INHERENT PROBLEMS OF LINEAR INDUCTION MOTORS AND OPTIMIZATION: AN OVERVIEW

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ABSTRACT
Linear Induction Motor (LIM) instead of producing rotary torque from a rotary machine produces linear force from flat one. To optimize the LIM, this paper looks at the construction features and fundamental equations of the LIM. Also presented are the inherent problems associated with LIMs, such as the Longitudinal End Effect (LEE), Edge Effects (EE) and other associated setbacks and then proposes how they could be minimized at the design stage through proper planning or optimizing the existing model using adequate interactive and iterative software programmes. Other LIM parameters presented and discussed are the objective functions for such designs and optimization form various works.

Keywords: Inherent Problems, LIM, LEE, EE, Optimization Constrains, Iterative Software.

1.0 INTRODUCTION

A linear induction motor (LIM) is basically a rotating squirrel cage induction motor opened out flat as shown in figure 1.

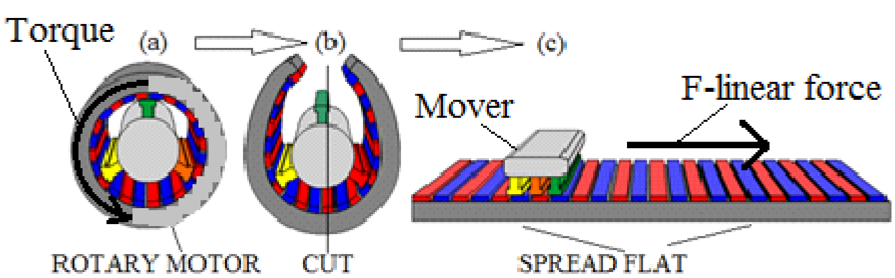

Figure 1: Imaginary process of unrolling a conventional motor to obtain a LIM

The arrangement which is a single-sided linear induction motor (SLIM), instead of producing rotary torque from a rotary machine it produces linear force from flat one. The thrust produced solely depends on the size of the machine and can get to several thousand Newton. The speed of the LIM depends on winding design and supply frequency and also it is important to note that the linear speed does not depend upon the number of poles but only on the pole pitch. From the illustration in figure 1, the SLIM rotor is replaced with a reaction plate called the forcer or mover. Load can directly be coupled to it. The forcer is usually made of a non-magnetic highly conductive material backed up with an iron plate to maximize the induced magnetism.

The iron plate serves to amplify the magnetic field produced in the coil. The air gap between the stator and the reaction plate must typically be very small, otherwise the amount of current through the stator becomes undesirable. When supplying AC current to the coils, a travelling magnetic wave is produced. Swapping the phases reverses the direction of travel. Current induced in the reaction plate by the travelling magnetic wave create a secondary magnetic field. A linear thrust is produced with the reaction between these two fields. There are two types of LIM- single sided (SLIM) and double sided (DLIM) [Vikas et al, (2017)].

Sijitha and Pooram (2017), the SLIM has the advantage of less mechanical loss, better acceleration, as well as deceleration when compared to the DLIM and old style motors. Linear induction motors (LIMs) have recently gained more interest in industries which need to apply linear motion, especially in medium and high-speed transportation. The main advantage of LIMs is producing linear motion directly, without any rotary to linear motion converters. Amir et al (2017), stated that absence of mechanical converters results in better performance of the motor. LIMs are used in several different forms such as tubular linear induction motor (TLIM), DLIM, and SLIM. In some applications of SLIMs, the secondary is cage-type or wound. The linear induction motor, is very useful at places requiring linear motion since it produces thrust directly and has a simple structure, easy maintenance, high acceleration/deceleration (Ashutosh et al, 2017).

2.0 SLIM CONCEPT AND EQUATIONS.

There should be relative motion between the conductor and the magnetic lines of flux, in order for voltage to be induced in the conductor which is applicable also with the primary and secondary of LIM. That is why induction motors normally operate at a speed ***Vr*** that is slightly less than the synchronous velocity ***Vs.*** This difference is called the Slip, **S**. Slip is the difference between the stator magnetic field speed and the rotor speed. The Slip **S** is the relative motion needed in the induction motor to induce a voltage in the rotor [Sarveswara 2015] and is given as:

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$$S = (V_s - V_r)/ V_s \quad \textbf{(1)}$$

The SLIM synchronous velocity *Vs* is the same as that of the rotary induction motor, given by

$$V_s = (2\omega R)/P = 2f\tau \quad \textbf{(2)}$$

Where, *R* is the stator radius of the rotary induction motor, as shown in Fig 2.

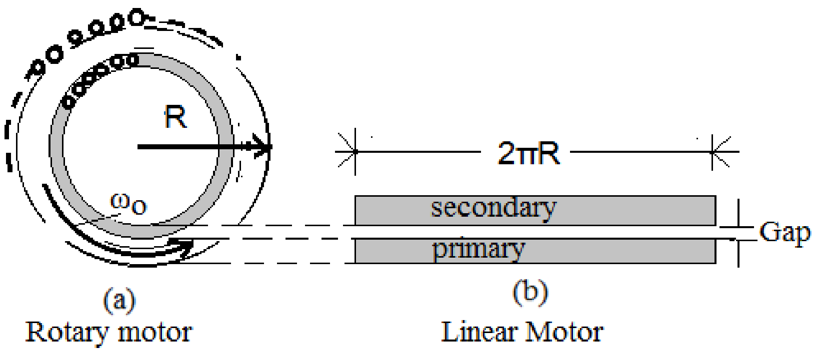

Figure 2: Radius of a rotary induction motor and length of a SLIM [Sarveswara (2015)]

The parameter τ is the distance between two neighboring poles on the circumference of the stator, called pole pitch, defined as:

$$\tau = (2\pi R)/P \quad \textbf{(3)}$$

The stator circumference of the rotary induction motor, *2πR*, in (2) is equal to the length of the SLIM stator core, *Ls*.

Therefore, the pole pitch of a SLIM is

$$\tau = (2\pi R)/P = Ls/P \quad \textbf{(4)}$$

If the velocity of the rotor is *Vr*, then the slip of a SLIM can be defined as

$$S = (Vs - Vr)/ Vs \quad \textbf{(5)}$$

The air-gap shown in Figure 2(b) is the clearance between the rotor wall and the SLIM stator.

3.0 INHERENT PROBLEMS OF LIMs

SLIM has the advantage of less mechanical loss, better acceleration, as well as deceleration when compared to DSLIMs and rotary motors. However, owing to the bigger air gap length, the SLIM is affected more by its low efficiency which becomes severe with lower load. In addition, the magnetic circuit of the stator is discontinued (cut-open) unlike that of the rotary motor, including the dissimilarity of secondary width and primary width of the rotor and stator respectively, some adverse special phenomena like the transversal Edge effect and longitudinal end effect (LEE) is experienced. Owing to the finite length of the stator and primary, the longitudinal magnetic field density distribution at the entry and exit as the secondary enters or leaves the air-gap during the motor operation causes some disturbances referred to as longitudinal end effect (LEE) (Sijitha, 2017). Due to this, unbalanced current flows in the various phases even when balanced voltages are applied at the terminals. The existence of the end effect has been confirmed by using analytical equations and defining end effect factor and also, the effect of design parameters on the end effect were investigated (Shiri, 2012).

These phenomena can be further explained by the fact that the primary core and windings of linear induction motor has finite length called the active length of the motor and due to this, SLIM has two ends. Working further on the problems associated with the SLIM, Andrew (2005), noted that end effects are described as one of the biggest negative factors in high-speed LIM efficiency, and that the LIM has an entry and an exit end, as opposed to a closed air-gap common to a rotary induction motor. This explains how LIM has both end and edge phenomenon. This causes discontinuities in the magnetic field of the LIM or the conducting part of the LIM when using a short primary or short secondary LIM respectively. These effects lead to additional losses causing reduction in the thrust of the LIM, which further deteriorates the performance and efficiency of LIMs.

Different parameters are involved in designing SLIMs and as such these parameters affect the performance of the machine in different manners. Increasing a certain parameter may increase an output, at the same time, it may decrease the output. One of the reasons linear motors -a technology nearly a century old, have not been adopted for a large number of linear motion applications is that they have historically poor efficiencies. This has restricted the progress of linear motor development [Andrew (2005)]. Buttressing this fact, Amir et al (2010) stated that undoubtedly, linear induction motors (LIMs) are the best solution to the problem of producing linear motion directly, but the low efficiency, low power factor, and longitudinal end effect (LEE) are their major problems. Manpreet (2010), also noted that the LEE degrades performance and this questions the feasibility of the use of SLIMs.

Another factor is phase unbalances due to motor winding. Thus, some machines are modeled with concentrated windings rather than distributed windings. Muhammad (2012), argues that for linear machines, the distributed winding is not often used as it leads to empty or half-used slots in the primary. Concentrated windings bring several benefits over the traditional distributed windings e.g., volume of copper used in the end-windings is reduced which effectively reduces the axial length (no overlapping windings). Lower amount of copper also helps in reducing joule losses and improving efficiency. Eastham et al (2008), argue that concentrated windings are preferred due to manufacturing and mechanical advantages.

According to Andrew (2005), due to minor differences in manufacturing and secondary flux linkage, the impedance for each coil of the motor is slightly different. Simply stated, when exact same voltage is applied across the terminals of two different coils of the LIM, a different current will flow through each. This is due to the different resistivity and inductances of each coil. Because of these minor differences, the magnetic field will distort to a certain degree depending on the degree of the phase unbalance, and this will in turn reduce the motor's overall efficiency through a number of different mechanisms. Andrew (2005), stated further that these mechanisms include magnetic field saturation in certain areas of the core due to excessive flux as well as eddy current generation in the secondary. That these eddy currents are generated by exactly the same phenomenon as spatial harmonics because of the step change in magnetic field that is experienced as the secondary traverses through two different adjacent magnetic field strengths. These eddy currents are a natural result of the application of the time-varying magnetic field across the secondary, which in turn generates a magnetic field to satisfy Faraday's Law. The components of the induced currents that flow in the x-direction serve to increase the effective resistance of the secondary. An increase in the effective resistance of the secondary in turn increases the magnetic time constant, which exacerbates end effects, as well as increases resistive heating losses.
Both of these serve to decrease the overall efficiency of the motor. As the amount of secondary overlap increases, the component of the current in the x-direction under the primary decreases, thus reducing the overall transverse edge effect. However, for many designs, this sort of overlap may not be possible, and the overlap itself can create other problems. [Andrew (2005)]. Another major problem that affects linear motor efficiency is the starting force. This of course affects all induction motor types. In the work of Im et al (1993), the ratio of starting force and weight of the motor was maximize at constant voltage using finite-element and neural network methods (NNMs). It was discovered that the decrease in motor weight results in lower cost and better performance of linear induction motors.

3.1 PROFERRED SOLUTIONS

In optimizing or design of the LIM, researchers have introduce different objective functions as recorded in literatures to minimize one particular deficiency or the other to improve efficiency. One or more of LIM parameters could be chosen as the objective function depending on the area(s) that needed to be optimized. In Amir et al (2010), the primary weight has been considered as objective function. In another research, Ali and Vedat (2009), the thrust and power to weight ratio are maximized. In Manpreet et al, (2010), the size of teeth air gap has been considered as main objective function and in Sarveswara (2015) the optimum winding design of LIM was considered. In the work of Isfahani (2008), the LIM was optimized to have maximum efficiency and power factor. In the work of He, et al (2018), pole number and thickness of aluminum were considered. In Hu et al 2014, eliminating the iron saturation issues was the objective. In Xu et al., (2015), actual winding distribution and structure dimensions were considered.
The interdependencies of these fields should be as minimal as possible and additional factors must be considered to ensure a reduction of attraction force, a balanced supply voltage, balanced phase impedance and eliminate phase differences caused by leading currents. Electromagnetic vibration in LIMs is associated with windings and cores especially at certain frequencies. This also affects the performance of LIMs and its optimization. [Amir et al (2010)]

4.0 OPTIMIZATION METHODOLOGY

Optimization software can be used to optimize a new design or to improve the performance of an existing design. The approach for these two problems is the same. The outputs of an optimization problem are the geometry parameters and the electrical quantities (Samuel, 2016).

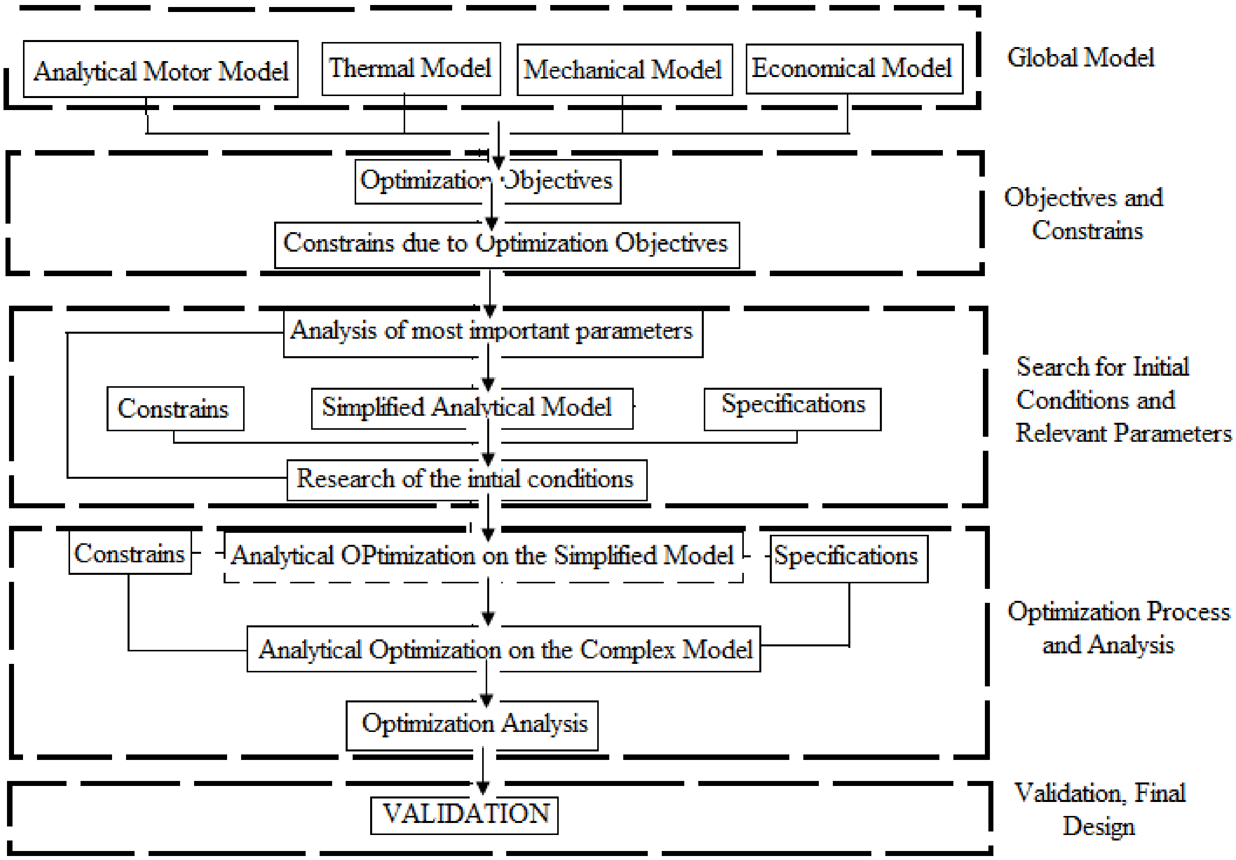

Figure 3: Schematic of an optimization process (Samuel, 2016).

Global Model-The first step is to define the global analytical model of the problem. In the case of motor designs and optimization, the global model is composed of specific models e.g., a magnetic model, a thermal model, a mechanical model and a cost model. Depending on the goal of the optimization, some of these specific models can be omitted to build the global analytical model. Samuel 2016, stated that for example, in a space project the price can be omitted and therefore the specific economic model is not introduced in the global model.

Optimization Constrains- The optimization constraints arise from three distinct aspects: constraints due to the validity domain of analytical models, geometrical and electrical constraints specific to the motor type and constraints due to optimization objectives. These last constrains lead to a pseudo multi objective optimization.

Choice of the Optimization Parameters

The choice of the optimization parameters is very important and not always straightforward. This choice is very useful in order to reduce the complexity of the problem and to permit a better understanding of the optimization result. Indeed, if too many parameters are used, the result cannot be efficiently analyzed and therefore the tendency would be to adopt the optimization result without analysis of the other parameters.

Determination of the Initial Conditions

Soft wares like the MATLAB interactive software and PRO@DESIGN, including other optimization software offer the possibility to begin the optimization even if the initial conditions lead to a solution situated outside the bound constraints. Initial conditions can be obtained either with a short analysis of a simplified model or from an existing design in the case of the optimization of a realized motor (Samuel 2016).

Optimization and Objective Function

As presented on Fig. 3, the choice of the objective function depends of course on the optimization objectives and the tendency is to combine several parameters to form the objective function. However, as stated by Yves and Nguyen (2003), such an approach must be used with care. The use of a sum of several quantities, can lead to inappropriate results if the summed quantities are not of the same order of magnitude. To avoid this problem, it is recommended to normalize the quantities and also to avoid the problems of quantity combinations it is preferred to have a simple objective function and to limit the objective constraints (Chevalier et al, 2004).

Optimization Analysis

It is interesting to optimize the same motor under several constraints and several objective functions. Such an approach is needed since the final motor design is always a compromise between several quantities. Therefore, mono objective program can produce some results which can be analyzed as the results of a multi objective program.

Validation

Once the optimized solution is defined, the motor is validated. If the analytical solution and the validated model are not in agreement, an iterative process is introduced to correct the model (Samuel, 2016). That is where the iterative and interactive computer optimization plays a vital role.

CONCLUSION

The LIM is an unrolled form of its rotary counterpart and because of its finite length it has an inherent setback like the longitudinal end effect and the edge effect which the latter is due to the overlap of the secondary on the primary. These greatly affect the performance and efficiency of LIM despite its numerous advantages over the rotary type in linear motion applications. However, some of its parameters can be evaluated to suits a particular performance efficiency during initial design or optimization of an existing model using adequate computer software programme.

REFERENCES

1. Ali Suat Gerçek and Vedat M. Karslı, (2009), *Performance Prediction of the Single-Sided Linear Induction Motors for Transportation Considers Longitudinal End Effect by Using Analytic Method*, Contemporary Engineering Sciences, Vol. 2, no. 2, pp. 95 – 104.

2. Amir Zare Bazghaleh, Mohammad Reza Naghashan, and Mohammad Reza Meshkatoddini, (2010), *Optimum Design of Single-Sided Linear Induction Motors for Improved Motor Performanc.* Power and Water University of Technology, Tehran, Iran. IEEE Transactions on Magnetics, Vol. 46, No. P-P; 3939-3947

3. Andrew P. Johnson, (2005), *High Speed Linear Induction Motor Efficiency Optimization.* Submitted to the Department of Ocean Engineering and the Department of Electrical Engineering and Computer Science in Partial Fulfillment of the Requirements for the Degree of Naval Engineer and Master of Science in Electrical Engineering and Computer Science at the Massachusetts Institute of Technology; pp1-189

4. Ashutosh Chattar, Kunal Nandanwar, Vishal Bharambe, Pratik Borse and Pooja Zurale, (2017).*Designing of Double Sided Linear Induction Motor*. Vol-3 Issue-3 2017 IJARIIE-ISSN (O), pp. 2395-2399

5. Chevalier, S., M. Markovic, M. Jufer, and Y. Perriard. (2004). Linear motor optimization using an analytical model. ICEM.

6. Eastham, J., T. Cox and J. Proverbs. *Comparison between plate and wound secondary for linear induction motors with concentrated winding primaries* in *SPEEDAM* 2008.

7. He. Y, Y.-S. Wang, Q. Lu1, L. Zhang, F. Liang (2018). *Design of Single-Sided Linear Induction Motor for Low-Speed Maglev Vehicle in 160 Km/H and Variable Slip Frequency Control*. Transportation Systems And Technology. 4(2):pp120-128

8. Hu D., Xu W., and Qu R., (2014). *Electromagnetic Design Optimization of Single-Sided Linear Induction Motor for Improved Drive Performance Based on Linear Metro Application*. Power Engineering Conference (2014), pp-1-6.

9. Im, D., S. Park, and J. Im, *Design of single-sided linear induction motor sing finite element method and SUMT*. *IEEE Trans. Magn.*, vol. 29, no. 2, pp. 1762–1766, Mar. 1993.

10. Isfahani, A.H., B. M. Ebrahimi, and H. Lesani, (2008). *Design optimization of low-speed single-sided linear induction motor for efficiency and power factor*. IEEE Trans. Magn., vol. 44, no. 2, pp. 266–272.

11. Manpreet Singh Manna, S. Marwaha and Navpreet Kaur, (2010). *Air Gap Field Analysis of Single Sided Linear Induction Motor with Time Harmonic Finite Element Method* Excerpt from the Proceedings of the COMSOL Conference 2010 India.

12. Muhammad Salman, (2012). *Analysis, design and control aspects of linear machines using Co-simulation.* Electrical Energy Conversion Master of Science. Degree project in Analysis, design and control aspects of linear machines using co-simulation, Stockholm, Sweden.

13. Sarveswara Prasad Bhamidi, (2015). *Design of A Single Sided Linear Induction Motor (Slim) Using A User Interactive Computer Program* A Thesis Presented To the Faculty of The Graduate School; University Of Missouri-Columbia in Partial Fulfillment of The Requirements For The Degree Master Of Science.

14. Samuel Chevailler (2016). *Comparative Study and Selection Criteria of Linear Motors.* Programme Doctoral En Systèmes De Production Et Robotique École Polytechnique Fédérale De Lausanne, pp.1-22..

15. Shiri, A., (2012). *Design Optimization and Analysis of Single-Sided Linear Induction Motor, Considering All Phenomena*; IEEE Transactions on Energy Conversion, Vol. 27, No. 2, pp.516-521.

16. Sijitha, Isaac and Poorani, S. (2018). *Optimal Design Selection and Analysis of Single Sided Induction Motor*. International Journal of Engineering and Technology. Vol. 7 (2.21) pp. 222-227.

17. Vikas. S. Bhandare ; Patil Keval N. ; Magdum Santosh D ; Patil Johar Habib (2017) *Prototype development model for conveyor using linear induction* motor International Journal of Engineering Trends and Technology (IJETT) Volume-45 Number2 : pp-2231-5381 http://www.ijettjournal.org. pp. 66

18. Xu W., Hu D., Mu C.X. (2015). *Novel Efficiency Optimization Control **A**lgorithm for Single-Sided Linear Induction Motor*, IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, pp. 48–49.

19. Yves, P. and V. Nguyen., (2003). *Transducer design with global parametric optimization*; IEEE transactions on Magnetics.