Speed Control for Linear Induction Motor Based on Intelligent PI-Fuzzy Logic

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***Abstract*—Nowadays, linear induction motors (LIM) are most used in applications such as transportation, liquid metal pumping, material handling, etc. These applications require large forces and high constant speed under changes in load. The LIM suffers from change in speed as a result of the force loads applied to it instantaneously, which causes high ripple in the force response and not constant speed. This research proposes solutions to these problems by designing an intelligent controller to improve the response variable-speed with different forces. LIM was represented by d-q model using MATLAB/Simulink based-on equivalent circuit equations for LIM and study dynamic performance of this machine. The motor was operated at different speeds and loads; the speed change was observed when the load changed. a PI-controller was designed to control velocity of the machine and keeping its velocity constant at load changes. the values of gains (Kp, Ki) was taken manually by using Ziegler method and this requires a long time as tuning the gain values at every reference speed. An intelligent self-tuning fuzzy-PI controller was prepared to select best values of gains and compared with PI-controller. The simulation outcomes display that fuzzy-PI controller has improved speed and force moving performances machine than PI-controller since we obtained least ripple in the force response. The results obtained in the simulation are interesting, given that the Fuzzy-PI controller designed has nonlinear behavior that achieves wide range of speeds operation for the machine at variable forces compared with traditional PI-controller, and this gave clear improvement in the engine's performance.**

Keywords*—Linear Induction Motor (LIM); Proportional Integral (PI)-Fuzzy Logic Controller; D-Q Mode (LIM); Speed Control.

I. INTRODUCTION

A linear induction motor (LIM) is a type of electric motor that produces linear motion rather than rotary motion. Unlike conventional induction motors, which generate a rotating magnetic field to generate torque, LIMs generate a traveling magnetic field to generate linear force and acceleration. Principles of construction and operation Basic and secondary features: Primary (stator): The primary section consists of a series of coils, usually supplied with alternating current (AC) to create a rotating magnetic field wound on a laminated metal surface. Secondary (rotor): The secondary material, commonly referred to as the feedback plate, is usually a conductive sheet (e.g. aluminum or copper) supported by a ferromagnetic material to enhance magnetic field interaction [1]-[5]. Modeling and simulating linear induction motors (LIMs) is essential to understanding their behavior, optimizing their design, and predicting their performance in various applications the process involves building mathematical models describing the physical principles governing LIM operation and use these models to simulate performance in a variety of scenarios. Considerations in LIM Modeling and Simulation for the d-q model. The d-q model or direct quadratic model is widely used in the analysis and simulation of linear induction motors (LIMs), due to its ability to simplify complex interactions in the motor by transforming it into a rotating frame of reference. Several assumptions to simplify the modeling process are made. Here are the basic ideas: Sinusoidal distribution of winding: The stator windings are assumed to give a uniform sinusoidal distribution of the magnetic field in space. [6]-[10] This simple design helps to optimize the d-q conversion. Linear magnetic distances: Magnetic materials are believed to act in the linear domain of their B-H curve, and magnetic saturation is ignored and no end-effect is considered, no friction is considered, three phases of the LIM are balanced. This assumption simplifies the analysis but may not be accurate at high magnetic field conditions. It is assumed that the current between the stator and secondary leakage is equal. Any changes or irregularities in the wind are ignored [11]-[13].

Ignoring endpoints: End effects, which refer to non-uniform magnetic fields, and other losses at the ends of the LIM are often neglected. Although this assumption simplifies the model, it can lead to erroneous results, especially in the case of short primary and secondary lengths. Three-dimensional balanced system for the LIM is assumed to be driven by a balanced three-phase AC supply [14]-[17]. Intelligent speed control techniques using the d-q model represent a major advance in the control of linear induction motors. They include neural networks, genetic algorithms, and other artificial intelligence techniques. These methods provide autonomous control of engine speed after setting a speed reference point. In this research, a fuzzy-pi control was used, which helped solve the off-line problem (at each speed reference point, the controller needs training) that the methods mentioned above suffer from [18]-[21]. Approach speed control methods effect on slip frequency to reduce uniform pressure while ensuring the force applied to the machine. This requires a controller who can respond independently without resorting to the expert person (Fuzzy-PI controller) used in this research [22]-[25]. The model, which was represented in the MATLAB environment, took into account operating conditions of the machine with different loads and variable reference speeds. The model demonstrated the possibility of controlling an acceptable range of speeds while reducing the ripple in the output waveform of the driving force of the machine. This idea solved the problem of choosing fixed reference speeds in applications. Which requires high forces [26]-[30]. This paper presents a new LIM motion control method using an Intelligent PI-Fuzzy Logic Controller (PI-FLC). The proposed model system combines conventional proportional integral (PI) controller with fuzzy logic to increase the robustness and adaptability of the motion control system Simulation results show that PI-FLC outperforms conventional PI controllers, it provides better motion regulation and reduces sensitivity to parameter variations and external disturbances, [31]-[34].

The Intelligent PI-Fuzzy Logic Controller offers a significant improvement in the speed control of Linear Induction Motors over traditional PI controllers. By combining the adaptive capabilities of Fuzzy Logic with the simplicity of PI control, the proposed approach enhances system robustness and performance. Future work will focus on implementing the PI-FLC in real-time applications and exploring further optimization techniques [35][36]. The integration of PI control with Fuzzy Logic offers a promising approach to enhance force control in Linear Induction Motors [37]. The proposed PI-Fuzzy Logic control system provides improved accuracy, robustness, and adaptability compared to traditional control methods. Future research will focus on real-world implementation and further optimization of the control system for industrial applications [38]-[40].

II. MODELING OF LIM

This research makes a specialty of the modeling of Linear Induction Motors (LIMs), which are electromagnetic devices extensively used in commercial programs for linear movement. A complete mathematical version is evolved to as it should be representing the dynamic behavior of the LIM, considering the complicated electromagnetic interactions in the system [13][41]. The model contains key parameters which include magnetic field distribution, winding configuration, and middle characteristics to capture the important features of LIM operation. Simulation research are carried out to validate the accuracy and reliability of the proposed LIM version. The simulation results are as compared with experimental records to make sure the version's fidelity in representing the actual overall performance of the motor. Additionally, sensitivity analyses are completed to analyze the impact of parameter versions on the motor's behavior and to identify critical factors influencing its operation. This process was done by projecting the machine parameters for equivalent circuit. into the model that was built using Matlab/Simulink, and the model proved the validity and accuracy of the simulation results as documented in the source [14][42][43]. The evolved LIM version serves as a valuable device for understanding the complicated interactions inside the motor, assisting within the design optimization and performance enhancement of LIM-primarily based systems. Furthermore, the insights gained from this modeling method make contributions to improvements in control techniques, efficiency improvements, and the overall integration of LIM era in diverse industrial applications [15][44][45].

III. DYNAMIC MODEL OF LIM

Through the start of the LIM and adjustments in the load situations, large currents are drawn by way of the motor which causes increase in oscillations, also voltage dips and injection of harmonics at the deliver aspect. The D-Q axis model in the stationary reference frame and synchronously rotating reference frame allows within the research of those troubles appropriately [15]. The d-q axis same circuit of LIM with give up outcomes is proven in Fig. 1. These circuits and their mathematical calculations are signaler for each the reference frames except for the value of ω. In case of synchronously revolving reference frame, ω is considered as synchronism pace and for desk bound reference frame, ω is considered as 0.

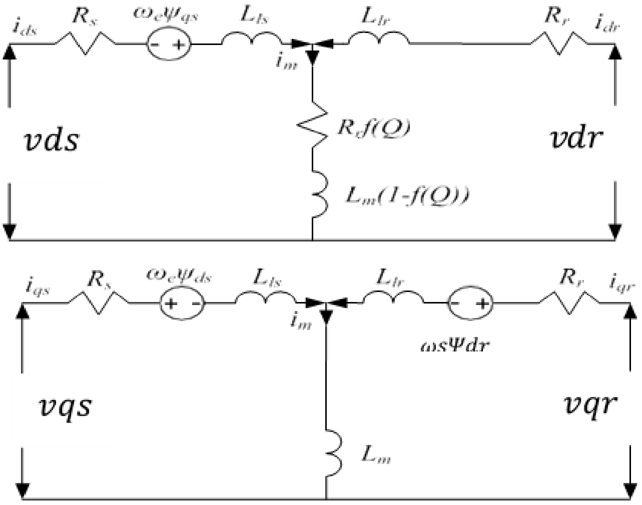


Fig. 1. Equivalent circuit for LIM based on d-q model

Through the equivalent circuit (d-q model) above for the motor, the voltage and current equations for the three-phase linear induction machine can be formulated as follows [16][17][46].

$$vds = Rs.ids + Rr\,f\,(Q)(ids + idr) + \Psi ds - \omega e\Psi qs \tag{1}$$

$$vqs = Rs \cdot iqs + \Psi qs + \omega e\Psi ds \tag{2}$$

$$vdr = Rr \cdot idr + Rr\,f\,(Q)(ids + idr) + \Psi dr + \omega r\,\Psi qr \tag{3}$$

$$vqr = Rr \cdot iqr + \Psi qr + (\omega e - \omega s)\Psi dr \tag{4}$$

The machine's magnetic flux equations, represented by the two perpendicular phase directions, can be interpreted as follows:

$$\Psi qs = LIs\,.iqs + Lm\,(iqs + iqr) \tag{5}$$

$$\Psi ds = LIs\,.ids + Lm[1 - f(Q)](\,ids + idr) \tag{6}$$

$$\Psi dr = LIr\,.idr + Lm[1 - f(Q)](\,ids + idr) \tag{7}$$

$$\Psi qr = LIr\,.iqr + Lm\,(iqs + iqr) \tag{8}$$

Alternating current equations can be written and formulated using magnetic flux equations as follows:

$$ids = \frac{\Psi ds - Lm[1 - f(Q)](\,ids + idr)}{LIs} \tag{9}$$

$$iqs = \frac{\Psi qs - Lm(\,iqs + iqr)}{LIs} \tag{10}$$

$$idr = \frac{\Psi dr - Lm[1 - f(Q)](\, ids + idr)}{LIr} \tag{11}$$

$$iqr = \frac{\Psi qr - Lm(\, iqs + iqr)}{LIr} \tag{12}$$

These equations are rewritten in suitable way to suit the basic Simulink. For example, refer to phase "d" the solve one phase current written of equation in the following from:

$$\begin{aligned} ids = \left(\frac{1}{LIs + Lm}\right) * \Big(vds - ids\big(\, Rs + \ Rr.f(Q)\big) \\ - idr\big(\, Rr.f(Q)\big) - idr(Lm) \\ + iqs\big(\omega r(Lm + LIs)\big) \\ + iqr(\omega r.Lm)\Big) \end{aligned} \tag{13}$$

Similarly the above equations can be arranged for the other three segments (iqs, idr and iqr) currents. In the context of a 3-phase linear induction motor (LIM) modeled using the d-q dynamic model, determining the Q element immediately in phrases of the d-q version parameters may be tough because of the complexity of the motor's dynamic behavior and the various factors affecting its overall performance. The d-q dynamic version of a three-segment LIM usually includes representing the motor's electrical and magnetic behavior in a rotating reference body, in which d-axis is aligned with the rotor flux and q-axis is orthogonal to the d-axis [18][47][48]. This model consists of equations describing the dynamics of flux linkages, currents, and voltages inside the dq reference body. To calculate the Q component in this context, one could commonly need to consider the energy stored inside the motor's inductances and the power dissipated according to cycle because of losses, basically resistive losses. However, immediately obtaining a closed-shape expression for the Q element won't be truthful and could involve complicated analysis and simulation as in the equations below [19][49][50].

$$f(Q) = \frac{1 - \ e^{-Q}}{Q} \tag{14}$$

$$Q = \frac{DR_r}{(L_m + L_{lr})v} \tag{15}$$

The motion equation: is the movement equation for a Linear Induction Motor (LIM) describes the connection among the applied forces, motion, and different parameters influencing the motor's conduct. The dynamic equation for the motion of a linear induction motor can be expressed in a simplified form. Consider a primary model of a single-sided LIM running in an instantly line. The movement equation for the LIM can be represented as (16)(17)[19][51][52].

$$F_e \ = \frac{3\pi p}{4\tau} \ (\Psi ds \; iqs - \Psi qs \; ids) \tag{16}$$

$$M = \frac{dv}{dt} \ = \ Fe - FL \tag{17}$$

Relation between primary velocity and secondary angular velocity is:

$$V = \frac{\omega e \; \tau}{\pi} \tag{18}$$

Where: $vds, vqs \; vdr, vqr$ is the machine voltages are represented the d-q axes (V). $ids, iqs \, , idr, iqr$ is the machine currents are represented the d-q axes (A). $\Psi ds, \Psi qs \, , \Psi dr, \Psi qr$ is magnetic flux linkages are represented the d-q axes (Wb). Rs, Rr is the resistance of primary and secondary of LIM (Ω). $LIs, \; LIr$ Leakage inductances of LIM winding (H). Lm is Magnetic induction of iron plat (H). τ is pole distance (m), p is indicates the pole pairs. $\omega e, \omega s$ is Indicates the angular speed of the primary and secondary motor (rad/sec). V is expressed in meters per second (m/Sec). F_e the machine's performance is described in terms of electromagnetic thrust, measured in Newton's.

IV. MODEL OF LIM USING SIMULINK

Modeling a three phase LIM in Simulink involves creating a representation of its electrical and mechanical characteristics using blocks to simulate its behavior. Fiq. 2 show the flow chart of the method used to build LIM. The dynamic model of a linear induction motor (LIM) is shown in Fig. 3, this model involves describing its electromagnetic behavior, taking into account factors like winding configuration, magnetic field distribution, also it involves on parameters such as the motor's inductances, resistances, mutual inductances, and other electrical characteristics which are shown in Table I below.

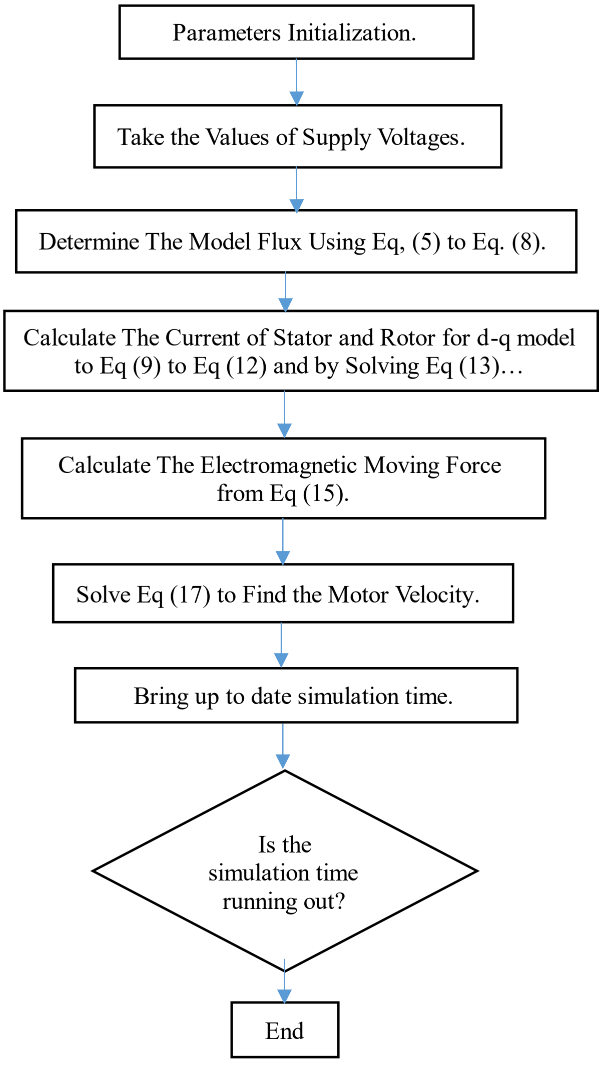


Fig. 2. Flow chart simulink of LIM d-q model

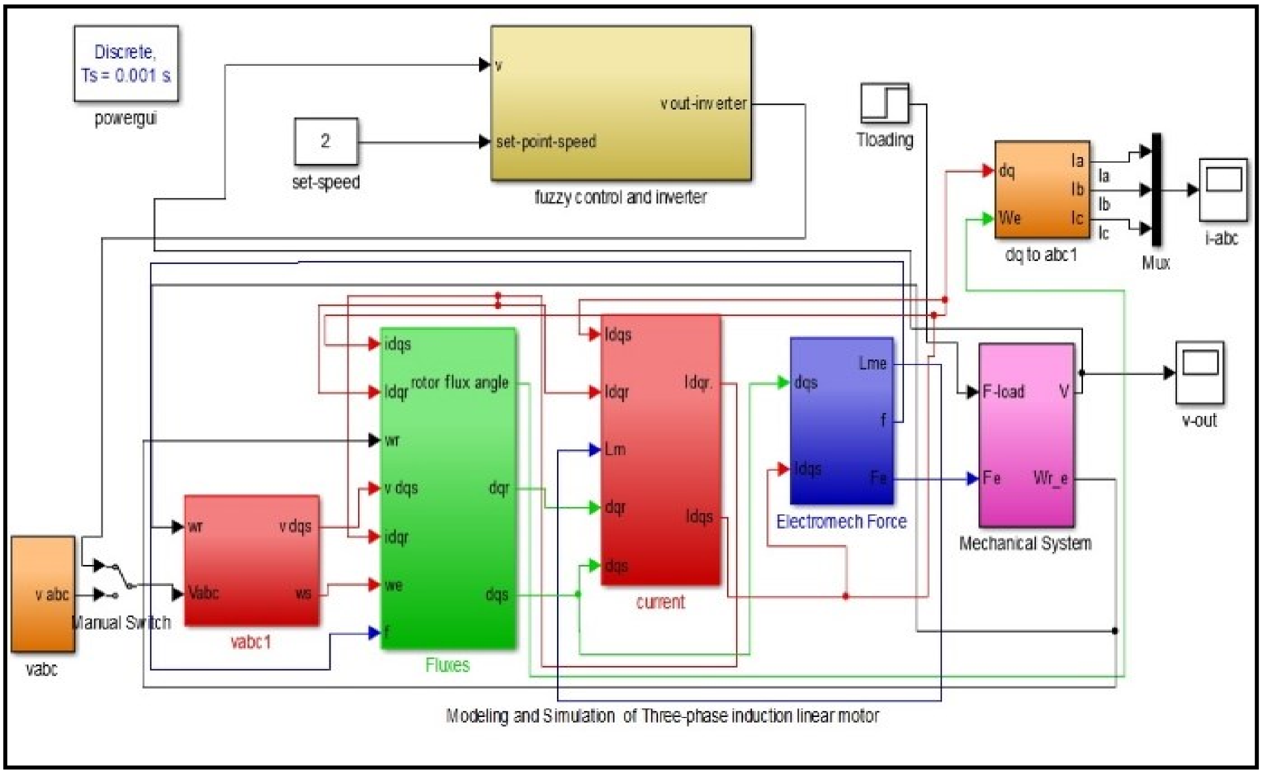


Fig. 3. Modeling and simulation of three phase LIM

TABLE I. LINER INDCTION MOTOR (LIM) SPECIFICATIONS

Rs	5.3685 ohm	F Frequency	50 Hz
Rr	3.5315 ohm	Rated power	5.5 Kw
Lm	0.0241 H	Rated voltage	180
Lls	0.02846 H	Number of poles	2
Llr	0.02846 H	D	36.0455

V. DESIGN OF FUZZY PI CONTROLLER

The drawbacks of this PI controller are the event of overshoot at the same time as beginning, at the same time as load utility and overshoot again while load elimination [1][2][53][54]. Fiq. 4 show the Fuzzy PI Controller diagram for LIM speed set point close loop control. The speed of the linear motor is controlled by using PI controller with Fuzzy logic controller, Mamdani Algorithm is used as an inference approach and center of gravity for defuzzification as shown in Fig. 5. In the fuzzification block, the inputs and outputs crisp variables are transformed into fuzzy variables (e), (de) and (du) using the triangular membership function [3][55][56] as shown in Fig. 7.

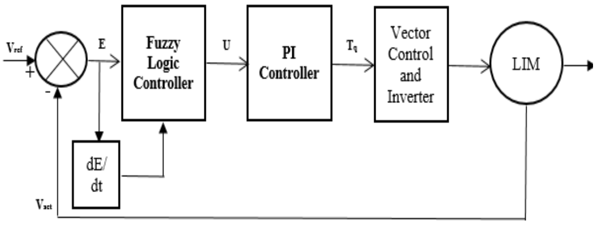
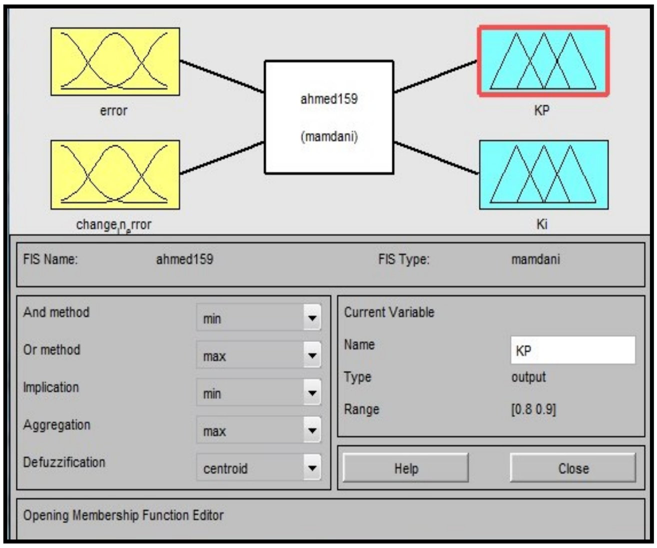


Fig. 4. Fuzzy PI controller diagram



FIS Name: ahmed159 FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: KP

Type: output

Range: [0.8 0.9]

Opening Membership Function Editor

Fig. 5. The model of Fuzzy logic controller (Mamdani Algorithm)

The fuzzy variables (e), (de) which generated from fuzzification block processed by using a set of control guidelines as shown in Fig. 6. These fuzzy rules are expressed because the IF-THEN form. The MAX-MIN inference process is used to obtain the output of fuzzy logic controller. The execution of fuzzy controller depends on the rule and the membership functions and their distribution, and there are no formal techniques to determine these parameters.

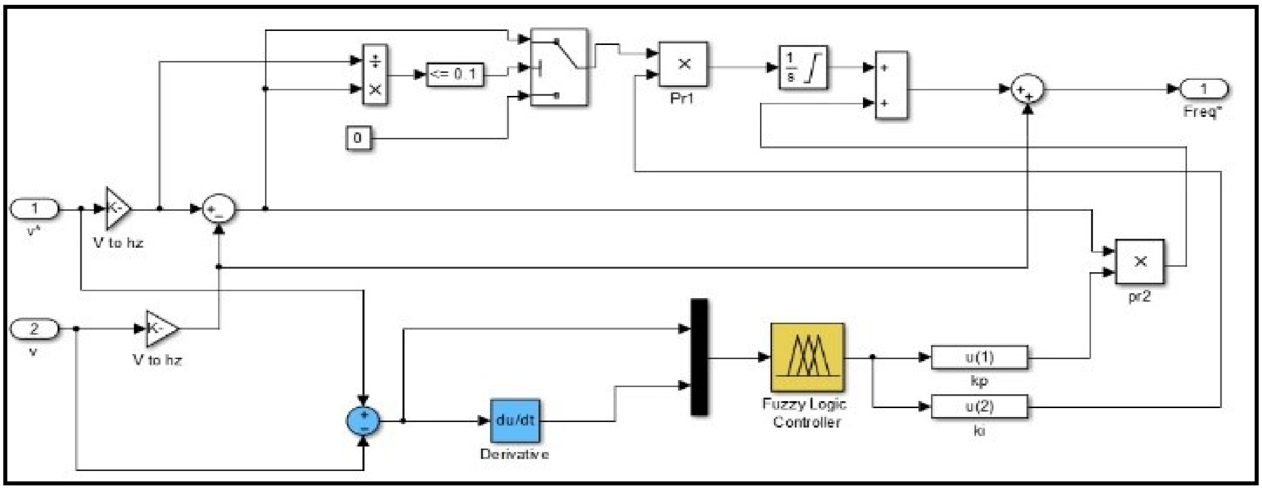
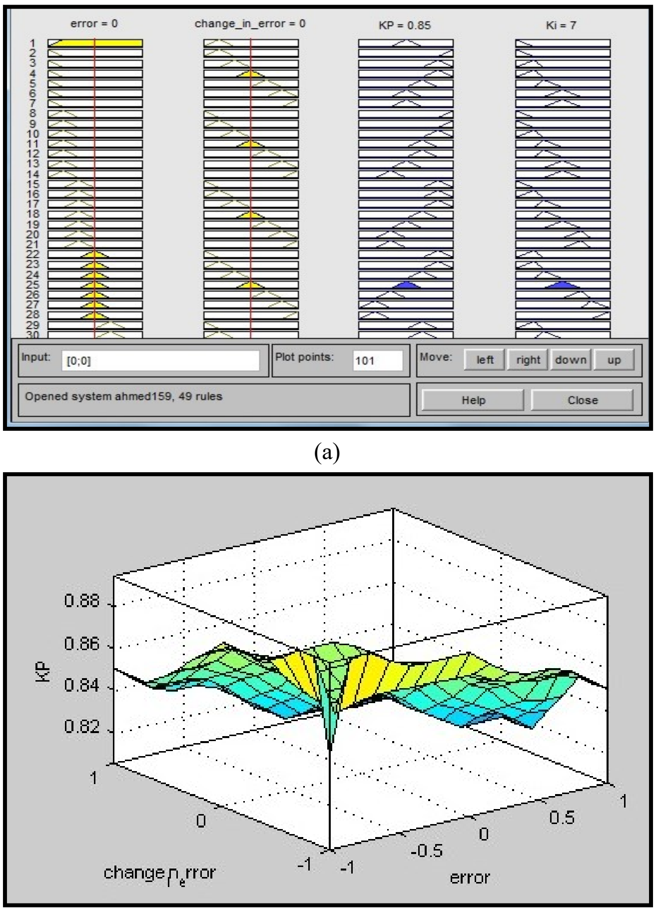


Fig. 6. Block diagram of Fuzzy PI controller



Input: [0;0]

Plot points: 101

Opened system ahmed159, 49 rules

(a)

(b)

Fig. 7. (a) The rules of the membership function. (b) The surface view of the membership function

The mechanism for selecting the values of the Kp and Ki for the PI controller occurs in an offline state, meaning that they must be manually tuned at every change in the system that we control. Therefore, it is difficult to choose the best Kp and Ki values that give the best response to the system. The process of using the Fuzzy PI hybrid controller makes the Fuzzy controller enable us to self-tune the Kp and Ki values of the PI controller that give the best performance to the system according to the error and the change in the error.

VI. SIMULATION AND RESULTS

The simulation of three phase linear induction motor was created using MATLAB – Simulink, the first step was to model the motor, and control then, this model is shown in Fig. 3. PI controller was prepared to control the velocity of the motor and simulate its behavior under different conditions of velocity and moving force. Fig. 8 show the performance of PI controller based on reference velocity of 2 m/sec with load 50 Newton. Fig. 9 show the performance of PI controller based on reference velocity of 1.5 m/sec with load 30 Newton. Fig. 10 show moving force of model with PI controller based on reference velocity of 2 m/sec with load 50 Newton. From Fig. 8 and Fig. 9, we notice that the speed response of the three-phase linear induction motor at the reference speed decreased at the moment the load entered. The presence of the PI controller enabled us to overcome this decrease in speed and return the motor speed almost to the reference speed, but this process took a period of time. therefore, a fuzzy logic controller with PI controller is suggested to control the velocity of the motor to be fixed when the load changes and also to overcome the decrease in speed and return the motor velocity to the reference velocity in short period of time compared to PI controller. Fig. 11 show the performance of Fuzzy-PI controller based on reference velocity of 2 m/sec with load 50 Newton. Fig. 12 show the performance of Fuzzy-PI controller based on reference speed of 1.5 m/sec with load 30 Newton. Fig. 13 show moving force of model with Fuzzy PI controller based on reference speed of 2 m/sec with load 50 Newton. From Fig. 13 we notice that the moving force response of the three-phase linear induction motor with Fuzzy PI controller at the reference speed 2 m/sec with load 50 Newton has ripple less than the ripple in the response of moving force for the three-phase linear induction motor with PI controller as shown in Fig. 10, this means that the use of the fuzzy controller with the PI controller has enabled us to improve the fluctuation in the force response. Likewise, the use of the fuzzy controller has overcome the drop in the speed response at the moment the load enters and the possibility of returning the engine speed to the reference speed in a shorter period of time than in the case of using the PI controller and this is shown in the Fig. 14 and Fig. 15. From Fig. 14, we notice that the speed response has improved in the presence of the Fuzzy PI controller compared to the first case in which there was the PI controller, where at the moment of entry of a load of 50 Newton’s, the speed decreased slightly from the reference speed of 2 m/sec, but in the presence of the Fuzzy PI controller, this instantaneous drop in speed was overcome and returning the motor velocity to the reference velocity in a faster period of time than the case of the PI controller.

The same is the case in Fig. 15, the load applied to the linear motor was changed and made it 30 Newton’s and the reference speed was made 1.5 m/sec.

The Table II shows the advantages of the adaptive tuning of the PI parameters and improving the controller performance in the PI-Fuzzy controller, significant benefits are obtained. This approach combines simple and efficient PI control with simple and complex fuzzy logic, resulting in superior control performance in terms of overshoot, rise time and overall complexity. The Table III show a coparision between statistical mesures such as standard deviation (STD), hypothesis testing and mean speed average transient, steady state.

TABLE II. PERFORMANCES COMPARISON BETWEEN PI AND FUZZY-PI CONTROLLER

Performances	Speed 2m/sec Force 50 N		Speed 1.5 m/sec Force 30 N	
	PI	Fuzzy-PI	PI	Fuzzy-PI
Rise time Tr	0.1062	0.1105	0.083	0.0849
Settling Time Ts	1.0045	0.6586	0.9422	0.58
Maximum Over Shoot m.o.sh	3.836%	2.136%	3.3952	2.184%
Peak Time	0.1672	0.169	0.1467	0.1449

TABLE III. STATISTICAL MESURES

Performances	Speed 2m/sec Force 50 N		Speed 1.5 m/sec Force 30 N	
	PI	Fuzzy-PI	PI	Fuzzy-PI
STD	0.3176	0.3579	0.2073	0.2124
Hypothesis	h=1 P=0	h=1 P=0	h=1 P=0	h=1 P=0
Mean (v)	1.8589	1.8926	1.4187	1.4521

The combination of fuzzy logic and conventional PI control in the PI-Fuzzy controller significantly improves the performance of the three-phase linear induction motor through improved dynamic response and nonlinearity management. The noticeable improvement in the machine's performance results from the controller's selection of the best gain values for the machine's drive, and this is consistent with the speed response at different loads, as presented in the operating results. Despite the many advantages of PI-Fuzzy controllers, such as improved nonlinearity control, adaptive control, and robustness to parameter variations, their limitations must be carefully considered Complexity in design tuning, increased computational burden, scalability issues, robustness concerns, maintenance challenges, edge cases Unpredictable behavior and the need for expert knowledge pose significant challenges.

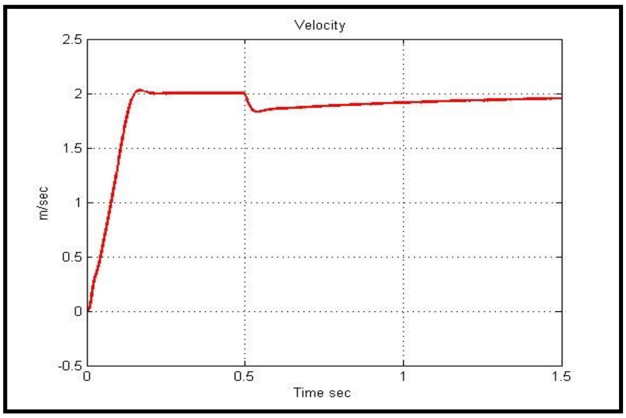


Fig. 8. Velocity of three phase LIM with PI controller under 50 N and 2 m/sec

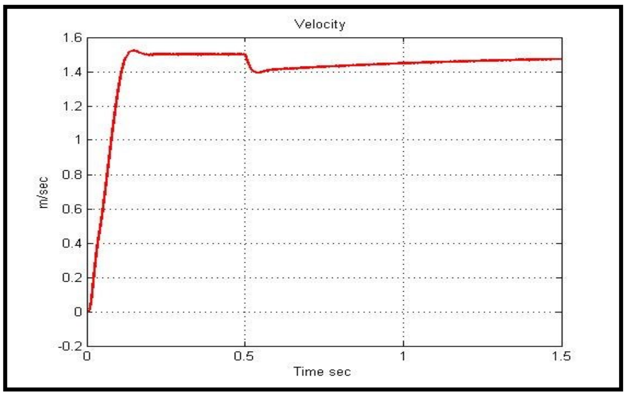


Fig. 9. Velocity of three phase LIM with PI controller under 30 N and 1.5 m/sec

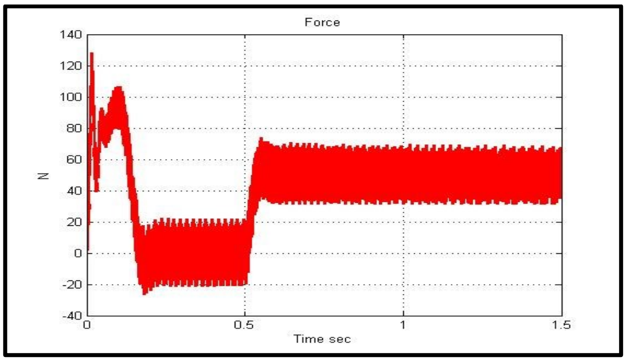


Fig. 10. Force moving of three phase LIM with PI controller under 50 N and 2 m/sec

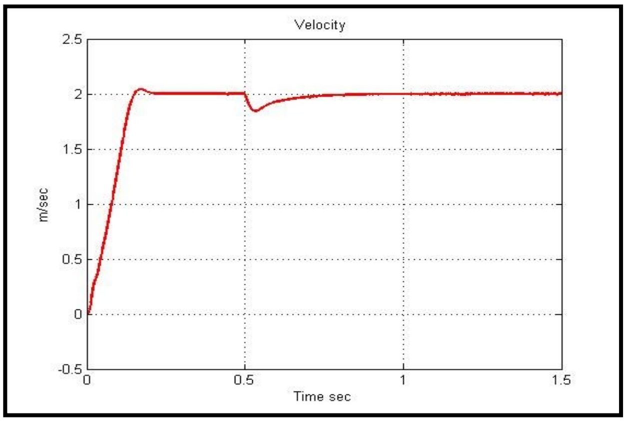


Fig. 11. Velocity of three phase LIM with Fuzzy PI controller under 50 N and 2 m/sec

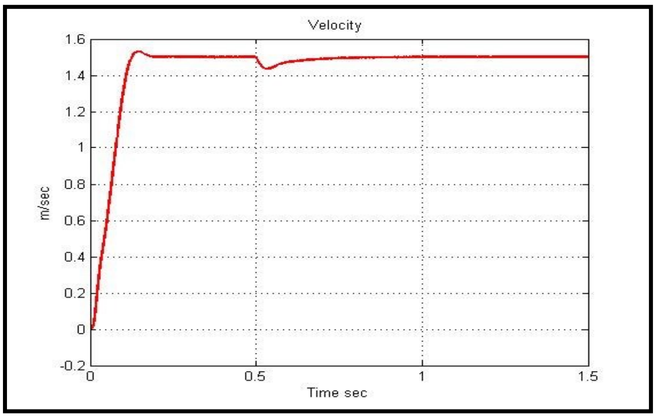


Fig. 12. Velocity of three phase LIM with Fuzzy PI controller under 30 N and 1.5 m/sec

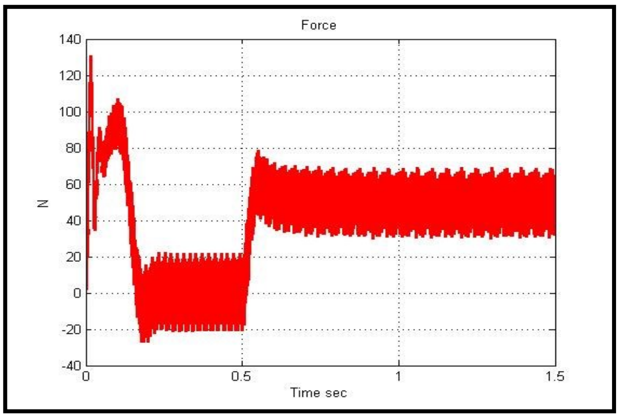


Fig. 13. Force moving of three phase LIM with Fuzzy PI controller under 50 N and 2 m/sec

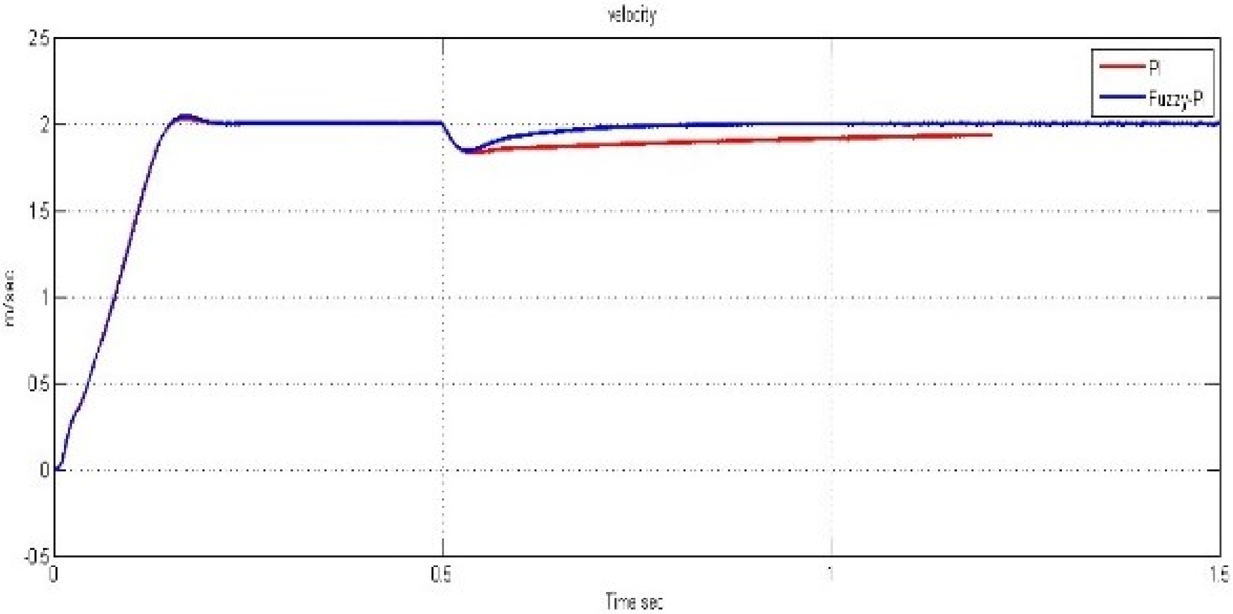


Fig. 14. Velocity of three phase LIM with PI controller and Fuzzy PI controller under 50 N and 2 m/sec

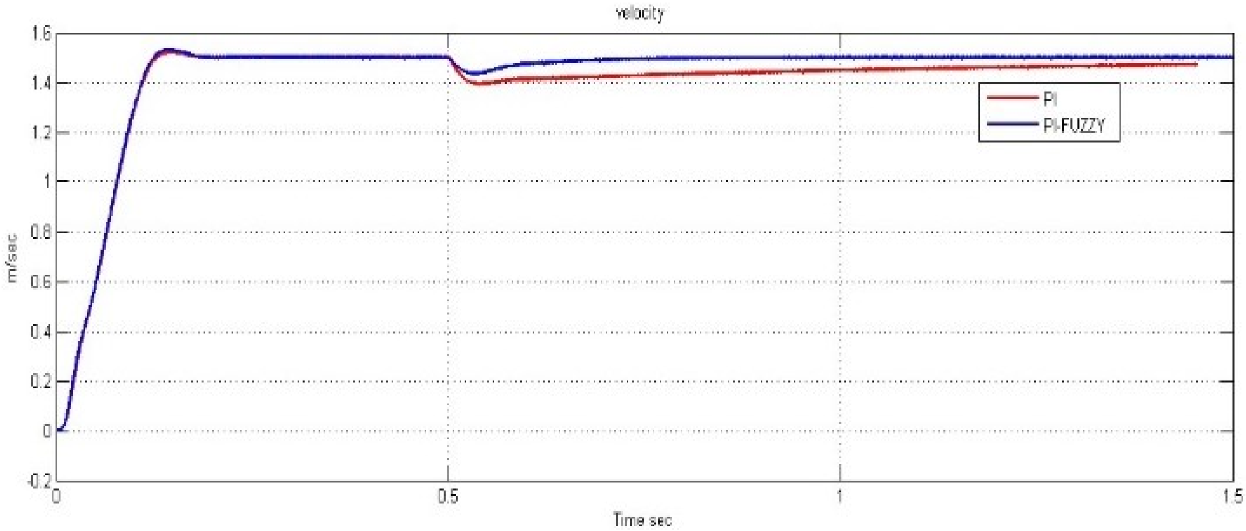


Fig. 15. Velocity of three phase LIM with PI controller and Fuzzy PI controller under 30 N and 1.5 m/sec

VII. CONCLUSIONS

This paper presents d-q model for three phase linear induction motor and simulate it in MATLAB / Simulink, then PI controller was designed for control PWM voltage fed linear motor drive to control the velocity of the linear motor and keeping its velocity constant at the moment the load changes or any external disturbances occur to the system, the values of gains Kp and Ki was taken manually, this process requires a long time, especially since it requires adjusting the gain values for every change in the reference speed. For this reason, a self-tuning of PI with fuzzy logic controller was prepared to select best values of Kp and Ki that give best performance for the system under any change in the load or any disturbance in the system. Also, the process of using the Fuzzy-PI hybrid controller makes the Fuzzy controller enable us to self-tune the Kp and Ki values of the PI controller rather than the manually tuned of the gains for the PI controller at every change in the system. The fuzzy controller was designed with Mamdani Algorithm as an inference approach and center of gravity for defuzzification with using triangular membership function. The designed fuzzy-PI controller was tested at more than one reference speed and more than one value of the applied force, as well as changing the value of the force applied to it suddenly. It was found that the system succeeds in returning the engine speed to the reference speed within a short time. This shows that the system has become more robust to varying load changes and engine inertia. The simulation outcomes display that the designed fuzzy-PI controller achieve a good dynamic action of the motor to unexpected changes with a smaller overshoot and fewer steady state rate compared with the overall performance of classical PI controller, where the results achieved with percentage improvement in the motor speed response performance, as the settling time values were improved by 34.43% and maximum over shoot by 44.4317%. Also, Good force moving response is gotten in fuzzy with PI controller compared with the performance of classical PI controller, since where we obtained the least amount of ripple in the force response.

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