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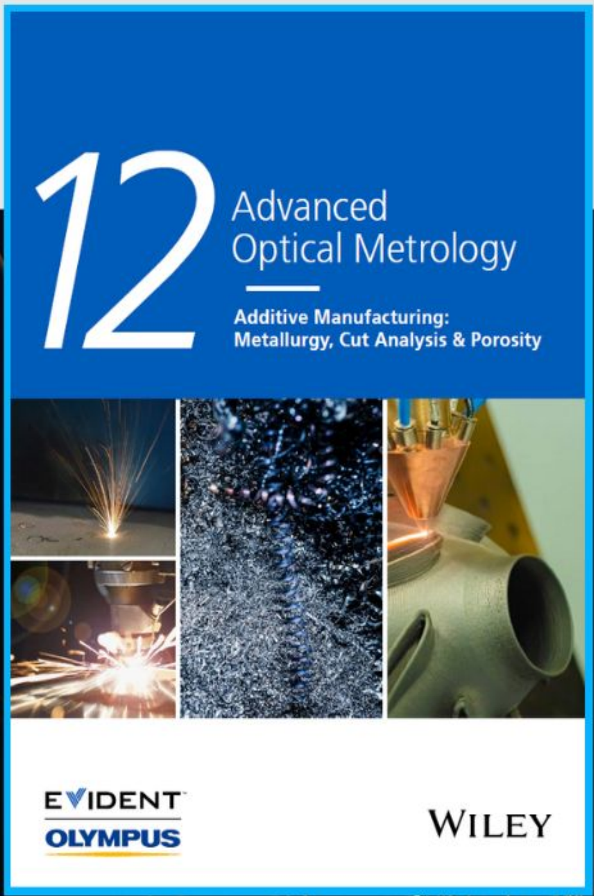

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Adaptive control strategy for velocity control of a linear switched reluctance motor

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Abstract: A new adaptive control strategy for a double-sided linear switched reluctance motor is proposed in this work. Switched reluctance motors inherently have non-linear dynamics that complicates their analysis and control. The Takagi–Sugeno fuzzy logic system has been used in this work to achieve an appropriate adaptive control system for the proposed linear motor. The fuzzy system has been heightened by non-linear rule consequences and a time-varying parameter. Updated laws have been designed to refresh the amount of the parameter consequently the suggested control system shows a stable performance in control of switched reluctance motors. The proposed control strategy is independent of the uncertainties of the motor dynamics and has an acceptable adaptability. This control method along with a conventional fuzzy logic based system have been studied on the proposed linear switched reluctance motor and their performances were compared in different performance conditions. An appropriate evaluation method has been used to compare the obtained results. The efficiency of the proposed method in different velocity commands has been examined and confirmed using appropriate simulation and experimental results.

1 Introduction

Switched reluctance motors (SRM) have some characteristics that make them very interesting in comparison with other electric motors. Some of these characteristics are the motor robustness, reliability and low price structure. These motors in two rotational and linear types have only one coil set on the stator (or translator) while the other side has poles without any winding. Linear motion SRMs have all advantages of the rotational types making them very interesting in linear movement applications such as sliding doors, transportation systems, launchers, etc. Different structures of linear SRMs (LSRMs) have been indicated in some papers [1–5]. These motors inherently have non-linear dynamics with some uncertainties which make it difficult to control them. Generated force of these motors totally includes high ripples that make their application difficult. Various velocity regulation strategies have been suggested by researchers which help to improve the motor performance and solve the force ripple problem in SRMs. Generated force of LSRMs can be controlled by an appropriate force distribution function (FDF) [6–8]. Fluctuations of the propulsion force affect the quality of speed and position of the translator. In order to overcome these disadvantages, some control techniques such as fuzzy logic based method (FLM), adaptive method (AM) and sliding mode control (SMC) have been utilised for a SRM control. A noticeable ability of the mentioned strategies is their efficiency in solving the different problems including unknown variables and compensation of disturbances. Analysis and regulation of non-linear systems may be done with FLM, [9, 10]. The method proposed in [10] includes low adjustable variables consequently computations may be done in a short time with an acceptable tracking accuracy. In [11] combined adaptive and fuzzy logic based controller have proposed which have been applied to a SRM. A Takagi–Sugeno fuzzy system has been used to model a discrete time non-linear system in [12]. The obtained method has been developed utilising a sliding mode controller. Another new fuzzy control system for a non-linear system has been presented in [13] which is based on predictive algorithm. In the work, according to the Takagi–Sugeno fuzzy model, a fuzzy prediction model of the system is obtained. An evolved type-2 FLM was examined in [14, 15], which encompass a new type of interval type-2 T-S fuzzy scheme. Using type-2 T-S fuzzy scheme has some benefits such as the feedback control ability [16], streamline [17, 18] and acceptable performance in recognition of fault [19].

An AM appropriate for a group of switched non-linear systems has been provided in [16] that the condition of switching signals dwell time should be satisfied. One of the important applications of a fuzzy logic system is modelling the systems including uncertain parameters. This is shown in [17] while the unknown parameter problems have been managed by up and down membership functions. The uncertain control direction was not considered in [16–18]. Adaptive control method can be very useful in non-linear systems control. The new combined AM and FLM has been presented for a SRM in [20]. The controller constructed with a fuzzy cerebellar model articulation controller (FCMAC) along with a compensating unit. The FCMAC examined the system dynamics while the compensating unit compensated the error of the FCMAC. In some articles special intelligent methods such as neural network has been combined with FLM to obtain a better performance [21].

Many researches including FLM [1, 19], AM [22] and SMC [2, 23] have been done in order to overcome the uncertainties problem. Totally, these methods are applied to incorporate the Nussbaum function in both control law [24] and adaptation law [25]. In [25] it is shown that we can select the adaptation laws to define the Nussbaum function. However, we can use control lows presented in [25], but it has some limitations such as its time derivative and low pass filter dependency.

A new adaptive fuzzy strategy for a double-sided linear SRM (DLSRM) has been presented in this paper. First, in Section 2 we describe the structure of the prototype DLSRM and its dynamic equations. Fuzzy unit of the proposed control system is introduced in Section 3.1 then the adaptation unit is demonstrated in Section 3.2. The total control strategy including the fuzzy and adaptive units is applied to the DLSRM in Section 4 and 5 consequently the obtained results are shown in the sections.

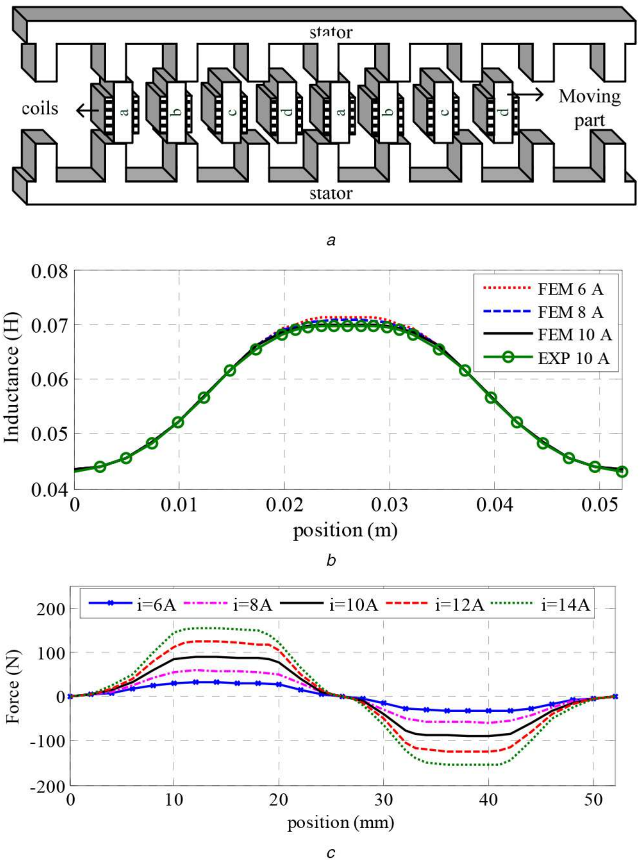

Fig. 1 *Selected DLSRM and data from FEM*
(a) DLSRM, ***(b)*** Phase inductance, ***(c)*** Force

2 Desired DLSRM

2.1 Selected structure

A four-phase DLSRM has been selected for this study which has a stator without any winding while four phase windings are located on four poles of the moving part [26]. This DLSRM has two similar stators on both sides of the moving part cause to high propulsion force generation while vertical force to the movement direction is about zero. It is obvious that DLSRMs inherently have totally non-linear characteristics, which make them very complicated and their performance control over the electrical motors. Achieving an appropriate model of the DLSRM including an accurate data of the motor inductance and force profiles is very useful in the motor analysis. This can be done by a precise three-dimensional finite element analysis. The obtained data of the selected DLSRM are shown in Fig. 1.

2.2 Dynamic equation

SRM dynamic study has been carried out in [26]. The dynamic equations of a four phase motor are

$$F_e = M\frac{\mathrm{d}v}{\mathrm{d}t} + Cv + F_{\mathrm{L}} \tag{1}$$

where F_e and F_{L} denote the propulsion and applied load forces, respectively. v, M and C are the velocity of the moving part (m/s), moving part total mass and frictional coefficient, respectively. k_{p} is a constant factor. Using (1) and (2), we can write:

$$\dot{v} = -\frac{C}{M}v + \frac{1}{M}[-Cv + F_e] \tag{2}$$

In linear SRMs similar to other electrical motors, the resistance of windings and friction coefficient vary with time. To consider these variations in the motor dynamic model, a time varying parameter $\xi(t)$ has been added to (2) as follows:

$$\dot{v} = -\frac{k_{\mathrm{p}}}{M}v + \left[-\frac{1}{M}F_{\mathrm{L}} + \frac{1}{M}F_e + \xi(t)\right] \tag{3}$$

where $\xi(t)$ is an unknown function and in $|\xi(t)| \le \varepsilon(t)$ $\varepsilon(t)$ is a known bounded continuous function.

3 Design of the controller

3.1 Fuzzy system

To have a precise analysis of the DLSRM and to design the proposed control system, let us consider (3) as the following:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}[f(\boldsymbol{x}) + g(\boldsymbol{x})\boldsymbol{u} + \xi(t)] \tag{4}$$

$$\boldsymbol{y} = C^{\mathrm{T}}\boldsymbol{x} \tag{5}$$

where $\boldsymbol{x} = [\boldsymbol{x}_1, \ldots, \boldsymbol{x}_{\mathrm{p}}]^{\mathrm{T}}$ indicates the state vector of the system which is measurable, $\boldsymbol{u} = [\boldsymbol{u}_1, \ldots, \boldsymbol{u}_{\mathrm{p}}]^{\mathrm{T}} \in R^{\mathrm{p}}$ shows the input vector and $\boldsymbol{y} = [\boldsymbol{y}_1, \ldots, \boldsymbol{y}_{\mathrm{p}}]^{\mathrm{T}} \in R^{\mathrm{p}}$ is the output vector. $\boldsymbol{A}$ and $\boldsymbol{B}$ are two matrices with $n \times n$ and $n \times 1$ dimensions, respectively. $f(\boldsymbol{x})$ and $\xi(t)$ are uncertain functions and $g(\boldsymbol{x})$ indicates an unknown continuous function gain. The system described by (4) and (5) is controllable if $g(\boldsymbol{x})$ is non-singular.

Assumption 1: The matrix $g(\boldsymbol{x})$ is non-singular.

Assumption 2: There is an unknown constant q and two known lower and upper positive functions of $g(\boldsymbol{x})$ that $0 < q < g_{\mathrm{L}}(\boldsymbol{x}) \le g(\boldsymbol{x}) \le g_{\mathrm{u}}(\boldsymbol{x})$.

In this work, design of a control system $u(t)$ has been presented. The goal of the control is that the output of the system y follows the reference variable $\boldsymbol{y}_{\mathrm{ref}} = [\boldsymbol{y}_{1,\mathrm{ref}}, \ldots, \boldsymbol{y}_{\mathrm{p,ref}}]^{\mathrm{T}}$ precisely with zero tracking error. In design process, all signals should be limited while the state x in (4) is converted to a small neighbourhood of the origin.

Assumption 3: The reference of the output signal $\boldsymbol{y}_{\text{ref}}$ and its derivatives are smooth and limited.

For a given positive definite matrix $\boldsymbol{Q}_1$, there exist a matrix $\boldsymbol{K}_c$ that the following equation is satisfied ($P_1 > 0$) [27].

$$(\boldsymbol{A} - \boldsymbol{B}\boldsymbol{K}_c)^{\text{T}}P_1 + P_1(\boldsymbol{A} - \boldsymbol{B}\boldsymbol{K}_c) = -\boldsymbol{Q}_1 \tag{6}$$

In general, a fuzzy system includes four essential units: a fuzzifier, data base unit including fuzzy rules, an inference engine, and a defuzzifier. The fuzzy inference engine creates a relative and map between the input vector $\boldsymbol{x} = [\boldsymbol{x}_1, \ldots, \boldsymbol{x}_n]^{\text{T}}$ and output variable y using IF-THEN fuzzy rules. According to the mathematical descriptions in [20, 21], Takagi–Sugeno fuzzy system with non-linear rule consequents (TS-FLC-NRCs) can be written as

$$\begin{aligned} &R^{(k)}: \text{IF } x_1 = G_1^k,\ x_2 = G_2^k, \text{and} \ldots x_n = G_n^k \\ &\text{THEN } y = F_k(x), \quad k = 1, 2, \ldots, N \end{aligned} \tag{7}$$

where G_k^i, $i = 1, \ldots, n$, indicates fuzzy sets and $y = F_k(x)$ denotes the non-linear continuous function. The system has 'n' fuzzy rules. Using singleton fuzzification method, central average defuzzification and product inference, the output is given as follows:

$$y = F(x) = \frac{\sum_{k=1}^{N} F_{k(x)}\left(\prod_{i=1}^{n} \mu_{G_i^k}(x_i)\right)}{\sum_{k=1}^{N} \prod_{i=1}^{n} \mu_{G_i^k}(x_i)} \tag{8}$$

where $\mu_{G_i^k}(x_i)$ shows the membership function of the G_i^k. Let's define a non-zero time-varying parameter $\sigma = \sigma(t)$ and put it in (8). Then we can write

$$y_{\text{f}} = F\left(\frac{x}{\sigma}\right) = \frac{\sum_{k=1}^{N} F_k(x/\sigma) \prod_{i=1}^{n} \mu_{G_i^k}(x_i/\sigma)}{\sum_{k=1}^{N} \prod_{i=1}^{n} \mu_{G_i^k}(x_i/\sigma)} \tag{9}$$

Considering $\pi(x)$ as the function vector, (9) can be written as

$$y\left(\frac{x}{\sigma}\right) = Y^{\text{T}}\pi\left(\frac{x}{\sigma}\right) = F\left(\frac{x}{\sigma}\right) \tag{10}$$

where $\boldsymbol{Y}^{\text{T}} = [\boldsymbol{y}_1, \ldots, \boldsymbol{y}_n]^{\text{T}}$ and $\pi(x/\sigma) = [\pi_1(x/\sigma), \ldots, \pi_n(x/\sigma)]^{\text{T}}$, such that

$$\pi_k\left(\frac{x_i}{\sigma}\right) = \frac{\prod_{i=1}^{n} \mu_{G_i^k}(x_i/\sigma)}{\sum_{k=1}^{N} \prod_{i=1}^{n} \mu_{G_i^k}(x_i/\sigma)}.$$

Assumption 4: Assuming that $F(x)$ is a continuous function on a compact set Ω_x, there exist a constant $\alpha > 0$ and a fuzzy system (10) such that

$$\sup\left|\frac{f(x)}{g(x)} - F(x)\right| \le \alpha, \quad x \in \Omega_{\text{x}}$$

Assumption 5: For any x_1 and x_2 in the compact set Ω_x, there exist a constant $\beta > 0$ such that

$$\beta \ge \frac{|f(x_1) - f(x_2)|}{x_1 - x_2}$$

so $f(x)$ satisfies Lipschitz condition.

3.2 Design of adaptive controller

Let us consider the estimation values of parameters α and β as $\hat{\alpha} = \hat{\alpha}(t)$ and $\hat{\beta} = \hat{\beta}(t)$, respectively. The corresponding estimated errors are $\tilde{\alpha} = \hat{\alpha} - \alpha$ and $\tilde{\beta} = \hat{\beta} - \beta$. To extract the proposed control system, we consider the system (4) with the following equations:

$$\dot{\sigma} = \tau\left(x, \sigma, \hat{\alpha}, \hat{\beta}\right) \tag{11}$$

$$\dot{\hat{\alpha}}\, \theta_1\left(x, \sigma, \hat{\alpha}, \hat{\beta}\right) \tag{12}$$

$$\dot{\hat{\beta}}\, \theta_2\left(x, \sigma, \hat{\alpha}, \hat{\beta}\right) \tag{13}$$

In this system, the adaptive laws of the estimated values of α and β are indicated by θ_1 and θ_2, respectively. Also, τ is the update law of the parameter σ. The proposed adaptive controller is written as follows:

$$u = u(x, \sigma) \tag{14}$$

This controller and laws (11)–(13) have to be designed to ensure the limitation of the state $\bar{\boldsymbol{x}} = \left(x^{\text{T}}, \sigma, \hat{\alpha}, \hat{\beta}\right)^{\text{T}}$ and the state of the (4) satisfies $x \to 0$ when 't' becomes infinite. This is the goal of the control system design. Then, we can write the control law for (4) as

$$u = \begin{cases} 0, & \| x \| > |\sigma|\delta \\ u_1 + u_2, & \| x \| \le |\sigma|\delta \end{cases} \tag{15a}$$

$$u_1 = kx + \omega \tag{15b}$$

$$\omega = \begin{cases} -\dfrac{\boldsymbol{B}^{\text{T}}Px}{|x^{\text{T}}P\boldsymbol{B}|}\dfrac{(g_u(x) + 1)|kx| + \varepsilon(t)}{g_{\text{L}}(x)}, & x^{\text{T}}P\boldsymbol{B} \ne 0 \\ 0, & x^{\text{T}}P\boldsymbol{B} = 0 \end{cases} \tag{15c}$$

$$u_2 = -F\left(\frac{x}{\sigma}\right) \tag{15d}$$

In order to solve the parameter uncertainty effect on the adaptation, the following strong adaptation laws are considered:

$$\dot{\alpha} = \begin{cases} 0, & \| x \| > |\sigma|\delta \\ 2\varphi_2 \| x \| \cdot \| P\boldsymbol{B} \| g_{\text{u}}(x) & \| x \| \le |\sigma|\delta \end{cases} \tag{16}$$

$$\dot{\beta} = \begin{cases} 2\mu \| \boldsymbol{B} \| \cdot \| x \|^2, & \| x \| > |\sigma|\delta \\ 2\delta\varphi_3 \| P\boldsymbol{B} \| \cdot \| x \| g_{\text{u}}(x)\Delta(\sigma, x) & \| x \| \le |\sigma|\delta \end{cases} \tag{17}$$

where μ and φ_j, $j = 1, 2, 3$, denote adjustable positive parameters and δ indicates a positive designing parameter. $\Delta(\sigma, x)$ denotes a certain positive function expressed as follows:

$$\Delta(\sigma, x) = \frac{(1 + |\sigma - 1|)g_{\text{u}}(x/\sigma) + g_{\text{u}}(x)}{g_{\text{L}}(x)g_{\text{L}}(x/\sigma)} \tag{18}$$

The control objects can be achieved using an appropriate update law. This law is written as

$$\dot{\sigma} = \begin{cases} \dfrac{1}{2\sigma\delta^2}\{d + c\}, & \| x \| > |\sigma|\delta \\ -2\varphi_1 \| P\boldsymbol{B} \| \cdot \dfrac{\delta\hat{\beta}\Delta(\sigma, x) + \hat{\alpha}}{\sigma} \| x \| g_{\text{u}}(x) & \| x \| \le |\sigma|\delta \end{cases} \tag{19}$$

where μ denotes an adjustable positive value and c calculated is as follows

$$c = \left[\mu_{\max}\left(\boldsymbol{A}^{\text{T}} + \boldsymbol{A}\right) + 2 \| B \| \hat{\beta}\right] \| x \|^2 + 2 \| B \| \cdot \| x \| \varepsilon(t) \tag{20}$$

Theorem 1: Assuming that the DLSRM dynamic equation was shown in form of (5), using the control law (15) and updating laws

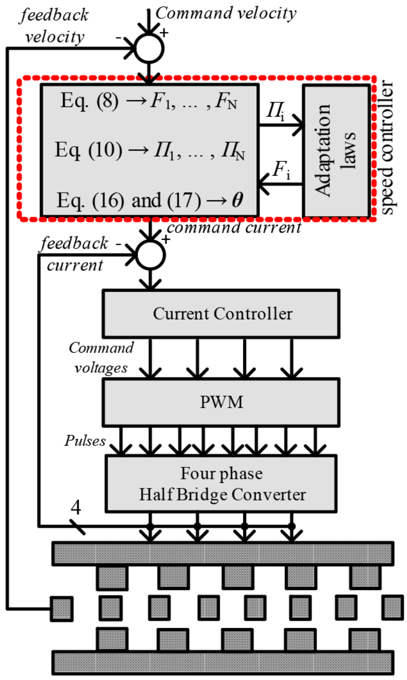

Fig. 2 *Structure of the proposed control system*

(16) and (17), the state vector $\boldsymbol{x} = \left(x^{\mathrm{T}}, \sigma, \hat{\alpha}, \hat{\beta}\right)^{\mathrm{T}}$ of the proposed system is limited and the tracking error is converted to a small neighbourhood of the origin.

Proof: As the control law (15) was presented in two conflicting periods, the above theory is proved in two separate sections as follows:

Section 1, $\| x \| > |\sigma|\delta$: Consider the following function.

$$s = \| x \|^2 - \sigma^2\delta^2 + 0.5\tilde{\alpha}^2 + 0.5\mu^{-1}\tilde{\beta}^2 \tag{21}$$

This is positive in $\| x \| > |\sigma|\delta$. Considering the positive function $\bar{V} = (1/2)s^2$ and using (11)–(17), the time derivative of $\bar{V}$ can be achieved as (see (22)) . *Section 2*, $\| x \| \le |\sigma|\delta$: According to the follow positive definite function

$$V(t) = x^{\mathrm{T}}Px + 0.5\varphi_1^{-1}\sigma^2 + 0.5\varphi_2^{-1}\tilde{\alpha}^2 + 0.5\varphi_3^{-1}\tilde{\beta}^2$$

and considering that Assumptions 1–3 are true, then we can write the time derivative of the $V(t)$ as follows:

$$\begin{aligned}\dot{V}(t) = & -x^{\mathrm{T}}Q_1x + 2x^{\mathrm{T}}\boldsymbol{PB}g(x)\left[\frac{-K_{\mathrm{c}}x + \xi(t)}{g(x)} + u_1\right] \\ & + 2x^{\mathrm{T}}P\boldsymbol{B}g(x)\left[\frac{f(x)}{g(x)} + u_2\right] + \varphi_1^{-1}\sigma\dot{\sigma} + \varphi_2^{-1}\tilde{\alpha}\dot{\hat{\alpha}} + \varphi_3^{-1}\tilde{\beta}\dot{\hat{\beta}} \\ = & -x^{\mathrm{T}}Q_1x + 2x^{\mathrm{T}}PBg(x)\left[\frac{(g(x)-1)K_{\mathrm{c}}x}{g(x)} + \omega\right] \\ & + 2x^{\mathrm{T}}P\boldsymbol{B}g(x)\left[\frac{f(x)}{g(x)} + u_2\right] + \varphi_1^{-1}\sigma\dot{\sigma} + \varphi_2^{-1}\tilde{\alpha}\dot{\hat{\alpha}} + \varphi_3^{-1}\tilde{\beta}\dot{\hat{\beta}}\end{aligned} \tag{23}$$

Substituting (16) in (23), we can write

$$\begin{aligned}\dot{V}(t) \le & -x^{\mathrm{T}}Q_1x + 2\,\| \boldsymbol{PB} \| \cdot \| x \|\, g_{\mathrm{u}}(x)[\left(\hat{\beta} - \tilde{\beta}\right)\delta\Delta(\sigma, x) \\ & + \hat{\alpha} - \tilde{\alpha}] + \varphi_1^{-1}\sigma\dot{\sigma} + \varphi_2^{-1}\tilde{\alpha}\dot{\hat{\alpha}} + \varphi_3^{-1}\tilde{\beta}\dot{\hat{\beta}} \\ = & -x^{\mathrm{T}}Q_1x + 2\,\| \boldsymbol{PB} \| \cdot \| x \|\, g_{\mathrm{u}}(x)\left[\delta\hat{\beta}\Delta(\sigma, x) + \hat{\alpha}\right] \\ & + \varphi_1^{-1}\sigma\dot{\sigma} + \tilde{\alpha}\left[\varphi_2^{-1}\dot{\hat{\alpha}} - 2\,\| \boldsymbol{PB} \| \cdot \| x \|\, g_{\mathrm{u}}(x)\right] \\ & + \tilde{\beta}\left[\varphi_3^{-1}\dot{\hat{\alpha}} - 2\delta\,\| \boldsymbol{PB} \| \cdot \| x \|\, g_{\mathrm{u}}(x)\Delta(\sigma, x)\right] \\ = & -x^{\mathrm{T}}Q_1x\end{aligned} \tag{24}$$

This inequality confirms that the state vector of the proposed system, $\boldsymbol{x} = \left(x^{\mathrm{T}}, \sigma, \hat{\alpha}, \hat{\beta}\right)^{\mathrm{T}}$ is bounded and so, Theorem 1 is proved.□

The schematic representation of the control system is indicated in Fig. 2. The system has two control loops including an inner loop regulating the phase current and an outer loop which regulates the speed of the DLSRM given in Table 1.

$$\begin{aligned}\dot{\bar{V}} = & s\left(\dot{x}^{\mathrm{T}}x + x^{\mathrm{T}}\dot{x} - 2\sigma\dot{\sigma}\delta^2 + \tilde{\alpha}\dot{\hat{\alpha}} + \mu^{-1}\tilde{\beta}\dot{\hat{\beta}}\right) \\ = & s\left\{x^{\mathrm{T}}\left(\boldsymbol{A}^{\mathrm{T}} + \boldsymbol{A}\right)x + 2x^{\mathrm{T}}\boldsymbol{B}(f(x) + \xi(t)) - 2\sigma\dot{\sigma}\delta^2 + \mu^{-1}\tilde{\beta}\dot{\hat{\beta}}\right\} \\ \le & s[\mu_{\max}\left(\boldsymbol{A}^{\mathrm{T}} + \boldsymbol{A}\right)\| x \|^2 + 2\,\| x \| \cdot \| \boldsymbol{B} \|\,(\beta\,\| x \| + \varepsilon(t)) - 2\sigma\dot{\sigma}\delta^2 + \mu^{-1}\tilde{\beta}\dot{\hat{\beta}}] \\ = & s[\mu_{\max}\left(\boldsymbol{A}^{\mathrm{T}} + \boldsymbol{A}\right)\| x \|^2 + 2\,\| x \| \cdot \| \boldsymbol{B} \|\left((\hat{\beta} - \tilde{\beta})\,\| x \| + \varepsilon(t)\right) - 2\sigma\dot{\sigma}\delta^2 + \mu^{-1}\tilde{\beta}\dot{\hat{\beta}}] \\ = & s\left[\mu_{\max}(\boldsymbol{A}^{\mathrm{T}} + \boldsymbol{A}) + 2\,\| B \|\,\hat{\beta}\right]\| x \|^2 + 2\,\| x \| \cdot \| \boldsymbol{B} \|\,\varepsilon(t) - 2\sigma\dot{\sigma}\delta^2 \\ & + \tilde{\beta}\left[\mu^{-1}\dot{\hat{\beta}} - 2\,\| \boldsymbol{B} \| \cdot \| x \|^2\right] = \mathrm{d}s\end{aligned} \tag{22}$$

Table 1 Selected DLSRM parameters

Variables	Value
air gap length, mm	2
stator pole width, mm	21
stator slot width, mm	31
stator pole height, mm	30
translator pole width, mm	13
translator pole height, mm	26
translator height, mm	220
winding turns	200
rated current, A	10
rated voltage, V	150
coefficient of friction, *C*	10 N/m/s
weight of translator, *M*	8 kg
phase resistance	2.5 Ω

Table 2 Proposed controller parameters value

Parameter	Value
Δ	10
d	50
μ	0.002
β_1	0.001
β_2	0.00002
β_3	0.00005
G	9.8

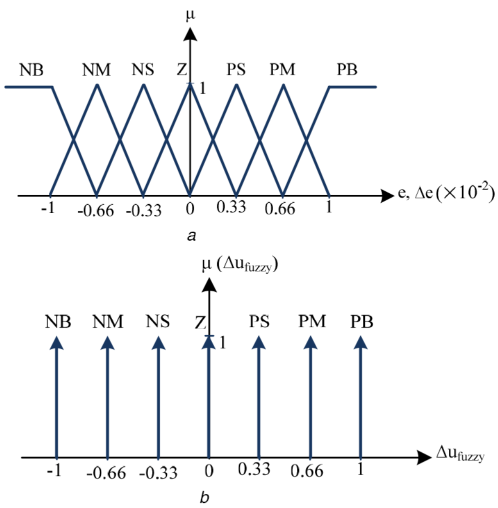

Fig. 3 *Fuzzy sets of conventional fuzzy controller*
(a) Input variables, ***(b)*** Output variables

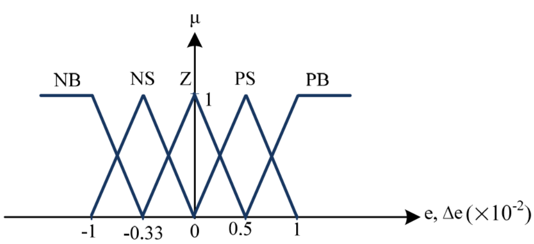

Fig. 4 *Fuzzy sets in the proposed controller*

A conventional PI controller has been selected to control the phase current. Parameters of the controller were achieved as 0.05 and 2.7 for proportional and integral gains, respectively. The number of fuzzy rules and adaptive laws are fewer in the presented method compared to the conventional strategies. In this study, four fuzzy rules have been used to design the control system with parameters given in Table 2.

4 Simulation results

Matlab/Simulink has been used to simulate the proposed system. In order to have more study on the proposed control system, the controller was implemented to the DLSRM and its performance was analysed in different conditions. Seven triangular fuzzy sets are used to introduce the variables as shown in Fig. 3. The error of speed error and its change are considered as input variables. Thus

$$\boldsymbol{x}^{\mathrm{T}} = [x_1\ x_2] = [e\ \Delta e] \tag{27}$$

Fuzzy sets shown in Fig. 4 are used to specify the input variables. According to (7), we can obtain the following fuzzy basis functions

$$\Pi = [\Pi_1\ \Pi_2\ \Pi_3\ \Pi_4]^{\mathrm{T}} \tag{28}$$

The algorithm of these calculations has been presented in [28], while the adaptation laws shown in (16)–(21) were used to calculate the parameters.

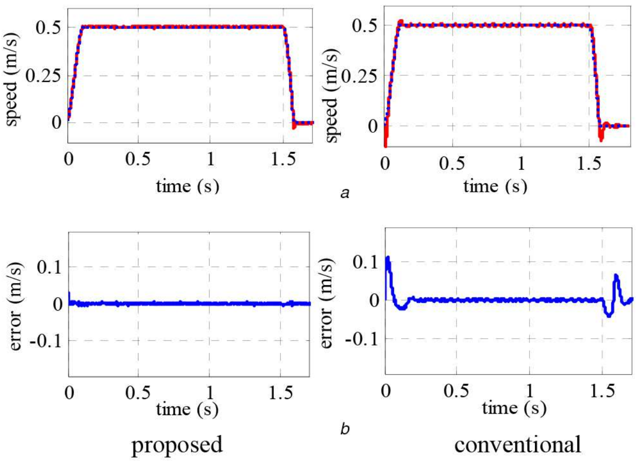

Fig. 5 *Speed results comparison*
(a) Speed, ***(b)*** Speed error

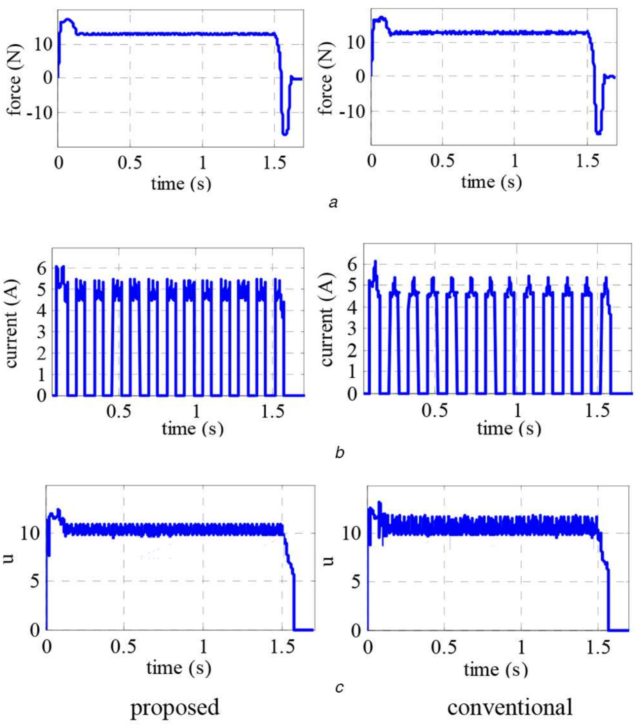

Fig. 6 *Simulations results in no-load*
(a) Force, ***(b)*** Current, ***(c)*** Output of the fuzzy controller (μ)

In order to enhance the motion quality, a speed profile has been applied which minimises jerk of moving part [26]. The proposed controller along with a conventional fuzzy speed controller has been applied to the DLSRM. The obtained results are indicated in Fig. 5. Total profile of the speed and its error with respect to the command value are presented in Figs. 5*a* and *b*. The low amount of the error confirms that the proposed control strategy has an acceptable performance with respect to the conventional fuzzy method. Total propulsion forces in two control methods are demonstrated in Fig. 6*a* while, phase current can be seen in Fig. 6*b*. The output parameter of the controller which is the sum of two phase currents and can be measured in the output of the converter are demonstrated in Fig. 6*c*.

In order to study the performance of the system in load variation conditions, an external 8 kg load was added to the translator in $t = 0.7$ s and simulation results were obtained. The results are shown in Fig. 7.

Performance of the control system under different speed references was performed and the obtained results for speeds 5 m/s and a sinusoidal reference speed sin(t) m/s are shown in Fig. 8. The

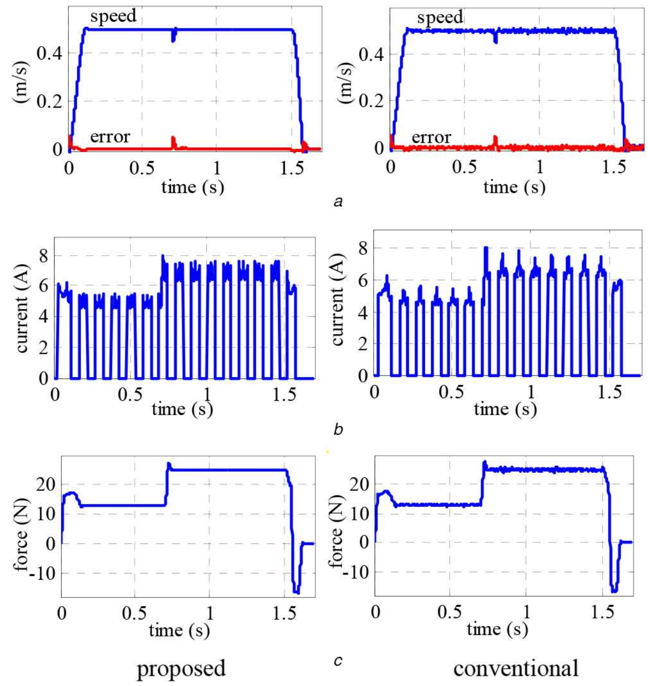

Fig. 7 *Simulations results in load variation*
(a) Speed and error, ***(b)*** Current, ***(c)*** Force

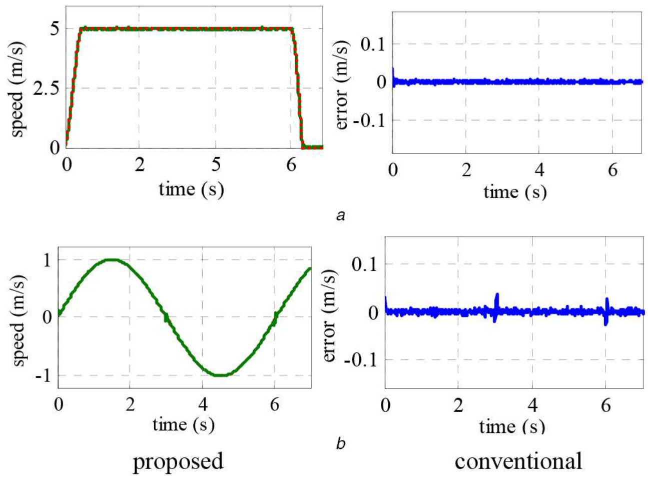

Fig. 8 *Controller performance under different speeds*
(a) 5 m/s, ***(b)*** sin(t) m/s

results confirm the robustness of the proposed system under different speeds.

The parameters adaptation is the major benefit of the proposed control strategy. This is performed by the equations written in the previous section. The parameters of variation for the speed equal to 0.5 m/s in this work are indicated in Fig. 9.

5 Experimental results

In order to conduct the experimental examinations of the proposed control strategy, four phase DLSRM introduced in Table 1 was constructed in this study and experimental tests were made as well as simulation tests in the previous section. Schematic representation of the experimental setup is demonstrated in Fig. 10. Steel sheets with a thickness of 0.5 mm were used to construct a laminated double-sided stator with thickness and length equal to 8 and 250 cm, respectively. Translator includes eight non-laminated cores wound by AWG#15 wires.

STM32f407 ARM microcontroller with the processing frequency of 72 MHz has been used to implement the control system. In order to measure the phase currents, four hall sensors have been located on four phases which save the value of phase current in the flash memory. Total propulsion force is calculated

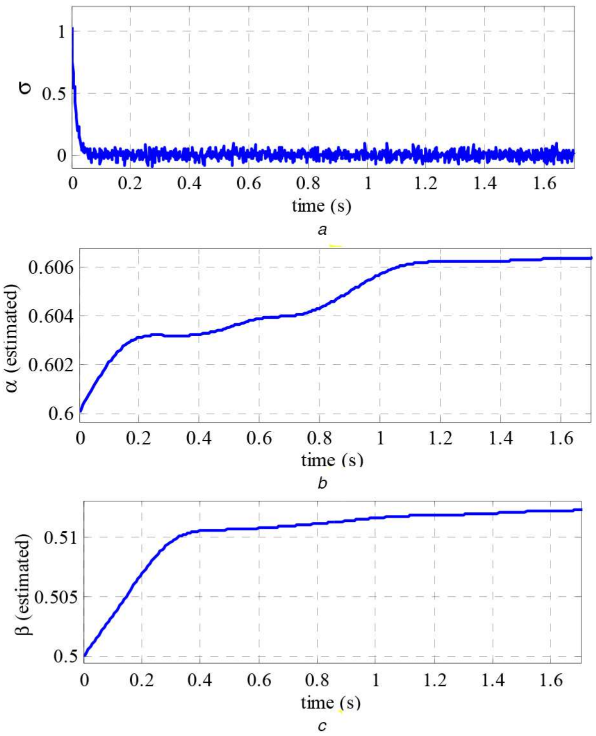

Fig. 9 *Response curve of parameters*
(a) Parameter σ with $\sigma(0) = 1$, ***(b)*** Estimated parameter $\hat{\alpha}$ with $\hat{\alpha}(0) = 0.6$, ***(c)*** Estimated parameter $\hat{\beta}$ with $\hat{\beta}(0) = 0.6$

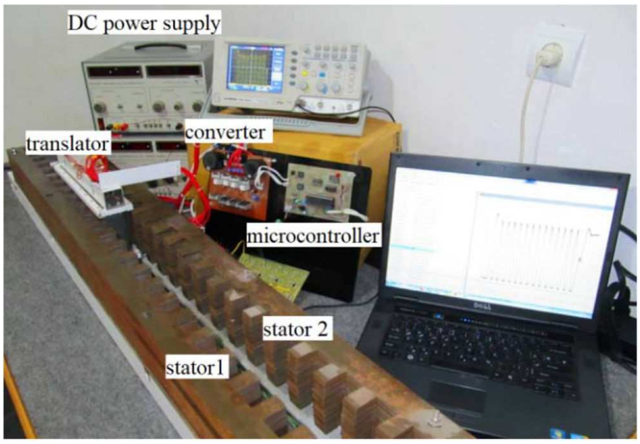

Fig. 10 *Experimental setup*

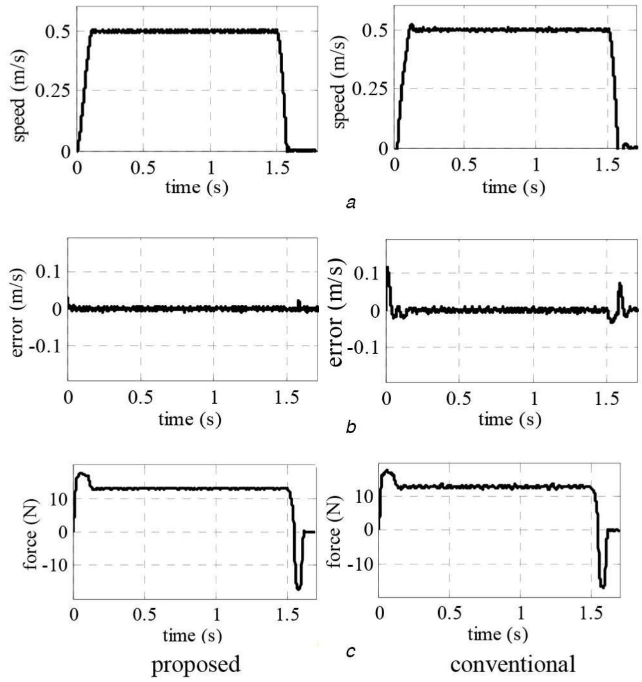

Fig. 11 *Experimental results*
(a) Speed, ***(b)*** Speed error, ***(c)*** Propulsion force

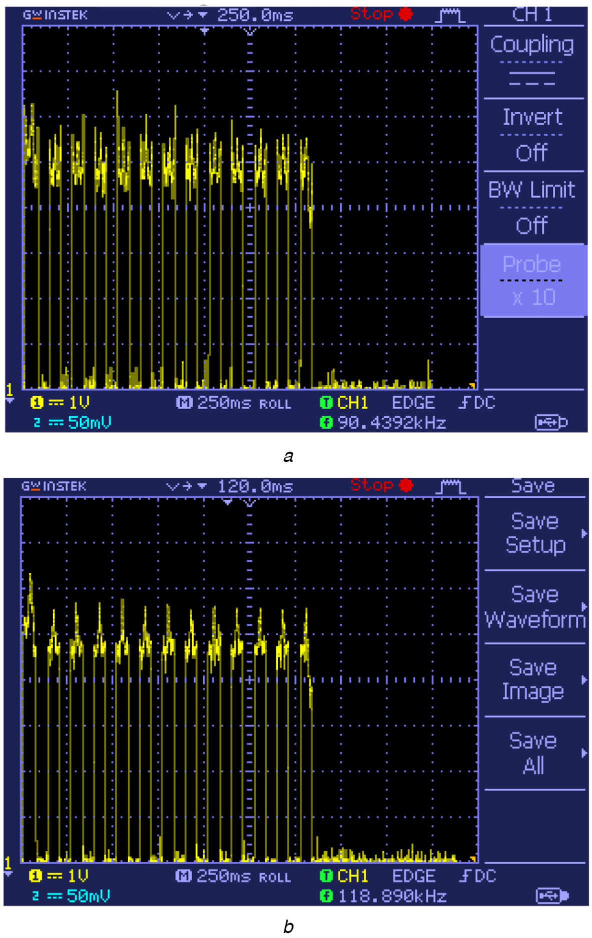

Fig. 12 *Experimental results, phase current*
(a) Proposed method, ***(b)*** Fuzzy method

according to the measured current and FEA data. Position data of the moving part are extracted using a magnetic sensor strip with a 10 µm resolution. Finally, the speed data is achieved through a capture channel of the timer inside the microcontroller.

The proposed and conventional fuzzy controllers were implemented and the proposed signals were measured. The measured data are shown in Fig. 11. In the experimental setup, instantaneous value of the propulsion force is calculated in microcontroller using the instantaneous current, position data and information obtained from finite element analysis. The experimental results confirm the outstanding performance of the proposed control strategy compared to the conventional fuzzy controller.

The phase current profile of the DLSRM during the experimental test is indicated as an oscilloscope screen in Fig. 12. These profiles are same as the results achieved by the simulation in the previous section.

There are some effective methods for evaluation of the control strategies performance that can be useful in comparison to different systems. A useful method has been discussed in [11] introducing the critical parameters of the results including percentage of overshoot, rising time, settling time, the criteria encompassing integral of absolute error (IAE) and integral of time absolute error (ITAE). The results obtained from experimental tests using the proposed controller in load variation conditions are shown in Fig. 13. Comparison of two control strategies in experimental load variation tests are shown in Table 3. In the test, a 8 kg load was

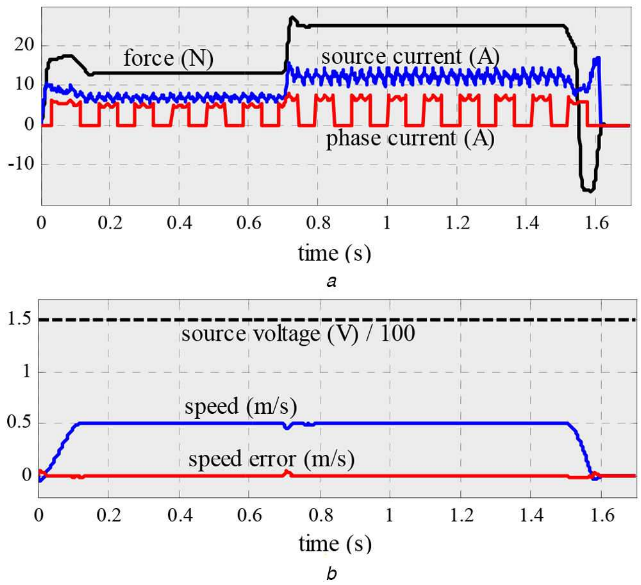

Fig. 13 *Experimental results*
(a) Force and current, ***(b)*** Source voltage, speed and error

Table 3 Critical parameters

	No load		Full load	
Parameter	Proposed	Fuzzy	Proposed	Fuzzy
overshoot, %	0.95	1.7	3.1	8
rising time	0.011	0.023	0.005	0.008
settling time	0.013	0.03	0.008	0.03
IAE	0.01	0.016	0.013	0.02
ITAE	0.001	0.003	0.001	0.005

added to the translator moving with a constant speed and then the above-mentioned parameters were measured again and written in Table 3. The data confirm that the proposed control strategy has better performance than the conventional fuzzy method in both no load and full load condition.

6 Conclusion

In this work, we proposed the TS-FLC-NRCs to design adaptive controller for a linear SRM with non-linear characteristics. At first, a time varying parameter was defined for the fuzzy logic system and then update laws were designed to recalculate the parameter and estimate the adaptation parameters. The proposed control strategy was implemented on a double-sided four phase SRM. Simulation test performed and the obtained results compared with the corresponding results achieved by conventional fuzzy controller. The experimental results confirmed that the adaptive fuzzy control method is a stable method with acceptable performance for the linear SRM.

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