Speed Control of Linear Switched Reluctance Motor

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ABSTRACT: *Position and force ripple are the major disadvantage of linear switched reluctance motor (LSRM), thing that can reduce the integration in high precision application. The work developed in this paper is a novel method to control this actuator in order to increase his performance. A model of the actuator is performed neglecting magnetic saturation. In order to make a smooth motion of the motor open and speed closed loop control are detailed and tested in this paper, this paper reports a study of speed control using a PI controller, hysteresis controller and force distribution function (FDF).*

Keywords: Linear Switched Reluctance Motor, Linear Actuator, Closed Loop Control, PID Controller, Force Distribution Function (FDF)

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1. Introduction

The linear switched reluctance motor/actuator (LSRM/LSRA) is an interesting alternative in many industrial applications where both speed and accurate positioning are needed especially in high precision application. [3] [6].This motor have the advantage of not having mechanical subsystems or rotary to linear motion converters to product a linear motion so decrease friction and maintain problems and increase performance so this motor is integrated in many applications.

This kind of actuator is characterized by its simple structure and low construction cost. 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 and force quality.

In recent years, control of this actuator is attracting much attention due to the development of control theory and computer hardware.

This type of 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 advances in power electronics and in computer science applications, LSRMs are used in closed loop control especially in robotics and in biomedical applications [8]. LSRM is subjected to disturbances and parameters variations and it's characterized by a non linear characteristic that make his command is very difficult. Also the major disadvantage of LSRM is the large force ripple so solving this problem is an important objective. In recent years, several control strategies has been proposed in the literatures in linear or rotary domain [15], [16], [17], [18], [19]. by using a force distribution function FDF.

The objective of this paper is double. The first part consists of modelling the LSRM neglecting magnetic saturation. Undesired oscillations in force and position are observed so the second part concerns the closed loop speed control of the actuator by controlling the current. An optimum strategy of control is present using PI controller to control the speed and force distribution function FDF to minimize force ripple.

2. Linear Switched Reluctance motor Configuration and Modelling

The proposed actuator is a single sided linear switched reluctance motor composed by a toothed sliding part on a rail namely mover (translator) and a plurality of stator modules regularly distributed namely stator, Figure (1).

The stator windings are laminated with copper and concentrated around the cylinder heads of the stator [7]. They are excited by DC currents.

The non-magnetic separations between the different modules impose a regular shift. If teeth of an active module are aligned with teeth of the mover, the other stator modules must be unaligned in order to create a translation force.

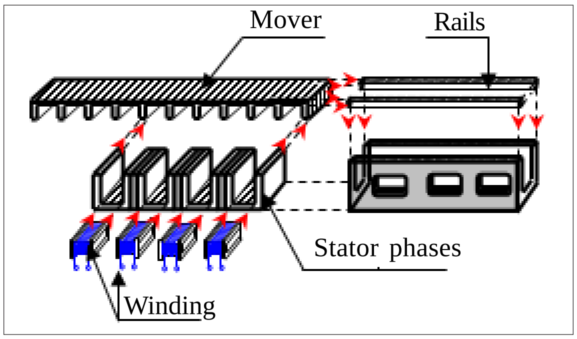

Figure 1. Structure of LSRM [7]

Notice that the actuator is composed by four phases and the mover length of the actuator is 10 cm with a tooth pitch of 6 mm

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

Consequently, the fundamental electrical and mechanical equations of an LSRM are, [10] [11] [12]:

$$u_A = Ri_A + L_0 \frac{di_A}{dt} + L_1 \cos\left(\frac{2\pi x}{\lambda}\right)\frac{di_A}{dt} + \frac{2\pi}{\lambda} L_1 \sin\left(\frac{2\pi x}{\lambda}\right) v i_A \qquad (1)$$

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

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

$$u_D = Ri_D + L_0 \frac{di_D}{dt} + L_1 \cos\left(\frac{2\pi x}{\lambda} - \frac{3\pi}{2}\right)\frac{di_D}{dt} + \frac{2\pi}{\lambda} L_1 \sin\left(\frac{2\pi x}{\lambda} - \frac{3\pi}{2}\right) v i_D \qquad (4)$$

$$\frac{dv}{dt} = -\frac{\pi L_1}{m\lambda}\left[i_A^2 \sin\left(\frac{2\pi x}{\lambda}\right) + i_B^2 \sin\left(\frac{2\pi x}{\lambda} - \frac{\pi}{2}\right) + i_C^2 \sin\left(\frac{2\pi x}{\lambda} - \pi\right) + i_D^2 \sin\left(\frac{2\pi x}{\lambda} - \frac{3\pi}{2}\right)\right] - \frac{\xi}{m} v - \frac{Fc}{m} - \frac{F0}{m} sign(v) \qquad (5)$$

Where u and i designate voltage and current of phases A, B, C and D, x the displacement, λ the tooth pitch, L_1 and L_0 the minimum and the maximum inductance, v the speed, Fc the load force, m and ξ the mass and friction.

Electrical parameters obtained by the finite element analysis FEA 2D are [7], [8]:

$$u = 18V, \mathrm{L0} = 225mH, \mathrm{L1} = 50mH, R = 18\Omega, m = 5Kg,\ \lambda = 6mm\ \xi = 65Nm/s, F_0 = 0.2N$$

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

3. Open Loop Control

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.

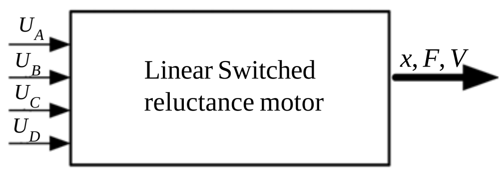

Figure 2. Open loop control of LSRM

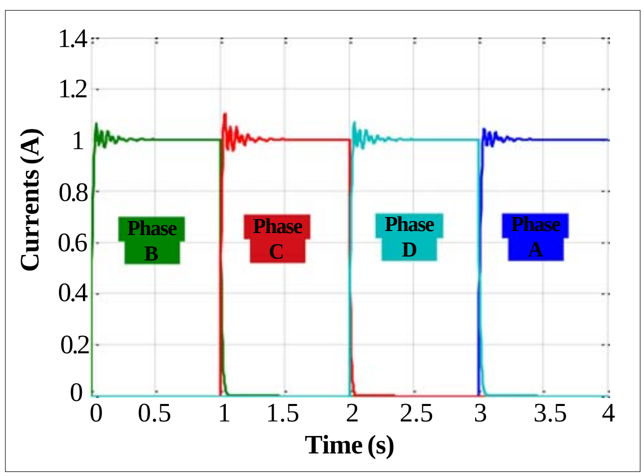

Figure 3. Phases currents

Figure (3)shown the phase current when in one step just one phase is supplied for 1 second.

The displacement of the mover shown in figure (4) and figure (5) demonstrates the disadvantage of this control when the motion is characterized by great over-shoot and strong oscillations.

When a load force is applied, the equilibrium position of the LSRM and the force are affected by an error due to the load force which opposes the motion of mover, figure (6).

3.1 Damping the motion oscillations (bang-bang control)

Bang-bang control is a command used to eliminate oscillations observed in the evolution of the motor position. The principle of

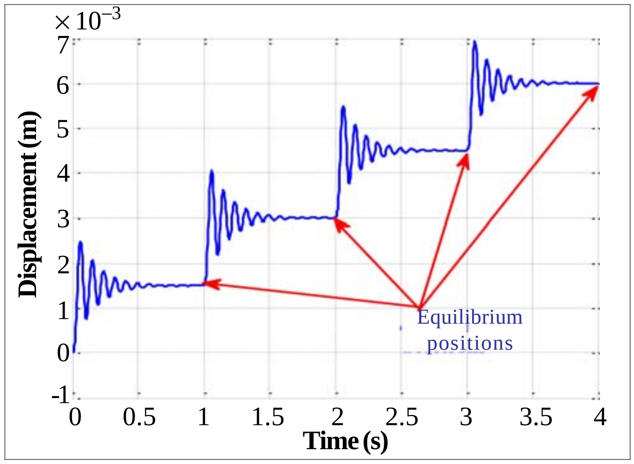

Figure 4. Displacement of the mover as function of time for 4 steps

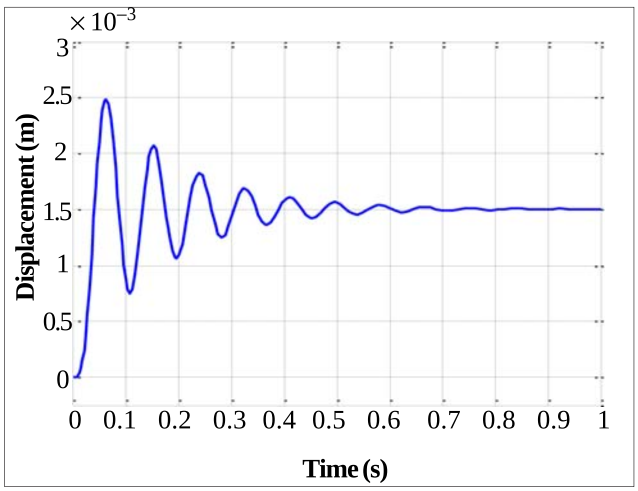

Figure 5. Displacement of the mover for 1 step

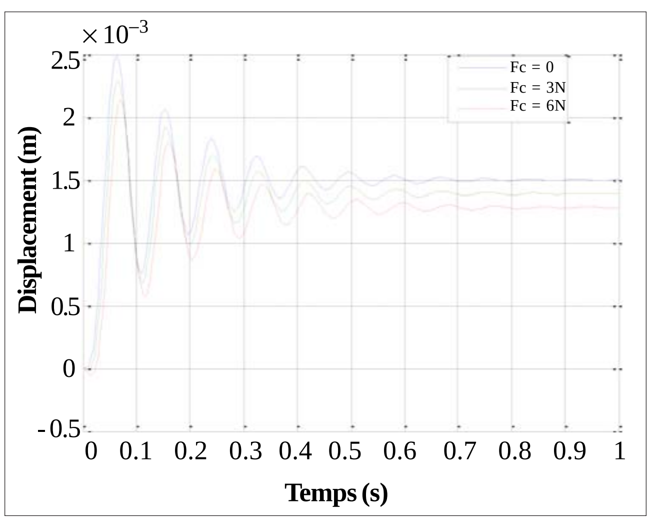

Figure 6. Displacements of the mover for different loads force

this method is the use of two phases to dampen these oscillations [9] [11].

Figure (8) explains the principle of the command, where the phase *B* is excited until the time *t*1. At *t*1, the system switches between the two phases *B* and *A*. the excitation of the coil *B* enables the eliminate the energy developed by the phase *A*. Phase *B* is excited again and at *t*2, phase *A* is turned off to keep the final equilibrium position. The braking removes all oscillations and mobile attained its equilibrium position without oscillations. [9].

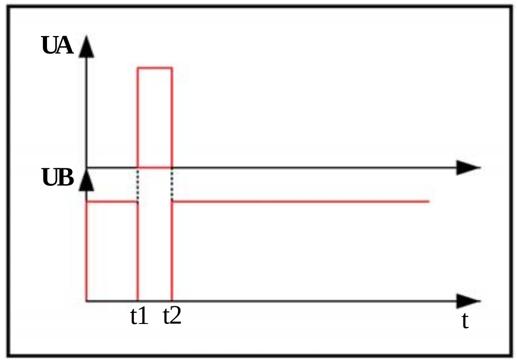

Figure 7. Principle of Bang-Bang control

The determination of *t*1 and *t*2 is strongly linked to various electrical and mechanical stepper motor parameters [12].

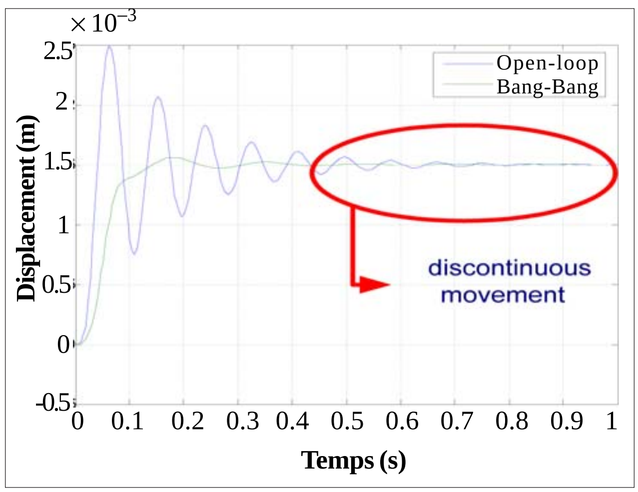

Figure 8. Evolution of the position with Bang-Bang correction

Figure (9) shown the evolution of position of the motor when the phase A is considered as a braking phase. We can see that the Bang-Bang control allowed minimizing overshoot and damping the oscillations.

The major disadvantage of this technique is that its switching moments control are strongly related to electrical and mechanical actuator parameters so any change requires dynamic adjustment of the switching times [9][11].

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.

4. Closed Loop Control

In order to an optimum control of the motor without oscillations and to smooth the displacement of the mover, we present in this part a speed closed loop strategies control.

The mover position and speed are detected and feedback into the control unit. Consequently, we can move from a step command to another only when the actuator responded satisfactorily to the previous command and so there is no possibility of losing synchronism [14].

In this section the global strategies of current controller of the actuator is study where the control of the current is done by hysteresis controller and a PI controller is used to control the speed. FDF is used to controlling force and reduce its ripples.

Figure (8) illustrate the current control strategies where U_j and i_j are the voltage and the current of different phase *A*, *B*, *C*, and *D*.

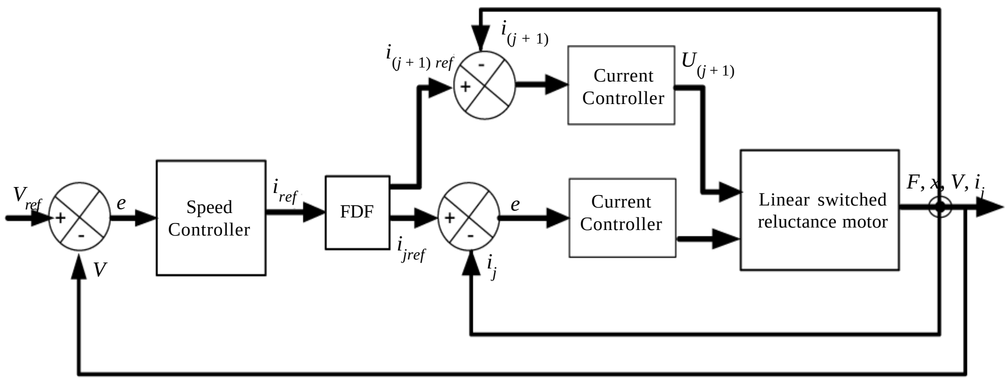

Figure 9. Proposed control strategy

4.1 Speed control using PI regulator

In this strategy of control, the reference speed is introduced into a PI controller to generate the current reference, figure 9.

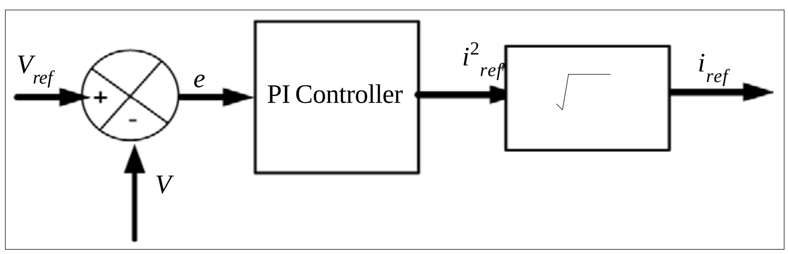

Figure 10. Speed control strategy

Figure (9) show the global strategies of current controller using a classical PI regulator, in this part we present the synthesis of regulator.

Based on mechanical equation (5) the transfer function speed/current of one phase is elaborate as follow:

$$\frac{dv}{dt} = -\frac{\pi L_1}{m\lambda}\left[i_A^2 \sin\left(\frac{2\pi x}{\lambda}\right)\right] - \frac{\xi}{m}v - \frac{Fc}{m} - \frac{F0}{m}sign(v) \qquad (6)$$

To simplify the study F_c and F_0 are neglected.

The displacement for one step is given by: $x = \frac{\lambda}{4} + \Delta x$

$$\sin\left(\frac{2\pi x}{\lambda}\right) = \sin\left(\frac{2\pi}{\lambda}\left(\frac{\lambda}{4} + \Delta x\right)\right) = \sin\left(\frac{\pi}{2} + \frac{2\pi}{\lambda}\Delta x\right) = \cos\left(\frac{2\pi x}{\lambda}\Delta x\right) \qquad (7)$$

Δx is small so $\cos\left(\frac{2\pi}{\lambda}\Delta x\right) \simeq 1$

$$\frac{dv}{dt} = \frac{\pi L_1}{m\lambda} i_A^2 - \frac{\xi}{m}V \qquad (8)$$

$$sv(s) - \frac{\xi}{m} v(s) = \frac{\pi L_1}{m\lambda} i_A^2(s)$$

The transfer function speed/current is:

$$G(s) = \frac{v(s)}{i^2(s)} = \frac{1}{\frac{m\lambda}{\pi L_1} s - \frac{m\xi\lambda}{\pi L_1}} \quad (9)$$

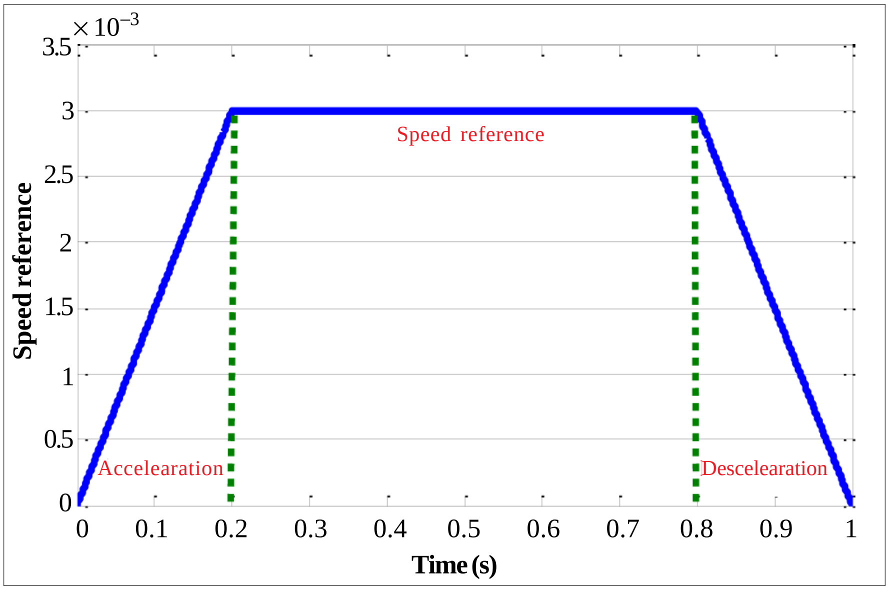

Figure 11. Speed reference

Figure 11 shown the forme of speed reference, which is characterized by acceleration and deceleration zone.

4.2 Current control using SMC regulator

Current phase have 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 Hysteresis controllers are used to control the current and generate command signals

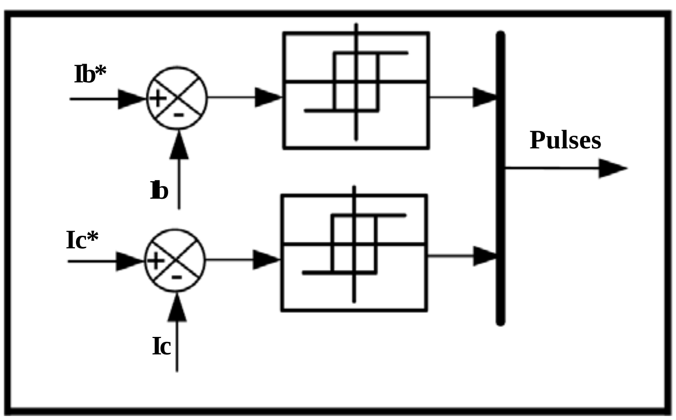

Figure 12. Hysteresis controller for generating command signals

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.

4.3 Force control

In order to suppress 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:

$$F_M = -\frac{\pi L_1}{\lambda}\left[i_B^2 \sin\left(\frac{2\pi}{\lambda} - \frac{\pi}{2}\right) + i_C^2 \sin\left(\frac{2\pi}{\lambda} - \pi\right)\right] \quad (10)$$

With

$$I_B = \sqrt{\frac{\frac{F_c}{F_M} + \sin\left(\frac{2\pi x_e}{\lambda}\right)}{\sin\left(\frac{2\pi x_e}{\lambda}\right) - \cos\left(\frac{2\pi x_e}{\lambda}\right)}}\, I_n \quad (11)$$

$$I_C = \sqrt{\frac{\frac{F_c}{F_M} + \sin\left(\frac{2\pi x_e}{\lambda}\right)}{\sin\left(\frac{2\pi x_e}{\lambda}\right) - \cos\left(\frac{2\pi x_e}{\lambda}\right)}}\, I_n \quad (12)$$

$$I_B^2 + I_C^2 = I_n^2 \quad (13)$$

Modulation of excitation current of the adjacent phase with equations (11), (12) allowed minimising force ripple and smoothing the motion.

5. Results and Discussion

The proposed strategy of closed loop speed control to smooth the motion of the motor is tested using matlab/simulik.

The performance of the control is tested for various speed references (3-6-12 mm/s) with force load equalize 5N. Figure (13) shown the displacement of the mover for these range of speed for one step . The obtained results are characterized by a smooth motion without oscillations and without strong over-shoot.

Figures (13) and (14) show the feedback current in the two adjacent phases (B, C) for the studied range of speed. The two phases current are modulated with equation (11) and (12) when we can see that the condition (13) is respected. The force and position of the motor depend on the form and value of the current as shown figure (13) and figure (16) when we can conclude that the control current have a strong impact on the force generated.

Figure (16) shown the load force and the force produced by the actuator when it's clear that the feedback force flow its reference

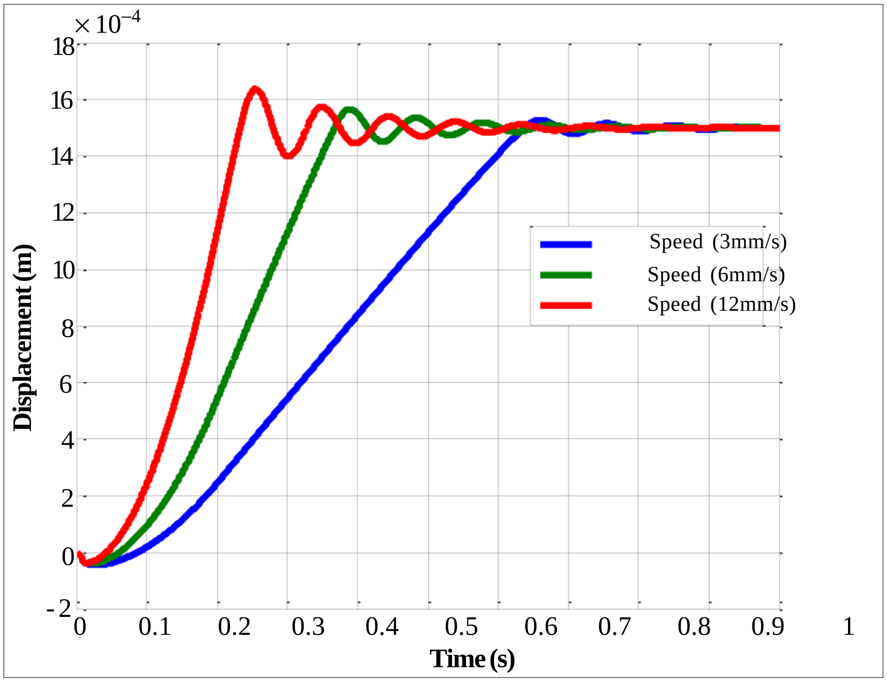

Figure 13. Position for different speed reference

and force ripple is minimized.

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

The performances obtained and the efficiency of this control strategy allows integration of LSRM into height precision application like biomedical application.

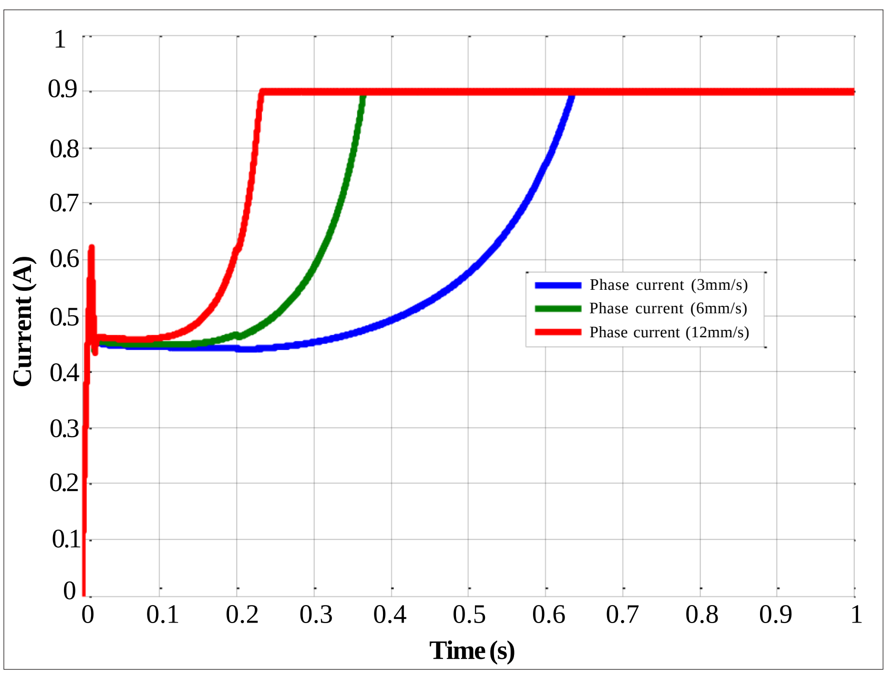

Figure 14. Phase B current for different speed reference

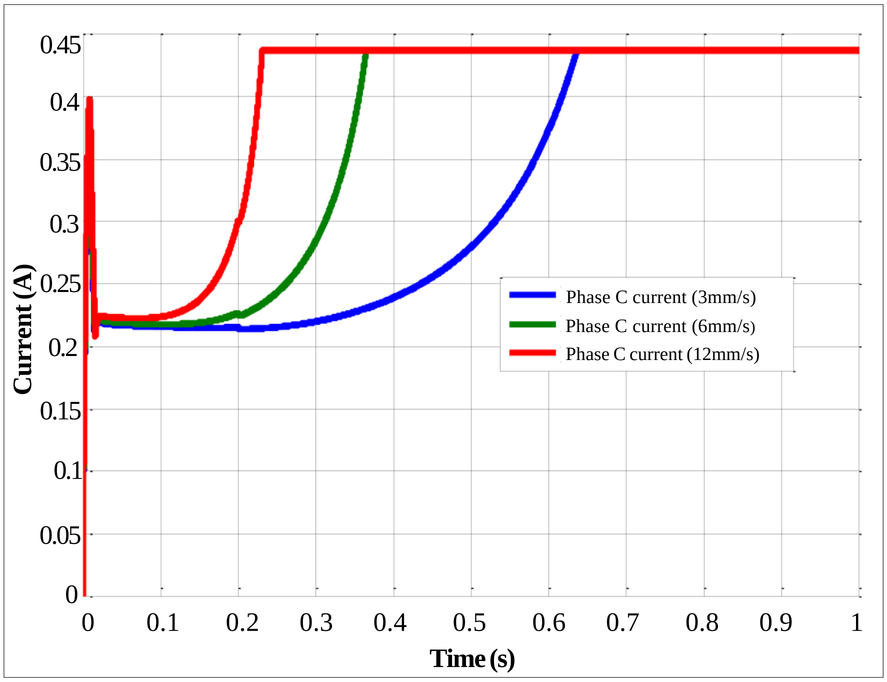

Figure 15. Phase B current for different speed reference

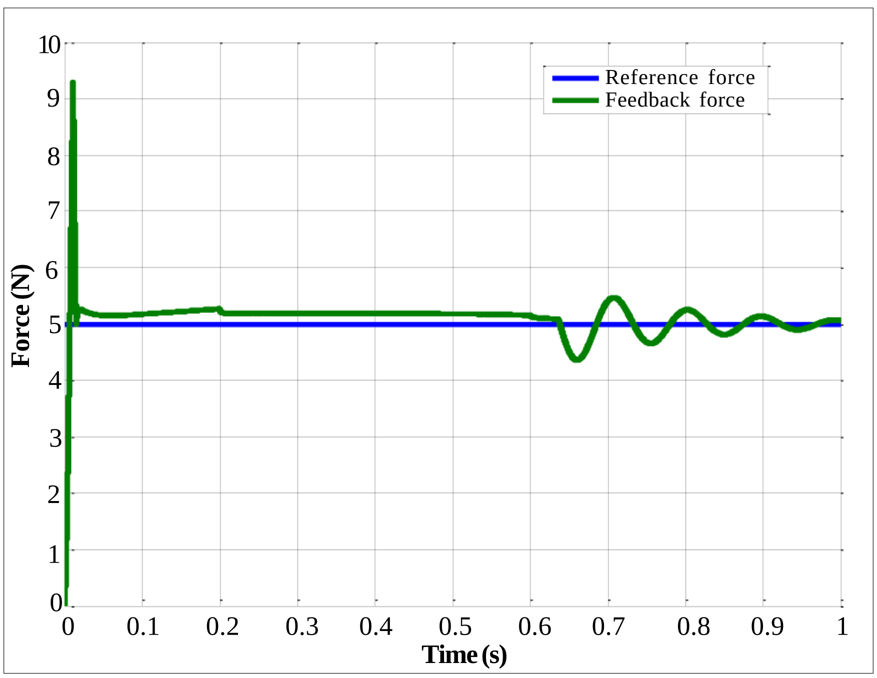

Figure 16. Reference and feedback force

6. Conclusion

In this paper, we presented a control of linear switched reluctance motor. 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 PID regulator and FDF.

The first part of the paper is devoted to the modeling, open loop control of the actuator and to smooth the positioning of the actuator in open loop method namely Bang-Bang control.

The proposed architecture of speed control strategy presented in the second part is a simple and optimized architecture based on the use of conventional PID controllers, 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.

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Habib Rehaoulia received the B.S. degree in 1978, the M.S. degree in 1980 and the doctoral degree in 1983, all from the ENSET (Institute of Technical Sciences), University of Tunis, Tunisia. He joined the teaching staff of the ENSET in 1978. Since 1995, he is with the ESSTT (Institute of sciences and technology of Tunis) where he obtained the Habilitation degree in 2007.

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