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# Performances Analysis of a Linear Motor for Sliding Door Application

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**ABSTRACT**

The present work deals to investigate the performance of linear switched reluctance motor designed for a sliding door application. The objective of this paper is to develop an analytical model in order to predict the dynamic behaviour of the studied motor. Firstly, the characteristics of the proposed motor in open loop operation was computed.Secondly, the effect of the load on the response of the motor was investigated. In this context, a two technoque in open loop were adopted to solve the error positioning with load and to damp the oscillation observed in the characteristics of the motor in order to obtain a smooth motion.



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## 1. INTRODUCTION

Linear motor is increasingly applied in the linear systems since they can produce a thrust force to directly drive the load without the gear. In addition, switched reluctance motor is an attractive solution for direct drive actuator due to it is low cost and it can be operated over a wide speed range with high efficiency. The application of linear motor in industrial systems has been widely reported in recent years, [1]-[3].

The switched reluctance motor has been investigated in many previous research works. In reference [2], a linear and a rotational switched reluctance motor are manufactured for a track of railway vehicles. A rope free elevator system for vertical transport based on planar positioners was investigated in reference [3]. To predict the characteristcs of switched reluctance motor there are many approaches such as analytical modeling, look up table method, finite element methods and magnetic equivalent circuit [4],[5].

The simplicity and the lower cost of linear switched reluctance motor (LSRM) makes it a viable candidate for sliding door application. A significant enhancement of door driving performance and improvements can be established by the introduction of linear motor in a sliding door.

The natural characteristics of the linear motor possess oscillatory behavior to reduce this oscillation there are solutions which can be classified into mechanical solution and electrical solution. The mechanical solution consists to add an additional viscous friction to the motor, but this solution gives rise of a limitation in the acceleration of the motor and can reduce the performance of the motor. As an electrical solution, a closed loop control is proposed in many research works. However, this solution needs the use of expensive sensor. In this study, a simple solution in open loop based on Bang Bang control was investigated.

In reference [6], the author presents a position sensorless in closed loop control of a switched reluctance linear motor to damp the position oscillation. This technique is based on back electromotive forces, which give information about the oscillatory behavior without need of the sensor. In reference [7], a low cost position control of a double sided linear switched reluctance motor with closed loop controls was studied.

This study presents a design, modeling and control of a new switched reluctance motor for sliding door application. Our contribution consists in proposing a new design for the whole system by using the innovative linear motor in order to ensure the linear movement of the door by eliminating the mechanical part of the motion transmission.

This paper is organized on the following lines the proposed motor was presented in section 2, section 3 consists of the modeling the proposed motor, the results and analysis of the performance in open loop operation of the motor is discussed in section 4. Finally section 5 contains the conclusion.

## 2. MOTOR DESCRIPTION

Usually the conventional sliding door system uses a rotary motor with the transmission motion system. The block diagram is given in Figure 1, this technology has the disadvantages of complex mechanical structure and low reliability. In this study, we propose to drive the door with linear motor. In fact, the door is directly assembled to the motor and the transmission motion system is eliminated. For this purpose, better performances can be achieved.

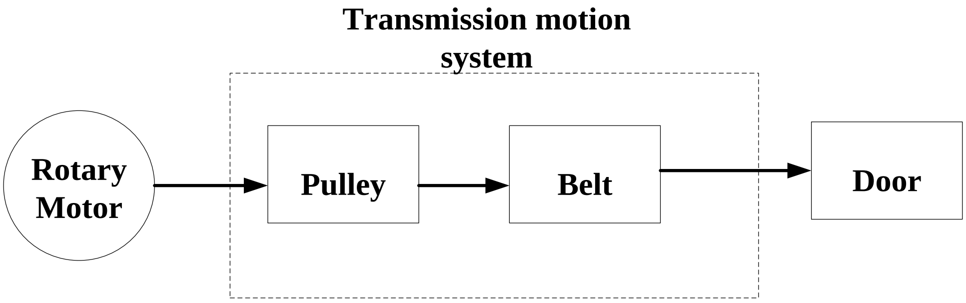


Figure 1. Block diagram of conventionel sliding door sytem

The motor under study is a three phase linear switched reluctance structure, it consists of a toothed stator and a toothed mobile which contains a winding concentrate around their poles. The power supply is carried out in unidirectional current, which makes it possible to use unidirectional current converters. For reasons of the search for a high reliability and a better availability so that a minimization of the manufacturing cost led us to the choice of this type of motor. The specification parametrs of the studied motor are presented in the Table 1.

Table 1. The specific parametrs of linear motor

| Variable | Value |
|---|---|
| Stator pole width (mm) | 30 |
| Stator slot width(mm) | 30 |
| Mobile pole width(mm) | 30 |
| Mobile slot width(mm) | 30 |
| Pole pitch (mm) | 60 |
| Seperation width(mm) | 50 |
| Air gap(mm) | 0.5 |
| Inductance $L_0$ (H) | 0.56 |
| Inductance $L_1$(H) | 0.11 |
| Nominale Voltage (V) | 24 |
| Phase resistance (Ω) | 8 |

Figure 2 shown a 3D computer aided design of the proposed motor, this motor is designed by using the geometric model previously determined. The operating principale of switched reluctance motor requires that only one module phase must be aligned with stator teeth when it is supplied. Therefore, to impose a regular step a non magnetic separation between different mobile modules is indispensable.

It can be observed from Figure 2 that the poles of the first phase are placed on aligned position with the poles of the stator. When the middle phase is excited the mobile moves and the magnetic circuit tends to choose the configuration which have a weak reluctance. Therefore, the pole of the excited phase will be aligned with the pole of the stator. The sliding door systems needs a linear movement for opening or closing the door. Then, to ensure a continuing movement a successive excitation of all phases is required.

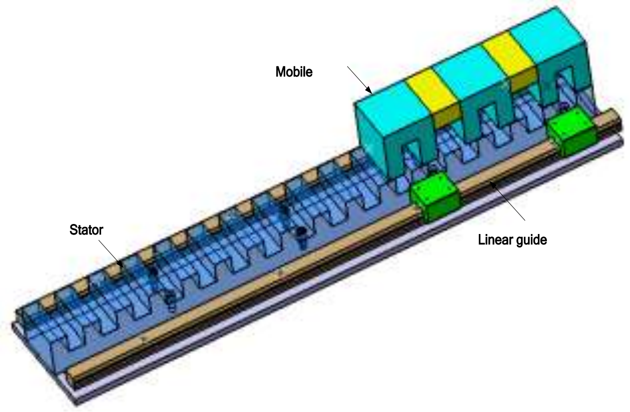


Figure 2. 3D Computer aided design of the studied motor

## 3. MODELING APPROACH INDUCTANCE BASED MODEL

### 3.1. Electric model

For switched reluctance motor with windings concentrated arount poles of phase the mutual between phases is neglected, so the voltage equation for each phase can be written in terms of flux linkage and currrent asggj [8].

$$U_j = R_j I_j + \frac{d\phi(x,I)}{dt} \tag{1}$$

The inductance is maximum in aligned position and minimum in the unaligned position. Therefore, phase inductance varies periodically as a function of the mobile position. Consequently, a continuous model for the inductance based on Fourier series representation is presented in this section, [9]. Therefore, the inductance in each phase can be represented as:

$$\begin{cases} L(x,I) = \sum_{k=0}^{n} L_k \cos(\frac{2\pi}{\lambda} x - (j-1)\frac{2\pi}{3}) \\ 0 < k < n \quad \text{and } j = 1,\ 2,\ 3 \end{cases} \tag{2}$$

Where $L_k$ is the coefficient, x is the mobile position, $\lambda$ is the pole pitch, n is the number of terms included in the Fourier series and j is the phase index. In this study only the first two terms of the Fourier series are considered. Therefore, the inductance phase is given by.

$$L_j(x) = L_0 + L_1 \cos(\frac{2\pi}{\lambda} x - (j-1)\frac{2\pi}{3}) \tag{3}$$

The two coefficients $L_0$ and $L_1$ can be calculated based on the inductance in two important positions by using the appropriate data obtained from the inductance curve as a function of position. Then, the coefficient $L_0$ and $L_1$ can be determined as follows.

$$L_0 = \frac{L_a + L_u}{2} \tag{4}$$

$$L_1 = \frac{L_a - L_u}{2} \tag{5}$$

Where $L_a$ is the inductance at the aligned position (x=0mm), $L_u$ is the inductance at the unaligned position (x=30mm). Since the saturation effectis neglected, therefore the flux linkage can be approximated by a linear equation.

$$\phi(x, I) = L(x, I)I \tag{6}$$

Where, $\phi$ and $L$ represent the flux linkage and the phase inductance respectively. In general the force in switched reluctance motor is developed by the tendency for the magnetic circuit to occupy a configuration of minimum reluctance. In this study, a simplified model is adopted in which the magnetic nonlinearity is neglected. Therefore, the developed electromagnetic force is proportional to the square of the current. For a given current, the force produced by each phase of the motor is given by.

$$F_j(x, I) = \frac{1}{2}\frac{\partial L_j(x, I)}{\partial x} I_j^2 \Big|_{(I=cte)} \tag{7}$$

Where, $F_j$ is the developed force of the phase j and $\partial L_j(x, I)/\partial x$ is the rate of change of the inductance of phase j. The inductance is dependent on the mobile position, the partial derivative of the inductance with mobile position can be expressed as:

$$\frac{\partial L_j}{\partial x} = -\frac{2\pi}{\lambda} L_1 \sin\left[\frac{2\pi x}{\lambda} - (j-1)\frac{2\pi}{3}\right] \tag{8}$$

By substituting Equation 8 in Equation 7, the electromagnetic force developed by each phase of the LSRM is expressed as:

$$F_j(x, I) = \frac{1}{2}\frac{\pi}{\lambda}\sin\left[\frac{2\pi x}{\lambda} - (j-1)\frac{2\pi}{3}\right] I^2 \tag{9}$$

### 3.2. Mechanical model

The dynamic behavior of the linear motor is governed by the second order equation as follows, [10] and [11]:

$$F_m = m\frac{d^2x}{dt^2} + \xi\frac{dx}{dt} + F_L + F_0 \text{sign}(v) \tag{10}$$

Where, $m$ is the moving mass, $F_m$ is the developed electromechanical force, $F_L$ is the external load force , $F_0$ static friction and $\xi$ is the viscous friction.

## 4. SIMULATIONS RESULTS

### 4.1. Open Loop Operating

The open-loop operation consists in feeding in order the different phases of the motor independently. For the case of the studied motor, the mobile is inially at the first equilibrium position, the excitation of the phase 1drives the mobile to a new equilibrium position x=0.02m.

The Figure 3 illustrates the dynamic behavior of the motor for unloading operation along a three-step federate, when a current passes through one phase winding that produce a thrust force that tends to align the mobile pole with the stator pole.It is clear that, the position response presents an oscillation during the advance of one step. Fortherfore, the increase in the oscillation amplitude may cause the loss of synchronism of the motor.

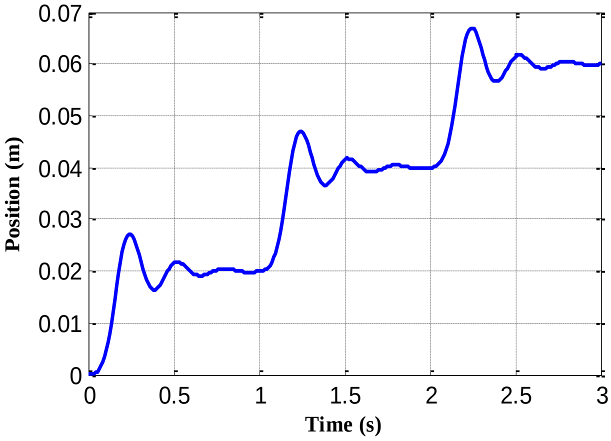


Figure 3. Motor response in open loop control

## 4.2. Load Positioning

During the load operation, a load force is applied to the LSRM, in fact the equilibrium position is affected by an error due to the load force which is opposite to the motion of mobile [12]. Therefore, it is clear from Figure 4 that this position error is more important when the load is greater.

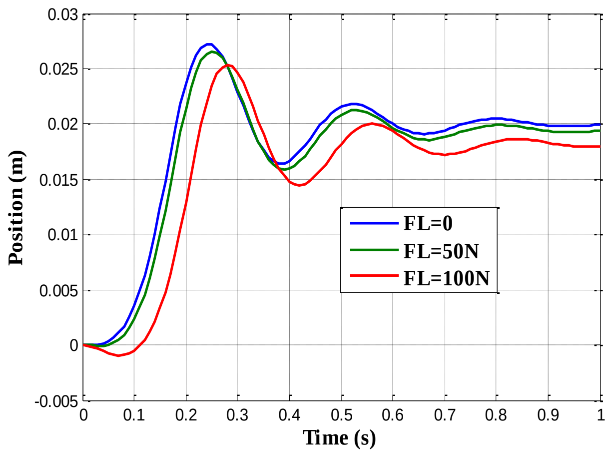


Figure 4. Motor response with different load force

To solve the problem under load operation, a novel strategy is used in open loop operation, this technic based on the simultaneous excitation of the two successive phases. In this case, the phase 2 and phase 3 are investigated. Then, the total force developed by the linear motor is described by the following Equation.

$$F_{23}(I,x) = -\frac{\pi L_1}{\lambda}\left[ I_2^2 \sin(\frac{2\pi x}{\lambda} - \frac{2\pi}{3}) + I_3^2 \sin(\frac{2\pi x}{\lambda} + \frac{2\pi}{3}) \right] \tag{11}$$

The equilibrium position is reached when the total developed force is equal to the load force $F_{23} = F_L$ In order to limit the joule losses, a condition on the current is expressed by the following Equation.

$$I_2^2 + I_3^2 = I_r^2 \tag{12}$$

Where $\mathrm{I}_2$ and $\mathrm{I}_3$ the excited current for the second phase and the third phase, $\mathrm{I}_r$ is the rate current. Then, the current of each phase need to correct the positioning when a load force is applied for the motor are given by:

$$I_2 = \sqrt{\frac{-\frac{F_L}{F_m} - \sin(\frac{2\pi x}{\lambda} + \frac{2\pi}{3})}{\sin(\frac{2\pi x}{\lambda} - \frac{2\pi}{3}) - \sin(\frac{2\pi x}{\lambda} + \frac{2\pi}{3})}} I_r \quad (13)$$

$$I_3 = \sqrt{\frac{-\frac{F_L}{F_m} - \sin(\frac{2\pi x}{\lambda} - \frac{2\pi}{3})}{\sin(\frac{2\pi x}{\lambda} - \frac{2\pi}{3}) - \sin(\frac{2\pi x}{\lambda} + \frac{2\pi}{3})}} I_r \quad (14)$$

Where, $F_m$ is the maximum force developed by the motor and $\lambda$ is the pole pitch. This method consists of modulating the currents of the two phases when a load force is changed by using the equation (12) and (13), the simulation results given in Figure 5 and Figure 6 shows that the phase current, the position response respectively for two different load force values.

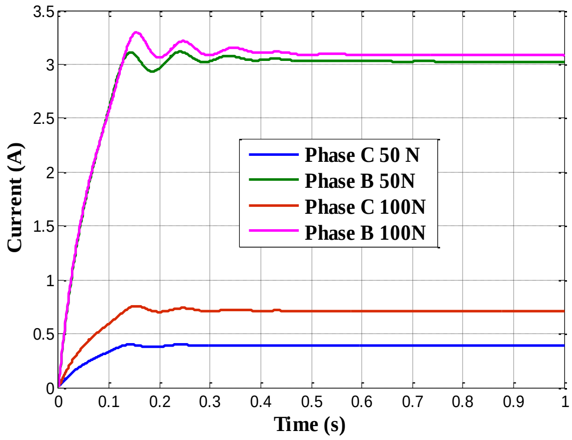


Figure 5. Suppling current for two successive phase for two load force

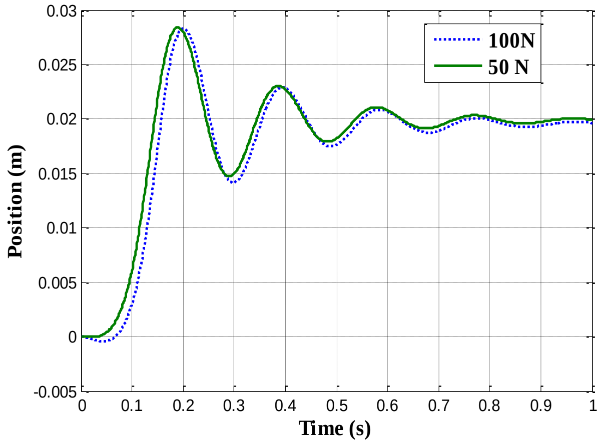


Figure 6. Motor response for two load force

The simulation results given by the Figure 5 and Figure 6 show the changes in current $I_2$ and $I_3$, the position of the mobile respectively for two values of load forces of 50 N and 100 N. For the two cases of operation, it is shown that the mobile reach its equilibrium position without error. Furthermore, with the proposed method we can eliminate the error in load mode, but without damping the oscillations.

### 4.3. Bang Bang control

During the advance of one-step, a strong oscillation is observed around the equilibrium position. These oscillations are intolerable (undesirable) for the sliding door system. To damp the oscillation observed in the response of the motor the technique of the command Bang-Bang with electric braking is well suited.

Bang-Bang control is a simple technique based on open loop control that can be adopted in order to mitigate the oscillation observed. It consists of an excitation of two successive phases during a specific time, [13]. We propose to apply this technical control to the proposed motor. This technique consists in controlling the motor on a single step. Initially at time t = 0, it is assumed that the phase 1 is energized and that the mobile is in the corresponding equilibrium position.

We launch the displacement of the mobile by supplying the phase 2 for a duration Ta that correspond to the acceleration period , then the phase 2 is turned off and the phase 1 is supplied to compensate the kinetic energy developed by phase 2 which correspond to the breaking period. Finally, the phase 2 is resupplied which allow for the mobile to reach the equilibrium position without overshoot.

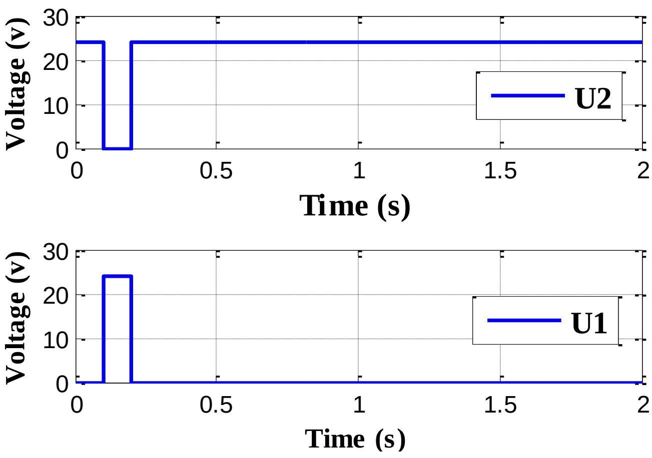


Figure 9. Supply sequence for Bang Bang control

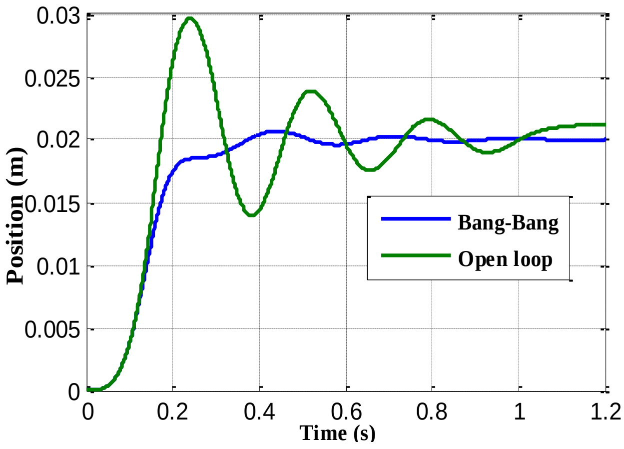


Figure 10. Phase response with Bang Bang control

## 5. CONCLUSION

In this paper the innovative solution for the conventional sliding door system was studied due to the use of linear motors as a driver. In the first part of this paper an analytic model of switched reluctance motor has been given based on inductance expression which allow to predict the dynamic performance of the motor. The second part is devoted to the control strategy in open loop operation. Firstly, position error correction with load operating have been investigated, secondly a Bang Bang method is adopted to damp the oscillation.

## REFERENCES


[1] Dursun M., *et al.*, "Design of Linear Switched Reluctance Motor Driver for Automatic Door Application," *International Journal of Information and Electroncs Engineering,* vol/issue: 3(3), pp. 237-241, 2013.

[2] Kolomeitsev L., *et al*., "Linear switched reluctance motor as a high efficiency propulsion system for railway vehicles," *SPEEEDAM International Sympsium on Power lectronics, Electrical Drives Automation and Motion,* Ischia, pp. 155-160, 2008.

[3] Trochimczuk R. and Huscio T., "Rope free elevator system based on planar positioners for vertical and horizontal transport," *Mechanika,* vol/issue: 23(1), pp. 120-125, 2017.

[4] Lenin N. C. and Arumugam R., "Design and Experimental Verification of Linear Switched Reluctance Motor with Skewed Poles," *International Journal of Power Electronics and Drive System*, vol/issue: 6(1), pp. 18-25, 2015.

[5] Dursun M., *et al.*, "Determination of Geometric Dimensions of a Double Sided Linear Switched Reluctance," *Wold Academy of Science Engineering and Technology,* vol/issue: 4(10), pp. 225-231, 2010.

[6] B. Saad K. and Mbarek A., "Half step position sensorless control of a Linear Switched Reluctance Motor based on Back EMF," *Automatika,* vol/issue: 57(3), pp. 660-671, 2016.

[7] Zaafrane W., *et al.*, "Low cost Linear Switched Reluctance Motor velocity and Position Control," *Journal of Circuits System, and Computers*, vol/issue: 5(4), pp. 1650021-1-1650021-16, 2016.

[8] Khalil A. H. I., "A Fourier Serier Generalized Geometry Based Analytical Model of Switched Reluctance Machines," *IEEE Transactions on Industry Applications,* vol/issue: 43(3), pp. 673-684, 2007.

[9] Grebennikov N. V., *et al.*, "Mathematical Model of Linear Switched Reluctance Motor with Mutual Inductance Consideration," *International Journal of Power Electronics and Drive System*, vol/issue: 6(2), pp. 225-232, 2015.

[10] Acarnley P., "Stepping Motors. A Guide to Modern Theory and Practice," London, England, Peter Peregrinus, 1986.

[11] Lachheb A., *et al.*, "Finite Elements Modeling of Linear Motor for Automatic Sliding Door Application," *International Journal of Advanced Computer Science and Applications*, vol/issue: 7(8), pp. 106-112, 2016.

[12] Wang W., *et al.*, "Position Control for the Linear Compound Switched Reluctance Machine," *International Symposium on Electrical Engineering,* China, vol. 6, pp. 211-215, 2016.

[13] B. Saad K., "Modélisation et commande d'un moteur pas à pas tubulaire à réluctance variable e à quatre phases Approches conventionnelles par logique floue, et par réseaux de neurones artificiels," Tunisia, PhD. Thesis, 2000.


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Aymen Lachheb was bonrn in Zaghouan, Tunis on 06 Febr 1985. He received the M .Sc degree in Electrical Engineering and Power Electronics from the High School of Sciences and Techniques of Tunis and Master degree in Electrical Engineering and Industrial Systmes in 2011. Since 2014 has joined the teaching staff as an Secondary teacher in Ministry of Education. His main research interests are Design, modeling and control of electrical machines

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