Changing Many Design Parameters in the Performance of Single-Sided Linear Induction Motor (SLIM) for Improved Efficiency and Power Factor

Hayder Hussein Kadhum, Hayder H. Enaw, and Karrar M. Al-Anbary

Abstract Linear induction motors (LIM) are applied obviously in industrial applications, mainly in linear motion models. In fact, these machines have two general problems which are low efficiency and low power factor. These issues cause different side effects such as high power consumption, high input current, and occupation. This research studies the dynamic behavior of a single-sided linear induction motor by changing the basic design parameters. The process of selecting the equivalent circuit elements was also carried out using a new algorithm to obtain a modified model to meet the requirement, which is to improve the efficiency and power factor simultaneously. The final equivalent circuit of the modified model was adopted as an input to a simulation program using MATLAB/SIMULINK, which helped build an integrated model using mathematical equations with the specified inputs and the required outputs. Also, the process of testing and comparing the results is implemented for the proposed model in different cases with and without load. Then, analysing the results of motor performance and response speed using a voltage source inverter (VSI) with and without using a PID controller to improve the dynamic performance of the model, and speed control. Finally, the optimization results are validated, and the results are compared. The outcomes of proposed algorithm are shown by the genetic algorithm (GA), particle swarm optimization (PSO), and Cuckoo search with respect to the power factor and efficiency.

Keywords Efficiency and power factor improvement · Analytical model · (SLIM) design · Thrust

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1 Introduction

During last decades, electrical systems started using SLIM obviously in transferring electrical power. This is because SLIM has important features as compared with rotary induction motor (RIM) which are higher generating power without mechanical contacts, longer life of wheels, better road line, lower radius of turns, and quicker deceleration as well as acceleration [1]. However, in many applications, which need linear motion, linear induction motors (LIMs) represent the best option due to their properties such as cheap price and maintenance, high deceleration or acceleration, and easy design. As a result, LIMs have been applied largely in different applications like transferring systems, processing materials, smart applications such as opening and closing doors and others automatically and so on [2, 3].

Charles Wheatstone designed first linear motor in 1845 [5–7]. During last decades, SLIM has been studied obviously in different analysis techniques. However, there are some reasons which make analysis of this motors type very difficult. The first main reason is the disability of identifying size of the electrical and magnetic loads. This prevents determining apparent power. One of the main steps in analyzing with single-sided LIM with a solid-steel reaction plate is calculating its mutual reactance. It is determined by two-dimensional field distributions between the air-gap as well as the secondary windings. The 2D FEM of field distribution is applied to find the parameters of a two-axis design. The static nonlinear vector potential technique has been used in determining flux distribution with iron at saturation. However, the linear time harmonic vector potential field is applied when computing inductance with analytical model. These inductances help effectively in determining the power factor in addition to the efficiency [8]. For developing LIMs response, the control as well as the design of these motors should be optimized continuously. Most of the researches ignore optimizing design for LIMs [9]. Generally, the researches focus on expenditure, starting torque, primary weight, and winding design, while other important factors, like efficiency as well as power factor (PF), did not take enough concentration. Furthermore, low efficiency means higher energy consumption. Additionally, low PF leads to more power losses during transferring. As a result, inverter cannot work optimally. In general, there are several main features which are adopted in optimization design like transverse edge influence, end effect as well as normal force aspects [10–13].

Moreover, end effect affects directly on the efficiency as well as power factor and that leads to change design features of SLIM as well. Furthermore, the structure of the motor changes its pole pitch. Also, identifying frequency and rated slip depends mainly on the rated speed of the motor [14–18]. This paper gives a modern technique depending on the air-gap flux density equation. This equation does not ignore the influence of end effects. As a result, several nonlinear equations have been built which satisfy highest efficiency with smallest primary weight. After that a suitable method is required for calculating independent variables like the ratio between slot width and slot pitch, number of poles, stack height, pole pitch, and so on [14–16].

The goal of this research is to study the performance of a modified model of SLIM by varying its parameters to reduce the power consumptions and increase the power factor. The design parameters and the equivalent circuit are used as optimization technique. They help effectively in enhancing efficiency as well as power factor of the final proposed model. This model is tested and simulated thorough applying MATLAB/SIMULINK programming. The characteristics and performance of this model are studied for different load conditions. For instance, it is connected directly to the supply voltage and then through voltage source inverter (VSI) with and without the aid of PID controller.

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2 Physical Structure and Magnetic Equivalent Circuit Models

Figure 1a and b below demonstrates the structure of the short stator and rotor of LIM which is used in this study.

In general, the changing of skin at rated frequency is very little. This is because the conductive sheets on secondary side are very slim. As a result, equivalent secondary inductance in the proposed design is ignored the resistance of any phase of the LIM stator windings. R_1 is measured by the following formula:

$$R_1 = \rho_w \frac{l_w}{A_w} \tag{1}$$

while ρ_w is the wire resistivity of stator winding, l_w is wire length for each phase separately, and A_w is cross-section area of the wire. This leakage reactance can be calculated as:

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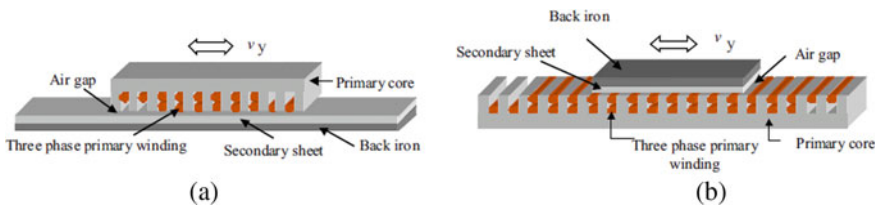

Fig. 1 Structures of LIM **a** short stator **b** short rotor

$$\lambda_s = \frac{h_s(1 + 3k_p)}{12w_s}, \quad \lambda_e = 0.3(3k_p - 1) \text{ and } \lambda_d = \frac{5\left(\frac{g_e}{w_s}\right)}{5 + 4\left(\frac{g_0}{w_s}\right)}$$

The magnetizing reactance X_m is shown in

$$X_m = \frac{24\mu_0\pi f W_{se}k_w N_1^2 \tau}{\pi^2 p g_e} \tag{3}$$

where W_{se}, stator width given as

$$W_{se} = W_s + g_0 \tag{4}$$

The goodness factor is defined as:

$$G = \frac{2\mu_0 f \tau^2}{\pi\left(\frac{\rho_r}{d}\right)g_e} \tag{5}$$

3 Thrust and Efficiency

Generally, electromagnetic torque as well as rotation speed represents the main output parameters of the rotary motors which are measured by N, M, and Rad/sec, respectively, while electromagnetic thrust and linear speed are mostly used as output elements of linear motors that measured by N and m/sec sequentially. Furthermore, the following formula is applied to calculate electromagnetic thrust [18].

$$P_o = mI_2^2 \frac{R_2}{S} - mI_2^2 R_2 = mI_2^2 R_2\left(\frac{1 - S}{S}\right) \tag{6}$$

$$P_o = F_s v_r \tag{7}$$

$$v_r = (1 - S)v_s \tag{8}$$

$$F_s = \frac{mI_2^2 R_2}{v_s S} \tag{9}$$

By putting Eq. (8) in Eq. (9) the SLIM electromagnetic thrust becomes:

$$F_s = \frac{mI_1^2 R_2}{\left[\frac{1}{(SG)^2}\right]v_s S} \tag{10}$$

Then, the efficiency as well as power factor of LIM will be as following:

$$\eta = \frac{F_s 2\tau f_1 (1 - S)}{F_s 2\tau f_1 + 3R_1 I_1^2} \tag{11}$$

$$\cos\phi = \frac{F_s 2\tau f_1 + 3R_1 I_1^2}{3V_1 I_1} \tag{12}$$

There are various factors effect on efficiency and power factor. Therefore, applying optimization technique between these factors helps effectively in identifying the suitable parameters.

4 Voltage Source Inverter (VSI) Technique

Inverters are the devices which are changing the electrical power from DC to AC. In these devices; the output power is taken with a specific voltage value as well as frequency. During voltage source inverter (VSI) technique, the output voltage can be varied with a specific frequency and vice versa. Changeable output voltage is determined through changing the input DC voltage or by gate signal of the inverter, which is normally accomplished by pulse width modulation (PWM) technique [21, 22]. The major reason of applying these methodologies is to supply a three-phase voltage source to LIM. In fact, the value and frequency of the voltages must be convenient. This helps greatly in controlling the speed of LIM easily. MATLAB program is used in simulating the performance of SLIM. Stationary reference frame helps largely in modeling the suggested motor. The block diagram of SLIM fed from VSI is shown in Fig. 2. The inverter phase voltages that fed to SLIM with modulation index equal to 1 and 0.5 are shown in Figs. 3 and 4, respectively.
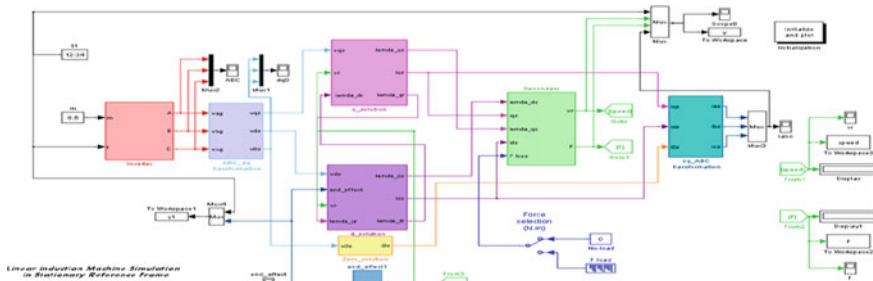

Fig. 2 Linear induction motor simulation using stationary reference frame fed from VSI
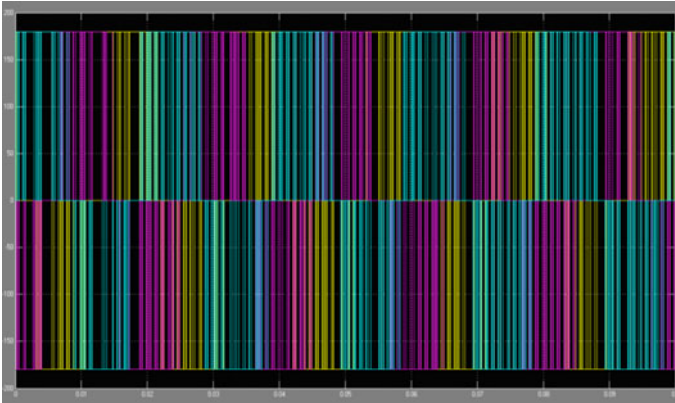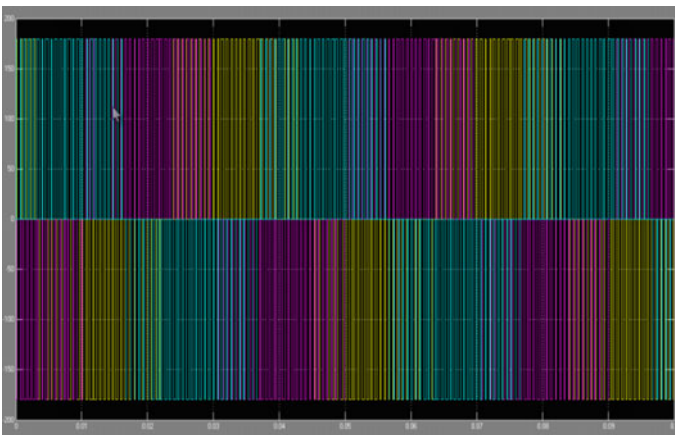
Fig. 3 Inverter voltage at modulation index = 1

Fig. 4 Inverter voltage at modulation index = 0.5

5   SLIM Design and Optimization

For enhancing the performance of SLIM, the elements which have major influ-
ence must be identified. For this model, these elements are efficiency, power factor,
maximum thrust slip, aluminum thickness, primary width or pole pitch, primary
current density, and the braking force on the end effect. In this paper, several design
factors of a reference SLIM design are used to investigate the dynamic performance
of this motor. After that the optimization technique is applied to achieve suitable
equivalent circuit of the modified suggested system. This methodology is achieved
by developing and using a computer program based on MATLABfor optimization

and enhancement evaluation, for the efficiency and power factor product. For evaluating the response of SLIM, the suggested elements are changed separately. Then, the optimal value for every factor is recognized. The analysis process is implemented through altering one factor with keeping the others constant. After that the effect of varying these parameters on the performance of SLIM is analyzed, and the results are discussed. The suggested design has to involve the optimal value of used factors for satisfying the higher efficiency and best power factor. The design steps and evaluation process of the SLIM analysis are summarized in the flowchart shown in Fig. 5. A computer program is developed to implement and processing the motor parameters and operation factors.

6   Simulation Results Using PID Controller

PID is a short of proportional–integrative–derivative. It is the best technique of controllers for processing the errors of data. In general, this method depends on the feedback data of the controller in overcoming the mistakes. In fact, a comparison has been performed between input data and the reference data to find the mistakes. After that the error has been adjusted before input to the system. In some situations, the optimization must be implemented for calculating and processing the outcomes to be suitable. The operating formula of PID controller is shown below:

$$U(t) = K_\mathrm{p} e(t) + K_\mathrm{t} \int e(t)\mathrm{d}t + K_\mathrm{D} \frac{\mathrm{d}}{\mathrm{d}t} e(t) \tag{13}$$

While $u(t)$ represents the output comes of PID controller, K_P, K_I, and K_D are the proportional, integrative as well as derivative gains, correspondingly. Finally, $e(t)$ is the error of the wave which is measured by the following equation:

$$e(t) = r(t) - y(t) \tag{14}$$

$r(t)$ represents the reference value, while $y(t)$ is the output of the circuit. The determination of these three parameters can be tuned by "Trial and Error" principle to get the best controller response. After many testing and running in the simulation, the final best parameters values are as follows:

- Proportional gain (k_p): 0.2.
- Integral gain (k_I): 60.
- Derivative gain (k_d): zero (in this project).

Through changing the gains of the PID controller, the performance of this controller arrives its optimal case at specific values [10]. In fact, proportional gain represents the most important factor. It plays an important role in varying its value with respect to input error. The output of the controller changes according to the
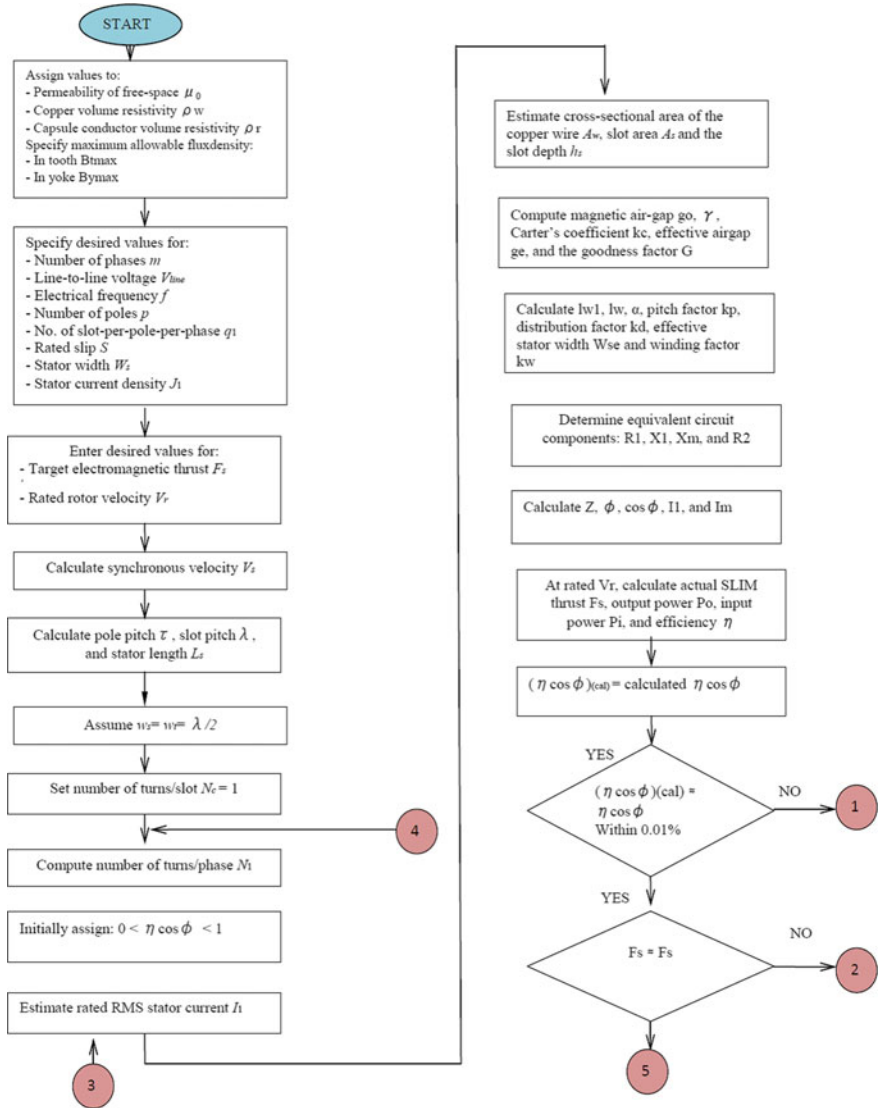
Fig. 5 Flowchart optimizations were implemented depending on the analytical system of the machine, and these data are given in Table 1

proportional gain which depends directly on the error of the input signal. In some time, the value of proportional gain increases largely and then leads to instable situation. Control block implements a PID controller which is reasonable of controlling the reference speed signal in different speed ranges (from zero upward rated speed).

Figure 6 shows the overall diagram of SLIM in MATLAB/SIMULINK using PID controller. In the beginning, KI and KD have been made zero, while KP is varied
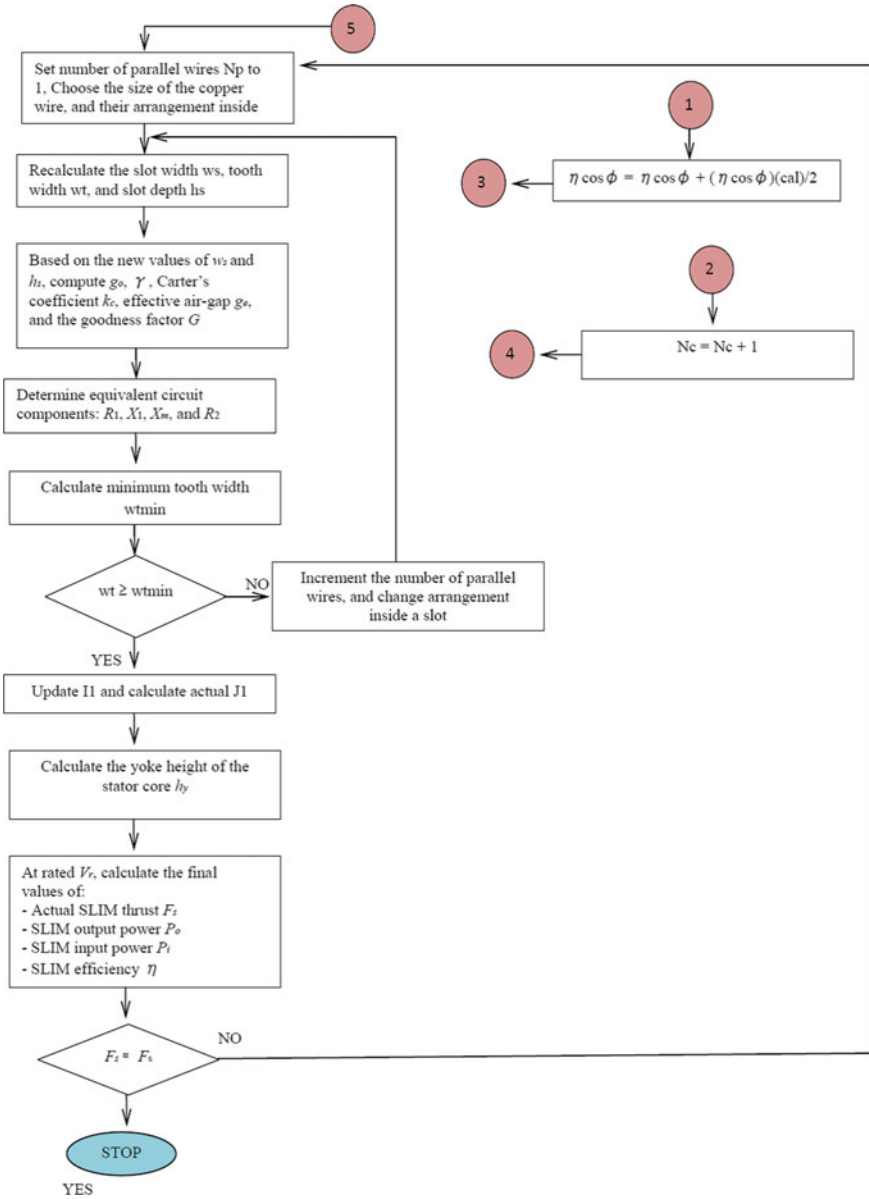
Fig. 5 (continued)

Table 1 Optimized motors specification

| Parameter name	Primary length (mm)	Primary depth (mm)	Slot width (mm)	Slip frequency)	Slot depth (mm)	Number of poles	No. of slots	Conductor area (mm^2)	Base velocity (Km)	Efficiency	Power factor
Original	1950	98.6	15.87	6	58	6	80	67.19	40	0.65	0.50
Optimal-1	2341	119.6	19.3	6	83.6	8	78	118.8	40	0.701	0.48
Optimal-2	2333	114.6	19	5.87	79.1	8	78	106.4	40	0.704	0.4657
Optimal-3	2333	114.6	18.8	5.7	74.2	8	78	101.83	40	0.709	0.478
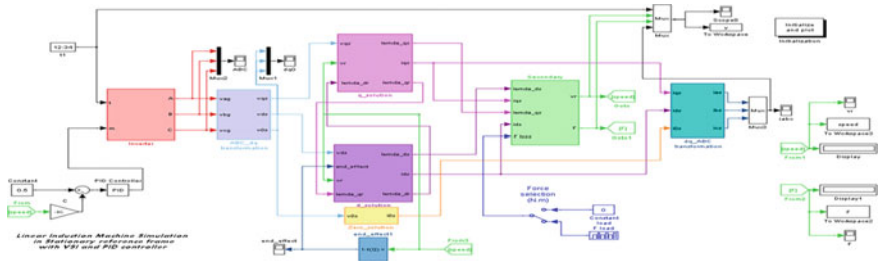
Fig. 6 Block diagram of SLIM with PID controller

in steps, and the response of SLIM is checked in each step until oscillation. Then, KP is made half of oscillation magnitude according to "quarter amplitude decay" type reaction. After that KI will be increased, with saving other gains constants, until overcoming any error in the response. Similarly, increasing KI too much will lead to unstable situation. Lastly, KD will be changed if the response of the system still unacceptable. KD helps the system to satisfy its normal performance in short time after any load disturbance. In the same way, KD can cause overshoot in the system performance if it increases so high.

7 Result

Table 2 below shows the suggested values of best design parameters than other methods (Conventional motor parameters, Cuckoo method, and PSO method) and thus improves the power factor and efficiency.

Table 2 Comparison of various optimization results

Parameter name	Conventional design [17]	Cuckoo search [16]	PSO [15]	Proposed model
Efficiency (%)	36	49.01	54.68	69.94
Maximum thrust slip	0.5	0.5	0.3	0.69
Power factor	0.32	0.5729	0.58	0.711
Primary current density (Amm-2)	4	3	6.5	7.6
Primary width/pole pitch (mm)	2	2	4	5.9
Aluminum thickness (inches)	2	1	4	5.3

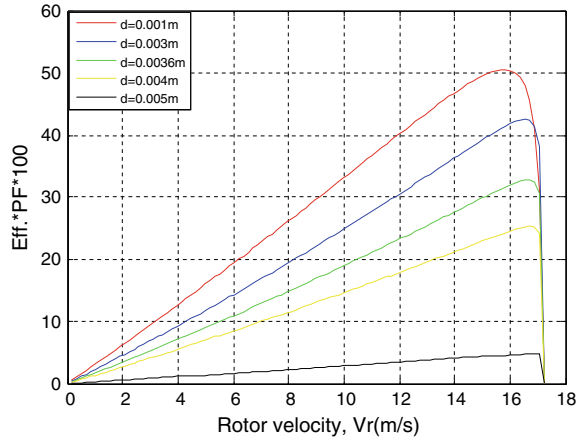**Fig. 7** Variation of $\eta \cos \varphi$ product with v_r for different (d)

Fig. 8 Variation of $\eta \cos \varphi$ product with v_r for different air-gap length (g_m)
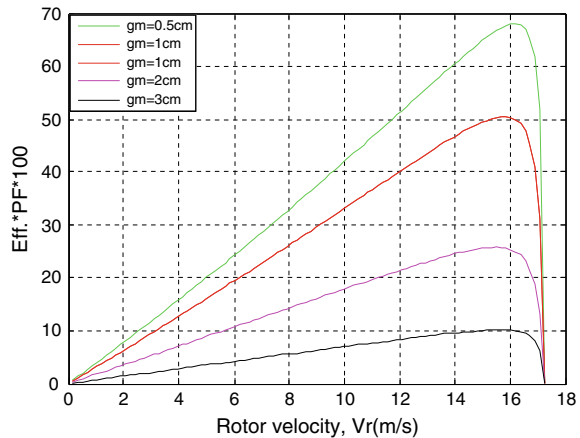

Figure 7 gives the clearly applied result between efficiency with respect to rotor speed of different thicknesses. In addition, this approach is repeated again at different air-gap length, different number of poles, and different slips. Figures 8, 9, and 10 below show these relationships observably.

7.1 Simulation Results for Speed Control Using VSI

Figures 11 and 12 show the thrust force and secondary speed v_r at variable load and at no load, at (modulation index 0.5 and modulation index 1). It is clear when comparing that the speed is reduced to about 7.8 m/s for modulation index = 0.5 as it was 15.7 m/s for m=1. Similar effect of modulation index on v_r is occurring for load

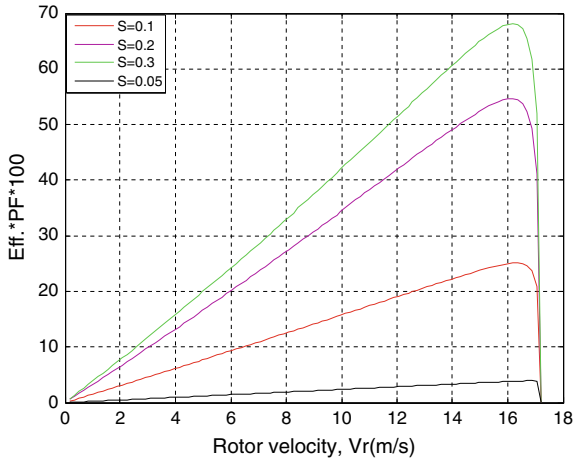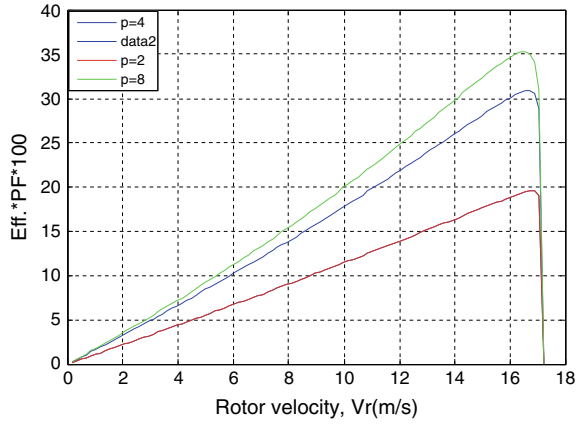**Fig. 9** Variation of $\eta \cos \varphi$ product with v_r

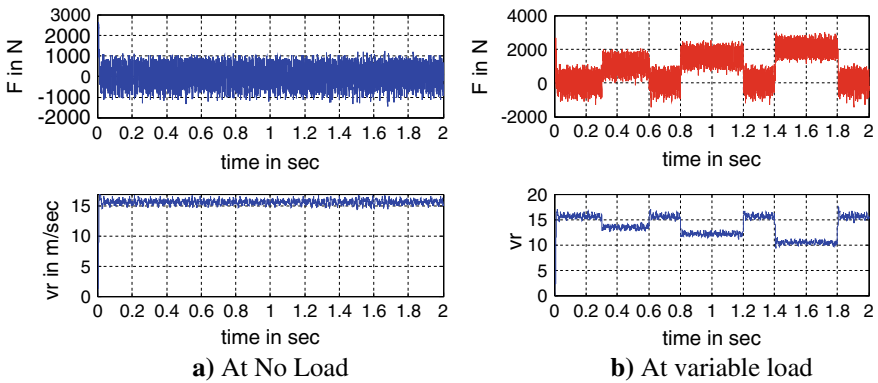**Fig. 10** Effect of changing slip (S) on the $\eta \cos \varphi$

a) At No Load

b) At variable load

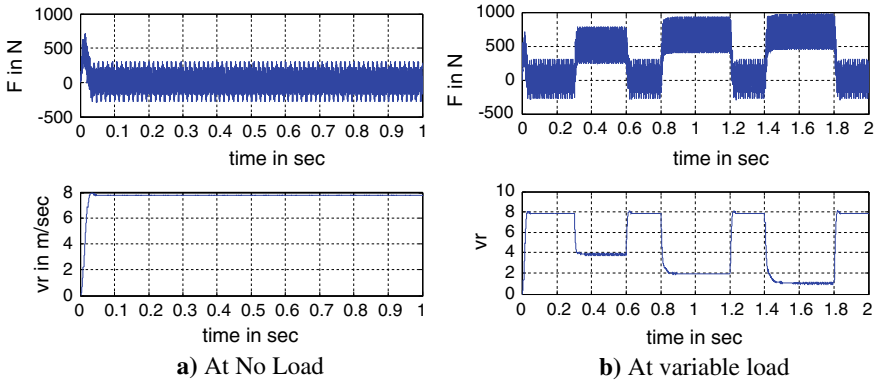**Fig. 11** Force and speed v_r (modulation index $= 1$)

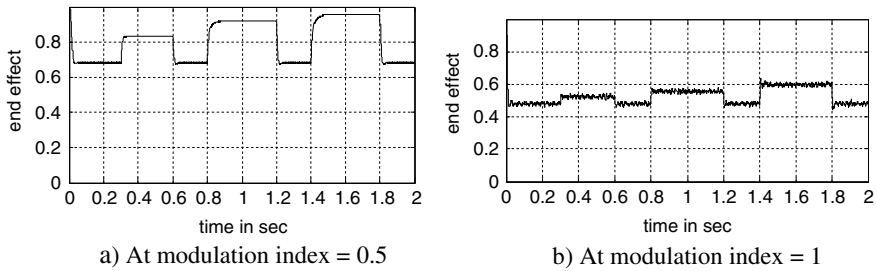**Fig. 12** Force and speed v_r (modulation index = 0.5)

Fig. 13 End effect with time

conditions. Also, it is clear from these results that a wide variable range in speed can be obtained by varying modulation index (*v/f* ratio) where when the modulation index equal to 1 the speed equals to the rated speed, and when the modulation index equals to 0.5, the speed reduced to half the rated speed, and the end effect factor is increased due to reduction in speed as shown in Fig. 13. At the instant of load application, there is an increase in force and a reduction in speed; these effects increased with increasing load.

7.2 Simulation Results Using PID Controller and Comparing with VSI

Figures 14, 15, and 16 show the speed and end effect during load intervals with modulation index equal to 1 and at equal to 0.5. If a comparison is made between the speed response without using of PID controller and with using PID controller, it is clear that at the intervals of applied load, the speed decreases without PID controller, while with PID controller, the speed maintains still at the steady-state
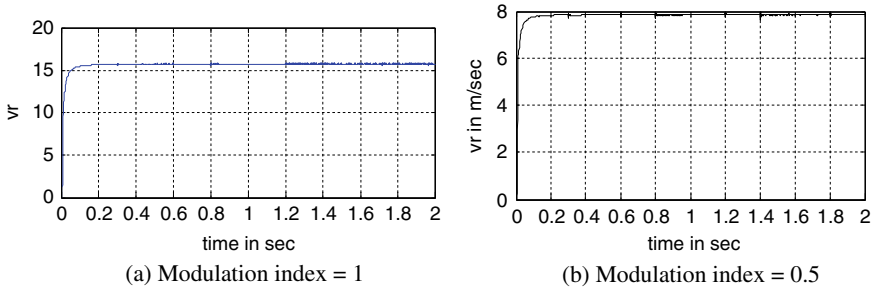
(a) Modulation index = 1

(b) Modulation index = 0.5

Fig. 14 Speed response of SLIM at variable load with PID controller

(a) With PID controller

(b) With VSI

Fig. 15 End effect of LIM at modulation index = 1

(a) With PID controller

(b) With VSI
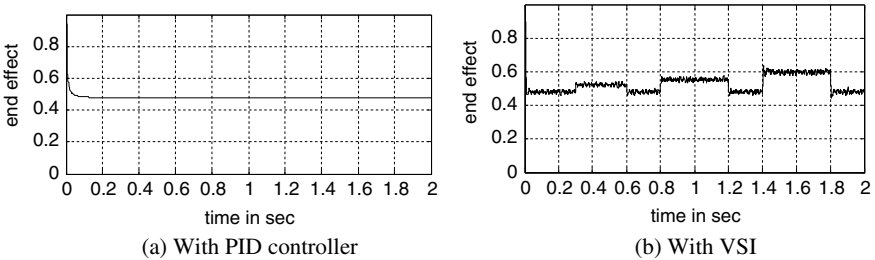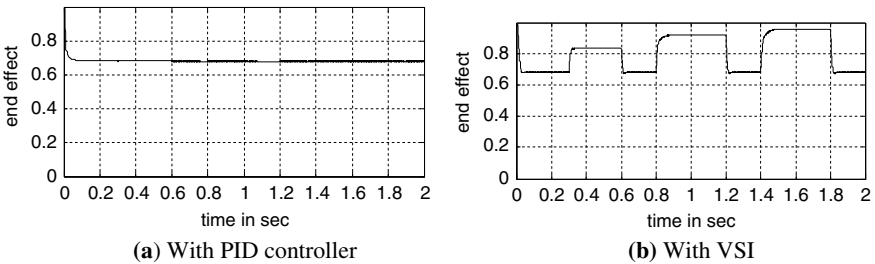
Fig. 16 End effect of LIM at modulation index = 0.5

speed value at the load intervals. This is the requirement of using PID controller for the speed control. Also, using of PID controller will reduce the steady-state error, and it eliminates the overshooting of the speed response with reasonable settling time.

7.3 Result Analysis

After checking the methods and analyzing the result, which is applied to the proposed model, it becomes clear that the power factor can be raised by 12%. Moreover, the

efficiency can also be improved by 15%, compared to particle swarm optimization (PSO) method as well as the power factor can be raised by 15%, and the efficiency can be improved by 20% when compared to Cuckoo search. Also, it is noted that increasing the number of poles causes large influence on the thrust of LIM (Velocity vs Force). Moreover, this influence decreases in the ends. However, the loss at end effect divides on the number of poles which means this loss reduces with increasing poles numbers. As a result, the response of the motor becomes better with high number of poles. Similarly, the thrust enhances with increasing poles numbers too. But, experimental outcomes show that increasing poles numbers can lead to shrink the efficiency of the machine. Therefore, the number of poles should be selected depending on the priority ratio between efficiency as well as thrust.

8   Conclusion

In conclusion, this paper gives a simple optimization technique which focuses mainly in enhancing the efficiency and power factor of SLIM. In the beginning, it gives a clear introduction which discuss the role of LIMs in transferring systems, processing materials, smart applications. After that it speaks about the properties of SLIM and the parameters with their limitations which should be applied in the proposed model. After that it demonstrates a brief structure with electrical circuit of the suggested design. Then, a clear theory has been given on the factors which are affecting mainly of the thrust and efficiency as well as power factor. Subsequently, the performance of SLIM is discussed briefly by using simple flowcharts to demonstrate the steps of proposed approaches. Next, the results of all approaches are shown clearly in separate curves. Moreover, all curves and results have been analyzed. Finally, the notes, which are obtained from this analysis, are given in several points. The result illustrates clearly that the power factor can be increased by 15% after applying this technique. Furthermore, the efficiency can be improved by 0.20% by this method, this suggested as one of the simple and cheap methods which can be used to enhance the performance of SLIM for different electrical applications.

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