A Equivalent Circuit Model to Assist Vector Control of a Linear Induction Motor for Urban Transportation System Considering End-effect

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1. Introduction

The great development of power electronics and control techniques brought very good prospects to use Linear Motors in railway applications, such as JR-Maglev and HSST in Japan, Transrapid in Germany and Linear Metros. In these linear motor applications, a linear induction motor (LIM) has advantage of low cost, robust structure, direct drive *etc.*, but it has disadvantage of the end-effect which deteriorates characteristics depending on its operational speed[1]. In addition, it is controlled by the old method, V/f control. It is expected to improve the efficiency of LIM and accuracy of position control for automatic train operation by applying vector control, and it is necessary to calculate circuit parameters that depend on secondary speed of LIM.

In this paper, we proposed the equivalent circuit of LIM by assuming circuit parameters as the function of mechanical speed, and vector control scheme based on new equivalent circuit and the control method of rotary induction motor is shown.

2. Problem of The End-effect of LIM

The end-effect of a LIM is understood as follows [2].

An observer standing on a secondary reaction plate in Fig. 1 feels relatively slow change of magnetic flux in spate of a spontaneous stepwise change of armature electro-motive force, since the eddy current in the secondary reaction plate relaxes the change of magnetic field at entry and exit ends. The resultant special form of the envelope of the alternate magnetic flux is deformed as shown in Fig. 2, which is the case of moving primary part.
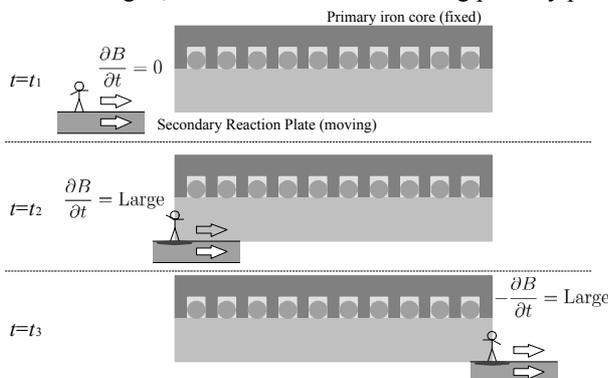

Figure 1: Intuitive understanding of longitudinal end-effect of a LIM.

The reduction of the flux of magnitude at the entry position is significant reason for the reduction of thrust in a high-speed drive. In addition, this reduction of the flux depends on the operational speed, so the end-effect make the characteristics of LIM change depending on the speed.
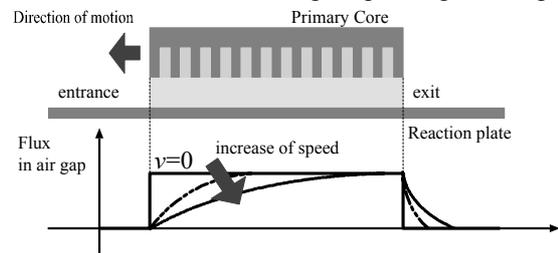

Figure 2: The reduction of the flux of air gap because of the end-effect.

3. Equivalent Circuit Model of a LIM for Control

3.1. Equivalent Circuit of LIM

It is helpful to use an equivalent circuit for a simple modeling of a LIM. Circuit constants are assume to be functions of speed because the end-effect depends mainly on its operational speed, in order to apply the frame of classical equivalent circuits of rotary induction motors to the LIM, in the region of actual operation point. These circuit constants are treated as "circuit parameters" and they are written as $L_0(v)$, $R_2(v)$, $L_2(v)$ as shown in Fig. 3.
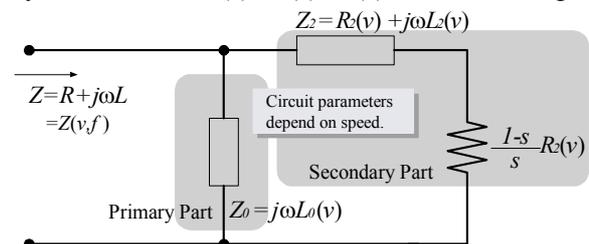

Figure 3: An equivalent circuit extended for a LIM.

If this conventional circuit frame is applicable to a LIM using only small modifications described above, then similar control theories to conventional rotary motors such as vector control can be applied to the LIM, which will contribute improving performance of a LIM-driven transport system.

3.2. Identification of The Circuit Parameters

The absolute value of impedance $|Z|$ and the power factor $\cos\phi$ (= $R/|Z|$) obtained from equivalent circuits (Fig. 3) must be identical to those obtained from

electromagnetic numerical analysis for an equivalent circuit truly corresponding to an actual motor well. Identification methods of circuit parameters using the impedance calculated from electromagnetic numerical analysis are described in this subsection.

Circuit parameters can be assumed to change depending on operating conditions in the case of the LIM. In new identification method of circuit parameters, these are obtained from an electromagnetic analysis or the actual measurements. The identification flow is explained in Fig. 4.
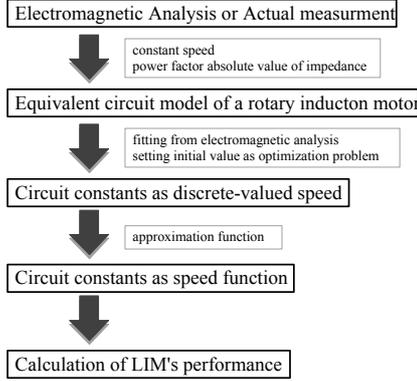

Figure 4: Identification method of equivalent circuit for a LIM.

Circuit parameters L_0, r_2, L_2 are identified based on curve-fitting scheme. The absolute value of impedance and power factor are represented by the function of frequency of power supply in the condition of fixed speed. These parameters are set by minimizing error between the curve from circuit parameters and analytical values at six points of frequency (or slip) under constant speed as shown in Fig. 5.

The $|Z_i|$ and $\cos\phi_i$ (i=1 to 6) are the absolute value of impedance and the power factor obtained from an equivalent circuit parameters, and $|Z_{mi}|$ and $\cos\phi_{mi}$ are those from electromagnetic analysis. The frequencies of power supply from f_1 to f_6 are chosen in the region of actual use of the LIM.

This scheme is an optimization problem which minimizes error between absolute value of impedance $|Z|$ and power factor $\cos\phi$ at the same time in six points of frequency conditions.

This problem can be formulated as follows:

$$\min F = \sum_{i=1}^{6}\left(\alpha\left(\frac{|Z_{mi}| - |Z_i|}{|Z_{mi}|}\right)^2 + (1-\alpha)\left(\frac{\cos\phi_{mi} - \cos\phi_i}{\cos\phi_{mi}}\right)^2 \right) \quad (1)$$

where the α is weighting coefficient for converting multipurpose problem to mono-purpose problem and this α is set to 0.5.

The evaluation function F shown in (1) is minimized by using optimization toolbox of MATLAB. The selection of an initial value is significant for an appropriate search of the optimal value.

Sampled speeds for identification of circuit parameters are set to v_1, v_2, …, v_n where $v_1 < v_2 <, … , < v_n$. Initial values of circuit parameters $L_0(v_1)$, $R_2(v_1)$ and $L_2(v_1)$ are determined from the same method of rotary induction motor, $i.e.$, those values are obtained by values when slip s = 1 and s = 0. Since the end-effects depend mainly on its

operation speed, the effect is negligible at the lowest speed v_1.

For $v_2 <, …, < v_m <, …, < v_n$, circuit parameters $L_0(v_m)$, $R_2(v_m)$, $L_2(v_m)$ are identified from initial values which are successively $L_0(v_{m-1})$, $R_2(v_{m-1})$, $L_2(v_{m-1})$, by using (1).
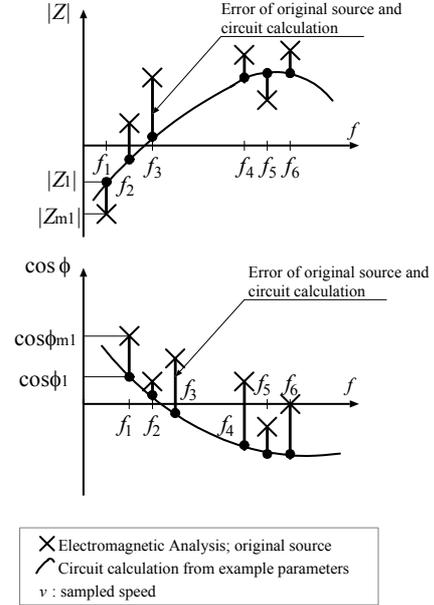

Figure 5: Curve-fitting scheme of identification of circuit parameters under constant speed.

3.3. Numerical Analysis Model of a LIM

Electromagnetic numerical analysis like FEM and FDM or actual testing result is needed and applied for the purpose of identification of circuit constants. A LIM is analyzed using two-dimensional FDM(2D-FDM)[4], here LIM's transversal edge-effect is not taken into account in such 2D-calculation, but substantial consideration of its end-effect can be included.
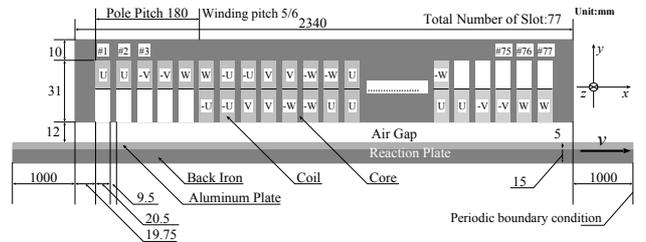

Figure 6: Analysis model of a LIM based on HSST-200.

And other design values and conditions for FDM are summarized in Table 1.

Table 1: Other Data of the Analysis Model LIM.

Conditions (Units)	Values
Rated current (A)	400
Rated frequency (Hz)	110
Slip frequency (Hz)	12.5(const.)
Turns of coil (Turns)	3
Magnetic resistance of primary core	$7.958*10^2$
Material of sec. conductor	Aluminum
Conductivity of sec. conductor (S/m)	$3.820*10^7$
Magnetic resistance of sec. conductor	$7.958*10^5$
Magnetic resistance of back iron	$7.958*10^2$

3.4. Speed Characteristics of Circuit Parameters

Fig. 7 shows speed characteristics of each circuit parameters based on the curve-fitting scheme from

2D-FDM analyses. Circle points indicate parameters that are identified from original data of speed and bold curves represent fitted approximate function of speed of each circuit parameters by interpolation using quadratic function.

In this Fig.7, R_0 becomes always zero because the core losses are neglected in this model. R_2 and L_0 correlate directly with operational speed on the other hand, L_2 does weakly with its speed.

The inductance L_0 decreases and the resistance R_2 increases with the increase of speed. It is qualitatively thought that the end-effect makes the thrust decrease as the increase of speed because the flux in air gap rises slowly and the interlinkage flux becomes small [4]. Thus, this phenomenon is expressed by decreasing the excitation inductance L_0. In addition, since the eddy current that denies the change of the flux comes significantly into existence in high-speed region, the secondary resistance R_2 increases.
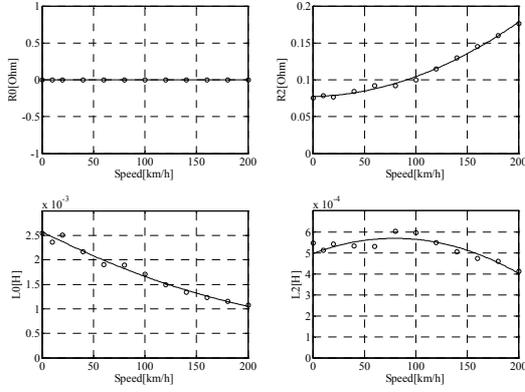

Figure 7: Characteristics of circuit parameters depending on speed.

3.5. Performance of the Equivalent Circuit Including the End-Effect

The characteristic of traction force is shown in Fig. 8 using circuit parameter in Fig. 2. This LIM is fed by slip frequency constant control in all operation modes.
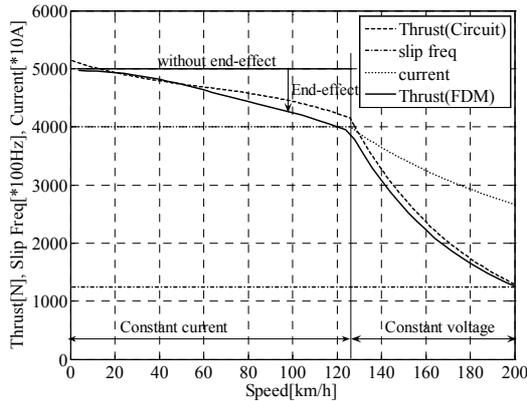

Figure 8: Characteristics of traction force.

The thrust characteristics of rotary induction motor must be constant in constant current mode, on other hand thrust decreases with the increase of speed even if this mode in LIM's. This equivalent circuit model can represent the characteristics including the end-effect, as shown in this result of the traction force.

This traction force calculated by using equivalent circuit corresponds with that from FDM analysis within the error of 10%.

4. Vector Control Scheme of a LIM

The circuit parameters of a LIM are function of mechanical speed unlike rotary induction motor, but the plant model of a LIM is established almost the same as that of rotary induction motor.

4.1. Rotary Induction Motor

In vector control for a rotary induction motor, the torque T is constant when the secondary flux Φ_2 and the primary d-axis current i_{1q} are kept constant based on (2) and (3) [5].

$$\Phi_2 = M i_{1d} \qquad (2)$$

$$T = P_0 \frac{M}{L_2} \Phi_2 i_{1q} \qquad (3)$$

Here, M and L_2 are mutual and secondary inductance, P_0 is the number of pole pair.

4.2. Linear Induction Motor

Circuit parameters are function of speed for considering LIM's end-effect in this paper.

On the other hands, the secondary flux and primary d-axis current are given as same as (2) and (3) because of applying consecutive theory of vector control for LIM.

The block diagram of LIM operated by vector control is shown in Fig. 9. Moreover, in order to delete interference terms between d-axis and q-axis for simplicity, d and q-axis voltage are electrically-compensated as shown in Fig. 10. In this Fig. 10, v'_{1q} and v'_{1q} are compensated voltage like (4) and (5).
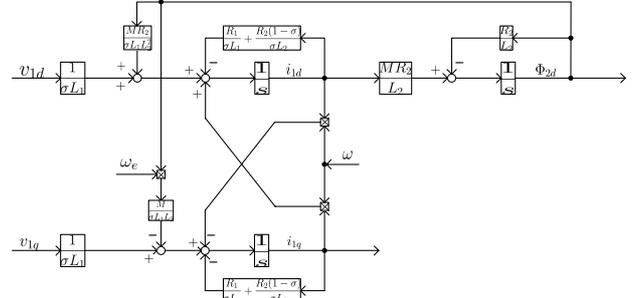

Figure 9: Block diagram of LIM operated by vector control.
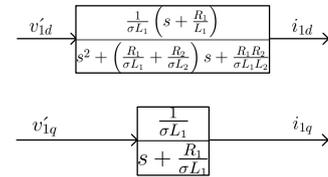

Figure 10: Block diagram of LIM for decoupling control.

$$v_{1d} = v'_{1d} - \omega_1 \sigma L_1 i_{1q} \qquad (4)$$

$$v_{1q} = v'_{1q} - \omega_1 \left(\sigma L_1 i_{1d} + \frac{M}{L_2} \Phi_{2d} \right) \qquad (5)$$

where ω_1 is angular frequency of power supply, L_1 and L_2 are primary and secondary inductance calculated from circuit parameters of the equivalent circuit. The σ is leakage factor, which is represented as follows;

$$\sigma = 1 - \frac{M^2}{L_1 L_2} \qquad (6)$$

5. Vector Control of a LIM

Characteristics of vector control for a LIM that is used for an urban transportation system are shown in this section by simulation using MATLAB/Simulink.

5.1. Constant Current Control

Rotary induction motors can generate the thrust (or torque) proportional to q-axis current when the LIM is driven in constant d-axis current, *i.e.* thrust becomes constant in constant q-axis current.

The thrust characteristics are shown in Fig. 11 and 12 when the LIM is driven by constant q-axis current.
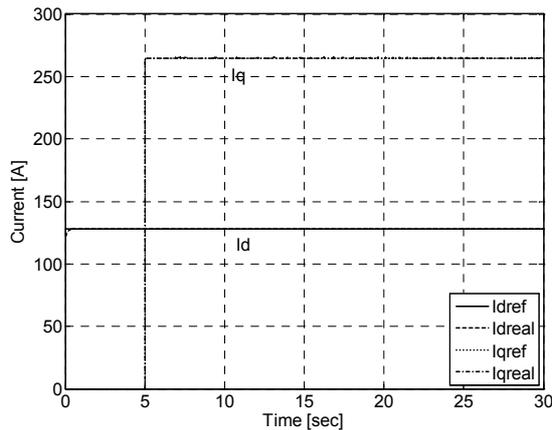
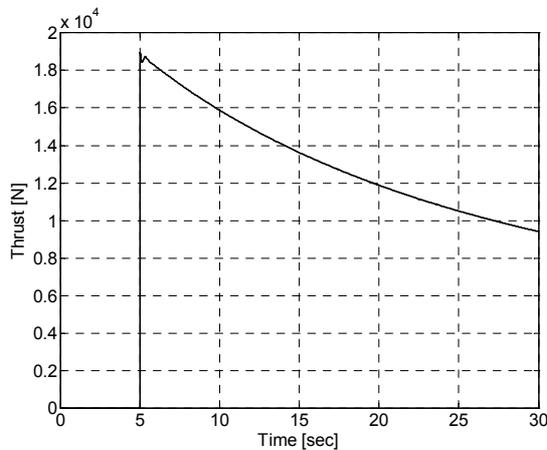Figure 11: Primary current under vector control.

Figure 12: Thrust under vector control.

It is found that because of end-effect, thrust does not constant using this control by seeing Fig. 11 and 12.

5.2. Constant Thrust Control

It is necessary for keeping thrust constant to correct i_{1d} and i_{1q} shown in Fig. 13 compared with constant current drive. The i_{1d} increases to compensate the reduction of mutual inductance, and i_{1q} is almost constant because thrust efficiency is almost constant. As a result, the thrust is kept constant shown in Fig. 14.

6. Conclusion

New identification method of a per-phase equivalent circuit for a LIM is proposed based on an equivalent circuit of a rotary motor, using the curve-fitting of absolute value of impedances and power factors that is obtained from numerical electromagnetic analysis or actual measurement.

The circuit of rotary type with a small modification that there circuit parameters depend on secondary speed, can represent the characteristics of traction force of a LIM within the error of 10% from source data which is calculated by numerical analysis in the actual region of use.

The plant model for vector control of LIM based on the equivalent circuit, which depend on secondary speed is established and its performance is described. It will be useful to consider operation method to improve efficiency and power factor of a LIM-driven transportation system.
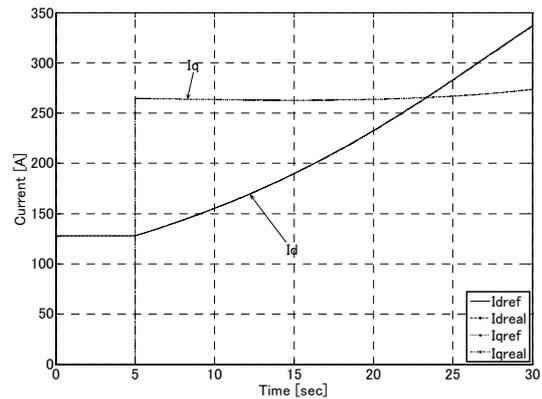
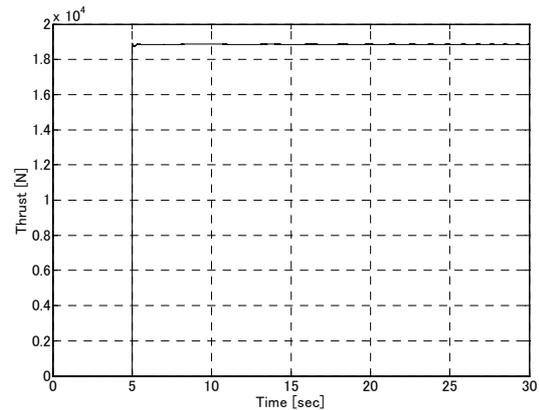Figure 13: Primary current under vector control.

Figure 14: Thrust under vector control.

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