Advanced Methodologies on Design and Control for Linear Induction Machine and Drive Adopted to Urban Transportation (Invited Paper)

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***Abstract*— Urban transportation, e.g., linear metro, driven by linear induction machine (LIM) has been paid more attention by both academia and industry recently for its direct thrust drive, strong climbing ability, flexible line choice, smaller cross section area, lower noise, *etc*. However, this system is greatly different with traditional rotary induction machine (IM) due to its cut-open primary (end effect), normal force resulted from the asymmetric structure, eddy current in the secondary, and so on. There exists great difficulty for accurate modelling and advanced control strategies for LIM influenced by nonlinear circuit, partial magnetic saturation, internal and external disturbance, *etc*. This paper will introduce one new reasonable equivalent circuit for LIM performance analysis, as well as some specific design and control case studies. Afterwards, advanced control strategies, like efficiency optimization control (EOC), model predictive control (MPC), will be employed to further increase the LIM drive indexes, such as average thrust, efficiency, *etc*.**

***Index Terms*—Linear induction machine (LIM), Rotary induction machine (RIM), Analytical model, End effect, Efficiency optimization control (EOC), Model predictive control (MPC), direct thrust control, Maximum thrust per ampere (MTPA), Parameter identification.**

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I. Introduction

ROTATING machine (RM) has been existing for almost 200 years (since 1820s). Their linear counterpart, called linear machine (LM), has been introduced at the turn of 20th century. In general, LMs can realize the conversion of electrical energy to linear motion mechanical energy (or vice versa) directly through magnetic fields. For the strict requirement for drive system, the LM has only been gained wide industrial attention after 1960s due to the development of power electronics for motion control (in absence of a mechanical transmission). Briefly, the LM can be applied in any case in need of linear movement, such as linear accelerator for air craft carrier, electromagnetic rail gun, linear metro or Maglev, Hyperloop transportation, linear driven compressor, linear driven wave energy conversion, extended transport system, linear servo system, linear elevator, and so on [1]-[8], which can be driven directly by the electromagnetic force, without transmission/gear box. In summary, the LM can be characterized by the following merits:

a) Low initial cost (especially in small excursion applications),

b) High reliability and stability,

c) Low energy consumption per job done,

d) Adhesion-free propulsion (lighter vehicles: lower Wh/passenger/km),

e) Better position tracking (no backlash or transmission) in industrial positioning, and so on.

In this paper, it will mainly discuss the application of urban transportation, like linear metro, medium- and low- speed MAGLEV, and so on, where the linear induction machine (LIM) is mostly employed. In order to outperform rotary induction machine (RIM) and drive system with included transmission or gear box, the LIM needs high performance power electronics control and application adapted topologies and design methodologies. It is very necessary to improve the drive performance from the point of system level, taking LIM, converter, and controller into consideration altogether [9], [10]. Authors in this paper have done lots of work in design and control of LIM and drive during the past over 10 years, which has been closely cooperated among Huazhong University of

Science and Technology, Xiangyang CRRC Motor Technology Co., Ltd., CRRC Zhuzhou Institute Co., Ltd., Tongji University, CRRC Zhuzhou Motor Co., Ltd., Guangzhou Metro Group Co., Ltd., Zhuzhou CRRC Times Electric Co., Ltd., and CRRC Zhuzhou Locomotive Co., Ltd. Main work in this paper has been organized as follows. Modelling and design method will be introduced in Section II. Control strategies will be summarized in Section III. In Section IV, brief conclusions and suggestions will be given out.

II. DESIGN OF LINEAR INDUCTION MACHINE

A. Key points and characteristics of LIM

The LM can be regarded as the RM cutting open along axis direction and rolling flat. In addition to different forms of motion, the LIM based on urban transportation has the following unique characteristics [11]-[19].

- Large air gap length

In urban rail transit, the primary of LIM is usually installed at the bogie located at the bottom of the train body, and the secondary is placed and fixed on the track. Its mechanical air gap must be large enough (usually greater than 10 mm) to ensure the safety of train operation, which would cause large field current, low efficiency, and low power factor.

- End effects

Due to the special structure of LIM, it has the following four end effects. (1) The first type of longitudinal end effect: As the primary core and winding break in the longitudinal direction, the magnetic circuit is not symmetrical and the three-phase mutual inductance is not equal. The three-phase currents are not completely balanced even when excited by three-phase balanced voltages, so as to generate the reverse order magnetic field and the zero-order magnetic field in the air gap. (2) The second type of longitudinal end effect (refer to as “longitudinal end effect”, assuming short primary motion, long secondary stationary): When the secondary entries or exits from the primary, an amount of eddy current on anti-direction to the primary current will occur in the secondary sheet due to the balance to the original air gap flux linkage, which would weaken the effective flux linkage in the air gap. (3) The first type of transverse end effect: When the secondary core width and primary core width are equal with each other, regardless of secondary existence, the transverse edge of the magnetic flux density will be weakened. (4) The second type of transverse end effect (referred to as “transverse end effect”): When there is secondary, the transverse magnetic flux density distribution will be uneven.

- Half-filled slots

For the cut-open primary magnetic circuit, there exists half-filled slots in the primary ends. Hence, the three phase magnetic circuits are not symmetrical with each other, which will affect the air-gap flux density distribution to result in some alteration in magnetizing inductance, leakage inductance, and secondary equivalent resistance.

- Normal force

The normal force is mainly composed of repulsive force produced by primary coil current and secondary guide plate eddy current, and attraction fore produced by primary coil current and secondary back iron. In different working states, the force value might reach 3-5 times of the traction force (thrust), which will increase the traction loss of the drive system and cause some disturbance to the control process and whole system.

B. Equivalent circuits of LIM

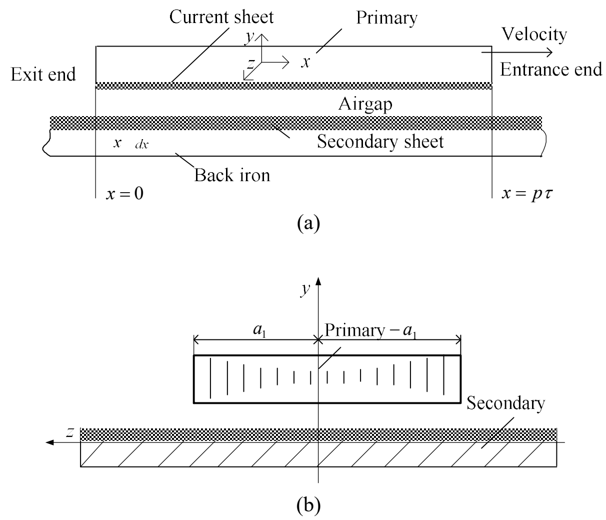

Fig. 1. One-dimensional analytical model of SLIM. (a) Longitudinal side view. (b)Transversal side view.

Equivalent circuit is a powerful tool to study the characteristics of LIM, which transforms complex electromagnetic relationship into concise equivalent parameters. Due to the unique characteristics, the electrical parameter solving process of LIM is more complicated than that of RIM. The analytical model of LIM is shown in Fig. 1. To simplify the analysis, some assumptions are put forward firstly as follows:

a) The surface current layer is used to stimulate the magnetic potential generated by the primary current, and only the fundamental component is considered.

b) The tooth effect with air gap coefficient is considered.

c) The air gap magnetic field has only the y-axis component, as independent of y.

d) The current flows in the direction z.

e) All field quantities vary with time according to sinusoidal law.

f) The iron permeability of the primary core is infinite. The magnetic flux density of $z>a_1$ or $z<-a_1$ in primary and secondary back iron is neglected.

The air-gap flux linkage can be obtained using Maxwell’s field equations and solved using the complex power method with a conformal transformation, which considers the effects of the half-filled slots, magnetic saturation, and back iron resistance. Using the equal complex power relationship between the magnetic field and the electrical circuit, it can obtain several circuit parameters, such as magnetizing inductance, secondary resistance, primary leakage inductance, secondary leakage inductance, longitudinal-end-effect coefficients K_r and K_x, and transversal-end-effect coefficients

C_r and C_x. The comprehensive derivations of the four coefficients can be referred in [12-14, 16, 17]. The T-model equivalent circuit is shown in Fig. 2.

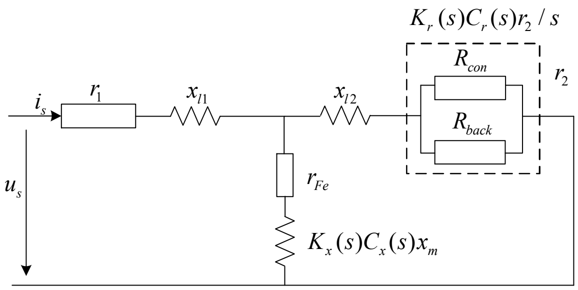

Fig. 2. T-model equivalent circuit of LIM.

C. Design and analysis of LIMs

The T-type circuit and hierarchical traveling wave theory are used to analyze and design the LIM, and the major process is illustrated in Fig. 3. As seen from this figure, the internal power factor is the cosine of the angle between the air gap electric potential and the primary phase current.

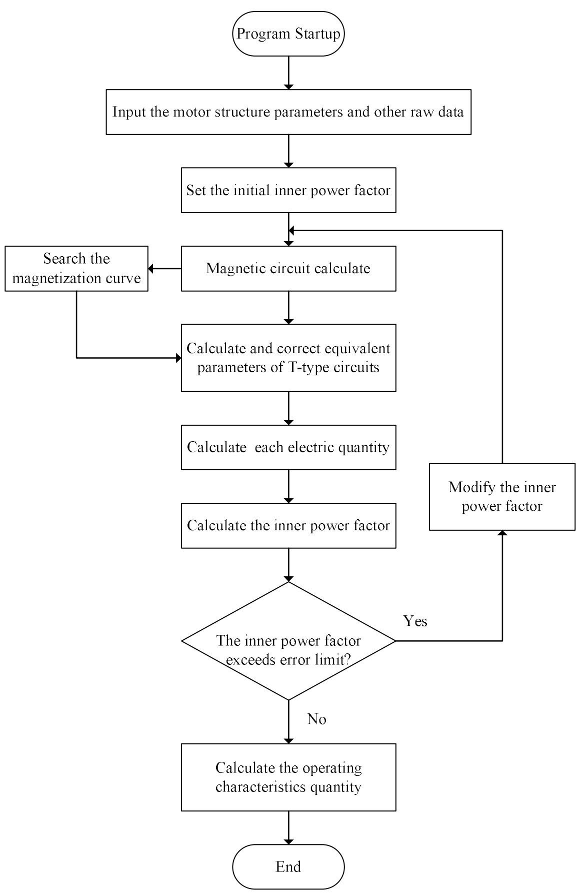

Fig. 3. Calculation flow chart of LIM characteristic.

III. Control of Linear Induction Machine

A. Efficiency Optimization Control of LIM

For the LIM system applied to high-power situation, such as urban transportation, one of the key performance indicators is the efficiency, which is mainly influenced by the following factors [17]-[19]:

a) To ensure the security of operation, the air-gap length should be large enough, which will lead to a lower rated operating efficiency compared with RIM.

b) The end effect will cause the decreasing of magnetizing inductance and increasing of secondary resistance, in which the current and copper loss will go up.

c) The conventional constant flux control is not suitable for low and heavy load condition, under which the loss will be huge.

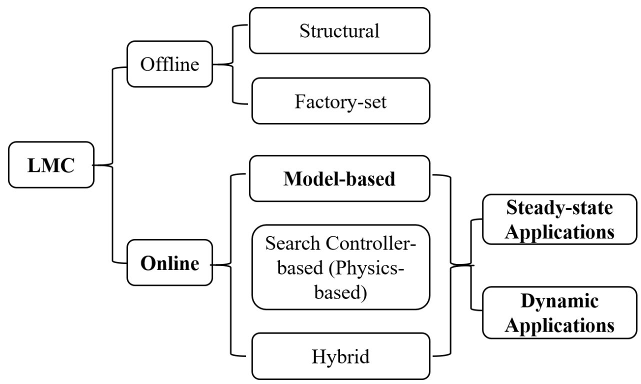

Fig. 4. Classification of the LMC.

To improve the efficiency of LIM system practically, except for the methods by optimizing the electromagnetic design scheme and adopting advanced modulation strategy of power converter, the loss minimization control (LMC) strategies are also effective. The classification of LMC can be briefly clarified as shown in Fig. 4. For the offline methods, there are no additional computational burden. However, the workload is repetitive and the flexibility is unsatisfactory, which makes it difficult for large-scale promotion and application. For the search controller-based online method, it is independent on the parameters but suffers heavy computation burden and long convergence time, which may incur the thrust and current ripples easily. In the following part, the model-based online LMC will be discussed in details, which has low computational burden but relies on the model and parameters of the LIM. The basic thoughts of model-based LMC are summarized as follows:

a) Selecting suitable equivalent circuit or mathematical model of motor (or drive system).

b) Analyzing the loss of motor (or drive system) and derive the corresponding loss model.

c) According to the loss model obtained in the last step, selecting suitable controlled variable and acquiring its optimal solution.

d) Accomplishing the control of optimal solution with the help of other basic control strategies (such as scalar control, vector control, direct thrust control, and so on).

Correspondingly, the basic control block diagram is illustrated in Fig. 5. It can be seen that the accuracy rating of loss model will directly influence the control effect. So, the key point is to establish accurate and practical loss model on the basis of acquiring the motor parameters precisely (through offline or online identification).

For the steady-state LMC, on the basis of existing research, an improved LIM *d*-*q* axis circuit with core-loss is presented in [15], as shown in Fig. 6. By evaluating the influence of primary and secondary leakage inductance on loss, a loss model is established, which is a convex function about secondary flux. So, the analytical solution of optimal secondary flux can be obtained by derivation directly. However, it only considers the loss in LIM.

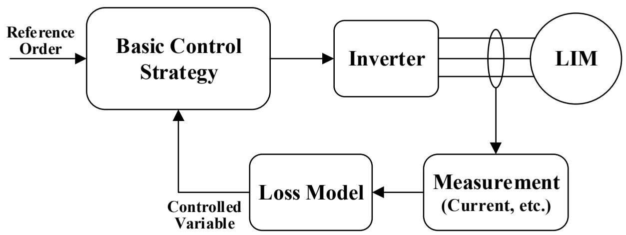

Fig. 5. Basic control block diagram of model-based LMC.

To make the loss model more comprehensive, the loss of inverter is taken into consideration in [16]. Regarding that the overall loss model of drive system is quite complex, the Newton-Raphson method is adopted to solve the optimal secondary flux condition. By setting the analytical solution in [15] as the iterative initial value, only 3-4 iterations are needed to obtain the optimal condition. So, the computational burden is light. According to the experimental results, the proposed method can reduce the loss of motor by nearly 3%, the loss of inverter by nearly 12%, and the total loss of drive system by nearly 4% compared with the conventional method.

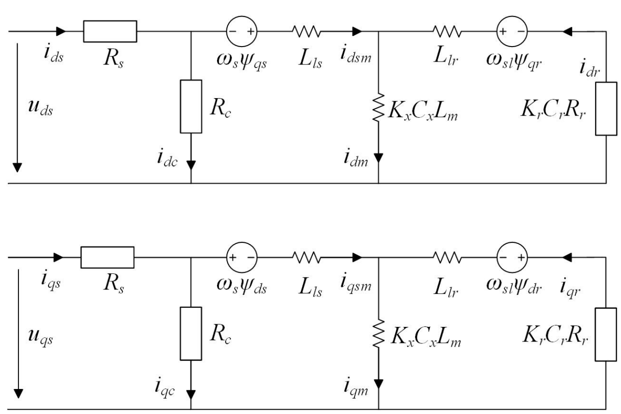

Fig. 6. Improved linear induction machine *d*-*q* axis circuit with core-loss.

In the LMC, the normal force of LIM also cannot be ignored, which mainly manifests as attraction force under the most conditions and can reach even more than 4 times of the thrust with small slip and high flux linkage. The normal force can significantly increase the apparent weight of the motor, resulting in increased loss, aggravating component wear and so on. A novel LMC method to simultaneously reduce the steady-state loss and normal force is proposed in [17]. Compared with the conventional LMC schemes, it can be stated that the proposed LMC method is effective in both motor loss and normal force reduction under various operating conditions. Besides, the parameter sensitivity analysis under this model is also given out, which has shown that the motor loss has strong robustness to parameter variation, while the normal force has strong dependence on the parameters of magnetizing inductance and secondary resistance.

Aimed at the dynamic operating condition, a dynamic loss model is presented in [18]. Based on the optimized objective function, the dynamic approximately optimal flux tracking can be acquired by solving corresponding Euler-Lagrange equation. According to the experimental results, in the dynamic process, the motor loss can be reduced by 4.76% and the dynamic performance is not significantly affected.

B. Model Predictive Control of LIM

The model predictive control (MPC) has been studied and applied to the LIM and drive system for urban transportation [20]-[31]. These existing techniques mostly concentrate on the reduction of thrust and primary flux-linkage ripples, the decreasing the distortion of the primary current, achieving the maximum thrust per ampere (MTPA) to increase the efficiency, and eliminating the weighting factor from the cost function. In [25], a new cost function is proposed to achieve the MTPA. The predictions are performed in stationary frame. This will improve the robustness and decrease the calculations. This cost function is called finite-set model predictive direct angle control (FS-MPDAC) because it is based on the angle difference. The block diagram of this control technique is shown in Fig. 7. As can be seen, this cost function uses only one weighting factor to make balance between the thrust error and the phase angle difference between primary current and secondary flux linkage error. The second term of the cost function is based on the cosine difference $|\cos(\alpha(k+1)) - \cos(\pi/4)|$ instead of the direct difference between these two angles $|\alpha(k+1) - \pi/4|$. The following reasons for what mentioned can be found as follows:

a) The direct difference between the two angles contains periodic changes, and when compared with a constant value, a higher periodic ripple is achieved. Therefore, to eliminate this variation or periodic ripple, a trigonometric function (i.e. cos, sin or tan) should be used and thus, no periodic change is generated.

b) According to the derivation of the second derivative of thrust that leads to the value of *d*-axis current must be positive, and the value of *q*-axis current may be positive or negative, only one of a trigonometric function must be selected.

c) Because the cosine function is positive in the first and the fourth quadrant and this matches the acceleration that happens in the first quadrant when both *d*-axis current and *q*-axis current are positive, and with the deceleration that happens in the fourth quadrant when both *d*-axis current is positive and *q*-axis current is negative.

d) In addition, using cosine function leads to fast deceleration because it allows negative *q*-axis current instead of sine function although sine and cosine have the same amplitude at $(\pi/4)$.

Three steps are used for the proposed control methods as follows:

a) Estimation for both secondary flux $\psi_2(k)$ and primary flux

$\psi_1(k)$,

b) Prediction of primary current $i_1(k+1)$ and flux $\psi_2(k+1)$ and thrust $F_e(k+1)$ of the next-instant,

c) Cost function optimization g.

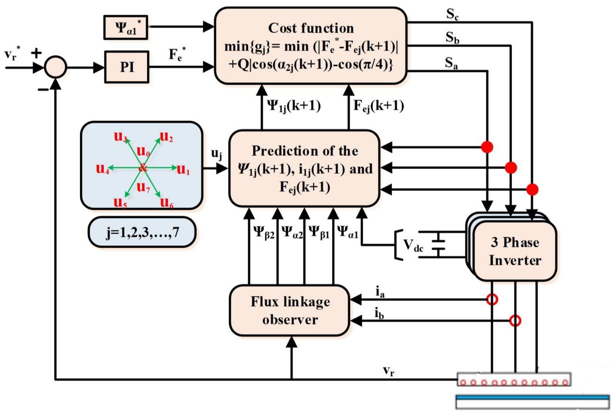

Fig. 7. Block diagram of the proposed adjustable speed drive based on FS-MPDAC.

More improvements have been made in [26] where the MTPA is achieved with less calculation steps, safety operation, self-starting, and lower flux linkage ripples. This control technique is mainly based on the optimum value of the primary flux-linkage, which is called finite-set model predictive direct thrust control (FS-MPDTC) cost function for this control. Meanwhile, the field orientation control is used to obtain the optimum value for the primary flux-linkage. Depending on some mathematical analysis, the relationship between the developed thrust and the primary flux linkage can be obtained. Hence, the reference primary flux linkage can be calculated from the reference thrust. The block diagram of the proposed control technique is illustrated in Fig. 8.

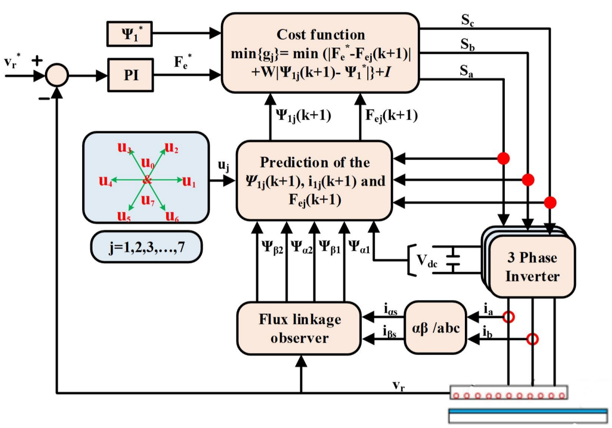

Fig. 8. Block diagram of the proposed adjustable speed drive based on FS-MPDTC with MTPA.

The main problems of the previous two control methods include more calculation steps and weighting factors, which would increase the computation burden. Therefore, the proposed method in [27] can be used to overcome the aforementioned problems. The cost function of this control method uses only the primary flux linkage. Thus, the weighting factor can be eliminated in this method. Moreover, extra improvement can be accomplished with the proposed control approach by achieving MTPA criterion. Therefore, both MTPA strategy and speed control of LIM are presented based on the proposed finite-set model predictive direct flux control (FS-MPDFC) in order to greatly improve the overall drive performance. The block diagram of the proposed MTPA based FS-MPDFC strategy is shown Fig. 9. As can be seen from this picture, the proposed cost function does not need any weighting factor. It depends only upon $\alpha\beta$-axis reference and predicted components of the primary flux-linkage. This results in a smooth regulation and tracking primary flux-linkage with considerably reduced ripples. To illustrate the effectiveness further, the proposed FS-MPDFC is compared with the FS-MPDTC in details. The percentages of both thrust and primary flux-linkage ripples are given in Table I. However, these ripple percentages can be decreased by increasing the switching frequency to 10 kHz or greater.

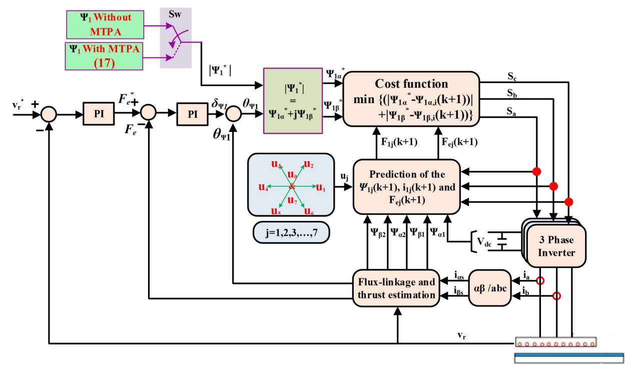

Fig. 9. The proposed MTPA based the FS-MPDFC for LIM drive system.

TABLE I
COMPARISON BETWEEN TWO CONTROL STRATEGIES FOR LIM IN TERMS OF THRUST AND FLUX RIPPLES

Quantity	FS-MPDTC	FS-MPDFC
TR%	$F_{ripple}\% = \frac{90}{280} * 100 = 32.14\%$	$F_{ripple}\% = \frac{70}{280} * 100 = 25\%$
FR%	$\psi_{ripple}\% = \frac{0.1}{0.8} * 100 = 12.5\%$	$\psi_{ripple}\% = \frac{0.0666}{0.8} * 100 = 8.333\%$

IV. CONCLUSIONS

In this paper, the research work of some design methodologies and control strategies, mainly coming from Prof Wei Xu's group in Huazhong University of Science and Technology, for LIM and drive system has been briefly discussed. With the help of advanced design and control techniques, some key issues existing in LIMs and drives can be well solved to some extent. However, it is still one great challenging task to strengthen and improve the drive performance of the LIMs and drives for the multi-domain multi-disciplinary traits. More collaboration should be made between academia and industry, especially to find out the ideal solutions in tracking parameters of LIM, e.g., magnetizing inductance, secondary resistance, and building up reasonable models considering machine, converter, and controller, *etc.* from the system-level point so as to improve the drive capability.

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