor.

EFFECTS OF LIM AND THEIR CORRECTION COEFFICIENTS

A. Longitudinal End Effects

Asymmetric air gap magnetic flux density at the end parts of a liner motor produces unbalanced normal force; as a result the air gap tends to increase at the entry and decrease at the exit part, called as End Effect. The longitudinal end effect can be evaluated by including the correction coefficients 'Q'.

The 'Q' factor is included in the magnetizing reactance to show the influence of end effect. "Q "is a dimensionless parameter but represents the motor length dependent on the motor velocity, so that at zero velocity, the motor length is infinity long. As the velocity rises, the motor length will effectively reduce. Therefore the position of the movement of the secondary on the primary is taken from x=0 to x=Q. This describes the effective distribution of flux along the motor length for any velocity. The expression for Q is given as

$$Q = \frac{D\,R_2}{(X_m + L_2)\,v} \quad \text{Eq. (6)}$$

At high velocity, there will be a significant loss of flux at the leading edge and at zero velocity, loss of flux will be negligible. Hence the reduction of these end effect require a The primary leakage reactance X1 can be determined from high value of Q. Hence this value of 'Q' will indicate the motors ability to resist the loss of output due to end effects.

B. Transverse Edge Effect

The different widths between the primary lamination and the secondary sheet can result in non-uniform flux density, which may increase the secondary equivalent resistance. The currents in the secondary member of a LIM flow roughly in elliptical paths. The secondary appears to have a resistivity greater than the natural value, and the cross gap flux density will vary across the primary width and will be greatest at the edges. This phenomenon is known as "transversal edge effects". The influence of these transverse edge effect will reduce the secondary conductivity by a factor ktr which is expressed as

$$k_{tr} = \frac{k_r}{k_x}\left[\frac{1 + \left(\frac{s\,G\,k_r}{k_x}\right)^2}{1 + (sG)^2}\right. \quad \text{Eq. (7)}$$

Where

$$k_r = \left(1 - \mathrm{Re}[(1 - jsG)(2\lambda / W_{se}\alpha)\tanh 0.5 W_{se}\alpha]\right)$$

$$k_x = [1 + \mathrm{Re}[(sG + j)(2sG\lambda / W_{se}\alpha)\tanh 0.5 W_{se}\alpha]$$

MODIFIED EQUIVALENT CIRCUIT WITH EFFECTS

The modified equivalent circuit of a LIM is shown in Figure 4, with change in the parameters of each branch, including the correction coefficients .As the demagnetizing effect of eddy currents is represented by means of inductance in the magnetizing branch, the modified value of this inductance influenced due to end effect is given by

$$X_m^1 = X_m\left[1 - \frac{1 - e(-Q)}{Q}\right] \quad \text{Eq. (12)}$$

With secondary back iron in conduction of the secondary current are taken into account, the effective conductivity is modified as

$$\sigma_{ei} = \frac{\sigma}{k_{sk}\ k_{tr}} + \frac{\sigma_i\ \ \delta_i}{k_{tri}\ \ d} \quad \text{Eq. (13)}$$

Hence the goodness factor is modified as

$$G_e = \frac{2\mu_o\ f\,\tau^2\,\sigma_{ei}\,d}{\pi\,g_e} \quad \text{Eq. (14)}$$

Finally the secondary resistance is calculated with the modified goodness factor as

$$R_2' = \frac{X_m}{G_e} \quad \text{Eq. (15)}$$

For calculation the secondary resistance,
the conductivity of the secondary sheet should
be modified due skin effects and secondary
back iron saturation.

C. Skin Effect

The conductivity of the secondary sheet is modified as

$$\sigma_2 = \frac{\sigma}{k_{sk}} \quad \text{Eq. (8)}$$

in which ksk is the skin effect coefficient given as

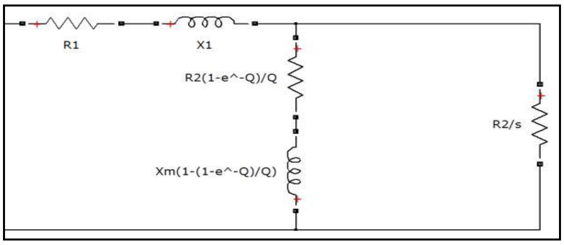

Fig. 4. *Equivalent Circuit Model With Effects.*

PERFORMANCE EVALUATION

The performance of LIM is based on the thrust that is produced on the secondary. Considering the equivalent circuit parameters, the expression for output thrust is derived expressed as

$$k_{sk} = \frac{2\,d}{\delta_s}\left[\frac{\sinh\left(\frac{2d}{\delta_s}\right)+\sin\left(\frac{2d}{\delta_s}\right)}{\cosh\left(\frac{2d}{\delta_s}\right)-\cos\left(\frac{2d}{\delta_s}\right)}\right.$$

Eq. (9) where δs is the depth of penetration in the secondary sheet which can be calculated using Eq (10) and (11).

$$F_x = \frac{3\,R_2' I_1^2}{2\,s\,f\,\tau}\left[\frac{R_m^2 + X_m'^2}{\left(\frac{R_2'}{s} + R_m\right)^2 + X_m'^2}\right]$$

$$k_s = \mu_o \left(\frac{\tau}{\pi}\right)^2 \left(\mu_i\ \delta_i\ g_m\, k_c\right)^{-1} \qquad \text{Eq. (16)}$$

Rm is the magnetizing branch resistance hich represents the power loss due to end effects and Xm the modified magnetizing reactance considering end effects.

$$k_s = \mu_o \left(\frac{\tau}{\pi}\right)^2 \left(\mu_i\ \delta_i\ g_m\, k_c\right)^{-1} \qquad \text{Eq. (10)}$$

$$\delta_i = Re\left[\frac{1}{\sqrt{\left(\frac{\pi}{\tau}\right)^2 + \frac{j\,2\,\pi\,f\,\mu_i\,s\,\sigma_i}{k_{tri}}}}\right] \qquad \text{Eq. (11)}$$

ANALYSIS OF RESULTS

In this section, the analysis on the performance of LIM is carried out on a realistic equivalent circuit model .The equivalent circuit parameters are derived based on considering the end and edge effects.

The specifications of LIM are shown in Table 1. The performance graphs between various output parameters are represented in Figure 5-8. As seen in LIM equation represented in previous section, the frequency and secondary sheet thickness has affected the performance of the motor.

Figure 5 represents the influence of change in frequency on Thrust and Rotor Velocity and Fig. 6 represents the influence of change in Thrust- Slip Characteristics of LIM.

The results show that by increasing the frequency with constant input voltage condition, the thrust acting on the secondary of the motor is decreasing. This is due to the increase in the input impedance, due to reduced input current.

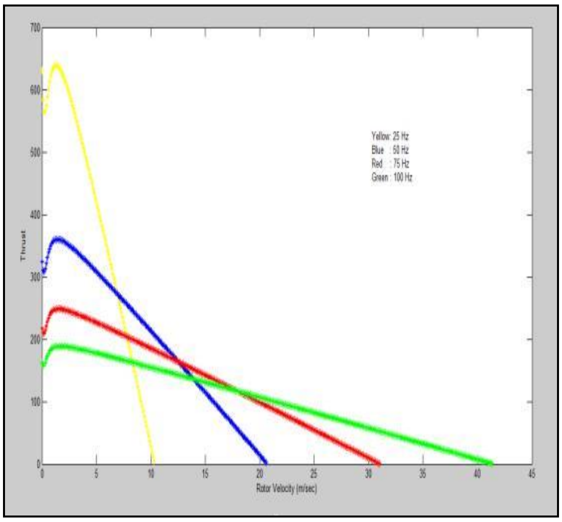

Fig. 5*. Effect of Frequency on Thrust and Rotor Velocity of LIM.*

Figure 7 represents the effect of change in secondary thickness on the thrust of the LIM with change in rotor velocity. Besides the frequency, the secondary thickness influences the saturation level of back iron.

It is observed that by increasing the secondary thickness the output thrust increases until its maximum value and decreases.

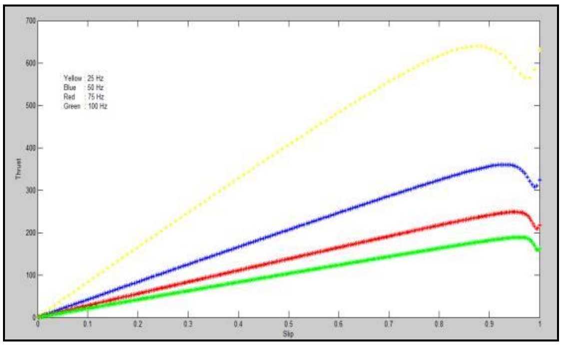

Fig. 6. *Effect of Frequency on Thrust-Slip Characteristics.*

Figure 8, represents the change in rotor resistance values with the change in speed of the motor .As the velocity of the rotor changes, the slip acting on the secondary changes, causing the resistance to increase.

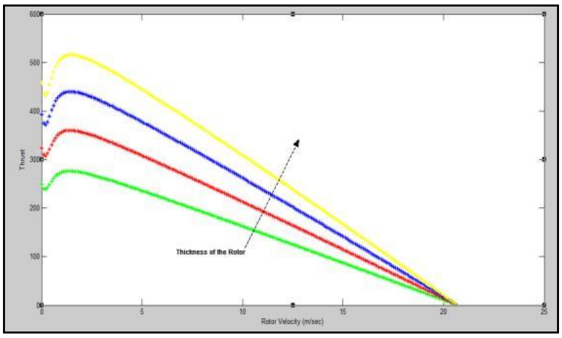

Fig. 7. *Effect of Secondary Thickness on Thrust and Rotor Velocity of LIM.*

Table 1. *Input Parameters.*

Permeability of free space (H/m)	4*pi*10^-7
Copper volume resistivity (ohms-m)	19.27*10^-9
conductor volume resistivity (ohms-m)	28.85*10^-9
Maximum tooth flux density (Wb/m2)	1.6
Maximum Yoke flux density (Wb/m2)	1.3
Aluminium thickness (in meters)-Secondary	0.001
Number of phases	3
Primary line to line voltage	440
Supply frequency	50
Number of poles	4
Number of slots per pole per phase	2
Rated slip	0.01
Width of the stator	0.3
Width of the rotor	0.35
Weight of the rotor	3
Length of the Rotor	0.5
Length of the Stator	0.1

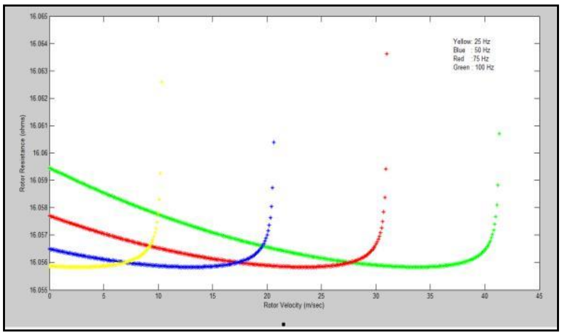

Fig. 8. *Effect of Frequency on Rotor Resistance and Rotor Velocity of the LIM.*

CONCLUSION

In this paper, a methodology is proposed to develop an improved equivalent circuit to predict the performance of a linear induction machine. This model is comprehensive and considers the longitudinal end effect, transversal edge effect, saturation effect and skin effect. This equivalent circuit is derived based on considering these effects in the air-gap, which are given by the correction coefficients ktr, Q, ks and ksk to describe the influence on the secondary resistance and magnetizing reactance respectively. The thrust is derived considering all the longitudinal end effects, saturation effect, transverse edge effect and the skin effect. Also the analysis is extended to short-stator effect, long-stator effect and a physical interpretation for the performance degradation due to end and edge effects.

This paper introduces a new approach that would be efficient when used for the design and analysis of LIM treating all the electromagnetic phenomena. The simulation results suggest that the proposed realistic equivalent circuit is efficient to improve the accuracy in thrust performance calculation.

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