AN EXAMPLE FOR DESIGN AND APPLICATION OF LOW-SPEED LINEAR INDUCTION MOTOR (LIM)

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ABSTRACT

In this study, procedure of low-speed linear induction motor design and an application of single-sided flat linear induction motor (LIM) have been analysed. In the application example, the performance of low-speed LIM whose pole pitch is changed is analysed. The typical force versus speed characteristic shows that there is a reasonable agreement between theoretical and experimental results.

I. INTRODUCTION

At present, most of the linear induction motors find applications at low speeds and at standstill. Especially, these include belt conveyors, material handling, door and curtain operators, overhead cranes, and short-stroke actuators. At low speeds, the longitudinal end effects are unimportant in most LIMs. Therefore, the theory of these machines may be considerably simplified. In fact, the equivalent circuit for the conventional induction motor may be used with appropriate modifications of parameter values. Thus, the difficulties in design process are minimised [1].

In addition, several problems that are very important at high-speed applications, such as friction, surface acoustic wave, magnetic vibrations are unimportant at low-speed. Usually, the machine operates at main frequency without additional components of power electronics. Therefore, the cost of system that is the most handicap in preference of LIM because of very high is significantly reduced at low-speed applications [2,3].

In this study, the structure of the single-sided linear induction motor, design criterions and considerations of the LIM and a typical application are given below.

II. STRUCTURE OF THE SINGLE-SIDED LINEAR INDUCTION MOTOR (SLIM)

The topology of linear induction motor is fairly complex and as a result, theoretical analysis is very difficult. A single-sided short primary LIM used in low-speed applications is shown in Figure 1. The width of primary core, secondary yoke and back iron are different each other. Primary core is symmetrical to secondary middle line. When the primary windings are excited with three phase currents, a voltage is induced in the secondary yoke. Thus, three axis forces are produced in the LIM [4].

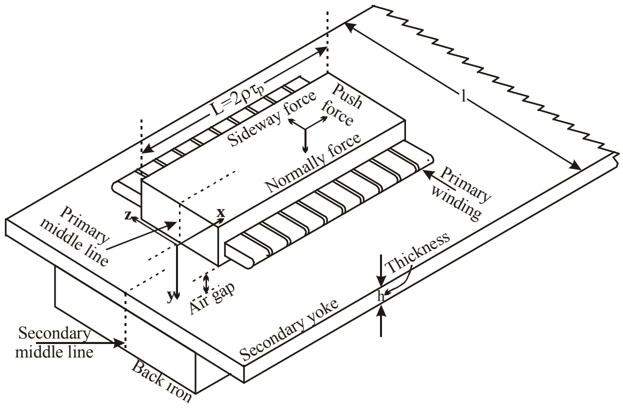

Figure 1. Geometry of single-sided linear induction motor

III. DESIGN OF THE LIM

For the analysis and design of a low-speed flat LIM, an approximate equivalent circuit will be used. To determine the parameters of the circuit, the design formulas of the rotary induction motor for application will be adapted to the LIM. As known, often the secondary of a LIM is made of a conducting sheet. The concept of surface resistivity is very useful in finding the resistance of such a secondary. Although, the analysis used in this study neglects the longitudinal end effects and in this case, a correction factor to determine the effective surface resistivity, as modified by end effects, may be used.

THE EQUIVALENT CIRCUIT

Nothing of the above-mentioned differences introduced by the presence of a sheet rotor and a short primary. For a low-speed LIM, an approximate equivalent circuit in Figure 2 will be used.

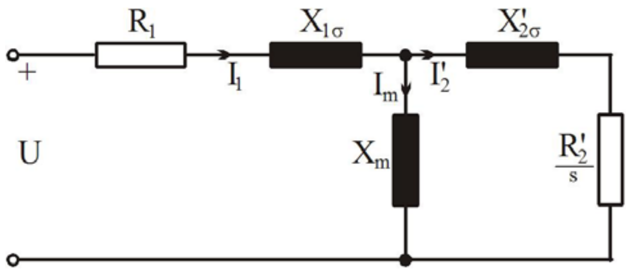

Figure 2. Equivalent circuit of a low-speed LIM that based on main frequency and iron losses are neglected.

In LIMs, secondary leakage reactance is very small according to primary, and can be neglected. Therefore, with $X_{2\sigma} \cong 0$, adapting the standard design formulas, the parameters of the equivalent circuit of the LIM are given as follows [1].

Primary resistance;

$$R_1 = \frac{\rho_c k_p{}^2 q m^2 l N^2 (1 + k_1 \tau_p / l)}{k_f k_d p \tau_p{}^2} \quad \Omega / \text{phase} \tag{3.1}$$

In equation (3.1); $k_p = \frac{t_c}{w} = 2 \sim 3$ and $k_d = \frac{t}{w} = 3 \sim 5$

Primary leakage reactance (for an open-slot primary core);

$$X_{1\sigma} \cong \frac{2\mu_0 \omega}{p}\left[\frac{(\lambda_c + \lambda_d) l}{q} + \lambda_e \frac{\tau_p}{\pi} k_2{}^2 m\right] N^2 \tag{3.2}$$

In this equation; $\lambda_c \cong \frac{1}{12} k_d (1 + 3\beta)$, $\lambda_e \cong 0.3(3\beta - 1)$ and $\lambda_d \cong (5g/w)/(5 + 4g/w)$

Secondary resistance:

$$R_2' = 6 l \rho_r' (k_w N)^2 / \tau_p \tag{3.3}$$

Magnetising reactance;

$$X_m = \frac{6\mu_0 \omega}{\pi^2} \frac{\tau_p l}{pg} (k_w N)^2 \tag{3.4}$$

Goodness factor;

$$G = X_m / R_2' = 2\mu_0 f \tau_p^2 / \pi g \rho_r' \tag{3.5}$$

PERFORMANCE CALCULATIONS

Performance of a LIM (whose equivalent circuit parameters are known and iron losses, additional losses produced by harmonics are neglected) can be calculated as follows:

Input power,

$$P_g = U_1 I_1 \cos\phi_1 \tag{3.6}$$

Primary copper loss,

$$P_{cu1} = I_1{}^2 R_1 \tag{3.7}$$

Secondary copper loss,

$$P_{cu2} = s(U_1 I_1 \cos\phi_1 - I_1{}^2 R_1) \tag{3.8}$$

Developed (mechanical) power,

$$P_{mek} = (1 - s)(U_1 I_1 \cos\phi_1 - I_1{}^2 R_1) \tag{3.9}$$

Force in the secondary in the x-direction per wavelength, for entire width l, and entire depth (h) of the secondary plate (in Newtons);

$$\begin{aligned} F_x = \frac{B_m{}^2 \sigma s v_s l \lambda}{4|\Delta|^2 |\gamma|^2} \Bigg[& |\gamma|^2 \left(\frac{1}{2m_1} \sinh 2m_1 h + \frac{1}{2m_2} \sin 2m_2 h \right) \\ & + a^2 \left(\frac{1}{2m_1} \sinh 2m_1 h - \frac{1}{2m_2} \sin 2m_2 h \right) \\ & + a \left(\cosh 2m_1 h - \cos 2m_2 h \right) \Bigg] \end{aligned} \tag{3.10}$$

In equation (3.10), $\mu = \mu_r \cdot \mu_0 \quad (H/m)$,

$\Delta = \cosh \beta g + \frac{\gamma \mu_0}{\beta \mu} \sinh \beta g$, $a = \frac{\mu \beta}{\mu_0}$, $\beta = \frac{2\pi}{\lambda}$, $\mu_0 = 4\pi \cdot 10^{-7} \quad (H/m)$ and $\gamma = m_1 + j m_2$ [1].

The symbols used in equations are given in Table I.

TABLE I
LIST OF SYMBOLS USED IN EQUATIONS

R_1:Primary resistance (Ω)	t_c:Slot pitch (m)
R_2:Secondary resistance (Ω)	w:Slot width (m)
$X_{1\sigma}$:Primary leakage reactance (Ω)	ρ_c:Volume resistivity of copper (Ω-m)
$X_{2\sigma}$:Secondary leakage reactance (Ω)	Bm:Max. magnetic flux density (T)
X_m:Magnetizing reactance (Ω)	ρ_r:Surface volume resistivity of secondary (Ω-m)
G:Goodness factor	k_f:Slot-filling factor (0,5 ~ 0,6)
P_g:Input power (W)	β:Chording (coil-span) factor
P_{CU1}:Primary copper loss (W)	m:Number of phases
P_{CU2}:Secondary copper loss (W)	q:Number of slots per pole per phases
P_{mek}:Developed (mechanical) power (W)	k_w:Primary winding distribution factor ≅ 0,9
M:Torque (Nm)	N:Number of turns per phase (for primary)
F: Force (N)	p:Pole pairs
w:Angular velocity (Rad/s)	τ_p:Pole pitch (m)
v_s:Synchronous speed (m/s)	k_2:Winding breadth factor
s:Slip	k_1:Ratio of the mean length of coil end connection to the pole pitch(1,2 ~ 1,8)
U_1: Primary phase voltage (V)	h:Thickness of the secondary sheet (m)
Cosϕ1: Input power factor	L:Length of the primary (m)
I_1:Primary phase current (A)	σ:Volume conductivity of secondary (mho/m)
f: Frequency (Hz)	λ:Wavelength (m)
μ_r:Relative permeability	l:Secondary width (m)
b_N:Tooth width (m)	t:Slot depth (m)
g:Total air gap (m)	

IV. DESIGN CONSIDERATIONS

Having presented a discussion of the performance calculations of a low-speed LIM, some design aspects of LIMs will be summarised in this chapter. The design of a linear induction motor involves many parameters that can be varied to affect the performance of the machine. The effects of varying some parameters are outlined below.

AIR GAP

The length of the air gap is very important parameter in machine design. A large air gap requires a large magnetising current and results in a smaller power factor. In the case of an LIM, exit-end zone losses increase with a larger air gap. Also, output force and efficiency decrease when the design incorporates a large air gap. As (3.5) indicates, the goodness factor is inversely proportional to the air gap. Using the goodness factor concept, machine design can be optimised, since for a low-speed LIM, to a certain extent, the larger the goodness factor, the better the machine. Thus, it is clear that the air gap should be as small as is mechanically possible.

POLE PITCH

Referring to (3.5), for larger goodness factor, the pole pitch should be as large as possible. Note that the pole pitch (τ_p) is squared in the expression goodness factor. However, too large pole pitch results in increased back iron thickness, which could tremendously increase the weight of the LIM. Also, if pole pitch increases, efficiency decreases, resulting in less active length of conductor (conductor in the slot) to the total length of the conductor (conductor in the slot plus the end connections). As known, end connections serve no useful purpose and can produce very high leakages and losses.

Synchronous speed (v_s) is related to frequency and pole pitch as follows: $v_s = 2\tau_p f_1$ (m/s). Thus, for a given frequency, the pole pitch alone determines the synchronous speed of the machine. For a given machine length, a large pole pitch results in a smaller number of poles, which is usually not desired.

NUMBER OF POLES

End effects are reduced with an increase in the number of poles, in the LIM. This is because more poles tend to share the constant end-effect a loss between them, resulting in a better performing machine. Thus, it would be advantageous to have a machine with a large number of poles.

SECONDARY SURFACE RESISTIVITY

The secondary thickness and the material play an important role in the performance of a LIM. The thicker secondary, the larger goodness factor. In case of a nonferrous secondary, a thicker material results in a larger air gap, which is undesirable. For nonferrous secondaries, then, the thickness must be small, but strong enough to withstand the magnetic-forces present. In ferrous secondaries, the air gap is independent of material thickness. However, a thicker secondary results in larger starting currents. As a result, the thickness chosen depends on the starting current limitations rather than the desired increase in the goodness factor.

The secondary material is as effective as thickness on secondary resistivity. Therefore, the lower resistivity improves the goodness factor and also gives less secondary loss. But low resistivity results in a shower decay of the end-effect travelling wave which reduces the output. Thus, a compromise between goodness factor and secondary resistivity is necessary. Of the two homogeneous materials, ferromagnetic material has the advantage of high permeability, which means less magnetising current; but a disadvantage is the strong magnetic pull between the primary and the secondary. A nonferrous but electrically conducting material reduces this large magnetic pull, but when the permeability of air-gap is low, magnetising currents are very large. A composite secondary of both ferrous and nonferrous materials combines the advantage of each (high permeability and reduced magnetic pull) and appears to be the best secondary electromagnetically. Cost considerations are not included in our discussions.

PRIMARY CORE

The variations in stator core design also affect the performance of a LIM. Given a constant cross-sectional area of copper in the slot, a machine with narrower teeth produces more force and has better efficiency and a better power factor than a machine with wider teeth. This is because a machine with narrower teeth has lower primary and secondary leakage reactance that results in a smaller secondary time constant. A smaller time constant produces an end-effect travelling wave of smaller magnitude, and this leads to larger machine output. To determine the narrowest tooth width, the flux density in the tooth must be considered, tooth saturation setting the limit on the narrowest tooth [1].

Table II summarises the effects of the above-mentioned parameter variations.

TABLE II
EFFECTS OF PARAMETER VARIATIONS

Parameter	In case of increasing	In case of decreasing
Air gap (g)	Larger magnetizing current Larger exit-end losses	Larger goodness factor Larger output force Larger efficiency
Pole pitch (τ_p)	Larger goodness factor Increase back iron thickness	Larger number of poles
Number of poles (2p)	Smaller end effects	Larger secondary leakage reactance
Secondary thickness	Larger goodness factor Larger starting current	Larger secondary leakage reactance
Secondary resistivity (ρ_r)	Smaller end effects	Larger goodness factor Less secondary loss
Tooth width (w)	Larger leakage reactance	Larger force, Larger efficiency

V. APPLICATION

Typical applications for low speed LIM are doors, specially sliding and turning doors. They are operated with a maximum speed of around 0.3 m/s. In most cases rotating machines in combination with a gear and a toothed rack will be used. But the operation of LIM is simpler and more reliable. To get a less cost and effective control system of linear propulsion the LIM has to operate at main frequency and without additional components of power electronics. In Figure 3, an application of LIM for sliding door is shown [1].

Analysed sliding door application in this study, a single-sided LIM is used because of providing easily design, low cost and an efficiently linear push force. The machine can be operated at main frequency without additional components of power electronics.

The synchronous speed of the LIM in Figure 4 is v_s = 3 m/s and nominal speed is v = 0.3 m/s. Because the synchronous speed equation is $v_s = 2\tau_p f_1$, pole pitch (τ_p) will be 30 mm in a 50 Hz frequency system. When the network frequency is constant, machine efficiency will be significantly low to obtain 0.3 m/s speed under nominal load operation. In this case, the slip ($s = (v_s-v)/v_s$) of LIM will be 0.9. Performance calculations show that the slip is very effective on output parameters of LIM. The synchronous speed (v_s) should be reduced to get lower slip when the speed (v) is constant. The LIM has to operate without additional components of power electronics. Consequently, main frequency is unchangeable. Therefore, the pole pitch (τ_p) was reduced from 30 mm to 18.5 mm with the aim of reducing the synchronous speed (to reduce the slip) and increasing the output performance of the LIM.

As known, the number of slots per pole per phase (q) can be equal to 1 at least. According to this, the pole pitch equation for calculating the speed of a three phase LIM is $\tau_p = 3(b_N+w)$. Thus, for a constant stator yoke, the pole pitch is depending on the slot width and the tooth width. At this situation, the tooth width and the slot width should be reduced. Unfortunately, as above-mentioned the tooth saturation limits this operation.

Usually, the smallest tooth width of low-speed linear motors is 5 mm. To get a 18.5 mm pole pitch, the tooth width should be 3 mm. In this case, slot width will be about 3.17 mm and sloth pitch will be 6.34 mm. In this study, a novel approach is suggested instead of punching the laminations at tooth widths of less then 3 mm. The suggested approach is based on teeth and stator yoke are produced separately. A number of soft magnetic and isolated sheets are glued together and form the total teeth width of about 3 mm. The sheets which are perpendicular to the stator-yoke lamination are inserted

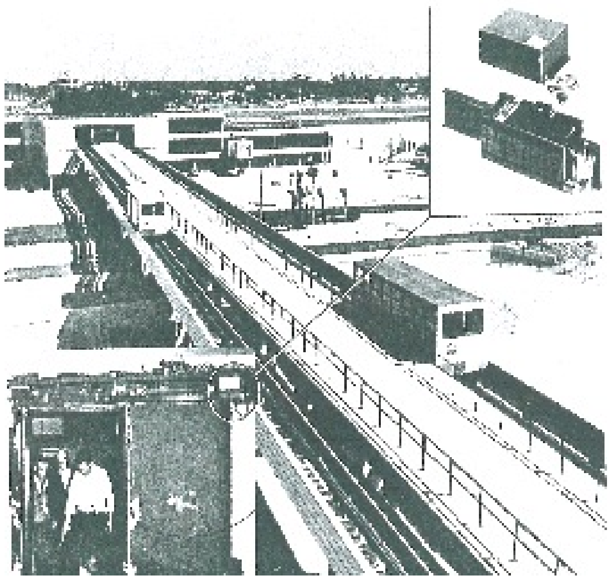

Figure 3. Application of low-speed LIM for sliding door.

and pressed into slots (Figure 4). Tests on the prototype with a stator depth of 40 mm shows that 600 N are needed to pull the sheets out of a single slot. The steel sheets used to build up the teeth should have constructed to guide the flux to the secondary. In this case, leakage flux could be reduced and the useful flux can be increased.

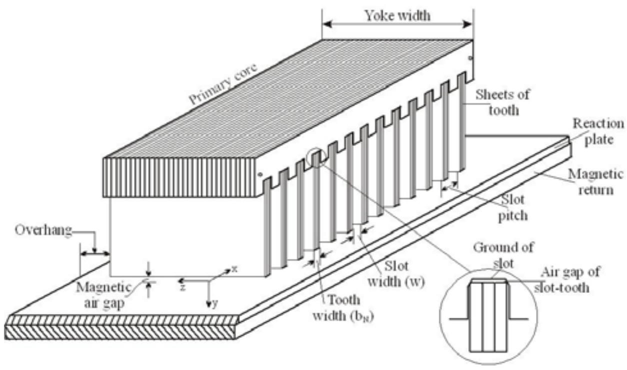

Figure 4. Primary core and sheets inserted into slots of stator-yoke of low-speed LIM used in application.

Due to the almost linear decrease of the force-speed characteristic, the maximum slip of the drive will be close to 0.5. Thus, the speed of machine in this slip is same with the speed of the door. For a nominal voltage of 38 V, no forced cooling is necessary. However, the forced cooling has to be applied with 54 m^3/h at 45 V. Due to the special test conditions, the temperature of the secondary was almost at room temperature. The stator winding temperature reached to 75^o C. The typical force versus speed characteristic in Figure 5 shows that there is a reasonable agreement between theoretical and experimental results [5].

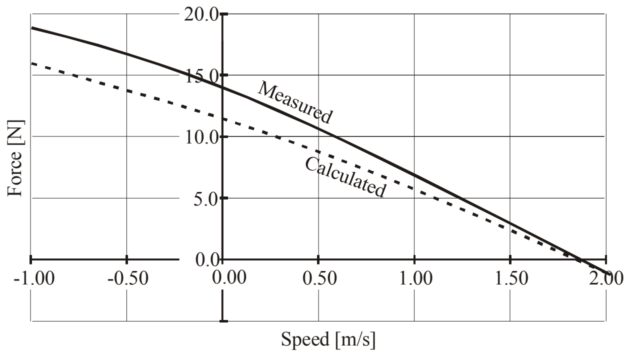

Figure 5. Calculated and measured force versus speed characteristic at 38 V, 50 Hz.

VI. CONCLUSION

In this study, the advantages of LIM used at low-speed applications have been analysed. In the design process of the LIM, the machine can be suitable for low-speed operation without additional components of power electronics with small structural changes. In the investigated application example, performance of LIM is analysed at low speed system whose pole pitch is changed. The typical force versus speed characteristic shows that there is a reasonable agreement between theoretical and experimental results.

To increase the performance of LIM in low-speed systems, it is necessary to minimise the parasitic air gap at the bottom of the teeth where the steel sheets are clamped and glued in to the yoke. In addition, to use amorphous material for the yoke to solve the teeth saturation problem is an efficient solution. But the using of amorphous material is still under research stage because of construction problems. The depth of slots for taking in the steel sheets of the teeth has to be optimised.

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