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Nonlinear Dynamic Simulation Model of Reluctance Linear Motor

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Abstract—**the reluctance linear motor (RLM) has been successfully applied in many applications. Despite of its simplicity of command, there are lots of difficulties in building its model. In this paper, the main simulation model of the developed reluctance linear motor based on the MATLAB is given with the simulation model of calculating phase current and the magnetic force.**

***Keywords*— Reluctance Linear Motor (RLM), Modeling methods, Analytical method, force, inductance**

I. INTRODUCTION

At the beginning of the century, several types of machines were invented, only some of them were introduced into the industrial applications. The synchronous machine with variable reluctance is structurally a synchronous machine with projecting poles deprived from excitation. Its stator is identical to that of the ordinary machines with Alternative course. The electromagnetic couple is made up exclusively of the couple of saillance.

The step by step machine with variable reluctance has an electromechanical converter having as function the transformation of electric information into a mechanical action being able to be a linear displacement or more classically angular [1], [2]. There, for a long time, exist applications with linear motors in the Industrial field. It is appreciated for several reasons: the robustness, its low cost of purchase and maintenance, its specific power and the higher maximum speed provided. The linear motors are developed through their ability to generate levitation systems. A linear motor helps to generate a pushing power directly without intermediate processing system of the rotational energy into a translation one. Reluctance Stepper motors are widely used in industry for control of position, especially in manufacturing applications [3] [4] [5]. These motors are designed to operate in open and closed loop positioning systems [6] [7]. As its name suggests, the stepper motor runs movements when no voltage pulses are applied to its phases. There are three types of stepper motors: variable reluctance, permanent magnet and hybrid.

In Contrary to the traditional engines (such as the engines with induction), the RLM's engine is intended to run in magnetic saturation deep to increase the density of power of exit and the conversion ratio of energy. Consequently, because of the effects of saturation and the magnetic variation of reluctance, all the relevant characteristics (e.g. the flow of connection, couple…) of the machines are strongly nonlinear functions at the same time of the position of the rotor and current phase [8]. These nonlinearities make the process of modeling RLM relatively difficult. Modeling is an important step in the process of analysis, design and control of a linear reluctance machine.

This paper is organized as follow: in section II we review the description of the Linear Reluctance Motor illustrated by the figure 1 followed by presenting a mathematical study a the supply circuit and we end our paper by simulation of some RLM's parameters using Simulink/Matlab.

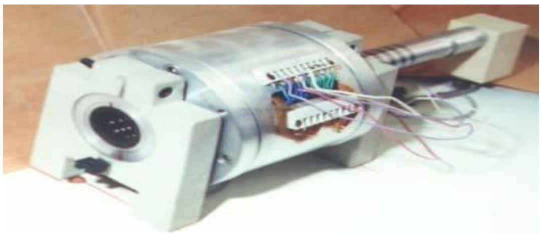

Fig.1 The ancient laboratory prototype

II. LINEAR RELUCTANCE MOTOR OVERVIEW

The operation of the linear reluctance motor is based on the principle of varying reluctance due to deformation of the magnetic circuit. This type is characterized by a toothed structure at the stator and the movable part. The magnetic circuit is generally assembled from laminations of high permeability. The windings of the electrical circuit are generally concentrated around the stator studs and therefore easy to achieve [9]. Each module has two blades around which are wound coils. Each phase of the machine is formed by the series connection of two coils of the same module. Nonmagnetic separations are required between stator modules to impose an offset. Indeed, if the pads of a module are aligned with the teeth of the mobile part, the stator terminals of the other modules must be offset in order to create a moving force. Each phase of the machine requires that the mobile part has a balanced position that corresponds to the alignment of the teeth with the pads of the phase stator fed. [10]

the engine, illustrated in Figure 2, has two main parts, the stator and the rotor. the internal part, usually a moveable element, is a solid cylindrical ferromagnetic part coaxial with peripheral slots. the housing which is usually a fixed element, is composed of four sets of coils (A, B, C and D) separated by non magnetic rings.

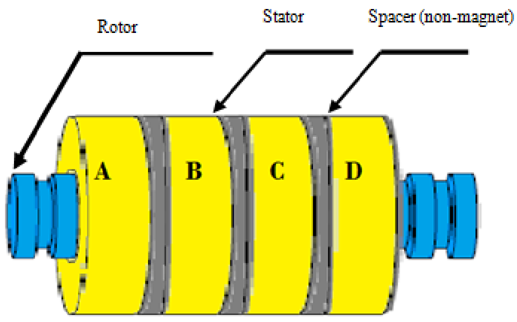

Fig.2 structure of the linear variable-Reluctance stepper Motor

III. MATHEMATICAL MODELING

Precise mathematical modeling of variable reluctance step motors requires knowledge of both the geometry of the machine and of the ferromagnetic material characteristics. These requirements will represent the basics to build assumptions which are made to simplify the model to a set of nonlinear differential equations

Assumption 1: The ferromagnetic material does not saturate. This is a poor assumption for variable reluctance step motors in that the motors are usually operated with a high degree of saturation. This assumption is replaced after the "non-saturated" model is presented. [11]

Assumption 2: The inductance for each phase varies in a sinusoidal manner around the circumference of the air gap. The linear switched reluctance stepping motor inductances are supposed to be sinusoidal. For the case of a four phases LRM. The inductance characteristics are off phased. Hence, the studied machine inductance is given by the following relation [11].

$$L_k(x) = L_0 + \sum_{k=a}^{d} L_k cos\,(k\frac{2\pi}{\lambda}x)$$

For the case of a stepper motor with variable reluctance four phases, stator coils are electrically phase shifted by $\frac{\pi}{2}$. During movement of the mobile, the inductance $L_k(x)$ oscillates around an average value equals to L_0.

The following figure shows the variations of the inductance:

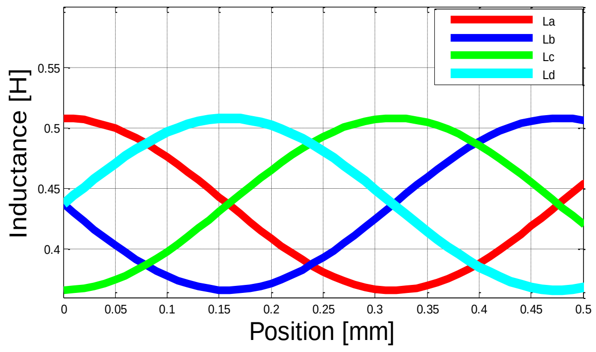

Fig.3 Inductance evolutions of the RLM

The operation of variable reluctance (VR) stepper motor is based up on the attraction of a soft magnet to an energized electromagnet or pole. The armature in the VR actuator moves to seek its minimum reluctance position. This position represents the lowest energy state for the actuator in the energized position.

The equivalent circuit diagram of a stepper motor with variable reluctance, it is assumed that the mutual inductance between phases is negligible so that it suffices to consider the single phase motor. Then the figure will be as follows*:*

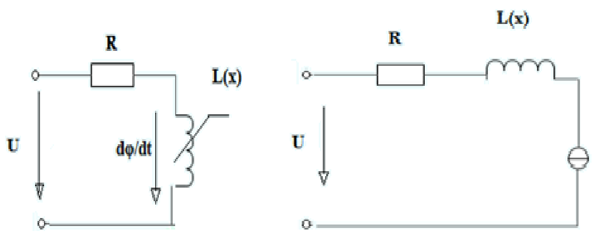

Fig.4 Equivalent circuit diagram of single phase RLM

This circuit comprises a resistance of a coil winding and an induced voltage caused by a variation of Stator inductance. For the one phase equivalent circuit the voltage equivalent is given by the following expression:

$$U_k = R_s i_k + \frac{d\varphi_k}{dt}$$

Where R_s is the winding resistance of a phase, and U_k and φ_k for $k = a, b, c, and\ d$ are the phase voltage and the total coil magnetic flux, generally the expression of the flow is expressed by:

$$\varphi_k = i_k . L_k(x, i)$$

The magnetic flux of the machine depends on the mutual position of the stator pole and the rotor tooth. In zone of the saturation, it depends on the excitation current too.

The period of $L_k(x,i)$ is $\frac{2\pi}{Nr}$; where Nr is number of rotor teeth.

Assuming that the machine is not saturated, the induced voltage of saturation is therefore neglected and the equation of the voltage will be given as follows:

$$U_k = R_s . i_k + L_k(x) . \frac{di_k}{dt} + i_k . \frac{dL_k(x)}{dt} \frac{dx}{dt}$$

The last term $i . \frac{dL(x)}{dt}$ represents the internal induced electromotive force.

The electrical speed of the motor is given by the change of rotor position in time.

$$v = \frac{dx}{dt}$$

The time in the relation above can be replaced by a rotor position, finally the voltage equation can be expressed as [12][13]:

$$U_k = R_s . i_k + L_k(x) . \frac{di_k}{dt} + i_k . \frac{dL_k(x)}{dt} v$$

The electromagnetic force of the stepper can be calculated from the change of fits magnetic co energy:

$$F(x) = \frac{\partial w_c'}{\partial x}$$

We can write the expression for the force in the form:

$$F(x) = \frac{1}{2} i^2 \frac{dL(x)}{dx}$$

Where i is the input current to the coil.

The linear position of the rotor satisfies the following second order differential equation [14].

$$m \frac{d^2x}{dt^2} + F_{max} \sin\left(\frac{2\pi x}{\lambda} + \varphi\right) + \xi \frac{dx}{dt} + F_0 sign\left(\frac{dx}{dt}\right) = F_c$$

Where:

$$F_{max} = \frac{\pi i^2 L_1}{\lambda}$$

The simulation model of the RLM drive consists of 2 modules: The RLM module and the power converter module (see Figure 4).

The RLMV module represents the electrical and mechanical equations of the RLM where as the power converter module corresponds to the power converter logic switching.

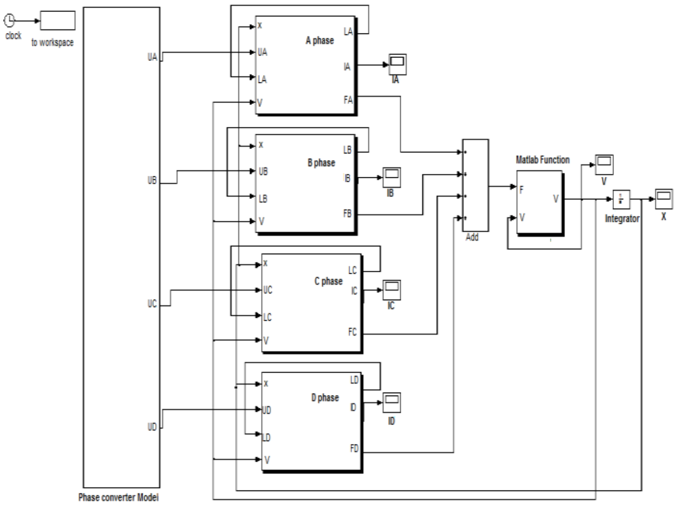

Fig.4. Main simulation model of the developed

In the model, "x" is the rotor position; "UA, UB, UC, UD" is supply voltage; "FA" is A phase electromagnetic force; "FB" ***is*** B phase electromagnetic force; "FC" is C phase electromagnetic force;"FD" is D phase electromagnetic force; IA is the A phase current; IB is the B phase current; IC is the C phase current; ID is the D phase current.

The toolkit ''Simulink'' provided by Matlab software could be used to model the variable reluctance motor. The simulation model for calculating the electromagnetic force "FK", the current phase "IK" and the speed of the moving of the mobile are represented in the two following figures (Fig.5 and Fig.6).

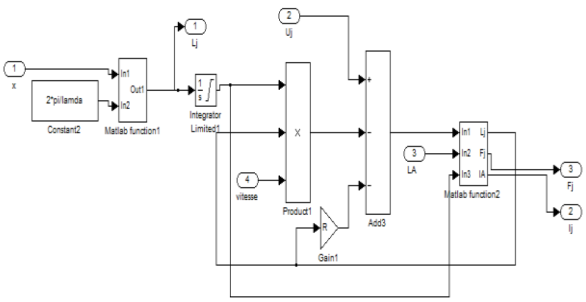

Fig.5. Simulink diagram of an electromagnetic force and phase current

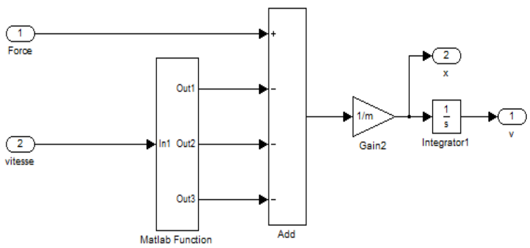

Fig.6. Simulink diagram representing the mechanical part

IV. A Power converter Module

The principle of the supply of the phases of a stepping motor is based on the use of transistors operating alternately blocked and saturated regime. This is well illustrated in the diagram below:

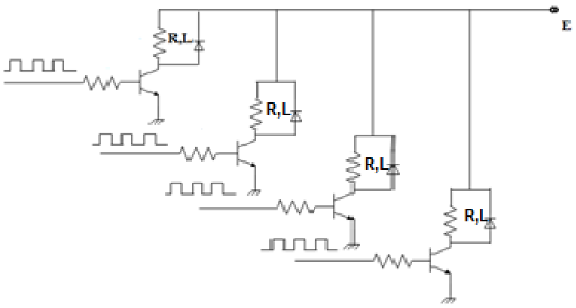

Fig.7 A power supply circuit of a stepping motor in four steps

In this diagram, L represents the inductance of the phase winding, R is the resistance of the phase winding and E is the voltage coils phases. The proper sequence of switching transistors must be generated for damping oscillations that may appear at the end of the execution of a step.

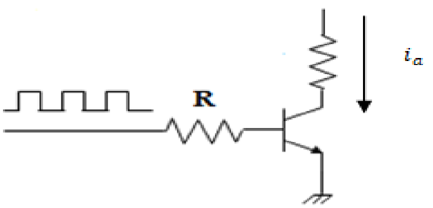

Fig.8 Modeling of the supply circuit

The current $\boldsymbol{i_a(t)}$ in phase supply (see Figure 6) is a solution of the following differential equation.

$$\boldsymbol{E = R.i + L.\frac{di}{dt}}$$

$\boldsymbol{i_a(t)}$ is given by the following relation:

$$\boldsymbol{i_a(t) = \frac{E}{R}(1 - e^{\frac{t}{\tau_e}})}$$

Where: $\boldsymbol{\tau_e = \frac{L}{R};}$

At the instant of blocking of the transistor, the quenching circuit, (see Figure 7), allows the dissipation of the energy stored in the coil.

Fig.9 Quenching circuit

The current $i_e(t)$ in this case is given by the following relationship:

$$\boldsymbol{i_e(t) = I_N e^{-\frac{t}{\tau_d}}}$$

V. Simulations and Results

The following figure shows a numerical simulation study to describe the stepping linear motor operation. The engine tests considered in this study are characterized by the principal parameters indicate in Table1:

TABLE I

Stepper motor parameters

Unload friction force	F_0	0.1N
Stator coil resistance	R	23.4Ω
Mean inductance term	L_0	437 mH
First harmonic inductance term	L_1	71 mH
Mass of moving part	m	2.46 kg
Loading force	F_c	0N
Dynamic viscous coefficient	ξ	70 Nm/s

The figure 10 presents the current forms of three phases of the transistors.

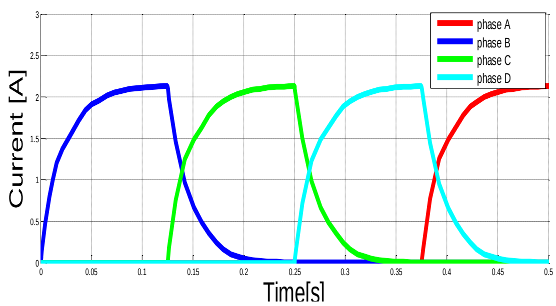

Fig.10 The phase current waveform

The following figure shows the evolution of the dynamic parameters of a variable reluctance stepper motor four fragments with not null force load.

Simulation results illustrated by Fig.11 and 12 show from the speed and strength, the behaviour of the engine for four stepper movement of non-empty load, half load and rated load.

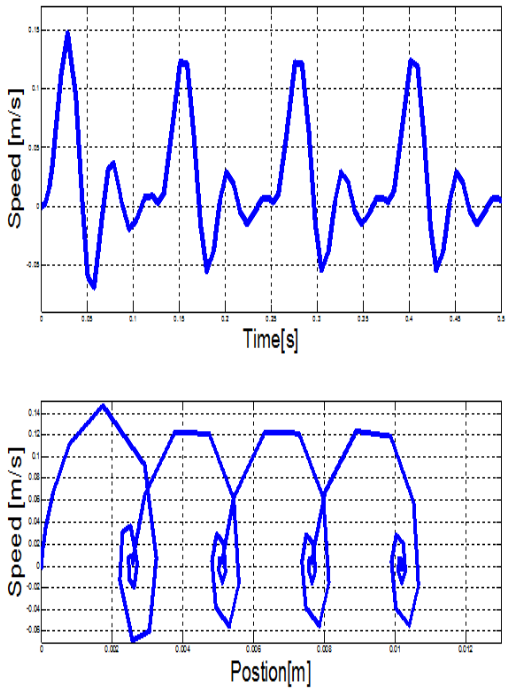

Fig.11 speed waveform

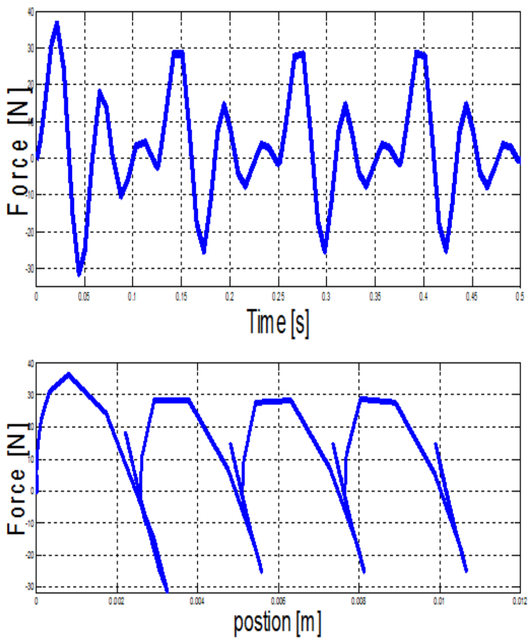

Fig.12 electromagnetic force waveform

VI. CONCLUSIONS

In the present paper there was shown a mathematical method for analytical calculus of the phase current, speed and the electromagnetic force of the reluctance stepper motor. The simulation results show that the reluctance linear machine can be commanded while varying one of the parameters used in the simulation.

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