# New Equivalent Circuits of Single-sided Linear Induction Motor

No. 4

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ABSTRACT: Recently, single linear induction motor(SLIM), which comes from rotary induction motor(RIM), has been widely applied in transportation systems, especially in intermediate speed arrange, because of its merits, such as ability to exert thrust on the secondary without mechanical contacts, high acceleration or deceleration, less wear of the wheels, smaller turn circle radius and more flexible road line etc. However, for cut-open magnetic circuit, inherent characteristics of SLIM such as longitudinal end-effect, transverse edge-effect and half filled slots etc are the main subjects by researchers all along. In this paper, T model equivalent circuit, achieved on the base of the one-dimensional magnetic equations of air gap is proposed first. The end effect and edge effect which affect excited reactance and secondary resistance can be rectified by coefficients *K*'r (s), *K*'x (s), *C*r(s) and *C*x(s). The half slots are considered by correcting poles number. From this T model equivalent circuit, two-axis equivalent circuits(*dq* or *αβ*) according flux linkage conservation, which unifies with those of RIM, are deduced. The four coefficients of equivalent circuits above are analyzed and the simulation curves are compared with experiments. The results indicate that this T model and new two-axis circuits are very reasonable to describe SLIM performance and control process.

## 1 INTRODUCTION

The vehicle drived by single-sided linear induction motor (SLIM) is a new type of railway transportation technology. This system has the following merits. First, it could achieve more propulsive thrust independent on friction. Second, it has smaller turn circle radius, stronger climbing ability, smaller sectional area of a tunnel.

The performance of SLIM is different from that of RIM for its special structure. An accurate equivalent circuit model can be made due to its pole symmetry in RIM. SLIM has transverse and longitudinal edge effects. The former brings some deformation in transverse air flux density. The latter weakens air valid linkage so as to decrease net thrust.

This paper sets out an improved T-model equivalent circuit and corresponding two-axis(*dq*) circuits, which can be used conveniently to analyze steady and dynamic performance of SLIM.

## 2 T- MODEL EQUIVALENT CIRCUIT

Depending on one-dimensional magnetic equations of LIM, it achieves the phase current and excited voltage expressions by dummy electric potential method. Then, it deduces the air-gap flux linkage expression by connecting Maxwell electromagnetic field equations, complex power method with conformal transformation method fully considering half-filled slots, york magnetic saturation, back iron resistance.

By the equal complex power relationship between magnetism and circuit, it obtains some expressions, like excited reactance $X_m$, secondary resistance $R_r$ , primary leakage reactance $X_{ls}$, secondary leakage reactance $X_{lr}$ , longitudinal end effect coefficients *K*'r (s) and *K*'x (s), transverse edge effect coefficients *C*r(s) and *C*x(s).

Four coefficients are expressed as follows[1] [2].

$$K_r^{'}(s)=\frac{sG}{2P_e\tau\sqrt{1+(sG)^2}}\frac{C_1^2+C_2^2}{C_1} \qquad (1)$$

Where $s$ is slip, $G$ is goodness factor, $\tau$ is pole pitch.

$$K_x^{'}(s)=\frac{1}{2P_e\tau\sqrt{1+(sG)^2}}\frac{C_1^2+C_2^2}{C_2} \qquad (2)$$

Where $P_e$ is the number of equivalent pole.

$$C_r(s)=\frac{sG\left\{\mathrm{Re}^2[T]+\mathrm{Im}^2[T]\right\}}{\mathrm{Re}[T]} \qquad (3)$$

$$C_x(s)=\frac{\mathrm{Re}^2[T]+\mathrm{Im}^2[T]}{\mathrm{Im}\ [T]} \qquad (4)$$

From (1) to (4), parameters like $C_1$, $C_2$, $T$ are functions of motor structure, velocity and frequency[1].

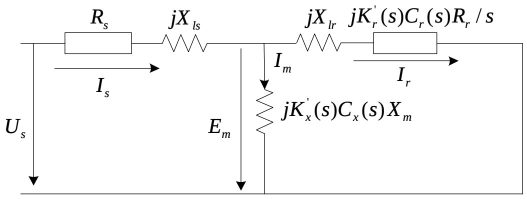



Figure 1. T-model equivalent circuit of LIM

Based on the T-model of RIM, it presents a new revised T-model circuit of LIM by superposition theorem, which is shown in Fig.1. $R_s$ is primary resistance. When coefficients $K'_r(s)=K'_x(s)=C_r(s)=C_x(s)=1$, the above circuit is the same as that of RIM. It is very easy to describe end effects and motor performance[3].

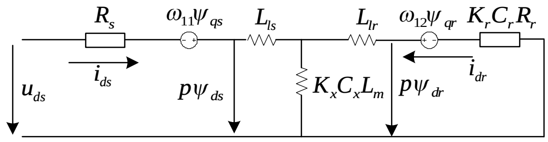
## 3 TWO-AXIS EQUIVALENT CIRCUITS

According to park coordinate transformation by power conversion rule, we can get two axis circuits indicated in Fig.2. The inductance matrix is,

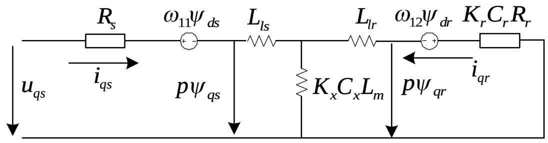
$$L=\begin{bmatrix} K_xC_xL_m+L_{ls} & 0 & K_xC_xL_m & 0 \\ 0 & K_xC_xL_m+L_{ls} & 0 & K_xC_xL_m \\ K_xC_xL_m & 0 & K_xC_xL_m+L_{lr} & 0 \\ 0 & K_xC_xL_m & 0 & K_xC_xL_m+L_{lr} \end{bmatrix} \qquad (5)$$

Here $K_r(s)$, $K_x(s)$ are simple forms of $K'_r(s)$ and $K'_x(s)$. If assumed single inductance is $L_{m1}$, then $L_m$ is $1.5L_{m1}$. We suppose $L_{mc}=K_xC_xL_m$, $L_s=K_xC_xL_m+L_{l1}$, $L_r=K_xC_xL_m+L_{l2}$, then gain its linkage expressions,

$$\begin{cases}\psi_{ds}=L_si_{ds}+L_{mc}i_{dr}\\ \psi_{qs}=L_si_{qs}+L_{mc}i_{qr}\\ \psi_{dr}=L_{mc}i_{ds}+L_ri_{dr}\\ \psi_{qr}=L_{mc}i_{qs}+L_ri_{qr}\end{cases} \qquad (6)$$




(a) *d*-axis circuit




(b) *q*-axis circuit

Figure 2. *dq*-axis equivalent circuits of LIM

Both inductance and linkage expressions are united with those of RIM. Equivalent circuits are illustrated in Fig.2. its special difference exists in mutual inductance and secondary resistance, which need rectification[6]. $\omega_{11}$, $\omega_{12}$ are angular frequencies of primary or secondary relative to *dq* axis.

## 4 FOUR COEFFICENTS ANALYSIS

T model parameters here include 5 variables. $R_s$ is 0.425Ω, $L_{ls}$ is 2.145mH, $L_{m1}$ is 7.670mH, $R_r$ is 0.221Ω, $L_{lr}$ is 0.550mH. In order to investigate the influence of end effects on mutual inductance and secondary resistance, we may analyze its starting point character.

The primary input frequency is from 1Hz to 30Hz. In each input frequency, phase current grows up from 10A to 30A. For slip is 1, the slip frequency $f_s$ equals to primary frequency. Four coefficients curves are shown in Fig.3-6. Mutual inductance, secondary resistance curves are in Fig.7 and 8. Thrust curve is in Fig.9. Because of end effect, the average air gap flux density is decreased, which reduces mutual inductance but increase secondary resistance [4][5].

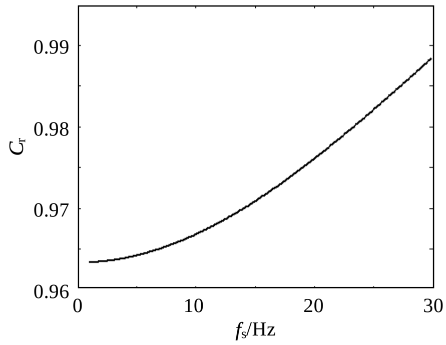



Figure 3. Coefficient $C_r$ curve under different slip frequency

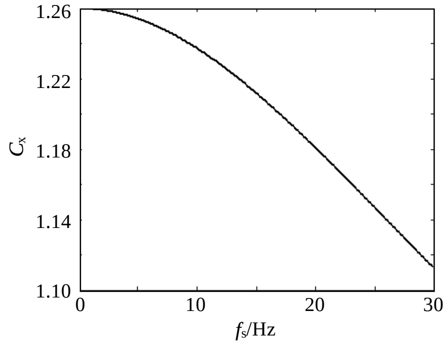



Figure 4. Coefficient $C_x$ curve under different slip frequency

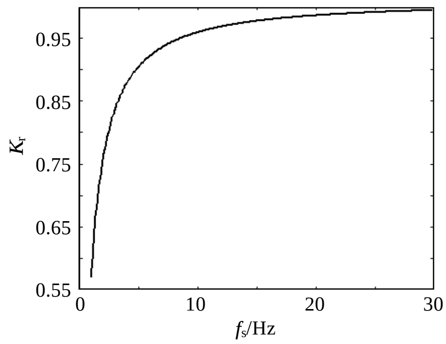



Figure 5. Coefficient $K_r$ curve under different slip frequency

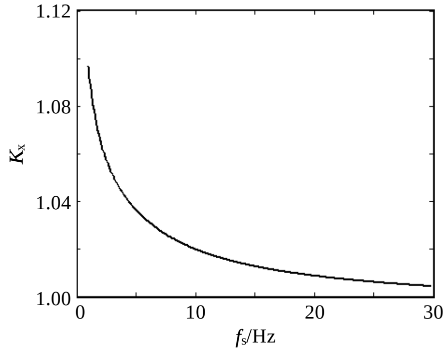



Figure 6. Coefficient $K_x$ curve under different slip frequency

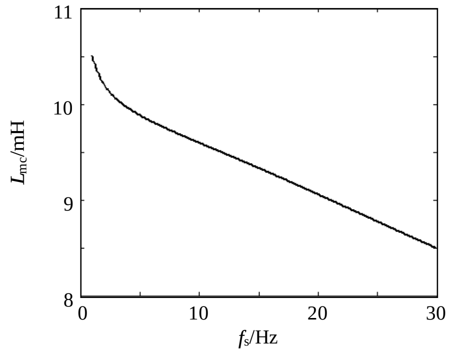



Figure 7. Modified mutual inductance $L_{mc}$ curve under different slip frequency

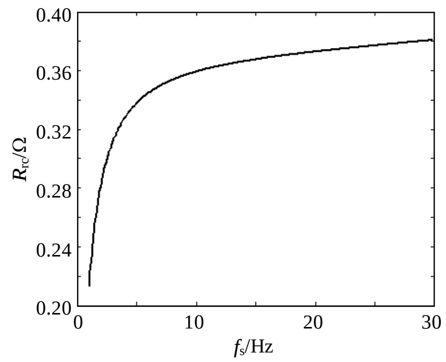



Figure 8. Modified resistance $R_{rc}$ curve under different slip frequency

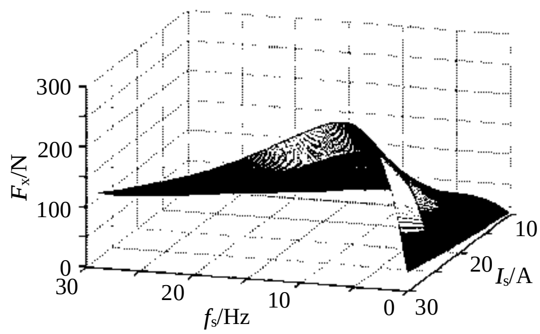



Figure 9 . Thrust $F_x$ curve under different phase current and slip frequency

## 5. EXPERIMENTS BY DIFFIRENT CONTROL SCHEMES

### *5.1 Constant Current Constant Frequency*

Fig.10 is thrust curves of LIM calculated by T model circuit. Its primary current is 20A. Dashed lines indicate thrusts without considering end effects, but real ones do. The other shapes are measured results. Due to end effects, the thrust should decrease as velocity goes up[7]. The experimental and the simulative results agree with each other closely.

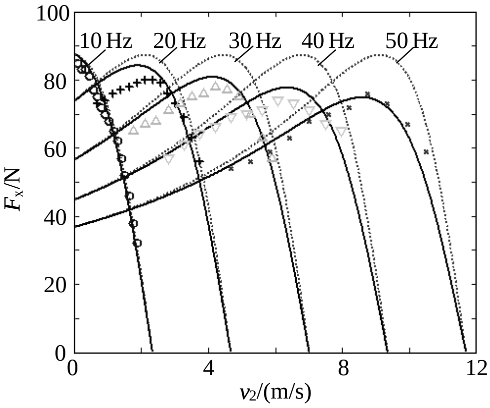



Figure 10. Thrust Fx calculation and measure curves under constant current constant frequency

### *5.2 Indirect Orientation Control Scheme*

Fig.11 is the indirect rotor field control scheme, which likes that of RIM control. There are three close loops, including speed, d axis current and q axis current loops, which are modified by three PI regulators[6]. Fig.12, 13 are thrust, velocity simulation and experiment curves separately, which validate effectively each other.

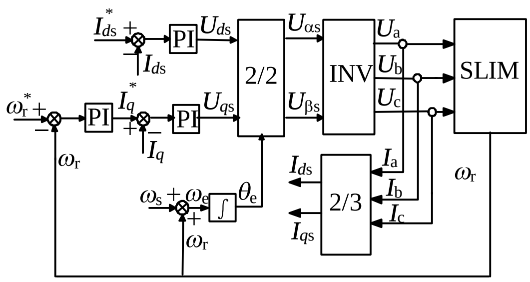



Figure 11. Indirect orientation control analysis diagram

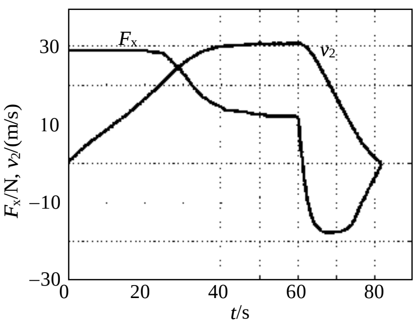



Figure 12. Thrust and velocity calculation curves

(Ratio about thrust or velocity is 1:5 or 5:1)

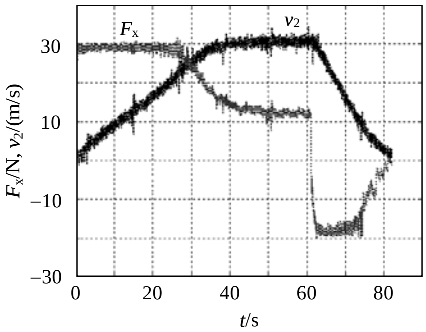



Figure 13. Thrust and velocity experiment curves

(Ratio about thrust or velocity is 1:5 or 5:1)

## 6 CONCLUSIONS

This paper has set out new equivalent circuits of SLIM. T-model circuit can analyze steady and dynamic states of SLIM in a similar way as those of RIM. The two-axis(*dq*) equivalent circuits may study performance of SLIM in different control schemes. Some calculation results agree with corresponding experiments very well.

## 7 REFERENCES


[1] Xialing Long, Theory and magnetic design method of linear induction motor, China: Science publishing company, pp.30-110,2006.

[2] Xu Wei , Sun Guangsheng, Li Yaohua, “Research on performance characteristics of linear induction motor, ” IEEE Conference on Industrial Electronics and Applications,Harbin,China, pp.86-89, May 2007.

[3] Xu Wei , Sun Guangsheng, Li Yaohua, “A new parameter measurement scheme for single linear induction motor, ”Transactions of China Electro Technical Society, Vol.22,No.4,pp.56-61,Jun. 2007.

[4] Tsuyoshi Higuchi, Sakutaro Nonaka, “On the design of high efficiency linear induction motors for linear metro,” Electrical Engineering in Japan,Vol.137, No.2, pp36-43,August 2001.

[5] Dawson, G.E., Eastham, A.R., Gieras, J.F, “Performance calculation for single-sided linear induction motors with a double-layer reaction rail under constant current excitation,” IEEE Transactions on Magnetics, Vol.22, No.1, pp.54-62, Aug.1986.

[6] Long Xialing, “A general method driving the equivalent circuit of linear induction motor,” Transactions of China Electro Technical Society, 1993, Vol.8, No.4, pp.55-60, Apr.1993.

[7] Yuichiro Nozaki, Takafumi Koseki, “Analysis of linear induction motors for HSST and linear metro using finite difference method,” IEEE Conference on Linear Drivers and Industry Applications, Kobe-awaji, Japan, Vol.25, No.4, pp.168-171, Jul. 2005