

Improving Quality of Movement in a Linear Switched Reluctance Motor Using a Fuzzy Logic System

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A *This work deals with minimizing fluctuations of propulsion force and improving the motion quality in a linear switched*
B *reluctance motor. In order to minimize the jerks in the moving part of the motor, a new profile has been used to generate an*
S *appropriate reference speed profile. The results indicate that at speed 0.5 m/s, the motor reaches its command speed at the*
T *proposed time while, using conventional speed profile it takes almost 1.4 times the desired time. In order to control the speed*
R *and increase the motion quality, a simple fuzzy logic system has been used which is able to overcome the uncertainties problem*
A *in nonlinear systems. The fuzzy control system can regulate the motor performance so that it tracks the reference speed with*
C *minimum error and fluctuation. To illustrate the performance of the fuzzy method, a conventional PI method along with a*
T *model reference adaptive control (MRAC) strategy have been applied to the motor and the obtained results for three control*
methods have been compared. Speed overshoot using conventional PI method is about 20 percent of the final speed while
this is about 6 percent for fuzzy and MRAC methods. The system is designed and its efficiency is shown through simulation
and experimental tests in different performance situations. The obtained results confirm that the fuzzy strategy outperforms
other methods.

Article Info

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I. INTRODUCTION

Switched reluctance motors (SRMs) have very interesting characteristics over electrical motors. They are very robust, low price, simple in structure, and fault tolerant with fewer thermal problems compared to other electrical motors. The linear type of these motors has all the above-mentioned benefits along with the ability of direct motion. They do not need any mechanical rotational to linear motion converters making them more suitable in special direct motion applications such as elevators, transport systems, etc. Different types of linear switched reluctance motors (LSRMs) have been presented by researchers previously which can be

used in different industries [1]. These motors have inherently nonlinear dynamics with some uncertainties cause to be complicated their analysis and control.

Generally, these motors generate a force with high ripples and so, low quality which again complicates their application. Various speed regulation strategies have been suggested by researchers to improve the motor performance and to solve the torque (or force) fluctuation problem in SRMs. Generated force in LSRMs can be controlled by an appropriate force distribution function (FDF) [2]–[4]. In order to minimize the torque ripple in a rotational switched reluctance motor, an advanced torque sharing function has been proposed in [5] which has used combination of the genetic algorithm and fuzzy PSO methods. An appropriate FDF has been presented in [6] which could noticeably reduce the force fluctuations in a LSRM. We know that considerable force fluctuation can occur

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in the phase commutation period. In recent papers, many efforts have been made to decrease the force (or torque) pulsations. In conventional control methods, it is possible to optimize the conduction angles in order to reach a flat force, but it has been shown that under higher loading conditions, noticeable force fluctuation is unavoidable [7]. Some interesting techniques for force (or torque) fluctuation reduction have been presented by researchers in recent years. In [8], dynamic equations of a SRM have been shown and the generated torque has been studied considering the contribution of the mutual inductances. Another current profile analysis has been done in [9] which cause to minimization of the torque pulsation over a wide range of speeds. Other current profile-based optimization methods have been suggested in [10]. In the methods, the current profile has been optimized to produce less ripple in the output current and torque. Destructive interference is the other method which has been used in [11] for improving the torque fluctuation in a SRM. Optimization of the SRM is another method to lower the force or torque pulsation. We have used a seeker optimization algorithm to optimize the LSRM construction in [12]. The obtained results indicated that the optimized structure generates better force with fewer ripples. In [13] and [14], new structures of SRMs have been proposed generating a torque with significantly low ripples. It is obvious that the fluctuated force will affect the speed of the translator; consequently, the actual speed would be different from the command value leading to disturbance in the LSRM performance. Accordingly, an appropriate speed controller can regulate the motor performance accurately. Fuzzy control is a practical alternative for a variety of challenging control applications as it provides a convenient method for constructing nonlinear controllers via heuristic information [15] – [18]. An interesting approach to the analysis of continuous time Takagi-Sugeno fuzzy systems using fuzzy Lyapunov functions has been presented in [16] which is independent of normalized fuzzy weighting functions. Some special systems such as nontriangular structural system have some problems complicating their analysis. In [17], an adaptive fuzzy switched control strategy has been investigated which solved the system problems. Another combined fuzzy control strategy has been proposed for a nonlinear system in [18]. Using Nussbaum function method, an adaptive output feedback control strategy has been proposed in [19] which is appropriate for nonlinear systems with output constraints. Fuzzy control strategy has the advantage of independence of the system parameters; thus, the method can be used for systems with unknown variables [20] and [21].

In this work, we have been used a fuzzy control strategy to smooth the output actual speed of the moving part of the LSRM. The controller has been implemented to the motor as a speed regulator. The proposed linear motor structure and its dynamic equations have been discussed in section 2. In section 3, block diagram of the control system along with the fuzzy

control method have been investigated. Also, a new speed profile to reach a smooth motion quality has been introduced in section 3. In order to have a comparison between the proposed control methods, a new model reference adaptive control strategy has been demonstrated in section 4 and finally, simulation results and experimental results for three control strategies have been demonstrated and discussed in section 5 and 6.

II. PROPOSED SYSTEM

A. The linear motor and its characteristics

Control of a four-phase double-sided linear switched reluctance motor (DLSRM) is proposed in this work. The motor has a moving part with eight winding sets located on it along with two stators on both sides of it [6]. Because of two stators located on both sides of a translator, two same electromagnetic forces are applied to the common translator between them. So, this double sided construction yields high propulsion force density thus making the motor appropriate for applications requiring strong drivers. It is obvious that DLSRMs inherently have complete nonlinear characteristics complicating their performance control over electrical motors. Achieving an appropriate model for the DLSRM with a complete and accurate data of the motor inductance and force is very useful in the motor analysis. This can be done by a precise 3-D finite element analysis. The obtained data of the selected DLSRM are shown in Fig. 1.

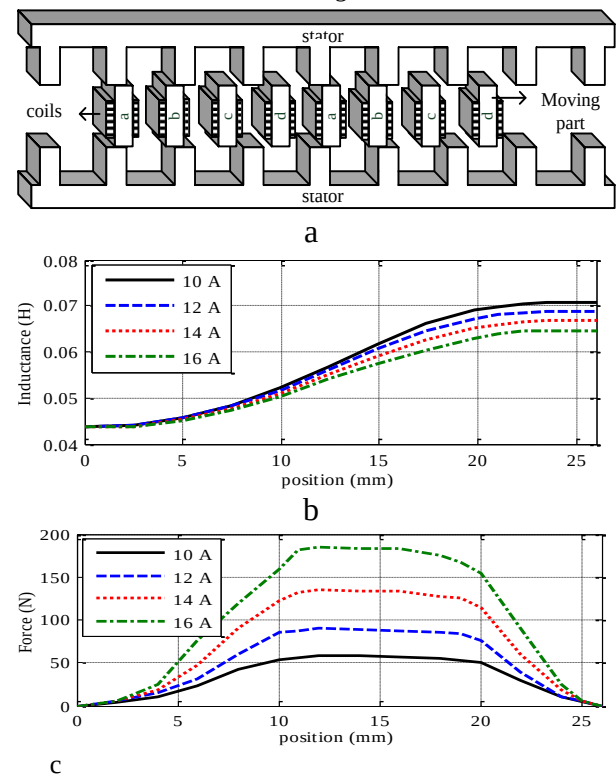


Fig. 1. Selected DLSRM and data from FEM, (a) Selected DLSRM, (b) inductance, (c) force

The dimensions of the proposed DLSRM are shown in

Table 1.

TABLE I SELECTED DLSRM DIMENSIONS		
Parameter	Value	Unit
Air gap length	2	mm
Stator pole width	21	mm
Stator slot width	31	mm
Stator pole height	30	mm
Translator pole width	13	Mm
Translator pole height	26	Mm
Translator height	220	Mm
Turns per phase	200	Turn
Rated current	10	A
Rated voltage	150	V
Friction coefficient (C)	10	N/m/s
Translator mass (M)	5	kg
Phase resistance	2.5	Ω

B. Electromagnetic Equation

Voltage balancing equation for any one phase can be represented as:

$$v_k = R \cdot i_k + \frac{d\lambda_k}{dt}, \quad \lambda_k = L_k(i_k, x) \cdot i_k \quad (1)$$

$$\frac{d\lambda_k}{dt} = L_k(i_k, x) \cdot \frac{di_k}{dt} + g_k \cdot v_x \cdot i_k \quad (2)$$

where, v_k , i_k , λ_k , R and L_k are voltage, current, linkage flux, winding resistance, and inductance of the k-th phase, respectively where k denotes the phases a, b, c, and d. In addition, $v_x = dx/dt$ and $g_k(x) = dL_k/dx$ are linear motion velocity and the force function respectively, in which $g_k(x)$ is defined as the rate of change of phase inductance according to position. Force of each phase (F_k) can be obtained from the phase current and translator position. The resultant propulsion force, F_e is the sum of the phase forces. SRM mathematical analysis has been carried out in [18]. The generated propulsion force in the LSRM can be written as:

$$F_e = M \frac{dv}{dt} + Cv + F_L \quad (3)$$

$$F_e = F_a + F_b + F_c + F_d \quad (4)$$

$$F_L = k_p v \quad (5)$$

where F_e and F_L show the propulsion and output load forces, respectively while F_k with $k = a, b, c$, and d denotes force of each phase. v , M and C are the speed of the moving part (m/s), moving part total mass and frictional coefficient, respectively. k_p is a constant factor.

Phase currents can be used to express an output force equation. To express the output force in terms of phase currents and translator position, the output force equation is derived from the coenergy W_c . From the definition of the coenergy and assuming that two “x” and “y” phases are on simultaneously, then according to $\lambda_x = L_x i_x$ and $\lambda_y = L_y i_y$, the differential coenergy is expressed as:

$$\begin{aligned} dW_c(i_x, i_y, x) &= \lambda_x di_x + \lambda_y di_y + F_e dx \\ &= (L_x i_x) di_x + (L_y i_y) di_y + F_e dx \end{aligned} \quad (6)$$

The coenergy can be found by integrating (6) along a path of integration. The most convenient integration path is to integrate over x holding i_x and i_y fixed at zero, integrate over i_y by holding i_x fixed at zero, and finally integrate over i_x . In the first part of the integration, the integral is zero because F_e is zero when both i_x and i_y are zero. Thus, the coenergy is calculated as

$$W_c(i_x, i_y, x) = \int_0^{i_y} \lambda_y(0, \varepsilon, x) d\varepsilon + \int_0^{i_x} \lambda_x(\varepsilon, i_y, x) d\varepsilon = \int_0^{i_y} (L_y \varepsilon) d\varepsilon + \int_0^{i_x} (L_x \varepsilon) d\varepsilon = \frac{1}{2} L_y i_y^2 + \frac{1}{2} L_x i_x^2 \quad (7)$$

where ε is an integration variable. Then, the propulsion force F_e is calculated as

$$F_e = \left. \frac{\partial W_c(i_x, i_y, x)}{\partial x} \right|_{i_x, i_y \text{ fixed}} = \frac{1}{2} g_x i_x^2 + \frac{1}{2} g_y i_y^2 \quad (8)$$

Now F_e is expressed in terms of variables, i_x and i_y , and the rate of change of phase inductance, g_x and g_y . After calculating the propulsion force, using (3) and (4), we can write:

$$\dot{v} = -\frac{k_p}{M} v + \frac{1}{M} [-Cv + F_e] \quad (9)$$

III. FUZZY CONTROL SYSTEM DESIGN

The block diagram of the system composis of the LSRM and its control system is demonstrated in Fig. 2. In this study, the speed of the motor has been controlled by the fuzzy logic control approach. The fuzzy system has two inputs: the speed error e and change in the speed error Δe . The output of the controller is the reference current of each phase.

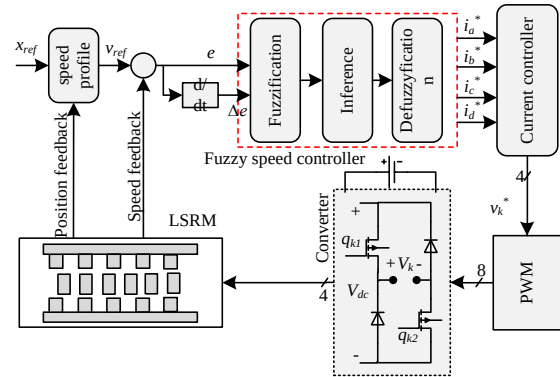


Fig. 2. Block diagram of the proposed control system

A. Jerk Minimization-Based Speed Profile

At the first step and after defining the desired position of the translator, it is necessary to produce a speed profile. An appropriate speed profile can reduce the jerks of the motion noticeably, and so it can enhance the motion quality [22]. Assuming that $x(t)$ indicates the position of the translator and t_d is the final time of motion, we can write the objective function as follows which should be minimized.

$$j = \int_0^{t_d} \left(\frac{d^3 x(t)}{dt^3} \right)^2 dt \quad (10)$$

If $x(t)$ be the response of the Euler-Poisson problem, then the function 'j' will have an extremum value. According this, we can write the obtained equation as:

$$\frac{d^6 x(t)}{dt^6} = 0 \quad (11)$$

This means the minimum jerk profile $x(t)$ is a polynomial like (12).

$$x(t) = \alpha_5 t^5 + \alpha_4 t^4 + \alpha_3 t^3 + \alpha_2 t^2 + \alpha_1 t + \alpha_0 \quad (12)$$

Consequently, the reference speed profile of the system is obtained as:

$$v_{ref}(t) = 5\alpha_5 t^4 + 4\alpha_4 t^3 + 3\alpha_3 t^2 + 2\alpha_2 t + \alpha_1 \quad (13)$$

In order to solve the equation (13), five boundary conditions are required which are $x(0) = 0$, $x(t_d) = x_d$, $\dot{x}(0) = v_0 = 0$, $\dot{x}(t_d) = v_d$, $\ddot{x}(0) = \alpha_0$, and $\ddot{x}(t_d) = 0$. Subscript 'd' indicates the parameters at the end of the motion period. Finally, the reference speed is obtained as:

$$\begin{aligned} v_{ref}(t) = & \left(-\frac{\alpha_0}{2t_d^3} - 3\frac{v_0}{t_d^4} - 3\frac{v_d}{t_d^4} - 6\frac{x_0}{t_d^5} + 6\frac{x_d}{t_d^5} \right) \cdot t^4 \\ & + \left(3\frac{\alpha_0}{2t_d^2} + 8\frac{v_0}{t_d^3} + 7\frac{v_d}{t_d^3} + 15\frac{x_0}{t_d^4} - 15\frac{x_d}{t_d^4} \right) \cdot t^3 \\ & + \left(-3\frac{\alpha_0}{2t_d} - 6\frac{v_0}{t_d^2} - 4\frac{v_d}{t_d^2} - 10\frac{x_0}{t_d^3} + 10\frac{x_d}{t_d^3} \right) \cdot t^2 \\ & + \alpha_0 t + v_0 \end{aligned} \quad (14)$$

The proposed speed profile was applied to the system and the obtained results were compared with the conventional trapezoidal approach findings. At speed 0.5 m/s and using a conventional trapezoidal profile, speed of the motor reaches its command value at $t=0.17$ s while this time is less than $t=0.12$ s using the proposed speed profile. This can be seen at speed 2.5 m/s in Fig. 3 (b). It can be seen from Fig. 3 that the proposed method has a better performance in reference speed tracking.

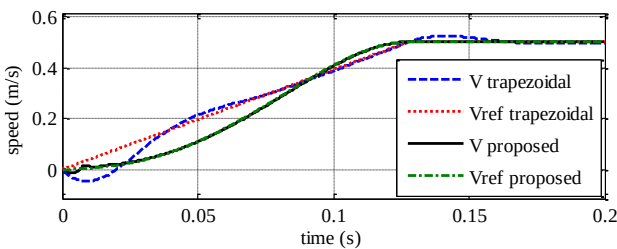


Fig. 3. a

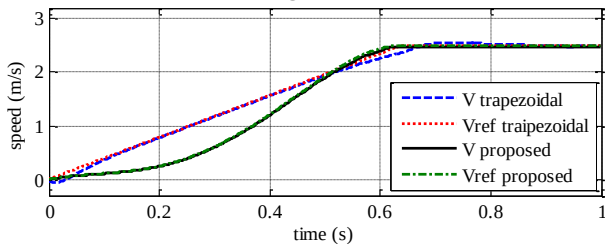


Fig. 3. b

Fig. 3. Speed profile comparison, (a) 0.5 m/s, (b) 2.5 m/s

B. Fuzzy Control Strategy

A zero order Takagi-Sugeno fuzzy system is selected to be applied to the DLSRM. The system is able to approximate the nonlinear characteristics of the motor. The proposed fuzzy system elements are shown in Fig. 2. The inference part consists of inference mechanism unit, database unit, and fuzzy rule base unit. The database unit includes all required data such as linguistic variables of input signals, membership function of each linguistic variable, and a set of fuzzy rules. The system consists of a mapping from an input vector $z = [z_1, \dots, z_m]^T \in \Omega_z \subset R^m$ to a scalar output variable $y_f \in R$, where $\Omega_z = \Omega_{z_1} \times \dots \times \Omega_{z_m}$ and $\Omega_{z_i} \subset R$. Assuming that each variable z_k has fuzzy sets $G_k^j, j = 1, \dots, M_k$, the TS fuzzy system can be introduced by a set of if-then rules such as the following:

$$\begin{aligned} R^{(i)}: & \text{If } z_1 = G_1^i \text{ and } z_2 = G_2^i, \text{ Then} \\ y_f = & y_f^i = q_0^i + q_1^i z_1 + q_2^i z_2 = \theta_i^T [1 \ z^T]^T \end{aligned} \quad (15)$$

where G_k^i indicate fuzzy sets, $k=1, 2, i = 1, \dots, N_r, z^T = [z_1 \ z_2]$ is the input vector, $\theta_i^T = [q_0^i \ q_1^i \ q_2^i]$ shows a vector of the adjustable parameters, y_f^i is the scalar output of the i -th rule, and N_r is the total number of fuzzy rules. By using the central average defuzzifier and product inference, the output of the TS fuzzy system can be expressed as:

$$y_f(z) = \frac{\mu_1 y_f^1 + \dots + \mu_{N_r} y_f^{N_r}}{\mu_1 + \dots + \mu_{N_r}} = \frac{\sum_{i=1}^{N_r} \mu_i y_f^i}{\sum_{i=1}^{N_r} \mu_i} \quad (16)$$

$$\mu_i = \prod_{k=1}^2 \mu_{G_k^i}(z_k) \quad (17)$$

where $\mu_{G_k^i}$ denotes the membership function of the fuzzy set G_k^i . We can rewrite the output of the fuzzy system expressed in (9) as follows:

$$y_f(z) = w^T(z) \theta \quad (18)$$

where $\theta = [y_f^1, \dots, y_f^{N_r}]^T$ is a vector grouping all consequent parameters, and $w(z) = [w_1(z), \dots, w_{N_r}(z)]^T$ indicates a set of fuzzy basis functions defined as

$$w_i(z) = \frac{\mu_i(z)}{\sum_{j=1}^{N_r} \mu_j}, \quad i = 1, \dots, N_r \quad (19)$$

Defining enough fuzzy rules, the fuzzy logic system (19) can be used for approximating any real continuous function. The speed error and change of the speed error represent the inputs of the fuzzy system. Each input and output variable have fuzzy sets as shown in Fig. 4. According to Fig. 4 (a), seven triangular fuzzy sets were used to introduce each input variable with fuzzy sets having 50% overlap with each other. For the output variable, a fuzzy inference mechanism was calculated using a singleton membership function shown in Fig. 4 (b). In this work, we have selected singleton membership function for the output of the system. this cause to fast response of the controller.

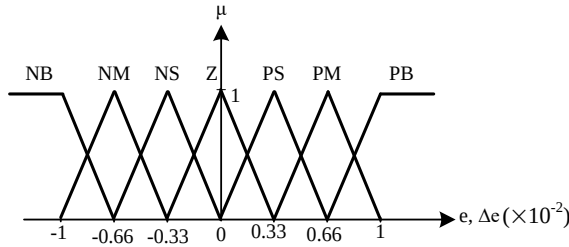


Fig. 4. a

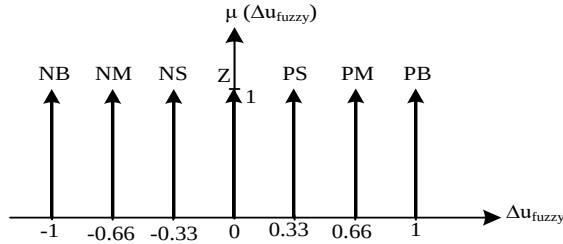


Fig. 4. b

Fig. 4. fuzzy sets (a) Input variables, (b) Output variables

The main advantage of the fuzzy control system is that it does not need lots of data to control the LSRM performance. Totally the used fuzzy controller has the following advantages over the other control strategies:

- Simplicity and flexibility
- Can handle problems with imprecise and incomplete data
- Can model nonlinear structure of the LSRM
- Cheaper and need very low memory in implementation
- Cover a wide range of operation conditions.

The fuzzy rules are listed in TABLE II.

TABLE II
Rules Of Proposed Fuzzy Controller

Δe	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

IV. MODEL REFERENCE ADAPTIVE CONTROL (MRAC)

A new MRAC system has been proposed in [23] which can be used for speed control of the electrical motors. Implementation of this control strategy needs state equation of the system same as [23]:

$$\dot{x} = f(x) + G(x)u \quad (20)$$

where $\dot{x} \in \mathbf{R}^n$ are state variables and $u \in \mathbf{R}^m$ is the input of the system. This equation can be written as

$$\dot{x} = A(x)x + B(x)u \quad (21)$$

where $f(x) = A(x)x$ and $G(x) = B(x)$. The speed is the time derivative of the position i.e:

$$\dot{x} = v \quad (22)$$

Using (6), we can write:

$$\dot{v} = -\frac{c+k_p}{M}v + \frac{1}{M}F_e \quad (23)$$

The matrix form of (22) and (23) is written as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{c+k_p}{M} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{M} \end{bmatrix} F_e \quad (24)$$

$$u(t) = F_e \quad (25)$$

In the proposed system, position speed $x_1 = v$ and derivative of the speed $x_2 = \dot{v}$ are state variables while, according to (25), propulsion force F_e is the output. In (10), $A(x)$ and $B(x)$ are the state-dependent coefficient matrices that represent the nonlinear system in the form (20) in a pseudo-linear form. In this work we examine the controllability of the LSRM system using the equation (3) discussed in the [23]. Using the state-dependent Riccati equation, all state variables should reach zero by minimizing the following integral quadratic cost function:

$$J = \frac{1}{2} \int_0^\infty (x^T Q(x) + u^T R(x) u) dt \quad (26)$$

where $Q(x) \in \mathbf{R}^{n \times n}$ and $R(x) \in \mathbf{R}^{n \times m}$ are the state-dependent weight matrices. For any x , it is assumed that

$$Q(x) \geq 0, \quad R(x) > 0 \quad (27)$$

Briefly description of the method has been demonstrated in [23]. This control strategy was implemented to the LSRM system and simulation results along with experiments results were obtained.

V. SIMULATION RESULTS

We use Matlab/Simulink to simulate the DLSRM along with the proposed control strategy. After generating the reference speed by the presented speed profile, the reference speed was compared with the actual value. Then, the error was introduced into the proposed fuzzy speed controller. Four phase currents were the output of the speed controller, which entered the PI current controller after comparison with the corresponding actual values. The proportional and integral parameters of the applied PI controller extracted by a trial and error approach were set to 0.05 and 2.2, respectively. In order to compare the performance of the proposed fuzzy system, a conventional PI controller along with a MRAC strategy discussed in [23] were

applied to the motor and the obtained results have been shown under all conditions. The proportional and integral gains of the PI speed controller were set to 1.3 and 3.2, respectively.

The simulation results including the speed, speed error, and total propulsion force for three control strategies are shown in Fig. 5. According to Fig. 5 (a), the profiles of the speed and position are same for all control methods, so only one curve is shown in the figure. In Fig. 5 (b), propulsion forces obtained from three control strategies are demonstrated. Generally, the figures are same and reach their final value in a same time. Pick value of force in MRAC and PI controllers are about 20 N.m while this is lower in the proposed fuzzy control method. Current of phase “a” is depicted in Fig. 5 (c). According to these figures, the current is high at starting while it reduces to a lower value in steady state. According to figures, proposed fuzzy control method has better performance than the conventional PI method while has the same performance as modern MRAC strategy discussed in [23].

The advantage of the fuzzy method is that it does not require accurate information about the nonlinear LSRM structure and

is easier to implement. Comparison of the speed between three control methods obtained by simulation and experimental have been shown in Fig. 9. There are some effective methods for evaluating the performance of control strategies which can be useful in comparing different systems. A useful method discussed in [12] introduces the critical parameters of the results including the percentage of overshoot, rising time, settling time, the criteria encompassing integral of absolute error (IAE) along with integral of time absolute error (ITAE). The parameters for the simulation test have been obtained and reported in Table 3. In order to study the performance of the system under load variations, an 8 kg load was added to the translator when it was moved at a constant speed. Then, the above-mentioned parameters were measured again and written in Table 3. The data confirm that the proposed control strategy has outperformed the conventional PI method in both no load and full load conditions, while it is approximately same as MRAC method. Considering the simple structure and implementation of the proposed fuzzy control method, it seems to be more appropriate than two other control strategies.

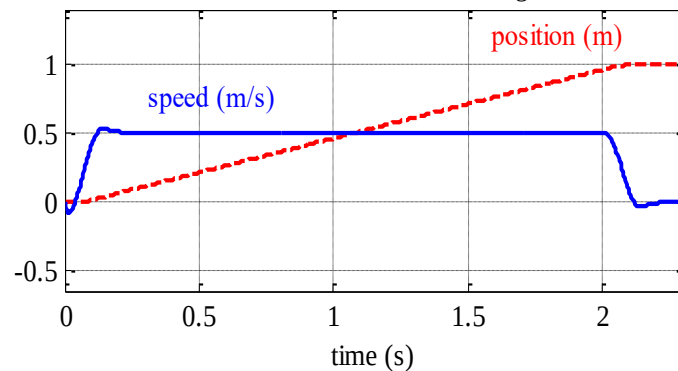


Fig. 5. a

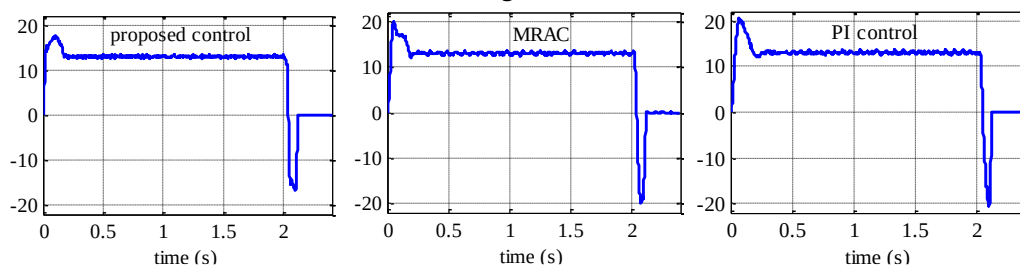


Fig. 5. b

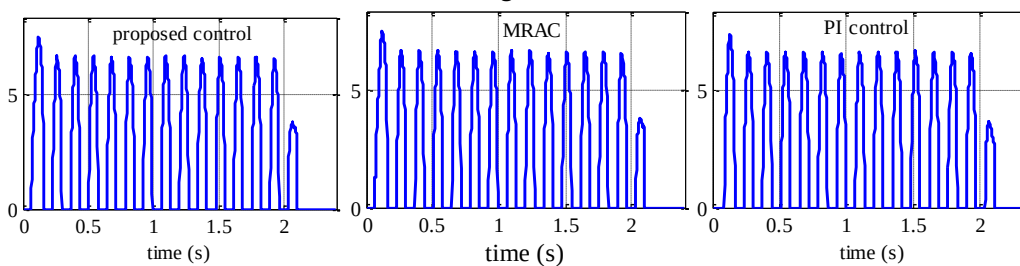


Fig. 5. c

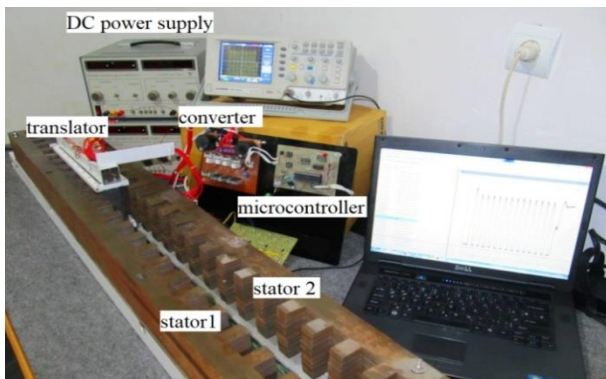
Fig. 5. Comparison of simulation results, (a) speed and position, (b) force (N), (c) phase current (A)

TABLE III. Critical Parameters

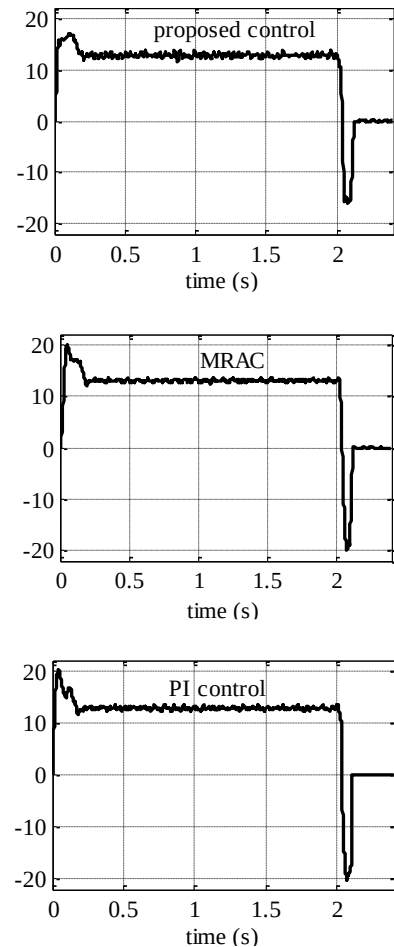
Parameter	No load			Full load		
	proposed	MRA C	PI	proposed	MRA C	PI
Overshoot (%)	0.87	0.88	1.5	2.8	3	6
Rising time	0.014	0.013	0.018	0.004	0.003	0.006
Settling time	0.016	0.017	0.031	0.009	0.010	0.026
IAE	0.01	0.01	0.015	0.014	0.014	0.025
ITAE	0.001	0.001	0.004	0.001	0.001	0.006

VI. EXPERIMENTAL RESULTS

In this study, a DLSRM with dimensions and parameters outlined in Table 1 was selected. Then the proposed control strategy along with a conventional PI controller was applied to regulate the motor performance. The motor and its experimental drive are shown in Fig. 6. Steel sheets with 0.5 mm thickness were used to construct the stator poles and yoke. For creating the translator, nonlaminated iron was used which coils of AWG#15 wire placed on translator poles. In order to implement the control system, an ARM Cortex-M4 microcontroller STM32f407 was used with 72 MHz processing frequency. Four Hall sensors sensed the actual phase currents and sent them to the current control unit. All signals were stored in a flash memory. Also, the propulsion force was calculated by the corresponding equations and finite element analysis information. A magnetic sensor strip with 10 μm resolution runs alongside the stator giving the position feedback signal. The speed information was also obtained through a capture channel of the timer inside the microcontroller.

**Fig. 6.** Experimental setup

The results measured in the experimental test for three control strategies are shown in Fig. 7. The test conduct under the same conditions as the simulation in Fig. 5. According Fig. 7, force in the steady state condition is 12 N. At start and to overcome the moment of inertia, the generated force is higher. The pick start force is 17 N, 20 N, and 20.5 N for proposed fuzzy method, MRAC, and PI method, respectively. This also happens during braking.

**Fig. 7.** Force comparison of three methods

The currents of a phase obtained from the experimental test for three control methods are demonstrated in Fig. 8. In order to have a better realization, the current is shown in all of the moving periods along with in a limited interval. Current profile in three strategies are approximately same, so only one profile is demonstrated.

The speed error for three control strategies obtained from simulation and experimental tests are shown together in Fig. 9. The figures indicate that the experimental results are approximately same as the simulation results. According to

Fig. 9, the speed error in proposed fuzzy control strategy and MRAC method has same overshoot about 0.03 m/s while this exceeds 0.1 m/s in the conventional PI controller. So, the proposed fuzzy control method and MRAC strategy have almost the same performance but fuzzy control method has some benefits explained in section 3.

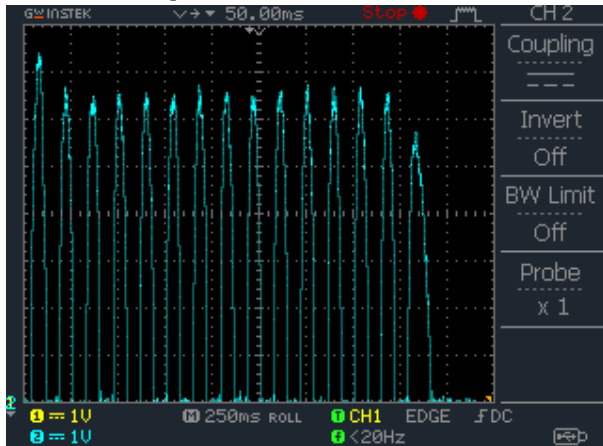


Fig. 8. a

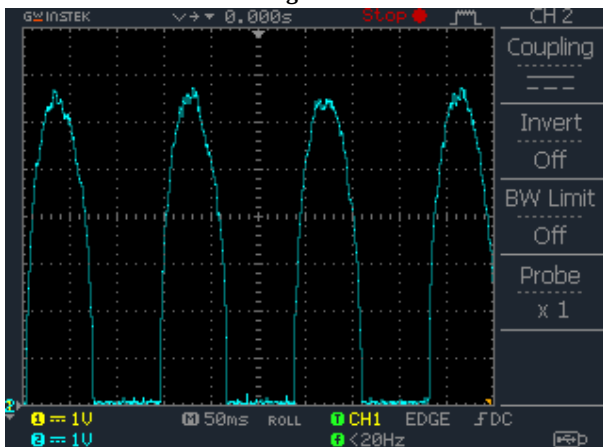


Fig. 8. b

Fig. 8. Experimental results, phase current, (a) total current, (b) current in a limited interval

VII. CONCLUSION

This work proposed the control of a double-sided linear switched reluctance motor by a simple fuzzy logic-based system. Linear switched reluctance motors are inherently non-linear systems with some unknown parameters such as saturation and end effect phenomena complicating their precise control. The proposed control strategy was applied to a motor along with a conventional PI and a modern MRAC strategies. The controller was able to control the position, speed, force and current of the motor simultaneously. To make the study more robust, simulation and experimental tests were performed and the obtained results were compared for three methods. The results confirmed that the fuzzy control approach outperformed the other methods. In addition, the proposed method was very simple requiring to

additional information about the system when compared with the other methods.

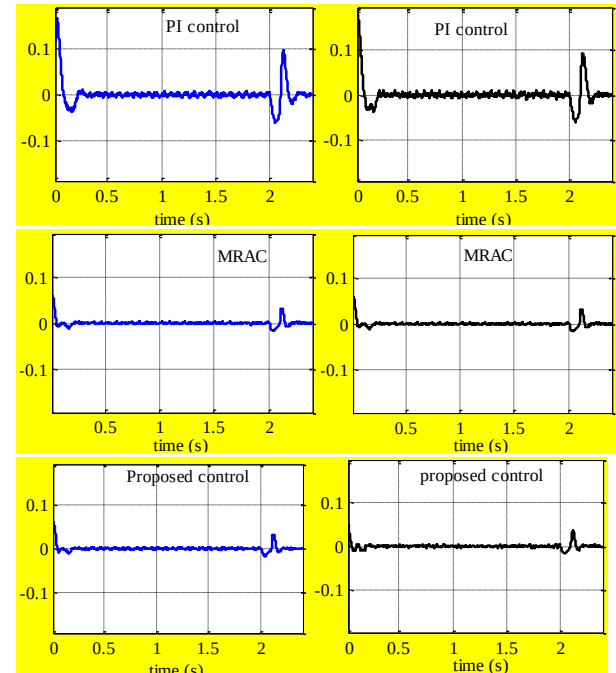


Fig. 9. a

Fig. 9. b

Fig. 9. Speed error comparison, (a) simulation, (b) experimental

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