Chapter

Incremental Linear Switched Reluctance Actuator

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Abstract

Linear switched reluctance actuators are a focus of study for many applications because of their simple and robust electromagnetic structure, despite their lower thrust force density when compared with linear permanent magnet synchronous motors. This chapter deals with incremental linear actuator have switched reluctance structure. First, the different topologies of linear incremental actuators are mentioned. Furthermore, a special interest is focused on the switched reluctance linear actuator then the operating principal is explained. In addition, an analytical model of the proposed actuator is developed without taking account of the saturation in magnetic circuit. Finally, the control techniques that can be applied to the studied actuator are presented.

Keywords: linear actuator, switched reluctance, modeling, control, hybrid actuator, simulation

1. Introduction

Nowadays, linear actuators are used more and more in various industrial fields. This type of actuator makes it possible to have a direct linear drive without recourse to an intermediate motion transmission system [1]. Indeed, unlike conventional approaches where linear movement is obtained by coupling a rotary actuator to a movement transmission system, the direct generation of linear movement makes it possible to reduce the number of mechanical parts and therefore the losses associated with them.

The absence of motion transformers improves the overall performance of the system. As a result, the linear actuator is essential when the speed and precision are required by the application (machining Tools, manipulator robots, etc.), for this type of actuator the thrust force generated is thus applied directly to the load, [2]. Linear displacement controls are often used in industrial devices. In most cases where rigidity is required, it is provided by the worm and worm wheel system or the straight rack. These solutions introduce problems of transforming rotary motion into linear motion: slip, drop in efficiency, and bulk [3].

In some cases, a linear actuator may offer a satisfactory alternative when its construction and cost issues are resolved [4].

Robotic systems offer vast opportunities for actuators and among these, those with switched reluctance structure, rotary or linear.

The purpose of this study is to reflect the principle of the operation, and control of a linear actuator with the study of the different topologies of linear actuators.

In the first part of this chapter the theory of switched reluctance machines well be explained. Then, the principle of operation as well as the analytical modeling of a linear actuator will be also studied. The last part of this chapter is devoted to the presentation of the control techniques dedicated for switched reluctance linear.

2. Classification of linear actuator

There are mainly three types of incremental linear actuator which differentiate by the physical phenomenon which is at the origin of their movement.

These three types of actuators can have structures with a planar or tubular geometry [5, 6]. Contrarily to rotating machines where the rotor and stator are generally coaxial. Linear machines can be presented in flat form or cylindrical form. They consist of a moving part and a fixed stator whose positions can be reversed.

For flat structures, it is possible to realize actuators with single stator or with double stator. For cylindrical structures, it is possible to consider tubular actuators with internal or external moving part.

The single stator actuator is a simple variance which is easily integrated in current applications but which presents a significant force of attraction between the stator and the moving part [7]. The double stator structure makes it possible to obtain, on the one hand, higher thrust forces than for the single stator structure and on the other hand to lighten the mobile part, because if the latter is well centered the resultant of the forces attraction is then zero. This structure is particularly well suited to the case where the fixed stator.

The linear actuator can also have two symmetrical inductors in order to create a greater force compared to its single inductor counterpart. Nevertheless, it has a complex geometry for its manufacture.

They are composed of a fixed part (the stator) and a mobile part (the translator) whose displacement is governed by the tendency of the magnetic circuits to be in a position of maximum flux.

2.1 Permanent magnet actuator

The permanent magnet linear actuator consists of an armature comprising one or more permanent magnets and a stator comprising a number of coils. There are two configurations of this type of actuator. The first is with fixed coils and moving magnets. The second is with moving coils and fixed magnets, **Figure 1** [6].

The operation of this type of actuator is provided by the action of an electromagnetic field on the armature made up of permanent magnets. The magnetic field in the air gap created by the supply of the phase coils orients the magnets in one direction.

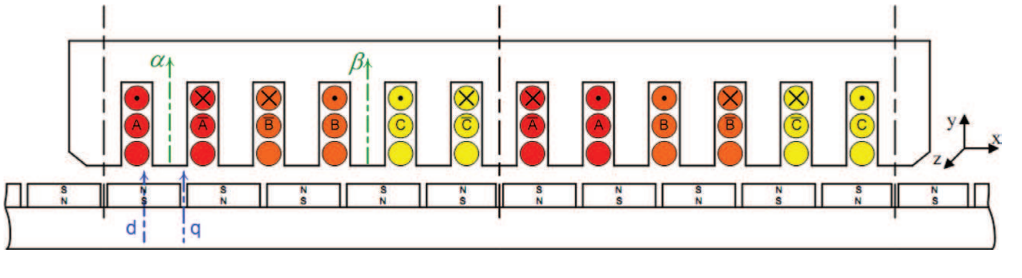

Figure 1.
Permanent magnet linear actuator.

2.2 Switched reluctance actuator

The switched reluctance actuator is among the simplest actuators. Regarding its construction, its basic structure consists of a coiled mobile part and an iron stator part which does not contain neither magnets or coils. The stator consists of an iron part rolled to form salient poles, **Figure 2**.

The principle of operation of a switched reluctance actuator is based on the tendency of an electromagnetic system to achieve a stable equilibrium position, which minimizes reluctance of the magnetic circuit. The aligned position of a phase is defined as the situation where the teeth of the stator and the modulus teeth of the mobile of the phase are perfectly aligned with each other reaching a position where reluctance is minimal [8].

Figure 3 shows an incremental reluctant linear actuator with transverse flux configuration comprising three modules separated by a non-magnetic material, each phase of the actuator is composed of two windings in series. The feeding of a phase creates a force allowing the movement of the mobile towards a stable equilibrium position, which it keeps as long as the power is maintained.

For this type of actuator, if the poles of one module are aligned with the poles of the stator then the poles of the other module must be offset in order to create a propelling force. Indeed, magnetic separations between the modules are necessary to impose a regular offset between the mobile modules.

2.3 Hybrid actuator

Hybrid stepping motors generally consist of a toothed mobile fitted with permanent magnets. The **Figure 4** shows the structure of a hybrid motor, [9].

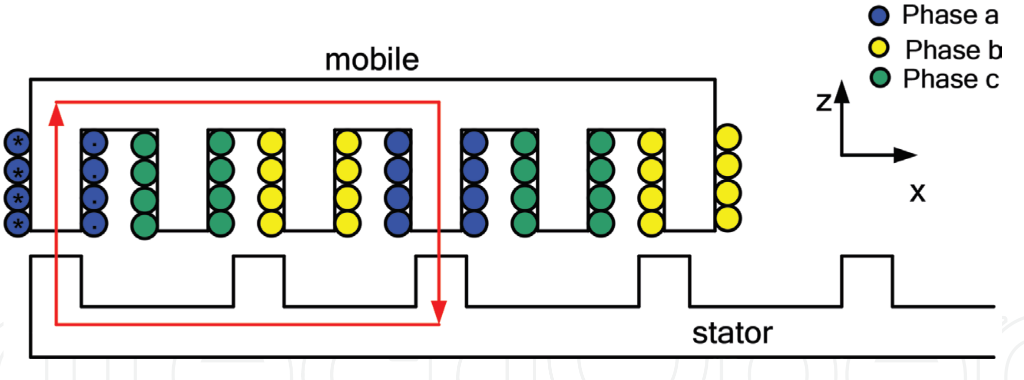

Figure 2.
Switched reluctance actuator with longitudinal flux configuration.

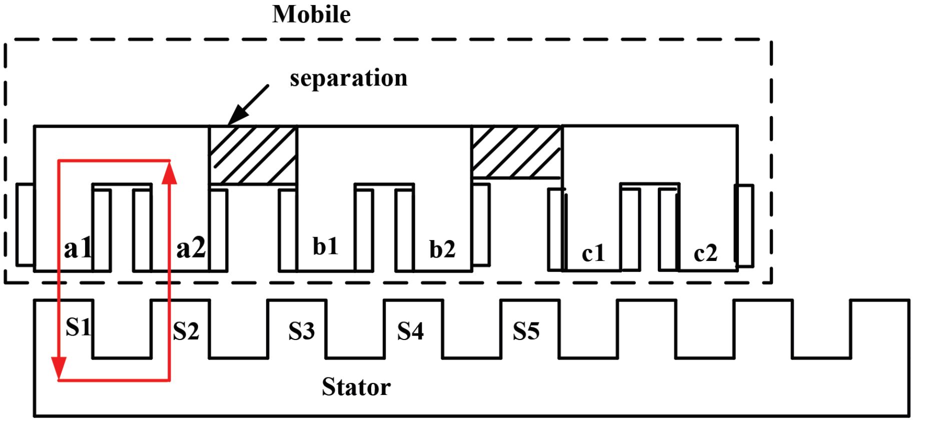

Figure 3.
Switched reluctance actuator with modular structure.

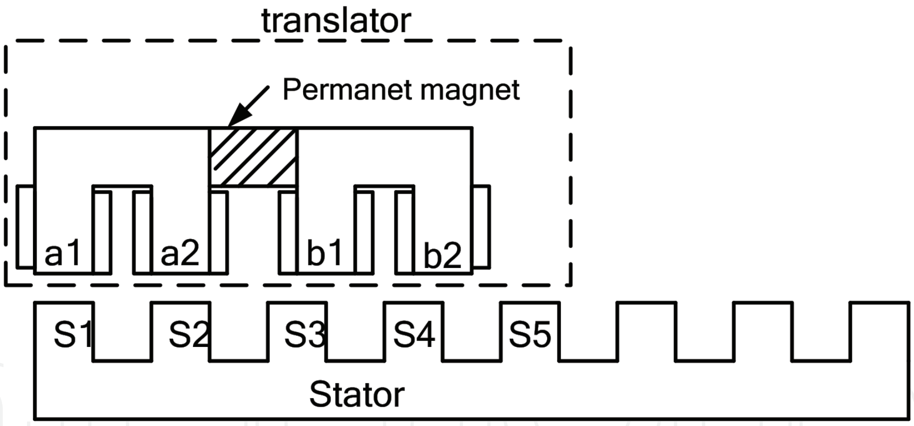

Figure 4.
Hybrid linear stepper actuator.

Type of actuator	Switched reluctance actuator	Permanent magnet actuator	Hybrid actuator
Resolution	High resolution	Medium	Medium
Thrust Force	Weak force	High force	High force
Operating frequency	high frequency	low frequency	high frequency

Table 1.
Comparison of different linear actuators.

This type of motor has both the advantages of the permanent magnet motor, which has a high torque, and those of the switched reluctance motor, which makes it possible to obtain a large number of steps per cycle. However, the iron losses are relatively large and therefore penalize this structure.

The movement of hybrid motors results from the superposition of the force developed by the reluctant effect of the teeth and the force created by the magnet.

The contribution of the amplitudes and the geometric periods of these forces makes it possible to achieve very diverse static characteristics. In fact, the magnet placed in the hybrid structure ensures a certain distribution of the field lines. The supply of the coils produces a switching phenomenon of the field lines more or less important depending on the intensity of the supply current by acting on the orientation of the fields it is possible to control the variation of the resulting force.

The **Table 1** gives a comparative study of the different configurations of the linear actuator studied above.

In what follows, our study will focus on switched reluctance actuators.

3. Operating principal of switched reluctance actuator

The force develop by a switched reluctance actuator is explained using the elementary principle of electromechanical energy conversion in a solenoid, as shown in **Figure 5**.

The switched reluctance machine belongs to the family of electromagnetic converters with single excitation.

Mechanical energy is produced by the displacement of a ferromagnetic material, placed in a magnetic field in order to maximize the flux in the circuit [10–13].

Generally, this type of actuator have only one degree of motion corresponding either to a translation or to a rotation around an axis, as shown in the figure.

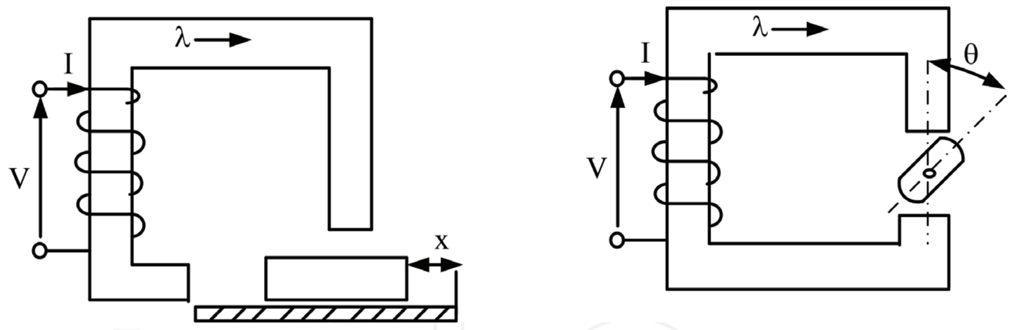

Figure 5.
Elementary circuit of a stepper motor.

The hatched parts represent the guiding of the moving part of which the position is identified by the distance x in the **Figure 5**. The position of the rotor in relation to the stator is indicated by the angle θ in the **Figure 5**.

Where ϕ and λ denote respectively the flow through a turn and the total flow of the winding.

$$\lambda = n\phi \tag{1}$$

For a given position of the moving part, the magnetic circuit is the seat of a totalized induction flux depending on the position and the supply current.

$$\lambda = \lambda(I, x) \tag{2}$$

To establish the equations governing the operation of the electromagnetic linear actuator, we consider the variations of the energy stored in the magnetic field when the moving part moves.

The axis of a moving tooth is identified by its distance x with the axis of a fixed notch. Thus, we define:

$$\text{Magnetic energy}: W_{mag} = \int I d\lambda \Big|_{I=cte} \tag{3}$$

$$\text{Magnetic } co-\text{energy}: W_{co} = \int \lambda dI \Big|_{\lambda=cte} \tag{4}$$

4. Analytic modeling of linear switched reluctance

Investigating the operational behavior of the switched reluctance actuator requires a mathematical model based on the electrical and mechanical equations governing its operation.

4.1 The electrical model

An elementary equivalent circuit for the switched reluctance actuator can be obtained by neglecting the mutual inductance between the phases. Assuming that each phase of the motor consists of a coil with resistance R and inductance $L(I, x)$, the applied voltage U to a phase is equal to the sum of the resistive voltage drop and the derivative of flux linkages $\lambda\ (I,x)$.

$$U_j = R_j I_j + \frac{d\lambda_j(x, I)}{dt} \tag{5}$$

j represents the index of the phase with j = 1, 2,3, indicates in order the phases A, B and C.

The flux linkage depends on the current and the translator position. Then the flux expression becomes:

$$U_j = R_j I_j + \frac{\partial \lambda}{\partial I}\frac{dI_j}{dt} + I_j \frac{\partial \lambda_j}{\partial x}\frac{dx}{dt} \tag{6}$$

By mean the magnetization curve **Figure 6**, the magnetic field energy can be determined for a fixed translator position as function of current and linkage flux.

$$W_{co} = \int_0^I \lambda dI \tag{7}$$

The force developed by the switched reluctance linear actuator is proportional to the change in mechanical energy as a function of mechanical displacement. It can be given by:

$$F(I,x) = \frac{\partial W_{co}}{\partial x} \tag{8}$$

The total instantaneous electromagnetic force Ft is the sum of the q individual phase forces.

$$F_t(I,x) = \sum_{j=1}^{q} F(I,x) \tag{9}$$

For a linear flux model of switched reluctance actuator it is $\lambda(x) = L(x)I$. Thus, neglecting magnetic saturation gives.

$$W_{co} = \int_0^I \lambda dI = \frac{1}{2}L(x)I^2 \tag{10}$$

Hence,

$$F(I,x) = \frac{1}{2}I^2 \frac{dL}{dt} \tag{11}$$

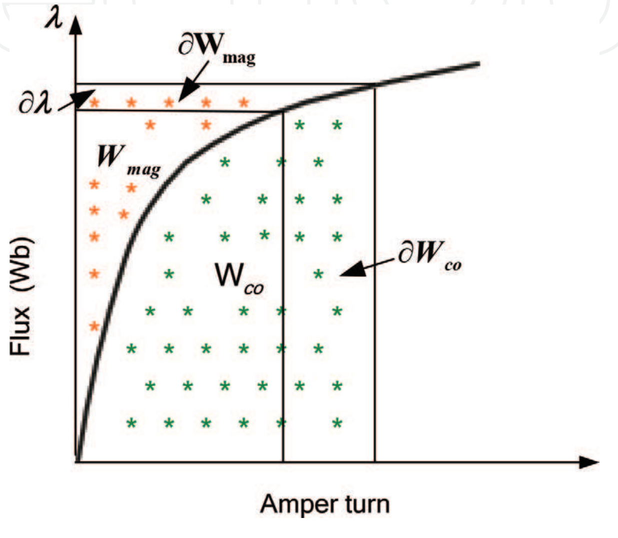

Figure 6.
Magnetization curve of the studied actuator.

The thrust force is then proportional to the derivative of the inductance with respect to the displacement of the mobile x and to the square of the supply current of a phase.

The inductance $L\ (I, x)$ is a periodic function of x, with a period equal to the dental pole pitch δ .

The inductance is minimal when the teeth are in unaligned position, and it is maximum when the teeth are in aligned position.

The inductance depends on the moving position. The partial derivative of the inductance with respect to the moving position can be expressed by:

$$\frac{\partial L_j}{\partial x} = -\frac{2\pi}{\delta} L_1 \sin\left[\frac{2\pi x}{\delta} - (j-1)\frac{2\pi}{3}\right] \tag{12}$$

By replacing Eq. (12) in Eq. (11), the electromagnetic force developed by each phase of the separately supplied switched reluctance actuator is expressed as follows:

$$F_j(x, I) = \frac{1}{2} I_j^2 L_1 \frac{2\pi}{\delta} \sin\left(\frac{2\pi}{\delta} x - (j-1)\frac{2\pi}{3}\right) \tag{13}$$

4.2 The mechanical model

The mechanical movement of the actuator is described by the equation deduced from the fundamental principle of dynamics characterizing a linear movement, (see Eq. (14)) [5].

$$m\frac{d^2x}{dt^2} + D_v \frac{dx}{dt} + f_s \text{sing}(v) + F_l = F(x, I) \tag{14}$$

5. Specificity of the control of linear actuator

The special feature of the switched reluctance linear actuator is to ensure a continuous incremental translational movement. In other words, each supply pulse must correspond to a constant elementary displacement, this is correspond to the mechanical step of the actuator.

Then, to ensure continuous movement, it is necessary on the one hand to have several phases, on the other hand, the successive supply of the phases must be synchronized with the real position of the moving part.

A determined number of pulses causes a corresponding number of steps by the actuator. In addition, the succession of determined pulses generated by a control circuit at a well determined frequency makes it possible to impose a continuous movement of the moving part at constant speed. At each pulse of the control, induce that the poles of the supplied phase closest to the stator poles, and they are positioned opposite the latter.

Like all electric motors Linear, actuators can be driven in open loop or closed loop for applications, which require high precision and high positioning quality.

The linear actuator is essentially an electric actuator, which requires an electronic power converter to change the operating frequency and the magnitude of the applied voltage. The main characteristics of electronic converters used for linear actuators generally require full operation of two quadrants (half H-bridge), a high switching voltage is necessary for the rapid establishment and extinction of the current.

Generally the linear incremental actuators are controlled by a static converter in most applications, the force generated by each phase of the actuator is proportional to the square of the phase current (see Eq. (13)). The circuit and the control strategy are directly related to the performance and characteristics of the actuator. Several topologies are presented with a reduced number of power switches, faster excitation, faster demagnetization, high efficiency and high power through continuous research [14]. Conventionally, there has always been a trade-off between obtaining some advantages and losing others with each topology.

Assuming that the edge effects is neglect, then the variation of inductance is linear as shown in **Figure 7**. The characteristic of the inductance is periodic and the periodicity of the inductance is equal to $2\pi / q$, q number of phases.

The physical meaning of the different regions in **Figure 7** is as follows.

In the [*x1-x2*] zone, the inductance begins to increase as the mobile moves. When the poles of the moving part meet the stator poles, the inductance reaches its maximum value. In this region, the actuator operates in an increasing inductance regime where the slope of the inductance is positive where a positive force is developed by the actuator.

The area in the gap [*x2-x3*] the teeth of the mobile and the stator are completely aligned. In this interval, the inductance is constant and in this case the actuator cannot generate any force even if the phase supply is kept constant.

5.1 Different control methods

Incremental actuator supplies are generally classified into five modes [14]:

Mode 1: only one phase is supplied by the nominal current I_n, in this case that the mechanical step of the actuator is defined, the phase supply sequences is shown in **Figure 8**.

Mode 2: two successive phases are supplied at the same time by the current. Indeed, the force is greater by a factor $\sqrt{2}$ than the first mode.

Mode 3: the alternating combination of the two previous modes allows operation in half-step, In this control mode, the phases of the actuator are supplied in order in accordance with the cyclogram shown in **Figure 9**.

Mode 4: this mode, commonly called "Ministepping" consists in multiplying the intermediate positions by supplying each phase with fractions of the nominal current, this corresponds to the extension of operation in mode 4.

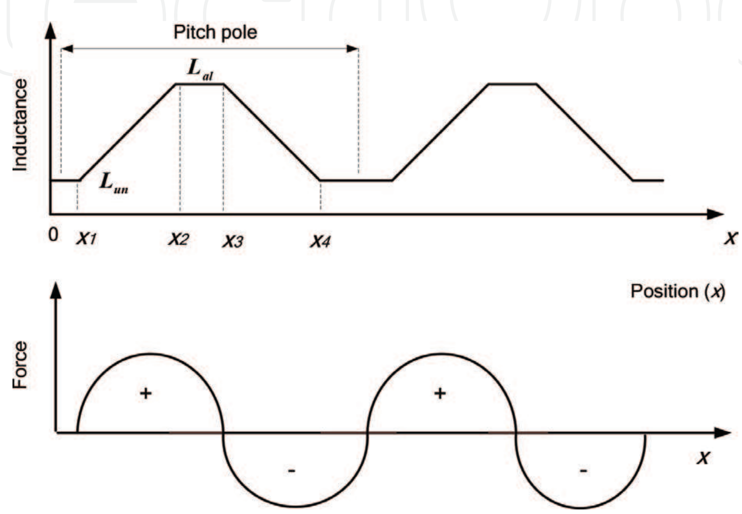

Figure 7.
Inductance and force curves as function of position.

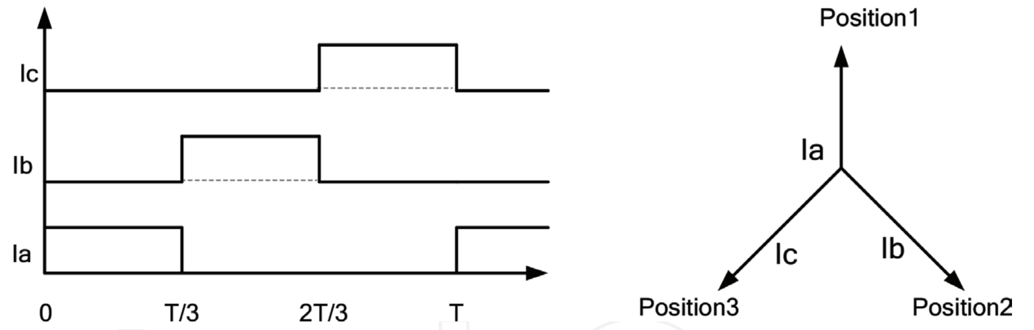

Figure 8.
Full step command.

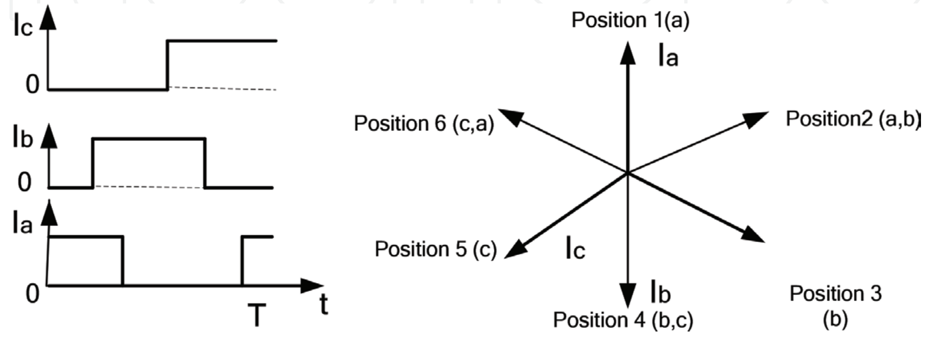

Figure 9.
Half steps command.

5.2 Drive circuit for switched reluctance actuator

Several application using linear switched Reluctance actuator using an adjustable speed drive. Asymmetric half bridge converter is very popular for switched reluctance actuators because of its ability to operate efficiently.

The power switch used in converter is a transistor. However, in industrial applications, the other types of power switches are used, mostly Thyristor, power IGBTs, or even MOSFETs. A dc voltage source is necessary for supplying the power converter and motor phases. The dc source may be from batteries or mostly a rectified ac supply with a filter to provide a dc input voltage source to the switched reluctance actuator converters (**Figure 10**) [14].

First, consider that the phase *1* is supplied when the upper and lower transistors *T1* and *T4* are switched on. Then, $+V_{DC}$ voltage applied to the phase winding. Therefore, a current is established and increases in the windings of the phase through both switches.

When the poles of the supplied phase reach the aligned position with the poles of the stator, in this case the switches are turned off. Phase current then slowly decreases by freewheeling through one transistor and one diode. When both transistors are off, the phase winding will supplied by voltage $-V_{DC}$. Indeed, the phase current then quickly decreases through both diodes. By appropriately coordinating the above three switching states, phase current of the switched reluctance actuator can be controlled. The major advantages of the asymmetric bridge converter are the independent control of each motor phase and the relatively low voltage rating of the inverter components.

By supplying the first phase maintains the translator in a stable equilibrium position, if the supply current of the first phase is cut off and if the second phase is supplied, then a positive force is developed by the second phase which moves the translator to the second equilibrium position. Conversely, if the excitation is changed from phase *1* to phase *3* the force developed by phase 3 is negative, moving the translator in the negative direction to the phase *3* equilibrium position.

The **Figure 11** presents the characteristics of the forces developed by a three-phase structure supplied separately. By applying a resistant force F_l when phase 1

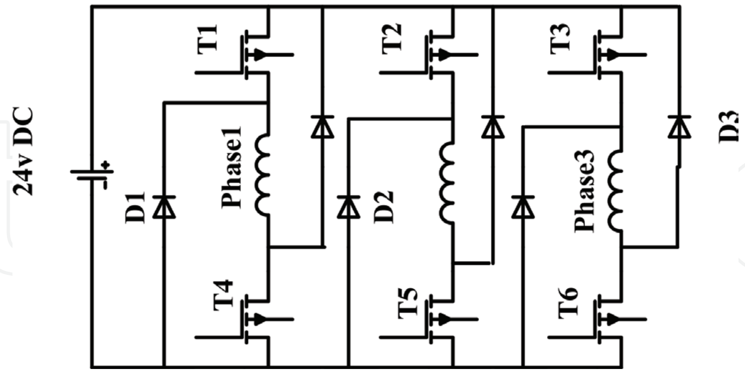

Figure 10.
A three-phase asymmetric half-bridge converter.

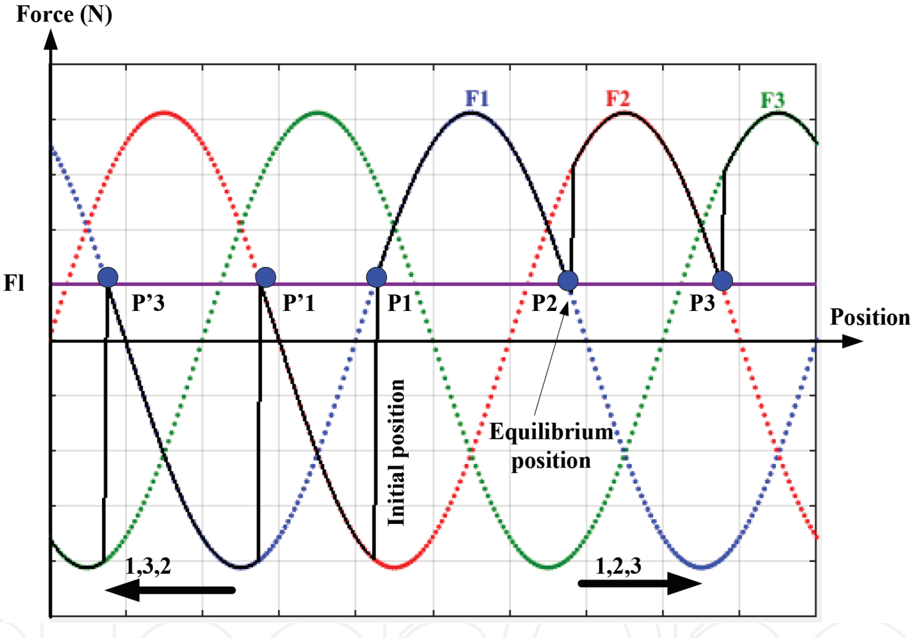

Figure 11.
Force characteristic of an actuator possessed three phase.

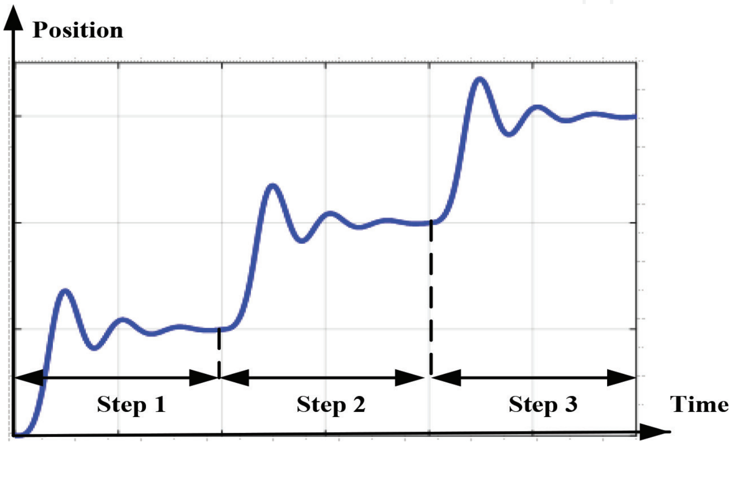

Figure 12.
Dynamic response of the actuator for full step command.

is supplied, the stable equilibrium position is at P1. If the second phase is powered, the mobile is brought to position P2 when phase 3 is powered in turn, it brings the mobile to P3 and so on. The power supply sequence in the order 1,3,2 makes it possible to move the mobile in the opposite direction from P1 to P′1 then to P’3.

The **Figure 12** show the response of the actuator when a full step command is applied. The successive feeding of the phases causing the moving of the mobile by three mechanical steps, we can see that at each step the mobile oscillates around its equilibrium position in order to reach a stable position.

6. Conclusions

In this chapter, initially, the different topologies of incremental linear actuators are studied and presented, operating principal of switched reluctance actuator was described. Then, an analytical model of linear switched reluctance actuator was proposed and established which allowed to determine the electromagnetic force developed by the actuator. Finally, the different control techniques that can be applied to the studied actuator have been presented.

Conflict of interest

The authors declare no conflict of interest.

Nomenclature

U	Voltage (V)
I	current (A)
R	phase resistor (Ù)
L	inductance (mH)
λ	Linkage flux (wb)
δ	Pole pitch
W_{co}	Co-energy (J)
m	mass of the moving part (Kg)
D_v	viscous coefficient of friction (Ns/m)
fs (N)	dry friction
v (m / s)	represents the mechanical speed of the mobile (m/s)
x	the displacement (m)
Fl	the load force (N)
F	the electromagnetic force (N)

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