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A DESIGN OF SINGLE SIDED LINEAR INDUCTION MOTOR FOR EFFICIENT PERFORMANCE FOR LOW SPEED APPLICATION

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I. THEORY OF SLIM

The basic principle of LIM operation is similar to that of a conventional rotating squirrel-cage induction motor. Stator and rotor are the two main parts of the conventional three phase rotary induction motor. The stator consists of a balanced polyphase winding which is uniformly placed in the stator slots along its periphery. The stator produces a sinusoid ally distributed magnetic field in the air-gap rotating at the uniform speed 2ω/p, with ω representing the network pulsation (related to the frequency f by ω= 2πf) and p the number of poles. Instead of rotating flux, the primary windings create flux in a linear fashion. The primary field interacts with the secondary conductors and hence exerts a force on the secondary. Generally, the secondary is made longer than the primary to make maximum use of the primary magnetic field. A linear electric motor primary typically consists of a flat magnetic core (generally laminated) with transverse slots which are often straight cut with coils laid into the slots. The secondary is frequently a sheet of aluminum, often with an iron backing plate. Two sorts of linear motor exist, *short primary*, where the coils are truncated shorter than the secondary, and a *short secondary* where the conductive plate is smaller. Short secondary LIMs are often wound as parallel connections between coils of the same phase, whereas short primaries are usually wound in series. The primaries of transverse flux LIMs have a series of twin poles lying transversely side-by-side, with opposite winding directions.

Basic idea of SLIM

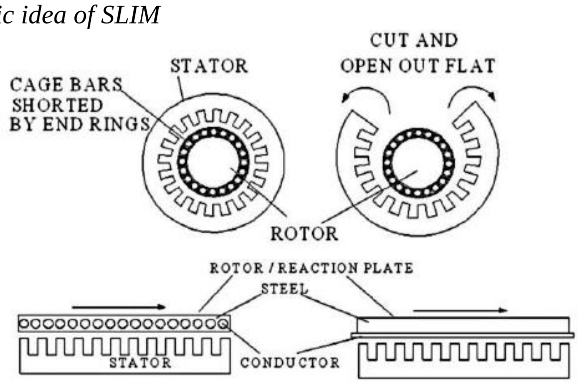


Fig 1. Cutting and Unrolling a RIM to a LIM

The stator produces a sinusoid ally distributed magnetic field in the air-gap rotating at the uniform speed 2ω/p, Slip is the relative motion needed in the induction motor to induce a voltage in the rotor, if the velocity of the rotor is *Vr* , then the slip of SLIM can be denoted as,

$$S = \frac{(Vs - Vr)}{Vs} \quad \ldots (1)$$

The same as that of the rotary induction motor, given by

$$Vs = \frac{2\,\omega\, r}{p} = 2f\tau \quad \ldots (2)$$

τ = pole pitch →the distance between two neighbouring poles on the circumference of the stator

$$\text{Pole pitch } \tau = \frac{2\pi r}{p} = \frac{Ls}{p}$$

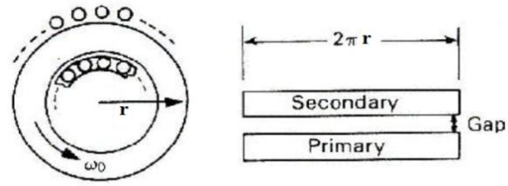


Fig 2. Radius of a Rotary Induction Motor and Length of a SLIM

The length of the SLIM stator core Ls $= 2\pi r$

The pole pitch of a SLIM $\tau = \frac{Ls}{p}$

II. CURRENT SHEET

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 mmf in the air gap as that produced by the conductors. The current sheet strength, i.e, the amount of current per unit stator length (*Ls*) in a current sheet of a SLIM, can be calculated as in Nasar and Boldea [10] as follows:

$$J_m = \frac{2\sqrt{2} m k_w N_c I_1}{L_s}$$

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

$$k_w = k_p k_d$$

$$k_p = \sin\left(\frac{\theta_p}{2}\right) \qquad k_d = \frac{\sin\left(\frac{q_1 \alpha}{2}\right)}{q_1 \sin\left(\frac{\alpha}{2}\right)}$$

$$\alpha = \frac{\pi}{m q_1}$$

The winding factor for the fundamental harmonic of a full pitch coil can be obtained

$$k_w = \frac{\sin(\frac{\pi}{2m})}{q_1 \sin(\frac{\pi}{2mq_1})}$$

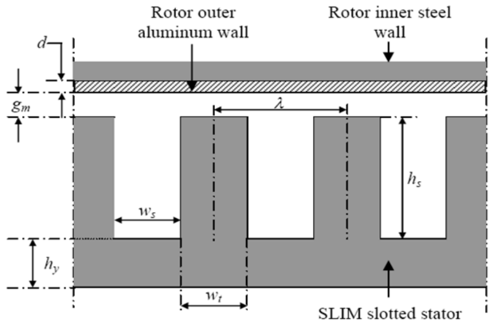


Fig 3 SLIM geometry

III. POWER RATING AND INPUT CURRENT

The electrical power input to the stator windings is converted into useful mechanical power by the principle of electrical induction,

- The power input to the stator windings is given by
  $P_i = mV_1 I_1 \cos\phi$
- The total mechanical power developed by the rotor of the SLIM is given by [3]
  Po = FsVr,
- The SLIM efficiency η is calculated from

$$\eta = \frac{P_o}{P_i} = \frac{F_s V_r}{mV_1 I_1 \cos\phi}$$

- Initially a suitable operating value for ηcosφ shall be assumed, and then the rated input phase current can be estimated from

$$I_1 = \frac{F_s V_r}{mV_1 \eta \cos\phi}$$

3.1.3 Flux Linkage and Induced Voltage

- The flux Φ in the air-gap is assumed to be purely sinusoidal, then it can be expressed as

$$\Phi = \Phi p \sin\omega t,$$

- The RMS value of induced voltage (e) per turn

$$E_1 = \sqrt{2}\pi f \Phi_p k_w N_1$$

- Average air-gap magnetic flux density, *B*gavg can be determined as

$$B_{gavg} = \frac{\Phi_p p}{L_s W_s}$$

having a maximum of B_{gmax}. Hence, the average value of the rectified magnetic flux density is

$$B_{g\,avg} = \frac{2}{\pi} B_{g\,max}$$

Various Forces in SLIM

The main forces involved with the LIM are thrust, normal force, and lateral force, as shown in Fig 4. This project is interested in thrust and its relation to other variable parameters. The normal force is perpendicular to the stator in the z-direction. Lateral forces are undesirable forces which are developed in a SLIM because of the orientation of the stator.

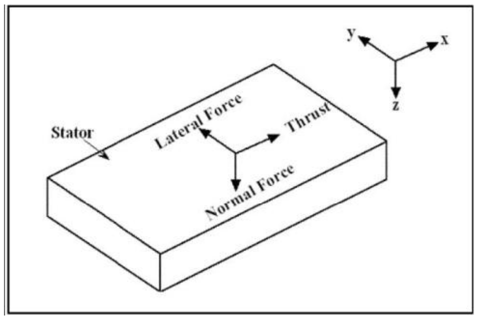


Fig 4. Forces in a LIM

Equivalent Circuit Model of SLIM

The approximate equivalent circuit of a LIM is presented [3]as shown in Fig. 3.5 This circuit is on a per phase basis.
The core losses are neglected because a realistic airgap flux density leads to moderate flux densities in the core and hence, rather low core losses. Skin effect is small at rated frequency for a flat linear induction motor with a thin conductive sheet on the secondary. Therefore, equivalent rotor inductance is negligible [5]

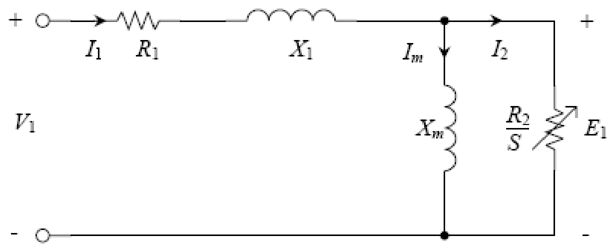


Fig. 5 Per-phase SLIM equivalent circuit

Per-phase stator resistance

$$R_1 = \rho_w \frac{l_w}{A_{wt}}$$

Per-phase stator-slot leakage reactance

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

Per-phase rotor resistance *R2*

$$R_2 = \frac{X_m}{G}, \qquad G = \frac{2\mu_0 f \tau^2}{\pi(\frac{\rho_r}{d}) g_e}$$

Per-phase magnetizing reactance *Xm*

$$X_m = \frac{24\mu_0 \pi f W_{se} k_w N_1^{\ 2} \tau}{\pi^2 p g_e}$$

Magnitude of Rotor current

$$I_2 = \frac{X_m}{\sqrt{\left(\frac{R_2}{S}\right)^2 + X_m^2}} I_1$$

Finally

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

3.3Efficiency and Thrust

The mechanical power developed by the rotor

$$P_o = mI_2^2 \frac{R_2}{S} - mI_2^2 R_2 = mI_2^2 R_2 (\frac{1-S}{S})$$

The electromagnetic thrust generated by the SLIM stator is

$$F_s = \frac{mI_2^2 R_2}{V_s S}$$

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

The SLIM input active power

$$P_i = P_o + mI_1^2 R_1 + mI_2^2 R_2$$

The efficiency of the SLIM is

$$\eta = \frac{P_o}{P_i}$$

IV. DESIGN CONSIDERING END EFFECT

A linear induction motor exhibits end effects. With a short secondary, the behavior is similar to a RIM, provided being at least 2 poles long. With a short primary reduction in thrust occurs at low slip (below about 0.3) until it is eight poles or longer. However, because of end effect, linear motors cannot 'run light'- normal induction motors are able to run the motor with a near synchronous field under low load conditions. Due to end effect this creates much more significant losses with linear motors. 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. [3], [4], [5], [6]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 *ktm*

$$k_{tr} = \frac{k_x^{\ 2}}{k_R} \frac{1 + \left(\frac{SGk_R}{k_x} \right)^2}{1 + S^2 G^2} \geq 1$$

$$k_{tm} = \frac{k_R}{k_x} k_{tr} \leq 1$$

$$k_R = 1 - \mathrm{Re}\left[(1 - jSG) \frac{2\lambda_t}{\alpha W_s} \tanh\left(\frac{\alpha W_s}{2} \right) \right]$$

$$k_x = 1 + \mathrm{Re}\left[(SG + j) \frac{2SG\lambda_t}{\alpha W_s} \tanh\left(\frac{\alpha W_s}{2} \right) \right]$$

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

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

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

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

$$\delta_i = \mathrm{Re}\left\{ \frac{1}{\left[\frac{\pi^2}{\tau^2} + j2\pi f_1 \mu_i \frac{S\sigma_i}{k_{tri}} \right]^{1/2}} \right\}$$

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

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

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

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

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

$$R_1 = \frac{\rho_w (2W_s + 2l_{ce}) J_1 N_1}{I_1'}$$

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

$$X_m = \frac{24\mu_0 \pi f W_s K_w N_1^2 \tau}{\pi^2 p g_{ei}}$$

$$R_2 = \frac{X_m}{G_{ei}}.$$

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

$$F_s = \frac{3I_2^2 R_2}{S2\tau f_1} = \frac{3I_1^2 R_2}{S2\tau f_1 \left[\left(\frac{1}{SG_{ei}} \right)^2 + 1 \right]}$$

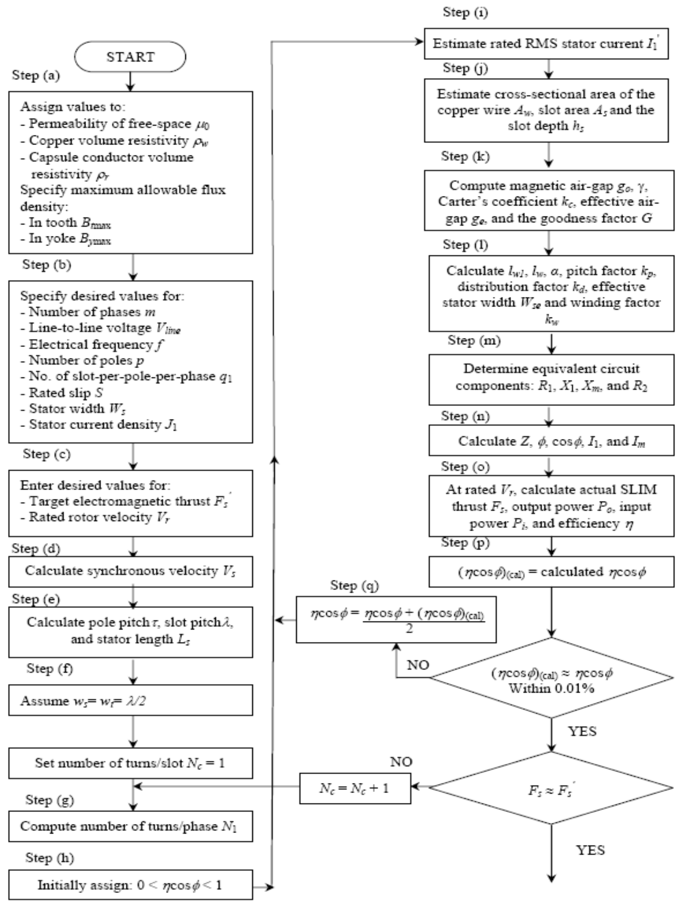
$$F_n = W_{se} \frac{p\tau^3}{\pi^2} \frac{\mu_0 J_m^2}{g_{ei}^2 (1 + S^2 G_{ei}^2)} \left[1 - \left(\frac{\pi}{\tau} g_e S G_{ei} \right)^2 \right]$$

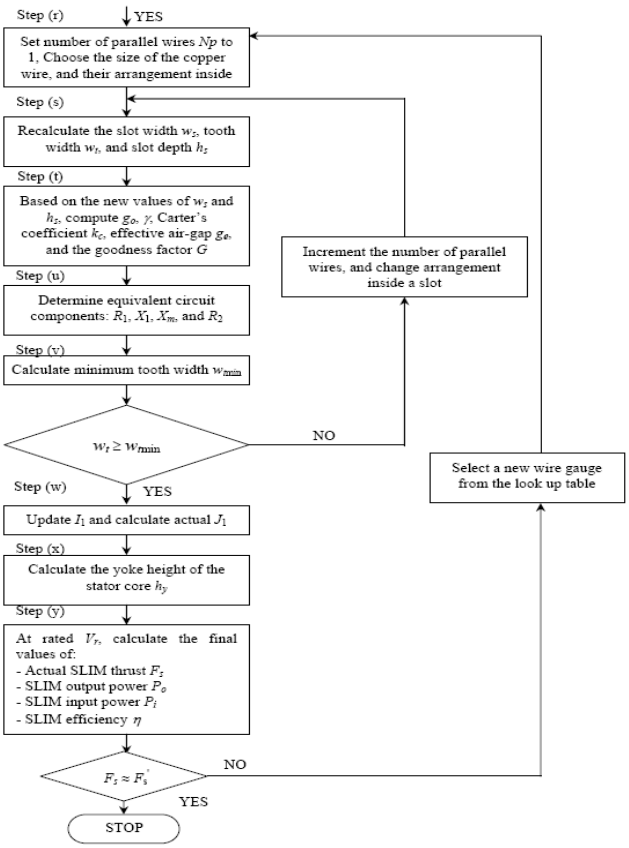
$$G = \frac{2\mu_0 f \tau^2}{\pi \left(\frac{\rho_r}{d} \right) g_e}$$

$$\eta = \frac{F_s 2\tau f_1 (1 - S)}{F_s 2\tau f_1 + 3R_1 I_1^2}$$

$$\cos\phi = \frac{F_s 2\tau f_1 + 3R_1 I_1^2}{3V_1 I_1}$$

FLOWCHART FOR DESIGN USING MATLAB SCRIPT





Optimized Result	
Parameter	**Value**
Input Phase voltage (V)	220
Supply frequency	146.5
No of Poles	4
slots/pole/phase	3
Primary width (mm)	130
Thickness- secondary sheet(mm)	2.0
Current density(A/mm^2)	6
Air gap length (mm)	5.1

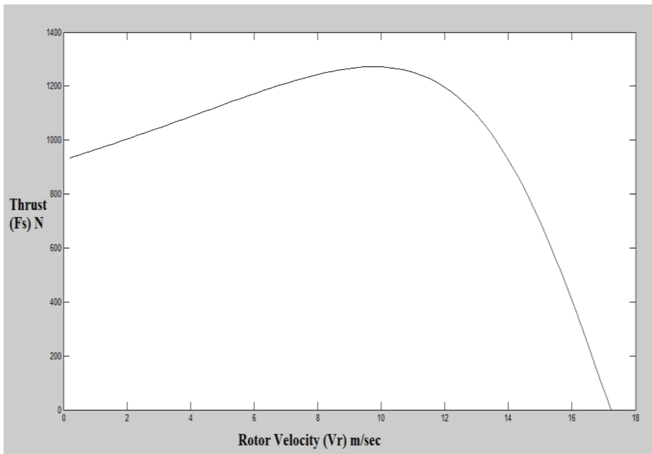
Table 2 Optimized Motor parameter by AI [3

V. OBSERVATION AND DISCUSSION OF RESULTS

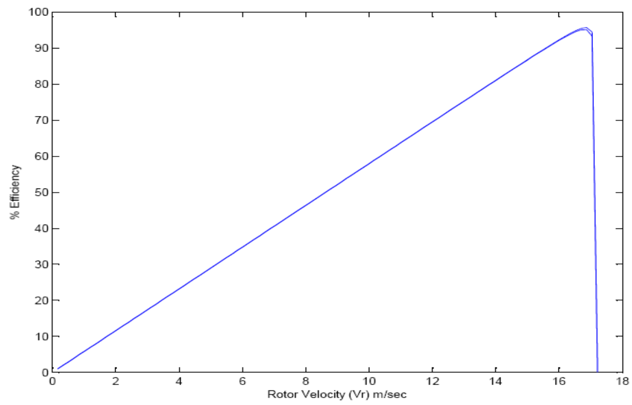
The performance curves of the SLIM are drawn and then analyzed for different target thrust values and rated slip for [3]

Motor Investigated	
Parameter	**Value**
Input Phase voltage (V)	220
Supply frequency	166
No of Poles	8
slots/pole/phase	3
Primary width (mm)	148.3
Thickness- secondary sheet (mm)	2.5
Current density(A/mm^2)	6
Air gap length (mm)	5.1

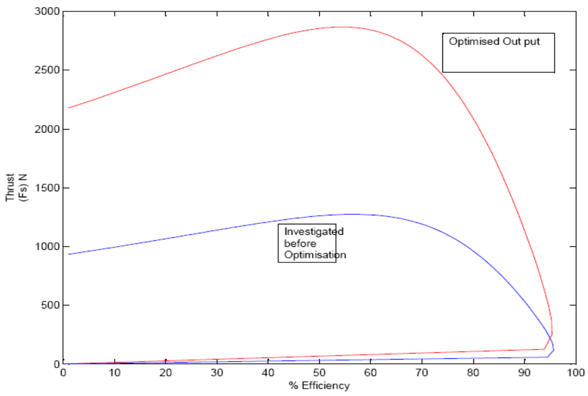
Table 1 Motor investigated before optimization [3]



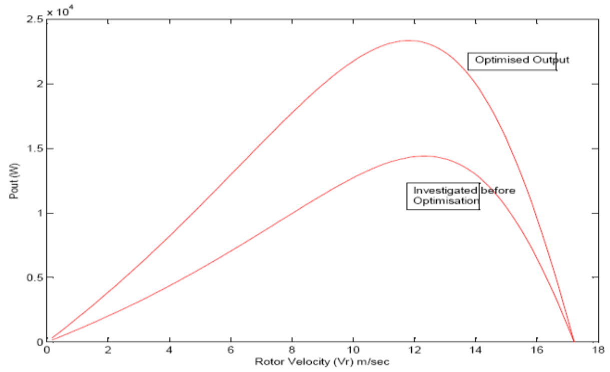
Thrust *Fs* → rotor velocity *Vr* of reference **[3]** SLIM at a rated slip of 0.2, a desired rotor velocity of 15 m/s, a target thrust of 1000N



Efficiency η → rotor velocity *Vr* of reference **[3]** SLIM at a rated slip of 0.2, a desired rotor velocity of 15 m/s, a target thrust of 1000N



Thrust *Fs* → Efficiency *η* of reference **[3]** SLIM at a rated slip of 0.2, a desired rotor velocity of 15 m/s, a target thrust of 1000N



Output power *Pout* → rotor velocity *Vr of* reference **[3]** SLIM at a rated slip of 0.2, a desired rotor velocity of 15 m/s, a target thrust of 1000N

VI. CONCLUSION

The air-gap has importance in performance of the SLIM. A small airgap contributes to better thrust and efficiency. The thrust increase undesirably along with magnetic air-gap with an increase in the thickness of the aluminum sheet. The optimized value of the thickness is to be chosen which provides maximum thrust at a sensible efficiency. Increasing the number of poles reduces the end effects at frequency >>60Hz and thrust is enlarged at the cost of efficiency. Hence care should be taken in choosing the length of air-gap, the aluminum sheet thickness and the number of poles for optimized performance based on target rotor velocity and thrust, at optimized value of efficiency. The optimized design parameters simulated in design with MATLAB program. The optimized design of the SLIM is showing that the final thrust from this design is very close to the target

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