A Novel Double Sided Linear Switched Reluctance Motor: Modeling and Performance Analysis

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***Abstract*—This paper presents a low-cost positioning application based on Linear Switched Reluctance Motor (LSRM). Design, analysis, modeling, simulation and experimental results are detailed and presented in this work. Open loop control is investigated to control this motor. Matlab Simulink is used as a simulation method in order to prove the developed. PIC18F452 and MOSFET inverter are designed and developed for the implementation of the proposed controls strategy, this solution is characterized by its low cost thing that can help to more integration of this actuator in industrial application. The confrontation between the simulation and experimental results give a good correspondence when it was seen that problems of force and displacement ripples of the LSRM are is solved.**

***Index Terms*—linear switched reluctance motor, LSRM control, low cost, positioning, PIC18F452**

I. Introduction

Nowadays, the development in industry and manufacturing increases the need for performance requirements in the field of automation [1], [2]. Acceleration, speed and high precision are indispensable characteristics and the linear motion presents an absolute prerequisite in almost all industrial applications.

Linear motion is provided in classical systems by rotary motor coupled with mechanical gears that convert rotary motion into linear motion. But, mechanical gears are sources of several problems. Recently, the Switched Reluctance Motor (LSRM) has received considerable attention because it helps to eliminate mechanical problems.

Consequently, it will lead to decrease friction problems and to increase performances which allow pushing the mechanical limits in terms of acceleration and speed.

The LSRM is an electromechanical actuator that has the advantage of eradicating the transmission systems to produce a linear movement. This motor is characterized by its simple structure and low cost manufacturing. Compared to permanent-magnet dc motors, LSRM offers many advantages in terms of avoiding the problems associated with magnet bonding, corrosion, and demagnetization [3], [4].

In a context where performance and cost issues are vital, it naturally follows that linear motors must be used to their maximum performances in terms of positioning quality and its force. Today, thanks to advances in power electronics and in computer science applications, LSRMs are used in closed loop control especially in robotics and in biomedical applications [4], [5].

Control of this actuator is attracting much attention thanks to the development of control theory and hardware computer. Many papers in bibliographies discuss LSRM control, [6] present a LSRM control in open loop. Although this strategy is simple, it is characterized by force and position ripple that hampers its integration into high precision application. Ref. [7] and [8] presents a simulation study of LSRM control by using Fuzzy Logic Control (FLC) and PI control, these methods are suitable for controlling this motor but they need high performance hardware.

D-space card is one of solutions used in many references [1], [3] with different control strategy but this is no industrial solution and it is costly.

Open loop control and closed loop control based on Proportional Integral Derivative (PID) are very simple control strategies. In fact, PID control is one of the conventional control strategies used for various industrial processes from many years due to their simplicity in operation.

In this study, to achieve the low cost and efficiency of a driver in linear motions double- sided, 6/4-poled, 3-phased, 8A, 24V, 250W LSRM, having a 250N pull force, was used in locations where a linearly moving accurate position, easy control, and rapid response are requested [8], [9].

The objective of this paper is double. The first part consists of design and analysis of the proposed motor. Finite Element Method (FEM) which is numerical method used in many research paper [10]-[12]. FEM is investigated to study to magnetic characteristic of the motor. The second part concerns modeling the LSRM

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neglecting magnetic saturation based on its equivalent circuit. The proposed control strategy has a low cost implemented with PIC 18F452. Different Experimental results show a good correspondence with theoretical and simulation studies.

The Control board based on PIC, MOSFET drivers and the motor are developed by the author's which decreases the cost of this application and the results obtained show the advantage of using this actuator in high precision application with a low cost.

II. Motor Configuration, Analysis and Modeling

A. Motor Configuration

Linear motors are presented in the bibliographies with various topologies which can be classified as tubular or flat geometry, long or short stator. Also linear motor can be with double or single sided, active or passive stator [13].

The actuator under study is a double sided linear switched reluctance motor composed by a toothed sliding part on a rail namely mover (translator) and a plurality of double stator modules regularly distributed namely stator (Fig. 1, Fig. 2).

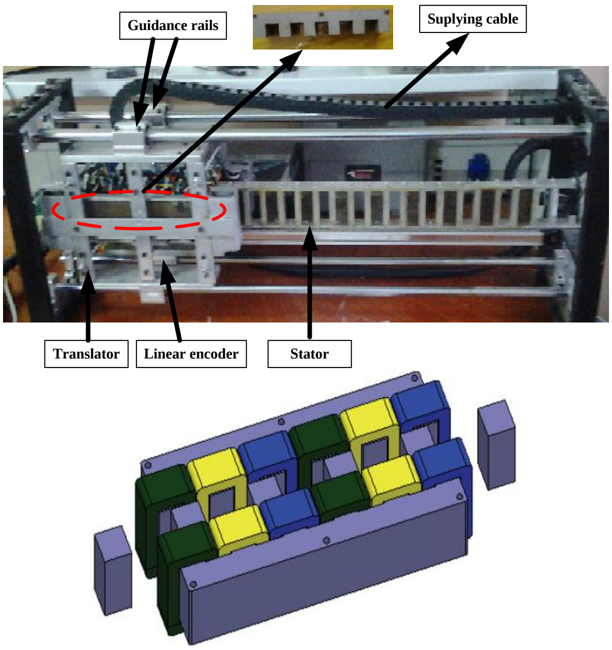


Figure 1. Real and 3D view of the motor

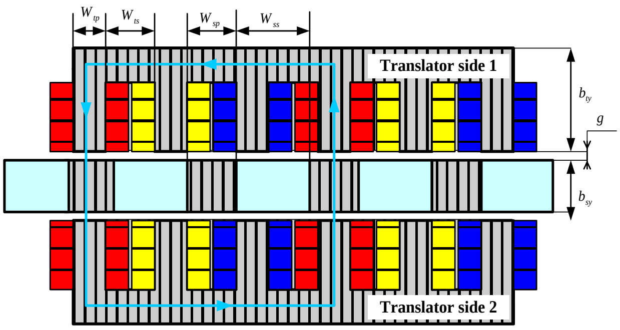


Figure 2. LSRM main geometric parameters

Linear motor can have winding either on the stator or translator. The active stator and passive translator configuration has the advantage of having the power supply and power converters being stationary, resulting in reduced the weight of the mover. This design, however, requires a large number of power converter sections, resulting in high costs [14]. However, a structure with an active translator and passive stator structure requires only one section of the power converter,

The structure of the designed motor is with an active translator composed by 3 phases and passive stator [15].

The electrical and geometric parameters of the motor are summarized in the Table I and Table II [5].

TABLE I. Motor Electrical Parameters

Symbol	Parameter	Value
L	Length of the motor	0.8mm
V_m	Maximum linear velocity	1m/s
t_a	Acceleration time	0.167s
m	Translator Mass	7Kg
F	Pull force	250N
P	LSRM Power	250W
I	Current	8A

TABLE II. Motor Geometric Parameters

	Parameters	Symbol	Value
Translator	Yoke thickness	C_{ty}	20mm
	Teeth width	w_{tp}	20mm
	Slots width	w_{st}	23mm
	Teeth height	h_t	26mm
Stator	Air gap	g	0.6mm
	Teeth width	w_{sp}	23mm
	Slots width	w_{ss}	43.3mm
	height	h_t	25mm
Coil	Number of turn	N	253
	Section of copper wire	S_c	0.153mm^2

Initially two translator poles are aligned with 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 non-magnetic separations between the different modules creates a radial magnetic flux path, this configuration is called longitudinal flux configuration.

B. Motor Analysis

The analysis of actuator is done by 2D-Finit element method (2-D FEA) which is very reliable numerical method used in many research paper [9], [10], [12]. The material witch used is a 1010 steel this later admits a characteristic B = f (H) shown in Fig. 3.

Fig. 4 shows the magnetic flux path in a three different translator positions that are parallel to motion line. It is clear from Fig. 4a 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 Fig. 4c 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.

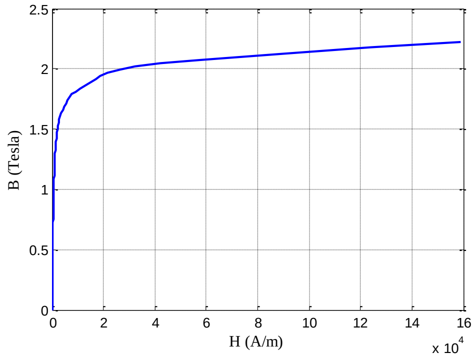
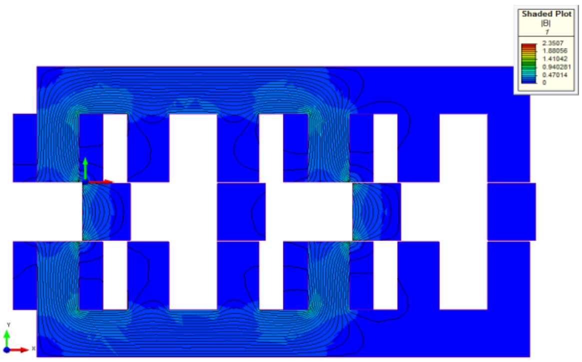
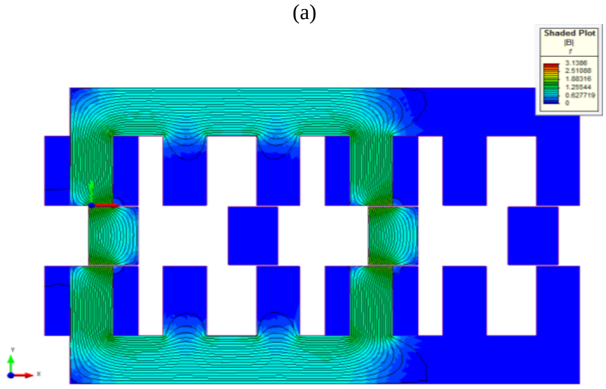


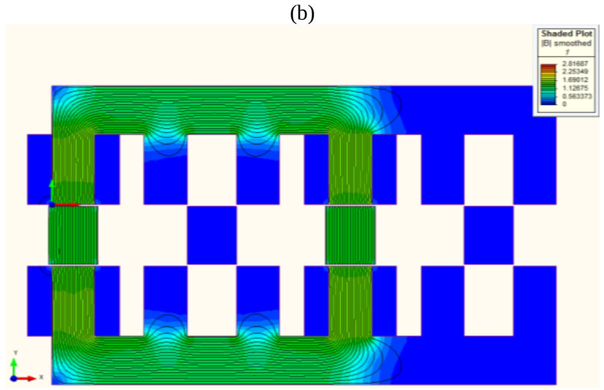
Figure 3. 1010 steel B = f (H)



(a)



(b)



(c)

Figure 4. Magnetic flux path and field density for different translator position regions: a) unaligned position, b) intermediary position, c) aligned position

C. Motor Modeling

The LSRM has a high nonlinear characteristic due to its nonlinear flux behaviors [11], [12]. In order to simplify equations, the modeling is performed without taking into account the magnetic saturation and mutual inductance between the phases. Different phases are considered identical and end effects are also neglected [13]. An equivalent circuit for a single phase of the LSRM is shown in Fig. 5.

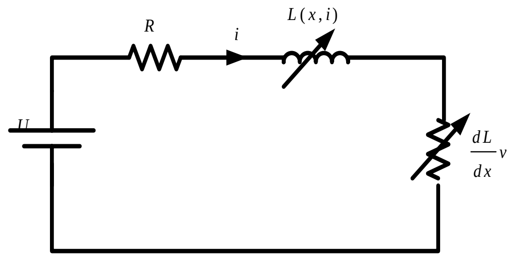


Figure 5. Single phase equivalent circuit

Consequently, the fundamental electrical are [10], [12], [13]:

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

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

Equation (1) shows that the applied voltage is equal to the sum of the resistive drop and the rate of the flux language.

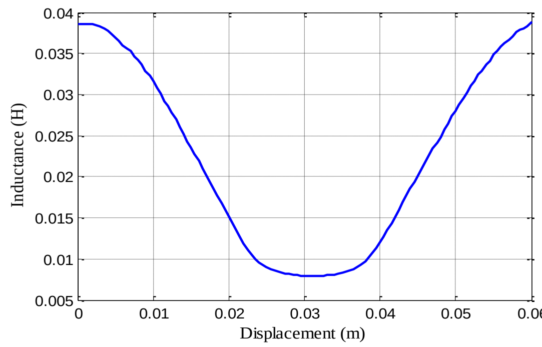


Figure 6. Inductance profile

The phase inductance is a function of position and phase current as shown in Fig. 6. The phase inductance as function of position with first Fourier terms is given by [14]:

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

where:

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

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

The forces generated by each phase of the motor are determined as follow:

$$F_A = -4*\frac{1}{2}\, i_A^2\, L_1 \frac{2\pi}{\lambda}\sin\left(\frac{2\pi}{\lambda}x\right)$$

$$F_B = -4*\frac{1}{2}\, i_B^2\, L_1 \frac{2\pi}{\lambda}\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{3}\right) \qquad (5)$$

$$F_C = -4*\frac{1}{2}\, i_C^2\, L_1 \frac{2\pi}{\lambda}\sin\left(\frac{2\pi}{\lambda}x + \frac{2\pi}{3}\right)$$

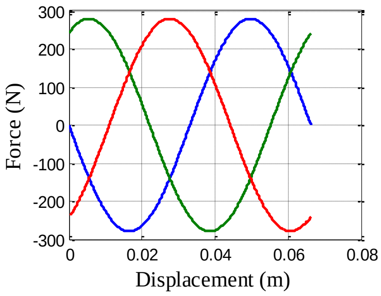


Figure 7. Theoretical force generated by the actuator 8A

Fig. 7 shows the theoretical force determined by equations 5 over the entire length of tooth pitch λ with a current of 8 Ampere. We can see the sinusoidal shape which is characterized by increasing zone and decreasing zone.

The voltage and mechanical equations are:

$$u_A = Ri_A + L_0\frac{di_A}{dt} + L_1\cos\left(\frac{2\pi x}{\lambda}\right)\frac{di_A}{dt} + \frac{2\pi}{\lambda}L_1\sin\left(\frac{2\pi x}{\lambda}\right)vi_A \qquad (6)$$

$$u_B = Ri_B + L_0\frac{di_B}{dt} + L_1\cos\left(\frac{2\pi x}{\lambda} - \frac{2\pi}{3}\right)\frac{di_B}{dt} + \frac{2\pi}{\lambda}L_1\sin\left(\frac{2\pi x}{\lambda} - \frac{2\pi}{3}\right)vi_B \qquad (7)$$

$$u_C = Ri_C + L_0\frac{di_C}{dt} + L_1\cos\left(\frac{2\pi x}{\lambda} + \frac{2\pi}{3}\right)\frac{di_C}{dt} + \frac{2\pi}{\lambda}L_1\sin\left(\frac{2\pi x}{\lambda} + \frac{2\pi}{3}\right)vi_C \qquad (8)$$

$$\frac{dv}{dt} = -\frac{\pi L_1}{m\lambda}\left[\begin{array}{l} i_A^2\sin\left(\frac{2\pi}{\lambda}x\right) + i_B^2\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{3}\right) + \\ i_C^2\sin\left(\frac{2\pi}{\lambda}x + \frac{2\pi}{3}\right) \end{array}\right] - \frac{\xi}{m}v - \frac{Fc}{m} - \frac{F0}{m}signe(v) \qquad (9)$$

D. Simulation Results

To test the developed models and to verify the effectiveness of the applied controls, MATLAB/ SIMULINK was used as a simulation tool. Firstly the electrical equations (6), (7), (8) are simulated in Matlab given the output current and this later is introduced into force (5). Finally the displacement is concluded by mechanical (6).

Fig. 8 illustrates the global idea of LSRM control in open loop where there is no regulation.

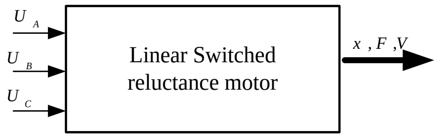


Figure 8. Open loop control of LSRM

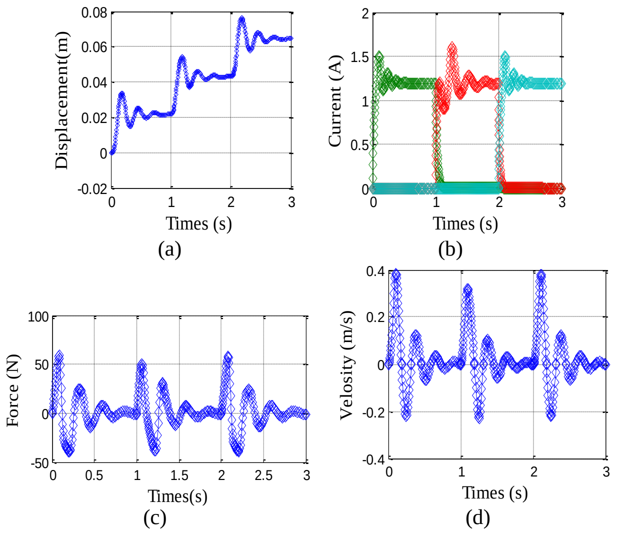


Figure 9. Simulation results: a) position versus times, b) velocity versus times, c) current versus times, d) force versus times

The different phases are separately excited for a constant period. The period of each step is 1 second.

Fig. 9b shows the phase current when just one phase is supplied for 1 second in every step.

The displacement of mover was shown in Fig. 9a prove that the motion is characterized by great over-shoot and strong oscillations. The oscillations are also observed in force and velocity in Fig. 9c and Fig. 9d.

The open-loop control have the merit of simplicity and consequent low cost, its consists to 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.

III. Experimental Results

The designed motor is manufactured by the authors corresponding to the main dimension in the Table II. Fig. 10 presents the drive scheme used for the experimental setup and Fig. 11 presents the photograph of the experimental board used in the laboratory.

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 Fig. 12, PIC18452 is used for the implementation. This microcontroller is a low coast solution with high and sufficient performance for this application. MOSFET driver is designed and manufactured by authors as shown in Fig. 13. The driver is composed by 3 legs 6 MOSFET.

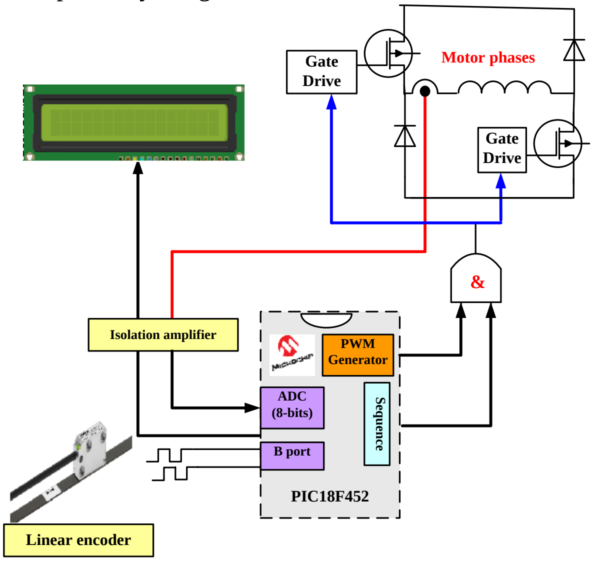


Figure 10. Scheme used for experimental setup for one phase

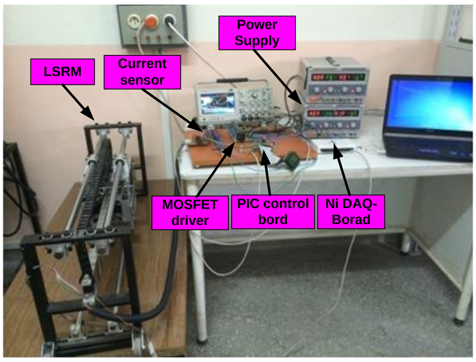


Figure 11. Photograph of the experimental test system

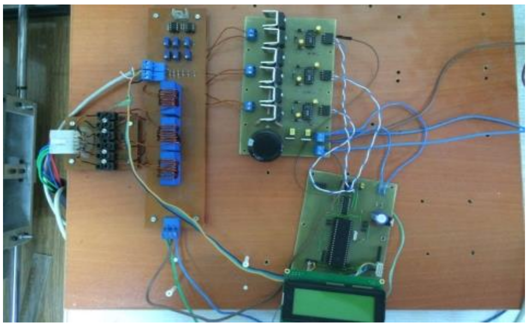


Figure 12. Photograph of the control unit

Figure 13. Photograph of the MOSFET driver

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 for one second.

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 0.5mm.

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.

A. Discussion

Experimental results of the open loop control are shown in Fig. 14 when we can see that there is good correspondence between simulation and experimental results. Fig. 14a illustrates the mobile displacement for three steps when each phase is separately energized for one second. It is clear that response of the phase A and C are the same but phase B response is different and this due to the end effect phenomena how occurred phases in the edge.

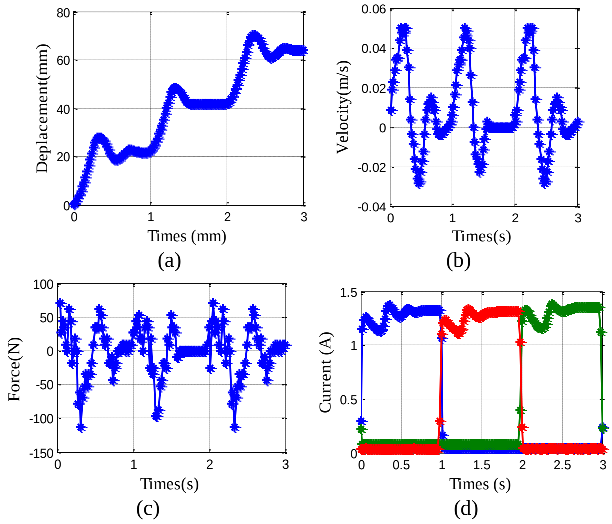


Figure 14. Open loop experimental results: a) position versus times, b) velocity versus times, c) current versus times, d) force versus times

Experimental results prove the theoretical study about the mobile equilibrium point when its can calculate by:

$$\frac{W_{sp} + W_{tp}}{3} = \frac{43 + 20}{3} = 21.1mm$$

Velocity and force oscillation observed in Fig. 14b and Fig. 14c are a really handicap for high precision application.

It can be seen from Fig. 14d the current waveform where the motor phases are separately exited for 1 second.

IV. CONCLUSION

In this study, design modeling of a double sided linear switched reluctance motor was studied and the studied motor has 6/4 poled, 3 phase, 250W power.

The control strategy is detailed and tested, experimental results shows a good correspondence with simulated results think that prove the studied model.

Open loop control is successfully experimented by using PIC18F452 microcontroller for low cost purpose. And it's clear that this method is appropriate to integrate this actuator in industrial applications.

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