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Estimation performance according to Goodness factor of Tubular Linear Induction Motor

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1. Introduction

Linear motors make good used of several applications as pumps and linear actuator. Generally rotary type electric machines are widely used; however, applying rotary machines to linear system have limitations. Also, when rotary machines are used for linear moving systems, additional mechanical losses due to gears, ball screw, and belts are inevitable, and the system become complex and inefficient. Various designs of linear motors are studied to overcome such limitations of rotary machines. One of them is the short primary member tubular linear induction motor (TLIM). Figure 1 shows the structure of TLIM. The primary core in TLIM is made of several disc or transversal lamination of ferromagnetic material. The main advantages of the TLIM are that it is rugged and easy to build. Because of TLIM is used at a very low speed, the dynamic end effects are negligible and the static end effect can be minimized by good design [1], [2]. However, due to the more complex geometry and difficult physical phenomena in TLIM compared to single-sided linear induction motor (SLIM), special attention must be paid particularly core saturation, eddy current induced in the core and skin effect analysis in the secondary conductor sheet.

The main object of this paper is concerned with the characteristic analysis to thickness of secondary conductor in TLIM which is capable of application to the elevator system. Characteristic equations of TLIM are obtained form voltage equation. Using by finite element method (FEM), parameters of voltage equation are calculated. To consider secondary conductor effect FEM is performed at time-harmonic field. And secondary resistance loss is calculated by eddy current using FEM.

Consequently, the thrust force of TLIM according to goodness factor of secondary conductor thickness is compared. And then, this paper presents how to decide secondary conductor resistance at motor design. The end results are presented in a useful form.

2. Methodology

2.1. Equivalent circuit

Figure 2 show the equivalent circuit of TLIM each phase in steady-state mode. Equation (1) and (2) are voltage equation of TLIM[3].

$$U_s = I_s(R_1 + j\omega_1 L_1) + (I_s + I_t)(j\omega_1 L_m) \quad (1)$$

$$0 = I_t[(\frac{R_2}{s}) + j\omega_1 L_2] + (I_s + I_t)(j\omega_1 L_m) \quad (2)$$

Where, U_S is effective value of secondary part voltage per phase, ω_1 is angular frequency of primary part, I_s and t_t are effective value of input current in primary and secondary part, R_1 and R_2 are resistance of primary and secondary respectively, L_m is mutual inductance and L_2 is leakage inductance of secondary part.

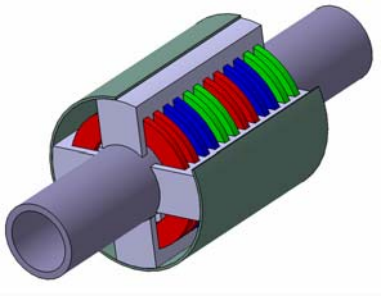


Figure 1: Structure of Tubular Linear Induction Motor

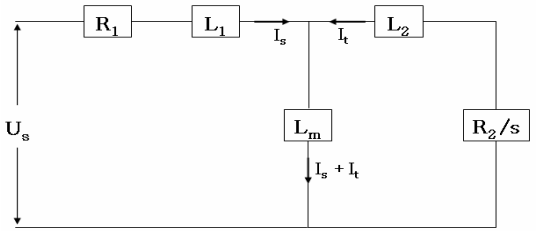


Figure 2: Equivalent circuit of TLIM per phase

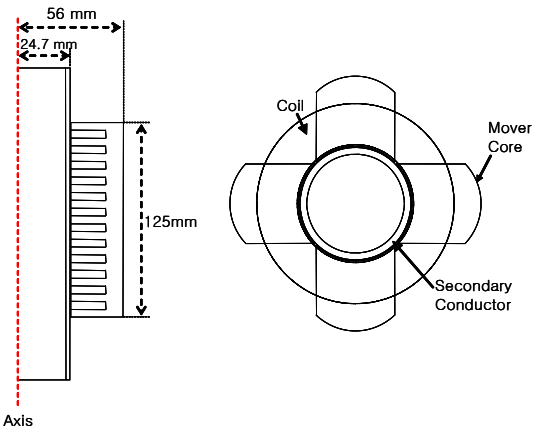
2.2. Analysis model

Figure 3 shows the cross-section view of TLIM. Primary part consists of iron core and armature coil, and secondary parts consist of aluminium tube (the secondary conductor sheet) and an iron rod for a magnetic return yoke. Table 1 shows the specifications of analysis model of TLIM.

2.3. Parameter Calculation

The main parameters can be separated four parameters in TLIM. Each parameter is shown in Figure 2. R_1 can be calculated linear parameter as $R=l/\sigma S$. $L1$, and Lm can be calculate by FEA(Finite Element Analysis). This model is solved the time-harmonic field analysis with real and imaginary terms. When the secondary circuit is open(slip=0), the leakage inductance can calculate by (3)

$$L_1 = \frac{\lambda_{leak}}{I_S}, \quad L_m = \frac{\lambda_{1T} - \lambda_{leak}}{I_S} \quad (3)$$



(a) side direction (b) upper direction

Figure 3: Structure & Cross-section view of TLIM

Table 1 : Specifications of TLIM.

Items	Specifications	Value	Unit
Normal	Voltage	110	Vrms
	Rating Current	10	Arms
	Frequency	60	Hz
	Length	125	mm
	Diameter	110	mm
	Pole pitch	60	mm
stationary part	Pole/slot number	4/12	
	Series Turn number/ Phase number	400	
mover	Material	Aluminum	
	Conductor Depth	3	mm
Air gap length		0.5	mm

2.4. Characteristic Analysis and Goodness factor

Characteristic equations are obtaining form equivalent circuit. First, thrust force per phase is calculated using by Lorenz's law. Thrust force (F_Z) is expressed

$$F_Z = 3p\frac{\omega_1}{v_0} I_S^2 \frac{M_{ts}^2}{L_{tt}} \frac{(\omega_1 s)T_t}{1+(\omega_1 s)T_t} \tag{4}$$

Where, v_0 is synchronous speed, M_{ts} is mutual inductance of secondary part, L_{tt} is self inductance of secondary part, s is slip and T_t is electric time constant.

And input current in equivalent circuit is calculated by input voltage.

$$I_S = U_S \frac{(R_2/s)+j\omega_1(L_2+L_m)}{[R_1+j\omega_1(L_1+L_m)][R_2/2+j\omega_1(L_2+L_m)]+(\omega_1 L_m)^2} \tag{5}$$

Also mechanical power output can be expressed by equation (5). Thrust force (F_Z) per phase times velocity (v_0) is equal to mechanical output (p).

$$P = F_Z v = F_Z(1-s)v_0 \tag{6}$$

Lastly, power factor ($\cos\phi$) and efficiency (η_1) are defined by mechanical power output per unit air-gap volt amps for TLIM is given by equation (7) and (8).

$$\cos\phi = \frac{F_Z 2\tau f_1 + 3R_1 I_S^2}{3pU_S I_S} \tag{7}$$

$$\eta_1 = \frac{F_Z 2\tau f_1(1-s)}{F_Z 2\tau f_1 + 3R_1 I_S^2} \tag{8}$$

where, τ is pole pitch and f_1 is frequency of primary part.

The goodness factor G is given by equation (9)

$$G = \frac{X_m}{r_2} \tag{9}$$

where, X_m is magnetizing reactance and r_2 is secondary resistance.

3. Result and Discussion

3.1. Equivalent parameter of analysis model

Table 2 shows the equivalent parameter of TLIM according to thickness of secondary conductors. In table 2, the value of G is means the goodness factor. This factor be smaller as thickness of conductor is larger.

Table 2 : Equivalent parameter according to secondary conductor thickness.

Items	Unit	Conductor thickness (mm)		
		2	3	4
R_1	Ω	0.3821	←	←
L_1	mH	13.4	←	←
R_2	Ω	2.04	1.36	1.02
L_m	mH	8.81	←	←
G @60Hz		1.63	1.73	3.25

3.2. Torque and Current Characteristic

Since the TLIM stator has 12 slots, a 4-pole TLIM requires on slot per pole per phase. This leads to a pole pitch of 60mm. As a result the synchronous velocity of the TLIM at 60Hz is 3.6 m/s. Figure 4 shows the phase current according to secondary conductor thickness and velocity. Since the secondary resistance is reduced with thickness, the phase current reduced. Figure 5 shows the thrust force according to mover velocity

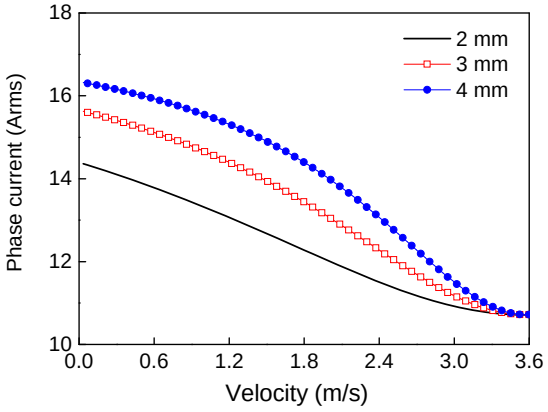


Figure 4: Phase current according to velocity

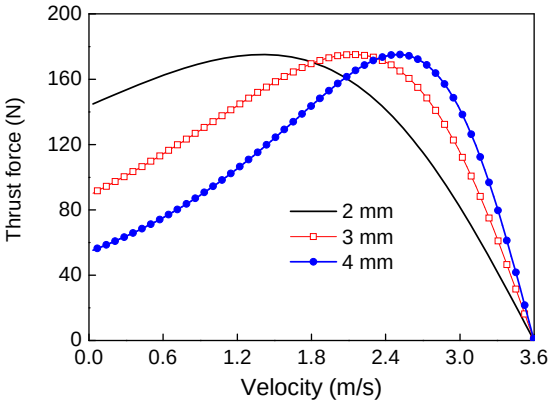


Figure 5: Thrust force according to velocity

Figure 6 shows the thrust force according to input frequency. When the frequency is reduced, the X_m is reduced proportion to frequency. Therefore the goodness factor is reducing to 1.

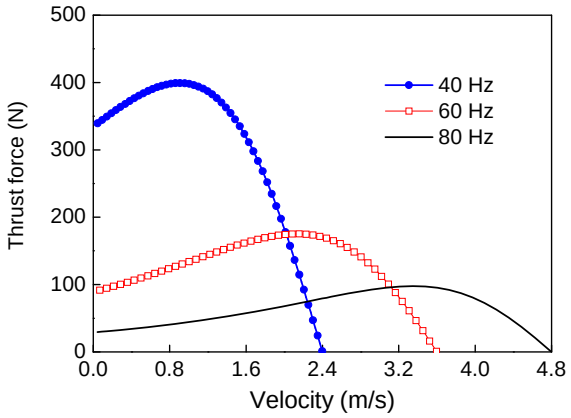
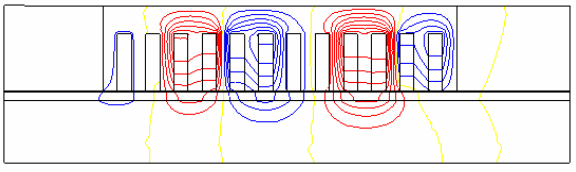


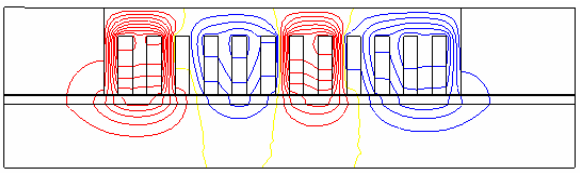
Figure 6: Operating region vs. input frequency

3.3. FEA Result and Conductor loss

Fig. 7 shows the equi-potential distribution. 4poles are formed by winding distributions. Fig. 7(a) is real parts of time harmonic files analysis, and 7(b) is imaginary parts.



(a) $\omega t = 0$



(b) $\omega t = 90$

Figure 7: Equi-potential line of TLIM

Figure 8 shows the secondary part current distribution. In this paper, conductor thickness is changed to 4mm from 2mm. The total conductor loss is shows in figure 9 according to the thickness. Eddy current loss is reduced according to increased conductor thickness.

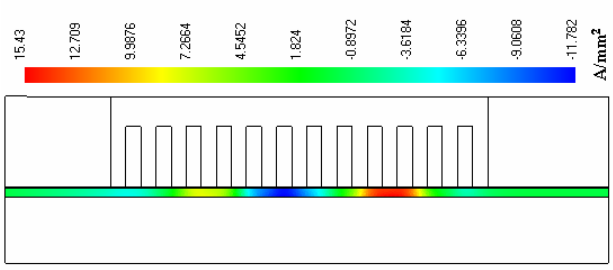


Figure 8: Current density of secondary conductor

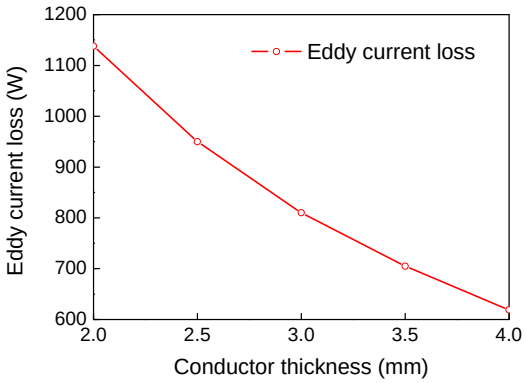


Figure 9: Eddy current loss of TLIM according to conductor thickness

4. Conclusion

This paper presents characteristic analysis to thickness of secondary conductor in TLIM which is capable of application to the elevator system. The modeling of the TLIM, with axis-symmetry, is used by the FEM. The eddy current loss of TLIM according to secondary conductor thickness is compared. In the paper, using by equivalent circuit analysis of TLIM according to secondary conductor thickness was conducted. And then, this paper presents how to decide secondary conductor resistance at TLIM design.

References

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