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Fuzzy Logic Control of Linear Switched Reluctance Motor

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***Abstract*—The work developed in this paper deals with a control of a Linear Switched Reluctance Motor (LSRM). The studied actuator is used in high precision application where the quality and the accuracy of positioning are vital. In this study the open and speed closed loop control are detailed and integrated to control this actuator. In order to improve the quality of positioning, we have implemented a LSRM control strategy with the help of Fuzzy Logic Controller (FLC). Problem of force ripples are solved by using Force Distribution Function (FDF). Paper reports a comparative study of speed control using a PI controller and FLC. Experimental setup board based on PIC 18F452 is designed and presented**

Obtained results prove the efficiency of the proposed control strategy and the superiority of FLC over PID controller.

Keywords—Linear Motor; Switched Reluctance Motor; Fuzzy logic control; Force distribution function; high precision application; PIC18F452.

I. INTRODUCTION

Industrial applications need more and more accuracy and performance with high speed especially in linear motion. This motion is provided in classical systems by a rotating motor associated to a gear unit to convert rotary motion to linear motion. In high precision application this converter , is bulky, expensive and a frequent source of failure. [25].

Linear Switched Reluctance Motor (LSRM) is an actuator that can provide a direct linear motion without the need of rotary to linear motion converter so there no mechanical limits.
LSRMs are now widely used in many industrial applications especially in high dynamic machinery production (machine tools, robots, etc.) they are strong candidates for both low speed and high speed mass transit applications. [3] [6].
The advantage of suppress mechanical converters to produce a linear motion decrease friction, maintain problems and increase performances. So this motor is integrated in many applications.
This kind of actuator is characterized by its simple structure also its low construction cost. LSRM only has concentrated windings on the stator or translator so it's easily controlled [6] [4].

Also this motor is characterized by a particular structure similar to that of the rotary stepper motor and it is widely used in open loop control. During the 1970s the closed loop control was introduced in stepper motor in order to increase the positioning accuracy and to reduce their sensitivity to disturbances load [1], [2].
Today, thanks to the development of control theory advances in power electronics and in computer science applications, LSRMs are used in closed loop control especially in robotics and in biomedical applications [8].

PID (Proportional Integral Derivative) control is one of the conventional control strategies used for various industrial processes from many years due to their simplicity in operation. It has a simple control structure which was understood by plant operators whose they found it relatively easy to adjust.
LSRM is subjected to disturbances and parameters variations also it's characterized by nonlinear characteristics in its torque production when it is operated in its saturated region.
Although the designs of traditional PI controller are done by linearization of transfer function [5] so its properties of stability and robustness are not guaranteed to hold under different operating conditions.
For those reasons it is necessary to employ a nonlinear control design tool. Among several techniques fuzzy logic controller (FLC) appears to be appropriate since it is shows the improvements in various control parameters like maximum overshoot, settling time for the many systems control as compared with PID control strategy. The basis of fuzzy logic is fuzzy set theory which was developed by Lotfi Zadeh in the 1960s.
FLC is introduced in the control of DC motor in references [15],[16] when they shows the superiority of fuzzy logic controller over PID controller . Reference [17],[18],[19] and

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[20] present FLC's application on switched reluctance motor in rotary domain.

The major disadvantages of LSRM are the large force ripple so solving this problem is an important objective. In recent years, several control strategies have been proposed in the literatures in linear or rotary domain [20],[21],[22],[23], [24], by using a force distribution function (FDF).

The major contribution of this paper is the integration of FLC in linear domain to control LSRM for high precision application. Also the proposed control is optimized by the use of efficiency FDF.

The objective of this paper is double. The first part consists in modeling the LSRM which is difficult to control reason of undesired oscillations in force, position and parameters disturbance. The second part concerns the closed loop speed control of the actuator by controlling speed and current. An optimum strategy of control is presented which use FLC to monitor the speed and hysteresis controller to control the current. FDF is presented and integrated into the control strategy in order to suppress the force ripple.

II. Linear Switched Reluctance Motor Modeling and Open Loop Control

A. LRSM presentation and analysis

In this work we study a planner longitudinal linear switched reluctance motor with an active mover and a passive stator which is composed by four phases. This configuration contain 8 translator pole and this similar to 8/6 (8 stator and 6 rotor poles) RSRM.

LSRM is composed by two elements the first one is a toothed magnetic material fixed to a support and called stator. The second is a sliding part by rails and is called the mover (translator).

The mover is formed by a different modules regularly distributed lodging the winding. This topology is a single sided LSRM with active translator and passive stator, figure (1). The stator windings are laminated with a copper and excited by a DC currents.

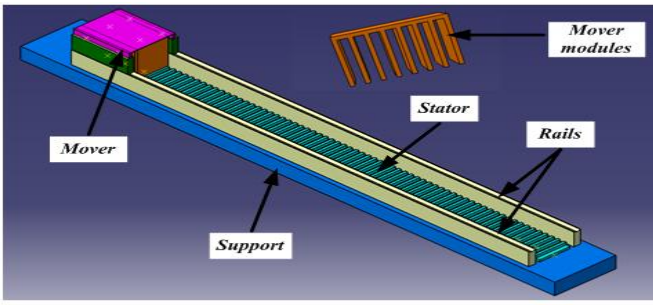
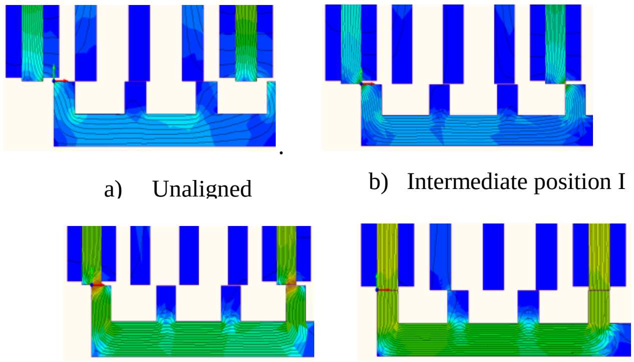


Fig 1: LSRM configuration

Initially two translator poles are aligned to the two stator pole; another set of translator pole is out of alignment with respect to a different set of stator poles. The winding excitation sequences in the increasing inductance region make the translator move. The lack of non- magnetic separations between the different modules creates a radial magnetic flux path, this configuration is called longitudinal flux configuration.



a) Unaligned b) Intermediate position I

c) Intermediate position II d) Aligned position

Figure 2: Magnetic flux path and field density for different translator position regions

Figure (2) show the magnetic flux path in a four different translator positions that are parallel to motion line. It is clear from figure (2, a) that the flux path in the unaligned position is very difficult to predict, thus the complexity of the steady state performance evaluation. The flux leakage in the aligned position shown in figure (2, d) is practically negligible, also we can see that there are two stator teeth aligned with mover teeth and other which are unaligned.

With an examination of these figures, it is observed that there is a local saturation occurs on stator tips and translator pole. This local saturation occurs when the relative positions of translator and stator pole is threshold of overlap or during partial overlap. In this region, the flux density is assumed to be the maximum value.

B. LRSM modelling

The LSRM has a high nonlinear characteristic due to its nonlinear flux behaviour [13]. In order to simplify equations, the modelling is performed without taking into account magnetic saturation, phases are considered identical and end effect is neglected [13].

Consequently, the corresponding voltage equation neglecting the mutual is given by: [10] [11] [12]:

$$u = Ri + \frac{d\Phi(i,x)}{dt} = Ri + L\frac{di}{dt} + i_n \frac{di}{dt}\frac{dx}{dt} \qquad (1)$$

where u is the applied voltage, i is phase current, R is the phase resistance, L is the phase inductance, ϕ is the flux linkage.

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The phase inductance as function of position with first Fourier terms is given by:

$$L_{\lambda}(x) = L_0 + L_1 \cos\left(\frac{2\pi x}{\lambda}\right) \quad (2)$$

Where:

$$L_0 = \frac{L_{\max} + L_{\min}}{2} = \frac{0.038 + 0.008}{2} = 0.023H \quad (3)$$

$$L_1 = \frac{L_{\max} - L_{\min}}{2} = \frac{0.038 - 0.008}{2} = 0.015H \quad (4)$$

Finally the voltage and mechanical equations are:

$$u_A = Ri_A + L_0 \frac{di_A}{dt} + L_1 \cos\left(\frac{2\pi x}{\lambda}\right) \frac{di_A}{dt} + \frac{2\pi}{\lambda} L_1 \sin\left(\frac{2\pi x}{\lambda}\right) v i_A \quad (5)$$

$$u_B = Ri_B + L_0 \frac{di_B}{dt} + L_1 \cos\left(\frac{2\pi x}{\lambda} - \frac{\pi}{2}\right) \frac{di_B}{dt} + \frac{2\pi}{\lambda} L_1 \sin\left(\frac{2\pi x}{\lambda} - \frac{\pi}{2}\right) v i_B \quad (6)$$

$$u_C = Ri_C + L_0 \frac{di_C}{dt} + L_1 \cos\left(\frac{2\pi x}{\lambda} - \pi\right) \frac{di_C}{dt} + \frac{2\pi}{\lambda} L_1 \sin\left(\frac{2\pi x}{\lambda} - \pi\right) v i_C \quad (7)$$

$$u_D = Ri_D + L_0 \frac{di_D}{dt} + L_1 \cos\left(\frac{2\pi x}{\lambda} - \frac{3\pi}{2}\right) \frac{di_D}{dt} + \frac{2\pi}{\lambda} L_1 \sin\left(\frac{2\pi x}{\lambda} - \frac{3\pi}{2}\right) v i_D$$

(8)

$$\frac{dv}{dt} = -\frac{\pi L_1}{m\lambda} \left[\begin{array}{l} i^2{}_A \sin\left(\frac{2\pi}{\lambda} x\right) + i^2{}_B \sin\left(\frac{2\pi}{\lambda} x - \frac{\pi}{2}\right) + \\ i^2{}_C \sin\left(\frac{2\pi x}{\lambda} - \pi\right) + i^2{}_D \sin\left(\frac{2\pi}{\lambda} x - \frac{3\pi}{2}\right) \end{array} \right] - \frac{\xi}{m} v - \frac{Fc}{m} - \frac{F0}{m} signe(v)$$

To test the developed models and to verify the effectiveness of various applied controls, MATLAB/ SIMULINK was used as a simulation tool.

The open-loop control has the merit of simplicity and a consequent low cost. It aims at supplying the motor phases in a fixed order according to the direction, so there is no return and no regulation possible and there is no guarantee that the actuator has responded to the command.

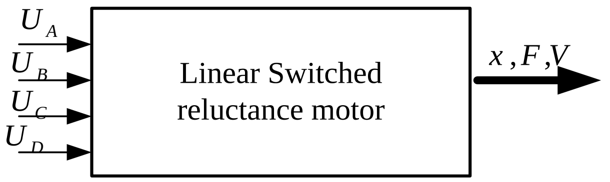

Fig 3 : Open loop control

Table 1 summarize the different parameters of the actuator

Table 1 : Various parameters of LSRM

Parameters	Designation	Value
u	Voltage	$18V$
i	Current	$1A$
R	Resistance	18Ω
x	Displacement	Variable
v	Speed	Variable
λ	Tooth pitch	$6mm$
L_0	Minimum inductance	$225mH$
L_1	Maximum inductance	$50mH$
Fc	load force	Variable
F_0	Friction force	$0.2N$
m	Mass	$5Kg$
ξ	Damping coefficient	$65Nm/s$

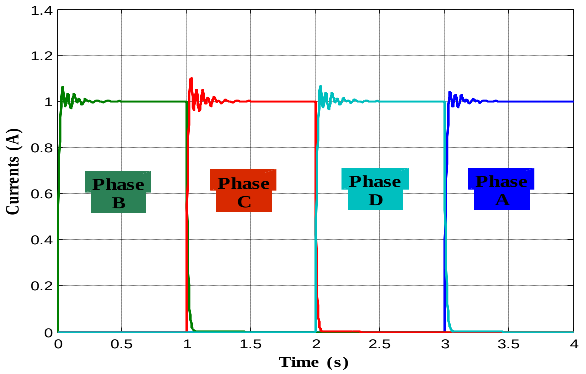

Fig 4: Current phases

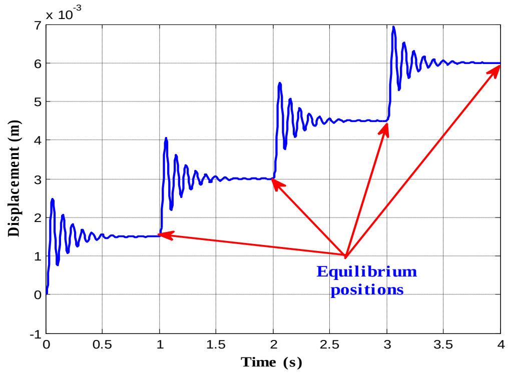

Fig 5 : Displacement of the mover as function of time for 4 steps

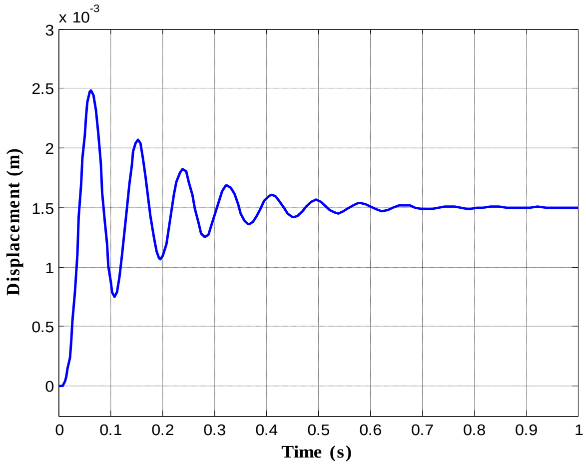

Fig. 6: Displacement of the mover for 1 step

The displacement of the mover shown in figure (5) and figure (6) demonstrates the disadvantage of this control when the motion is characterized by great over-shoots and strong oscillations.
The only method to vary the speed is to vary the alimentation sequence of phases but this method does not satisfy the control the requirement of high precision application.

III. Speed Control Using Fuzzy Logic Control

Fuzzy logic is a method of rule-based decision making used for expert systems and process control that emulates the rule of thumb through a process used by human beings.
Due to nonlinearities in the actuator its performance is greatly distorted by using conventional PI controller and the efficiency is reduced. The new technique which uses fuzzy controllers is complex. However nonlinear controllers can solve those problems.

Reference [5] present PI speed control where the result motion is characterized by overshoots and the control is not robust in case of parameter disturbance.

A fuzzy logic controller has four main components as shown in Figure (7): fuzzification interface, inference mechanism, rule base and defuzzification interface..

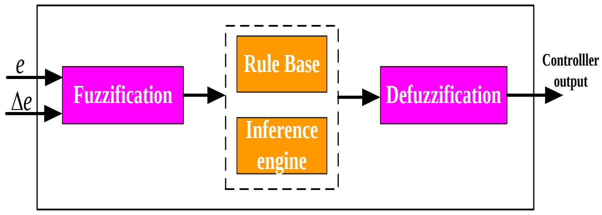

Fig 7 : Main components of FLC

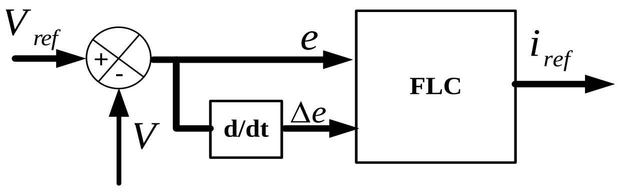

Fig. 8: **Fuzzy logic speed control strategy**

The fuzzification of the studied FLC is composed of five triangular membership's functions for the error, denoted by NB (Negative Big), NS (Negative small), Z (Zero), PS (Positive small) and PB (Positive Big) as shown in figure (11). For the error variation figure (9) just two memberships' functions are used VN (Variation Negative) and VP (Variation Positive).

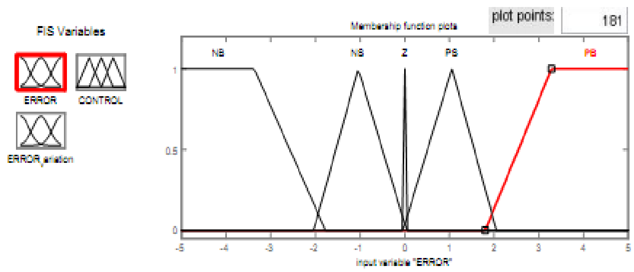

Fig .9: Error membership function

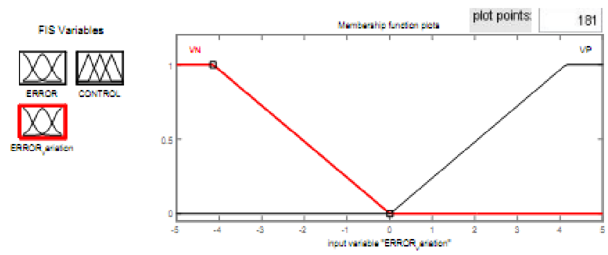

Fig. 10 : Error change

Figure 11 shows five triangular memberships used for output signals and the IF-THEN rule base are summarized in table (2)

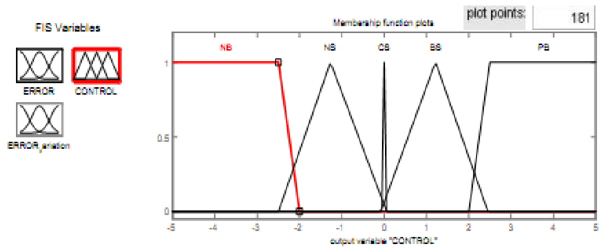

Fig. 11 :Output signals

Table 2: IF –THEN rule base for fuzzy logic control

		$e(t)$				
		NB	**NS**	**Z**	**PS**	**PB**
$\Delta e(t)$	**VN**	NB	NS	PB	PS	PB
	VP	NB	NS	NB	PS	PB

LSRM is subject to a large force ripple that can be a handicap to integrate this actuator into industrial application. The FLC output is the current control that is the innermost loop followed by the force control with FDF.
In the following section force control with FDF is presented and introduced in the control of biomedical systems.

A. Force control : force distribution function

In order to remove the force ripple and the error of positioning with force load this part is devoted to present an effective force control method using force distribution function.
The basic idea of FDF is to distribute a desired force to two adjacent phases during phase commutation interval. The phase force is individually regulated and varied smoothly with the position of the mover. FDF corresponds to TDF (Torque Distribution Function) in rotating SRM (RSRM).

$F_M = \frac{\pi L_1 i_B^2}{\lambda}$ is the maximum force developed by the LSRM.

The equilibrium position is attained when the thrust force which is generated by the motor for simultaneous excitation of two phases, equalizes that of the load: $F_m = F$, [12].

In the case of phase B and C, the force generated is:

$$F_m = -\frac{\pi L1}{\lambda}\left[i_B^2 \sin(\frac{2\pi}{\lambda} - \frac{\pi}{2}) + i_C^2 \sin(\frac{2\pi}{\lambda} - \pi) \right] \quad (9)$$

With

$$I_B = \sqrt{\frac{-\frac{Fc}{F_M} + \sin(\frac{2\pi x_e}{\lambda})}{\sin(\frac{2\pi x_e}{\lambda}) - \cos(\frac{2\pi x_e}{\lambda})}} I_n \quad (10)$$

$$I_C = \sqrt{\frac{\frac{Fc}{F_M} + \sin(\frac{2\pi x_e}{\lambda})}{\sin(\frac{2\pi x_e}{\lambda}) - \cos(\frac{2\pi x_e}{\lambda})}} I_n \quad (11)$$

$$I^2_B + I^2_C = I^2_n \quad (12)$$

B. Current control using hysteresis controller

The phase’s current has a great influence on the motion and the force of the motor. So having a smoothed current allowed having a smoothed motion. In this work the hysteresis controllers are used to control the current and generate command signals

Hysteresis controllers are built with Simulink blocks. The currents of the four phases are provided by measure and compared with the reference current. The error of the current then passes through a hysteresis controller to produce the pulses of the control circuit power.

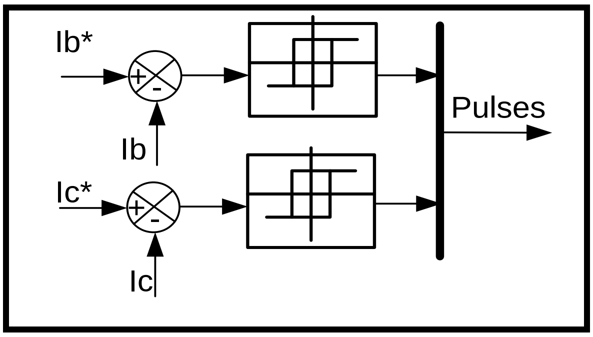

Fig. 12:Hysteresis controller for generating command signals.

IV. RESULTS AND DISCUS

The proposed strategy of closed loop speed control of the motor is tested using matlab/simulik.
The performances of the control are tested for speed references (3 mm/s) and for load force equalize 5N

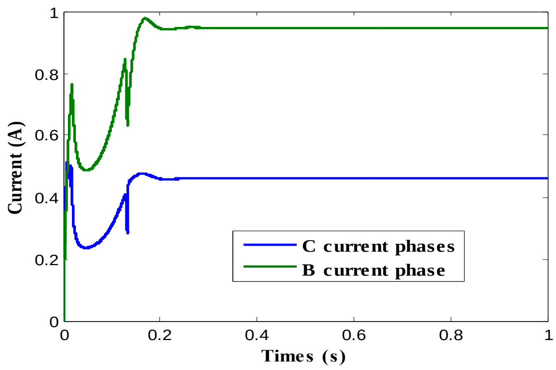

Fig. 13 B and C phases currents

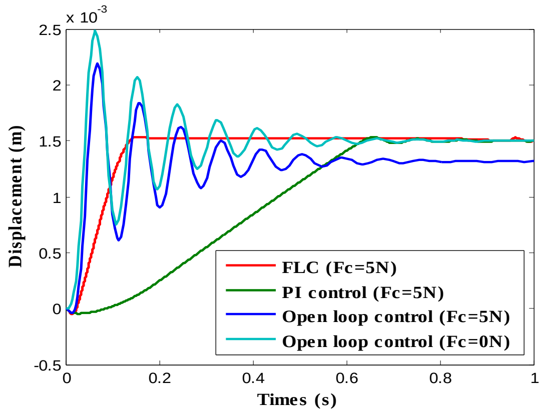

Fig 14: Motion of the mover for different control strategy

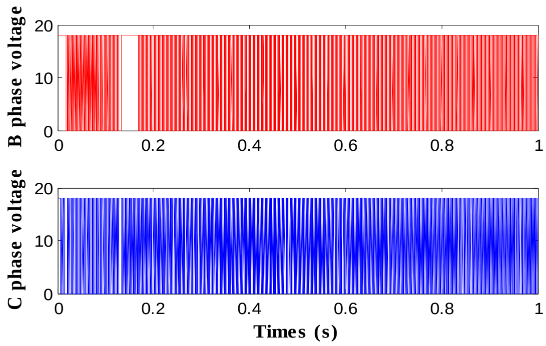

Fig. 15:B and C Phases voltage

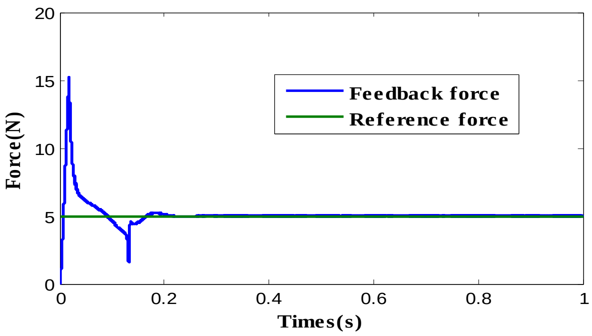

Fig 16: Feedback and load force

Figure (14) shows the displacement of the mover for this range of speed for one step. It also illustrates results in classical PID controller and open loop control which are presented in this figure.

The obtained results for FLC are characterized by a smooth motion without oscillations and without strong over-shoots or errors.

Compared to PI controller, FLC shows a better control of motor especially in overshoots and also in settling time.

The motor position also its force depend on the form and value of the current as shown in figure (13), (14) and figure (16) where we can see that the control current has a strong impact on the force generated. Also its clear that the current is modulated by using equation 3

Figure (17) shows the voltage supply of the two adjacent phase of the motor that depends on the motion of the motor.

Figure (16) shows the load force and that produced by the actuator. Therefore it's clear that the force generated by actuator flow its reference and the force ripple is minimized.

The strategy of command proposed in this work allows the speed control of LSRM in different range without position oscillations, force ripple and error something which proves the efficiency of the proposed FDF and control strategy.

The obtained performance of this control strategy allows integrating the LSRM into height precision application like biomedical application.

V. EXPERIMENTAL SETUP

The designed motor is manufactured by the authors corresponding to the main dimension in the table 2. Figure 17 present the drive scheme used for the experimental setup.

To check the performance of the proposed method, a prototype implementation of the different proposed control strategy of LSRM drive was carried out. As shown in figure (17) PIC18452 is used for the implementation. This microcontroller is a low cost solution with high and sufficient performance for this application.

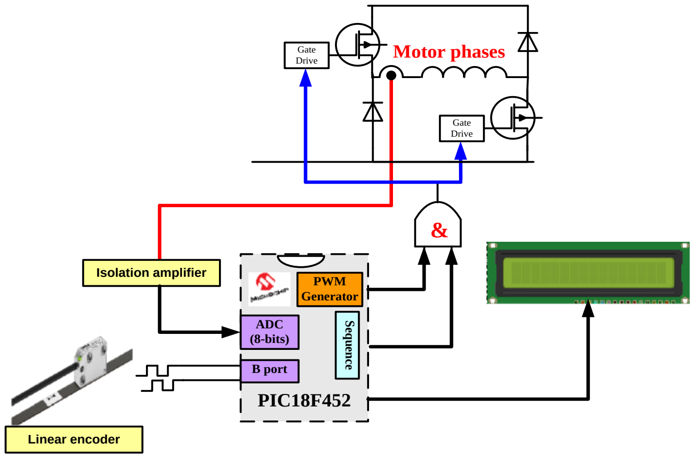

Fig. 17 Scheme used for experimental setup

First the phases sequence is carried out as function of the position of the translator; this sequence can be one phase supplying in every step or one phase two phase supplying.

In this study LSRM phase sequence is choose to supply every phase according to the reference velocity.

LSRM phase currents are measured as an analog value produced by LEM brand LA 55-P model. For every phase current measured was used one current sensor. LCD screen is established in the board to show the different result (position, energized phase…).

Linear incremental sensor was used for sensing motor position. It produces square wave pulse per 62.5 µm and also one reset signal per 0.5 mm.

The different experimental data are collected using the data acquisition board NI-DAQmx 6212 and saved using lab view as excel file after that they are drawn by MATLAB.

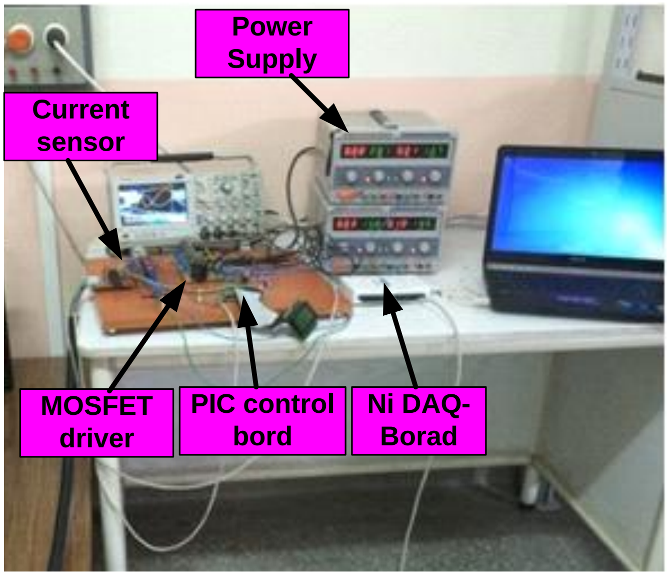

Fig. 18 : Photograph of the experimental test system

Fig.19: Photograph of the MOSFET driver

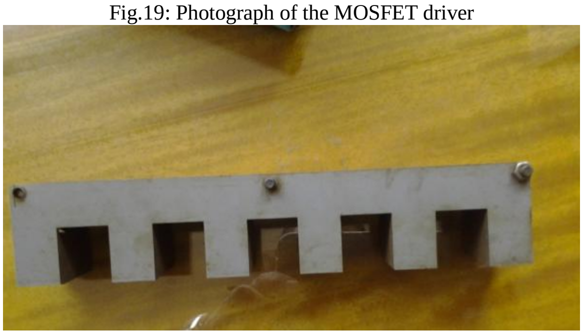

Fig. 20**:** Photograph of LSRM mover.

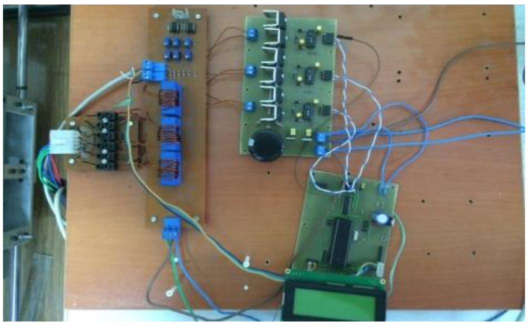

Fig. 21**:** Photograph of the control unit

VI. CONCLUSION

In this paper, we presented a control of linear switched reluctance motor for high precision application. A mathematical model of an LSRM neglecting magnetic saturation is performed. This model is used to study the open loop and speed closed-loop controllers using classical FLC, hysteresis controller and FDF.

The first part of the paper is devoted to the presentation, modeling, analysis and open loop control of LSRM.

The proposed speed control strategy presented in the second part is an intelligent and optimized strategy based on FLC, hysteresis controller and FDF.

This control technique is very reliable in the case of high precision application because it allowed having a smoothed motion and decrease force ripple thing that can help the integration of this actuator in industrial application. A low cost experimental setup based on PIC 18F452 is designed to control this actuator.

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