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DESIGN AND FABRICATION OF LINEAR INDUCTION MOTOR FOR TRACTION APPLICATION

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ABSTRACT

This paper deals with the design and fabrication of basic Linear Induction Motor (LIM), suitable for Traction application. The different concepts of the motor that are in common with other rotating machines, are identified and studied. An Aluminum sheet lay over iron core, acts as the rotor and the stator is designed for Double Layer winding, having 2 poles. The use of Linear Induction Motors (LIM) ranges from slow moving sliding doors to high speed trains across the globe.

KEYWORDS: Linear Induction Motor (LIM), Traction, Design of Stator, Design of Rotor, Design of Windings.

INTRODUCTION

A Linear Induction Motor (LIM) is an Asynchronous motor that works on the same general principle as that of other induction motors, but the structure of it is altered to produce motion directed in a straight line direction. Typically, linear induction motors have a finite length primary, which generates end-effects, whereas with a conventional induction motor the primary is arranged in a never-ending loop, It is credible that all linear induction motors do not produce the linear motion; some linear induction motors are in use for generating rotations of large diameters, the usage of the continuous primary is even very high cost.

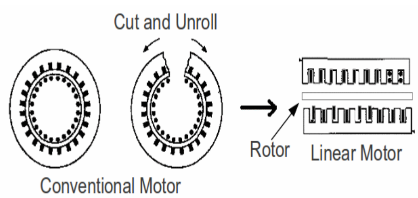

Figure 1: Structural Diagram of LIM

The LIMs can support very high speeds like other Rotating Machines. But, these machines produce reduced force due to end effects and hence are less energy efficient in comparison with normal rotary motors for any given required force output and it's often not possible to fit a gearbox to trade off force and speed. LIMs are often used where contactless force is required, which desires low maintenance, or which leads to the duty cycle ratio is low. LIMs practical uses include magnetic levitation, linear propulsion, and linear actuators. They are also being used in pumping liquid metals.

Slim Concept and Details

By visualizing that, if we cut and unroll the motor, we can obtain the linear motor, as shown in Figure, which causes the motor to have a linear motion

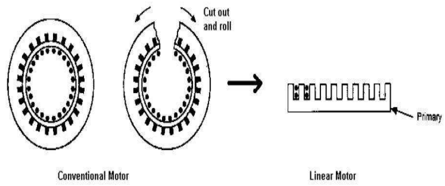

Figure 2: Unrolling Motor

Instead of rotating flux, the primary windings now create flux in a linear fashion. The primary field interacts with the secondary conductors and hence exerts a force on the secondary. Generally, the maximum use of the primary magnetic field is attained by making the secondary is longer than the primary.

In order for a voltage to be induced in the conductor there should be a relative motion between the conductor and the magnetic lines of flux. That's why induction motors, normally operate at a speed V_r that is slightly less than the synchronous velocity V_s. Slip is the difference between the stator magnetic field speed and the rotor speed. The relative motion needed in the induction motor to induce a voltage in the rotor, is slipping and it is given by

$$S=\frac{V_s-V_r}{V_s} \quad (1)$$

$$V_s=\frac{2\omega R}{p} = 2f\tau \quad (2)$$

Where, R is the stator radius of the rotary induction motor, as shown in Fig.3. It is important to make a note of that the linear speed depends only on the pole pitch but does not depend upon the number of poles.

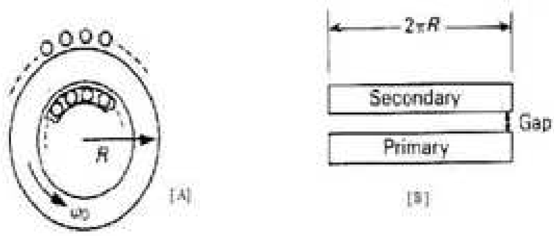

Figure 3: Radius of a Rotary Induction Motor and Length of a SLIM

The parameter τ is the distance between two neighboring poles on the circumference of the stator, called pole pitch and it is defined as

$$\tau = \frac{2\pi R}{p} \quad (3)$$

The stator circumference of the rotary induction motor, 2πR, is equal to the length of the SLIM stator core, L_s. Then,

$$\tau = \frac{2\pi R}{P} = \frac{L_s}{P} \quad (4)$$

If the velocity of the rotor is V_r, then the slip of a SLIM can be defined as

$$S=\frac{V_s-V_r}{V_s} \quad (5)$$

The air-gap shown is the clearance between the rotor wall and the SLIM stator in a PCP-SLIM system.

The Concept of Current Sheet

As mentioned earlier, the stator of an induction machine consists of several coils, each having many turns embedded in laminated iron slots. The current carried by the windings can be replaced by a fictitious and infinitely thin layer of current distributed over the surface of the stator facing the air gap. This current is called the "current sheet." The current sheet produces the same sinusoidal magneto motive force (mmf) in the air gap as that produced by the conductors.

The amount of current per unit stator length (L_s) in a current sheet of a SLIM can be known as the current sheet strength, and it is considered as in Nasar and Boldea as follows:

$$J_m = \frac{2\sqrt{2} m K_w N_c I_1}{L_s} \quad \textbf{(6)}$$

Jm is the current sheet strength (amp/meter); m is the number of phases of the motor; kw is the winding factor, defined below; Nc is the number of turns per slot; I1 is the RMS value of the input current; Ls is the length of one section of the stator of the LIM, which is equivalent to the circumference of a rotary motor, namely, Ls= 2πR= pτ.

The winding factor, kw, is defined as the product of pitch factor kp and the distribution factor kd.

Kw = KpKd

Where, kp is the pitch factor of the coil, which is given by

$$k_p = \sin\left(\frac{\theta_p}{2}\right) \quad \textbf{(7)}$$

Where, θ_p is the coil span in electrical degrees. k_d is the breadth or distribution factor, given by

$$k_d = \frac{\sin\left(\frac{q_1 \alpha}{2}\right)}{q_1 \sin\left(\frac{\alpha}{2}\right)} \quad \textbf{(8)}$$

Where, α is the slot angle in electrical degrees given as

$$\alpha = \frac{\pi}{m q_1} \quad \textbf{(9)}$$

One pole pitch is equal to 180 electrical degrees. So, in a full pitch coil where the coil span is equal to one pole pitch, the pitch factor becomes one. Therefore, the winding factor for the fundamental harmonic of a full pitch coil can be obtained by substituting

$$K_= \frac{\sin\left(\frac{\pi}{2m}\right)}{q_1 \sin\left(\frac{\pi}{2 m q_1}\right)} \quad \textbf{(10)}$$

q_1 is the number of slots-per-pole-per-phase in the stator iron core.

Power Rating and Rated Input Phase Current

The power balance expression is derived as follows. The Input Power to the stator windings is given by the equation

$P_i = mV_1 I_1 \cos\varphi$,

Where m is the number of electrical phases, V1 and I1 are the input phase voltage and current, respectively, which are RMS values, and the power factor is given as φ, which is the corresponding phase angle between V1 and I1. Included in this input power are a component, for the copper losses in the stator windings, and a component of the iron losses in the stator core and teeth. The remaining input power is transferred to the rotor through the magnetic field of the air-gap. Neglecting the rotor conductor losses and friction and windage losses, the power transferred to the rotor can be equated to the mechanical power developed by the rotor.

The total developed mechanical power by the rotor of the SLIM is given as

$$P_o = F_s V_r \quad (11)$$

Where F_s is the electromagnetic thrust generated on the rotor by the stator, and, as stated before, V_c is the speed of the rotor. The efficiency η of the SLIM is calculated from

$$\eta = \frac{P_o}{P_i} = \frac{F_s V_r}{m V_1 I_1 \cos\varphi} \quad (12)$$

Initially by assuming a suitable operating value for ηcosφ, and then the rated input phase current can be estimated from

$$I_1 = \frac{F_s V_r}{m V_1 \eta \cos\varphi} \quad (13)$$

Flux Linkage and Induced Voltage

Let us Consider a coil of N turns carrying a current of I amperes and the resulting flux linking the coil beΦ. Let's assume that the flux density Φ in the air-gap is purely sinusoidal, and then it is expressed as

$$\Phi = \Phi_p \sin \omega t$$

Where the amplitude of the flux linkage per pole is given by Φp and by flux linkage, the mean of the product of flux in Weber's and the number of turns N with which the flux is linked. The induced voltage per turn in the above coil due to a change of flux is given by the first derivative of the above equation, and is represented as

$$e = \frac{d\varphi}{dt} = \omega \varphi_r \cos\omega t \quad (14)$$

The RMS value of e is

$$E_l = \frac{2\pi}{\sqrt{2}} f \varphi_r = \sqrt{2}\pi f \varphi_r \quad (15)$$

If the coil has N_1 turns per phase and a winding factor kw, becomes

$$E_l = \sqrt{2}\pi f \varphi_r k_w N_1 \quad (16)$$

Magnetic flux density is found by dividing the flux by the cross sectional area. Hence, the average air-gap magnetic flux density, B_{gavg} can be determined as

$$B_{gavg} = \frac{\varphi_r P}{L_s W_e} \quad (17)$$

Where Ws are the width of the SLIM stator iron core, and Ls is the length of the stator and p is the number of poles, by assuming that, the flux produced in the air-gap is sinusoidal, having a maximum of Bgmax. Hence, the average value of the rectified magnetic flux density is

$$B_{gavg} = \frac{2}{\pi} B_{gmax} \quad \textbf{(18)}$$

Equations for SLIM Slot Geometry

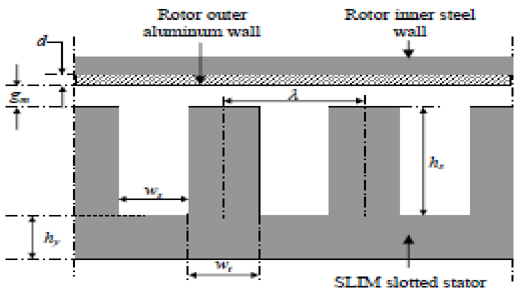

Figure 4: SLIM Slot

Because of the slotted structure of the stator, the effective air-gap g_e of the SLIM is different from the physical air-gap, g_m. The air-gap is a very important parameter in a machine.

According to Gieras,

$$g_e = k_c g_0 \quad \textbf{(19)}$$

Where, g_0 is the magnetic air-gap, it is given by

$$g_0 = g_m + d \quad \textbf{(20)}$$

Where d is the thickness of the conducting layer on the surface of the rotor, and k_c is known as Carter's coefficient, it is given by

$$k_r = \frac{\lambda}{\lambda - y g_0} \quad \textbf{(21)}$$

The distance between the centers of two consecutive teeth is given by parameter λ, which is the slot pitch, it is given by

$$\lambda = \frac{\tau}{m q_1} \quad \textbf{(22)}$$

The quantity γ can be expressed as

$$\gamma = \frac{4}{\pi}\left[\frac{w_t}{2g_o}\arctan\left(\frac{w_s}{2g_o}\right) - \ln\sqrt{1 + \left(\frac{w_s}{2g_o}\right)^2}\right] \quad \textbf{(23)}$$

Slot pitch is the sum of tooth and slot widths, hence the slot width can be estimated with

$$w_s = \lambda - w_t \quad \textbf{(24)}$$

Where, w_t is the tooth width. To avoid magnetic saturation in the stator teeth, there is a minimum value of tooth width w_{tmin}, which depends on the maximum allowable tooth flux density, B_{tmax}.

The quantity w_{tmin} can be determined from.

$$W_{tmin} = \frac{\pi}{2} B_{gavg} \frac{\lambda}{B_{tmax}} \quad \textbf{(25)}$$

The stator slot depth h_s, shown in Fig., can be calculated from

$$h_s = \frac{A_s}{w_s} \quad (26)$$

Where, A_s is the cross-sectional area of a slot. Generally, 30% of the area of the slot is filled with insulation material. Therefore, A_s can be calculated from

$$A_s = \frac{10}{7} N_c A_w \quad (27)$$

Where, N_c is the number of turns per slot, determined from

$$N_c = \frac{N_1}{Pq_1} \quad (28)$$

The variable A_w is the area of a cross section of a conductor winding without insulation, which can be obtained with

$$A_w = \frac{I_1}{J_1} \quad (29)$$

Where, I1 is the rated input phase current defined, and J1 is the stator current density. The value of J1, which depends on the machine output power and the type of cooling system, is assumed to be 6A/m2 at the beginning of the program and later modified appropriately. The yoke height of the stator core hy is the portion of the core below the teeth, as shown in Fig. If it is assumed that the flux in the yoke is one-half of the flux in the air-gap, then it can be expressed as

$$h_y = \frac{\varphi_p}{2B_{ymax} w_s} \quad (30)$$

Equivalent Circuit Model & Components

The approximate per phase equivalent circuit of a LIM is represented as shown in Fig. 5. The core losses are neglected because a realistic air gap flux density leads to moderate flux densities.

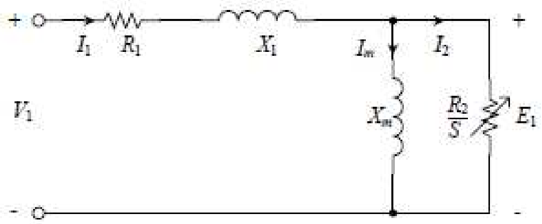

Figure 5: Equivalent Circuit of LIM

Per-Phase Stator Resistance R_1

The resistance of each phase of the SLIM stator windings i.e. per phase stator resistance. R_1 is calculated from

$$R_1 = \rho_w \frac{l_w}{A_{wt}} \quad (31)$$

Where, ρ_w is the volume resistivity of the copper wire used in the stator winding, l_w is the length of the copper wire per phase, and A_{wt} is the cross-sectional area of the wire as given. The length of the copper wires l_w is calculated from

$l_w = N_1 l_{w1}$ **(32)**

Where

$l_{w1} = 2(W_s + l_{ce})$ **(33)**

Is the mean length of one turn of the stator winding per phase and l_{ce} is the length of end connection given by

$l_{ce} = \frac{\theta_p}{180^0}\tau$ **(34)**

Per-Phase stator-slot leakage reactance X1

The flux produced by the stator winding does not completely link with the rotor conductors. There will be some leakage flux in the stator slots and hence stator-slot leakage reactance X_1. By the slot openings of the stator iron core, it generates the leakage flux from an individual coil inside of a stator slot. In a SLIM stator having open rectangular slots with a double-layer winding†, the X1 can be determined from

$X_1 = \frac{2\mu_0\pi f[\left(\lambda_s\left(1+\frac{3}{p}\right)+\lambda_d\right)\frac{w_s}{q_1}+\lambda_e l_{ce}]N_1^2}{P}$ **(35)**

Where

$\lambda_s = \frac{h_s(1+3k_p)}{12w_s}$

k_p is the pitch factor given by. Also,

$\lambda_e = 0.3(3k_p - 1)$ **(36)**

And

$\lambda_d = \frac{5(\frac{g_e}{w_s})}{5+4(\frac{g_0}{w_s})}$

Per-Phase Magnetizing Reactance Xm

The per-phase magnetizing reactance, X_m, is shown in Fig. 5 and is given by

$X_m = \frac{24\mu_0\pi f W_{se} K_w N_1^2 \tau}{\pi^2 P_{ge}}$ **(37)**

Where, k_w is the winding factor defined as in, g_e is the equivalent air gap given by and W_{se} is the equivalent stator width given as

$W_{se} = W_s + g_0$ **(38)**

Per-Phase Rotor Resistance R_2

The per-phase rotor resistance R_2 is a function of slip, as shown in Figure 5. R_2 can be calculated from the goodness factor G and the per-phase magnetizing reactance X_m as

$G = \frac{2\mu_0 f\tau^2}{\pi(\frac{\rho_r}{d})g_e}$ **(39)**

In ρ_r is the volume resistivity of the rotor conductor outer layer, which is aluminum here.

From the equivalent circuit shown in Fig. 5, the magnitude of the rotor phase current I_2 can be seen to be

$$I_2= \frac{X_m}{\sqrt{(\frac{R_2}{s})^2+X_m^2}} I_1 \quad \textbf{(40)}$$

By substituting the value of R_2 from (3.45), the rotor phase current I_2 becomes

$$I_2= \frac{I_1}{\sqrt{\frac{1}{(SG)^2}+1}} \quad \textbf{(41)}$$

Thrust and Efficiency

The input power to the stator windings is utilized in producing useful mechanical power which is exerted on the rotor and to account for the rotor copper losses. In terms of the equivalent circuit components, the mechanical power developed by the rotor is the power transferred across the air-gap from the stator to the rotor.

$$P_0= mI_2^2 \frac{R_2}{s} - mI_2^2 R_2 = mI_2^2 R_2 (\frac{1-s}{s})$$

$$F_s= \frac{mI_2^2 R_2}{V_s S} \quad \textbf{(42)}$$

This is the most general form of expressing electromagnetic thrust for a SLIM determined from the rotor phase current I_2. However, considering the per-phase SLIM equivalent circuit as shown in Figure., where the core losses are neglected, F_s can be expressed in terms of stator phase current I_1. Substituting, the SLIM electromagnetic thrust becomes

$$F_s= \frac{mI_1^2 R_2}{[\frac{1}{(SG)^2}+1] V_s S} \quad \textbf{(43)}$$

The Active Input power of the SLIM is the summation of the output power and the copper losses from the stator and rotor

$$P_i=P_0+mI_1^2 R_1 + mI_2^2 R_2 \quad \textbf{(44)}$$

Where, $mI_1^2R_1$ is the stator copper loss. Substituting yields

$$P_i=F_s V_s+mI_1^2 R_1 \quad \textbf{(45)}$$

The efficiency of the SLIM is found by calculating the ratio, i.e

$$\eta=\frac{P_0}{P_i} \quad \textbf{(46)}$$

Edge Effects Due to Secondary Overhangs

In a LIM, the width of the primary stack is usually less than the width of the secondary plate resulting in a physical feature called transverse edge effects. Due to this, transverse and longitudinal components of current densities exist, consequently increasing the secondary resistance R2 by a multiplicative factor ktr, and a reducing the magnetizing reactance by a multiplicative factor k_{tm} *where*

$$K_{tr}= \frac{k_x^2}{k_r} \frac{1+(\frac{SGK_R}{K_x})^2}{1+S^2G^2} \geq 1 \quad \textbf{(47)}$$

$$K_{tm}=\frac{K_R}{K_x} K_{tr} \leq 1 \quad \textbf{(48)}$$

$$K_r=1-R_e\left[(1-jSG)\frac{2\lambda t}{\alpha W_s}\tanh\left(\frac{\alpha W_s}{2}\right)\right] \quad (49)$$

$$K_x=1+R_e[(SG+j)\frac{2SG\lambda_t}{\alpha W_s}\tanh\left(\frac{\alpha W_s}{2}\right)] \quad (50)$$

$$X_t=\frac{1}{[1+\sqrt{1+jSG}\tanh\left(\frac{\alpha W_s}{2}\right)\tanh\frac{\pi}{\tau}\left(c-\frac{W_s}{2}\right)]} \quad (51)$$

$$\alpha=\frac{\pi}{\tau}\sqrt{1+jSG}$$

$$k_{sk}=\frac{2d}{d_s}\left[\frac{\sinh\left(^{2d}/_{d_s}\right)+\sin\left(^{2d}/_{d_s}\right)}{\cosh\left(^{2d}/_{d_s}\right)-\sin\left(^{2d}/_{d_s}\right)}\right] \quad (52)$$

$$k_p\approx\frac{\mu_0\tau^2}{\pi^2}\left(\frac{1}{\mu_i\delta_i g_0 k_c}\right) \quad (53)$$

$$\delta_i=R_e\left\{\frac{1}{\left[\frac{\pi^2}{\tau^2}+j2\pi f_1\mu_i\frac{s\sigma_i}{k_{tri}}\right]^{\frac{1}{2}}}\right\} \quad (54)$$

$$k_{tri}\approx\frac{1}{\left[1-\frac{2\tau}{\pi W_s}\tanh\left[\frac{\pi W_s}{2\tau}\right]\right]} \quad (55)$$

$$G=\frac{2\mu_0 f_1\sigma_e\tau^2 d}{\pi g_0 k_1 k_{sk} k_c(1+k_p)}$$

$$g_{ei}=\frac{k_1 k_c}{k_{tm}}\left(1+k_p\right)g_0 \quad (56)$$

$$\sigma_{ei}=\frac{\sigma}{k_{sk}k_{tr}}+\frac{\sigma_i\delta_i}{k_{tri}d} \quad (57)$$

$$G_{ei}=\frac{2\mu_0 f_1\tau^2\sigma_{ei}d}{\pi g_{ei}} \quad (58)$$

In summary, the main outcomes of transverse edge effects appear in the forms of:

- An increase in secondary resistivity.
- A tendency toward lateral instability.
- A distortion of air gap fields.

The wear and tear of the LIM performance, due to the first three factors and by considering the boundary problems, the equivalent circuit parameters of a SLIM can be written as follows:

The factor g_e in the magnetizing reactance X_m is replaced by g_{ei} and the goodness factor G in the secondary resistance R_2 is replaced by G_{ei} so that

$$X_m=\frac{24\mu_0\pi f W_s K_w N_1^2\tau}{\pi^2 P g_{ei}} \quad (59)$$

$$R2=\frac{X_m}{G_{ei}}$$

$$R_1=\frac{\rho_w(2W_s+2l_{ce})J_1N_1}{I_1} \quad (60)$$

$$X_1=\frac{8\mu_0\pi f[\left(\lambda_s\left(1+\frac{3}{p}\right)+\lambda_d\right)\frac{W_s}{q_1}+\lambda_e l_{ce}]N_1^2}{P} \quad (61)$$

where λ_s and λ_e are given by

$$\lambda_d=\frac{5(\frac{g_{ei}}{w_s})}{5+4(\frac{g_0}{w_s})} \quad (62)$$

$$G=\frac{2\mu_0 f\tau^2}{\pi(\frac{\rho_r}{d})g_e} \quad (63)$$

All specific phenomena are included ing_{ei} and $\sigma_{ei,}$ which are functions of the primary current I_1 and slip frequency $s\omega$. Further, for low speed LIMs, the expression of thrust and normal force become simplified. Thus, the total thrust F_s may be written as

$$F_s=\frac{3I_2^2R_2}{S2\tau f_1}=\frac{3I_2^2R_2}{S2\tau f_1[\left(\frac{1}{SG_{ei}}\right)^2+1]} \quad (64)$$

The efficiency η and power factor cosφ are given as below by neglecting the iron losses:

$$\eta=\frac{F_s 2\tau f_1(1-s)}{F_s 2\tau f_1+3R_1I_1^2} \quad (65)$$

$$\cos\varphi=\frac{F_s 2\tau f_1+3R_1I_1^2}{3V_1I_1} \quad (66)$$

The normal force F_n is composed of an attractive component and a repulsion component. The final force expression is:

$$F_n= W_{se}\frac{p\tau^3}{\pi^2}\frac{\mu_0 J_m^2}{g_{ei}^2(1+S^2G_{ei}^2)}[1-\left(\frac{\pi}{\tau}g_e SG_{ei}\right)^2] \quad (67)$$

DESIGN OF STATOR (LIM)

A linear electric motor's primary in general consists of a flat magnetic core (generally laminated) with transverse slots which are often straight cut with coils laid into the slots, with alternate polarity given to each phase respectively and so that the different phases are physically overlapped.

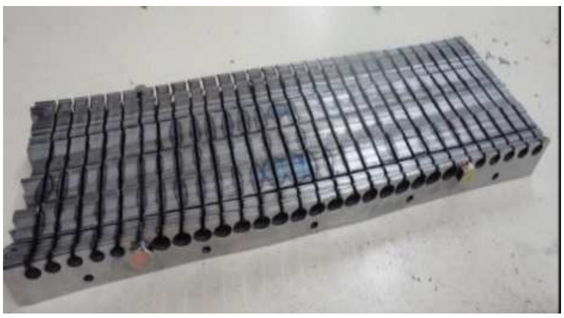

Figure 6: Laminated Silicon Steel (STATOR)

Materials used in stator: We have used Silicon Steel in the designing of stator in linear induction motor. Because of the following properties Silicon steel is used for the stator. The electrical steel also called as lamination steel, silicon electrical steel, silicon steel, relay steel or transformer steel, is the modifies steel to produce certain magnetic properties, such as small hysteresis area (small energy dissipation per cycle, or low core loss) and high permeability. The material is usually manufactured in the form of cold-rolled strips which are less than 2 mm thick. These strips when stacked together to form a core and strips are called as laminations.

Physical Properties

- The Melting point: ~1,500 °C (example for ~3.1% silicon content).
- The Density: 7,650 kg/m^3 (example 3% silicon content)
- The Resistivity: 47.2×10^{-8} (Ω·m) (example 3% silicon content).

Magnetic Properties

The magnetic properties of electrical steel are dependent on heat treatment, as increasing the average crystal size decreases the hysteresis loss. Hysteresis loss is determined by a standard test, and for common grades of electrical steel may range from about 2 to 10 watts per kilogram (1 to 5 watts per pound) at 60 Hz and 1.5 tesla of magnetic field strength. Semi-processed electrical steels are delivered in a state that, after punching the final shape, a final heat treatment develops the desired 150-micrometer grain size.

Fully processed steels are usually produced, with good grade insulating coating, full heat treatment, and defined magnetic properties. Where as in the application of punching operation, does not notably degrade the material properties. With excessive bending, incorrect heat treatment, or even rough handling of core steel can adversely affect its magnetic properties and may also increase noise due to Magneto striation. Internationally standardized Epstein frame method is used for testing the Magnetic properties of electrical steels.

Table 1: Stator Configurations

S.No.	Specifications of Stator	Measures
1.	Stator length	420mm
2.	Thickness	0.5mm
3.	Number of Laminations	100
4.	Height of stator	29mm
5.	Depth of slot	15mm
6.	Slot pitch	17mm
7.	Width	90mm
8.	Pole pitch	105mm
9.	Number of slots	24
10.	Type of material used	Steel

DESIGN OF ROTOR (LIM)

Rotor (Secondary)

Aluminum sheet is used for rotor (secondary), often with an iron backing plate. Some LIMs are double sided, with one primary either side of the secondary, and in this case no iron backing is needed. Here we have used Aluminum as the secondary of the linear induction motor the figure shows the aluminum sheet.

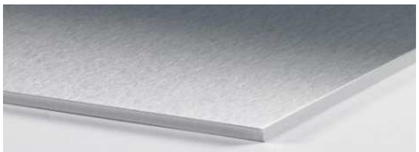

Figure 7: Aluminum Sheet

Properties of Aluminum

Physical Properties

Aluminum is a relatively soft, durable, lightweight, ductile and malleable metal with appearance ranging from silvery to dull gray, depending on the surface unevenness. It is non magnetic and does not easily catch fire. A fresh film of aluminum serves as a good reflector (approximately 92%) of visible light and an excellent reflector (as much as 98%) of medium and far infrared radiation.

Table 2: Physical Properties

Physical Properties	
Phase	solid
Density (near r.t.)	2.70 $g \cdot cm^{-3}$
Liquid Density at m.p.	2.375 $g \cdot cm^{-3}$
Melting Point	933.47 K1220.58 °F 660.32 °C
Boiling Point	4478 °F 2470 °C, 2743 K,
Heat of Fusion	10.71 $kJ \cdot mol^{-1}$
Heat of Vaporization	284 $kJ \cdot mol^{-1}$
Molar Heat Capacity	24.200 $J \cdot mol^{-1} \cdot K^{-1}$

Chemical Properties

Owing to its resistance to corrosion, aluminum is one of the few metals that retain silvery reflectance in finely powdered form, making it an important component of silver-colored paints. Aluminum mirror finish has the highest reflectance of any metal in the 200–400 nm (UV) and the 3,000–10,000 nm (far IR) regions; in the 400–700 nm visible range it is slightly outperformed by tin and silver and in the 700–3000 (near IR) with silver, gold, and copper. Aluminum is oxidized by water to produce hydrogen and heat:

$$2\,Al + 3\,H_2O \rightarrow Al_2O_3 + 3\,H_2$$

This conversion is of interest for the production of hydrogen. Challenges include circumventing the formed oxide layer, which inhibits the reaction and the expenses associated with the storage of energy by regeneration of the Al metal.

Figure 8: Metal Sheet

Aluminum sheet is used as the secondary of the linear induction motor. It is placed below the core as the rail track in traction application. In the same manner we have used aluminum as the path for the motor. The above figure shows the placement of the aluminum sheet in the linear induction motor.

Router Configuration

Table 3: Rotor Configuration

S. No	Specifications	Measures
1.	Type of material	Aluminum
2.	Thickness	3.3mm
3.	Length of Sheet	1500mm
4.	Breath	90mm

WINDING DESIGN OF LINEAR INDUCTION MOTOR

Winding

A current through any conductor creates a circular magnetic field around the conductor due to Ampere's law. By using a coil shape, the main advantage is that it increases the strength of the magnetic field produced by a given current. The magnetic fields generated by the separate turns of wire all pass through the center of the coil and add (superpose) to produce a strong field there. The stronger the field is produced by using more turns of wire. Conversely, a changing external magnetic flux induces a voltage in a conductor such as a wire, due to Faraday's law of induction. By winding the wire into a coil the induced voltage can be increased, because the field lines intersect the circuit multiple times.

The direction of the magnetic field produced by a coil can be determined by the right hand grip rule. If the fingers of the right hand are enclosed around the magnetic core of a coil in the direction of conventional current through the wire, the thumb will point in the direction the magnetic field lines pass through the coil. The wire or conductor which represents the coil is called the winding. The hole in the center of the coil is called as the core area or magnetic axis. Each loop of wire is called a turn. In windings the turns touch each other, the wire must be insulated with a coating of insulation such as plastic or enamel to prevent the current passing between the wire turns. The winding is often enclosed around a coil form which is made up of plastic or other material to hold it in place. The ends of the wire are brought out and attached to an external circuit. Windings may have additional electrical connections along their length; these are called taps. A winding which has a single tap in the center of its length is called the center-tapped.

Coils can have more than one winding, insulated electrically from each other. If there are two or more windings around a common magnetic axis, then the windings are said to be inductively coupled or magnetically coupled. A time-varying current through one winding will create a time-varying magnetic field which passes through the other winding, which induces a time-varying voltage in the other windings.

Fundamentally, there are two physical types of the windings. They are

- Single layer winding
- Double layer winding.

For both these types of windings, the arrangement of coils sequentially around the armature is different.

Double Layer Winding

It consists of identical coils with one coil side of each coil in the upper half of the slot and the other coil side in the lower half of another slot which is nearly one pole pitch away.

In the figure (a), there are two coil sides per slot while in figure (b) there are eight coil sides per slot. Each layer may contain more than one coil side if large numbers of coils are necessary. Open slots are used for placing double layer windings.

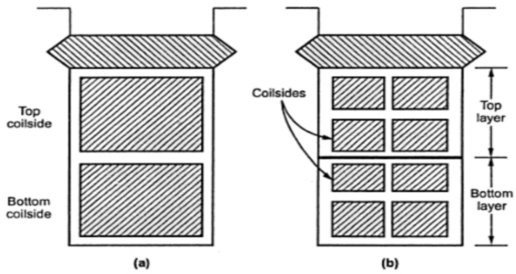

Figure 9: Double Layer Winding

Here we have used 3-phase double layer wave winding in the linear induction motor.

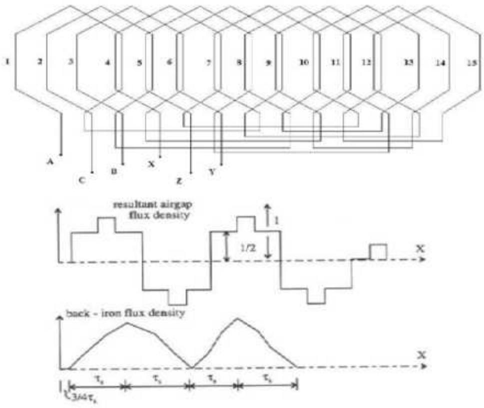

Figure 10: Air Gap and Flux Density Representation

3-phase double layer winding in the linear induction motor and the Air gap flux density result waveforms were done, by using wave winding.

Table 3: Winding Details

S.No	Specifications	Desired values
1.	Type of Winding	Wave winding (double layer)
2.	Number of Coils	12
3.	Pole pitch	105mm
4.	Number of poles	4
5.	Number of Phases	3
6.	Type of winding connection	Star
7.	Number of turns in each coil	50
8.	Type of material used	copper

CONSTRUCTION OF TRACK AND WOODEN WORK

For the construction of track for linear motion of the stator on the rotor following equipment they are.

- Steel Rods
- Linear motion Bearings.

- Stand made up of wooden for supporting of the rods and to place the secondary (Aluminum).

All these equipments are required to overcome the following force which is shown in the figure7. 1

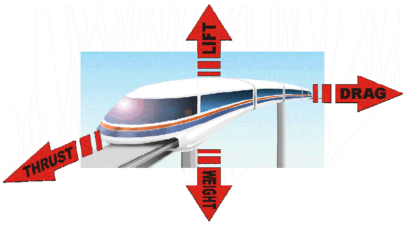

Figure 11: Forces to Oppose

Steel rods of 16mm diameter are used to maintain the air gap between the stator and the rotor. Which up lifts the stator and maintains a gap between them. These steel rods are placed and supported by wooden made stands at a certain height with required clamping to adjust the height according to the required air gap.

Figure 12: Steel Rods Used For the Track

These Steel rods are used for the elimination of the lateral forces on the either side of the stator and help to maintain the air gap between the stator and rotor.

Types of Bearings used for linear motion

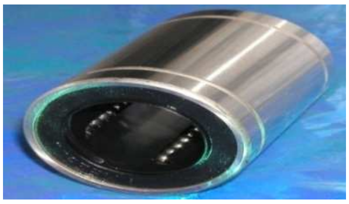

Figure 13: The 16mm Linear Round Shaft Bearing

There are many different types of linear motion bearings. Motorized linear slides such as machine slides, XY tables, roller tables and some dovetail slides are bearings moved by drive mechanisms. Not all linear slides are motorized and non-motorized dovetail slides, ball bearing slides and roller slides provide low-friction linear movement of equipment powered by inertia or by hand. Based on type of bearings all linear slides provide linear motion, whether they are ball bearings, linear roller bearings, magnetic or fluid bearings and dovetail bearings. XY Tables, linear stages, machine slides and other advanced slides use linear motion bearings to provide movement along both X and Y multiple axis.

Figure 14: Bearing (Linear Motion)

Here we have used linear round shaft ball bearings for smooth linear motion of stator on steel rods because of the following advantages.

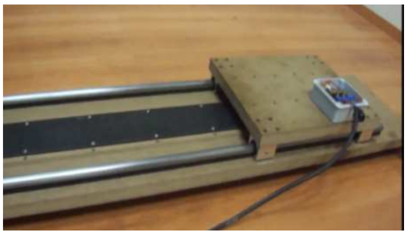

Figure 15: Wooden Frame for the Track

The wooden frame is designed for the following.

- Supporting of the Steel rods.
- Placing the aluminum sheet.
- Frame to fix the stator, terminal box.

Using the wood frame steel rods is fixed and by that air gap will be maintained and supporting will be provided with the rods as the stand. The rotor will be laid on it as a path, i.e. aluminum sheet is fixed to this wooden frame with the help of screws. Another part of the woods is that to fix the stator and it is winding, on this all the connections for the winding can be connected to supply in terminals which are placed upon the wooden frame.

RESULTS AND DISCUSSIONS

Practically Obtained Values

- Stator per phase current rating is 14 Amperes.
- Stator per phase voltage rating is 60 volts.
- The input power factor of the stator is 0.4.

The input power to the stator is given by

$P= 3VI\cos\phi$

$P= 3\times14\times60\times0.4$

Input power = 1008 watts.

Stator Parameters Values

- The per phase input impedance is 4.28Ω.
- The per input resistance is 1.7Ω.
- The per phase input Reactance is 15.83Ω.

Magnetic Parameters

The velocity of the magnetic field is given by

$V_s= 2\times f\times\tau$

$\tau = \frac{2\pi R}{p}$

$V_s = 2\times50\times0.105$

$V_s = 10.5$ meters/second.

The magnetic flux is given by

$\text{Ø} = \frac{\text{Ampere turns}}{\text{Reluctance}}$

$\text{Ø} = \frac{700}{144000}$ = 4.86milli webers.

Magnet flux, $\phi = 4.86\sin\omega t$ milli Weber's.

Average air gap flux density is given by

$B_{avg} = \frac{\phi\times p}{L_s\times W_s}$

$B_{avg} = \frac{4.861\times10^{-3}\times4}{0.42\times0.09}$

B_{avg}=0.732milliweber's.

Output power is given by

$P_{out} = F_s\times V_s$

Where, F_s is force on the stator.

V_s is velocity of the stator.

Required Parameters

- The voltage withstanding capacity of the winding must be 220 volts.
- The slot depth of the stator must be 1.75 centimeters.
- The gauge of the winding must be 26.
- The winding should distribute lap winding.
- The current carrying capacity of the winding must be 10 amperes.
- The volume density of the steel stamping should be less.
- The track adopted should posses low friction.
- Stator Impedance required is 22Ω.
- The stator resistance required is 11Ω.
- Stator reactance required is 19.05Ω.
- Required input power is 3300 watts.

CONCLUSIONS

In this paper, efforts are put into design and fabricate a Simple Linear Induction Motor and the results are validated. It is concluded that the air gap plays an imperative role on the machine performance and it needs to be as small as possible to have a better thrust and Efficiency. The other curial design parameter is the thickness of the aluminum. As the thickness of the Aluminum sheet increases, the thrust also increases along with the length of magnetic air gap which is undesirable. The care has been taken in choosing the value of Aluminum thickness, which yields maximum thrust at a reasonable efficiency. The Linear Induction motor performance can be observed by varying the number of stator poles At the same time driving force is increased at the cost of efficiency. Hence there is a transaction between the driving force and the efficiency with increasing the number of poles.

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