Dynamic Instability Phenomenon of the Linear Tubular Stepping Machines: Analysis and Solution

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Abstract: A digital control method for monitoring a linear Variable Reluctance Stepping Motor is developed in this paper. It improves the quality of movement and largely eliminates problems of overshoot and resonance.
In this work, an analytic survey and the formulation of the control law are considered. The validation of the proposed approach by numeric simulation is then presented.

Keywords: Linear stepping motor; overshoot and resonance; tubular structure; Dynamic instability, positioning by microsteps.

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1. Introduction

The linear variable reluctance stepping motors have the advantages of lower cost and simplicity in construction. They are well adapted for many industrial applications such as data processing devices, car industry and robotics. Within these applications, linear tubular version of variable reluctance stepping motors is designed for a linear positioning purpose without request to rotary-to-linear gearing mechanism. The axi-symmetry for tubular structures allows the generation of an important axial force applied on the actuator plunger and theoretically null radial force. Hence, linear tubular variable reluctance stepping motors establish a simple and efficient solution for generating fast linear displacements.

But a major limitations in the use of the motor under open loop control, is that their quality of movement who is accompanied often by a large overshoot and resonance problems. Indeed, in the "start-stop" working regime, the linear stepping reluctance variable motors shows some important rotor oscillations and a large overshoot, which harm some applications by their generated noise or by the longer time response. In practice, these oscillations may induce dynamic instability and can cause significant problems when the stepping rate is anywhere near a resonant frequency of the system; the result frequently appears as random and uncontrollable motion [1- 4].

Usually, a controlled functioning in resonance domains can only be guaranteed through the following alternatives:

- either by connecting a mechanical reductor to the motor which is often costly;
- or by increasing friction at the expense of machine output,
- or by using a method of electric braking which obviously needs regular maintenance.

In order to overcome these problems and disadvantages, we present in this paper a digital control strategy based on the use of a particular PWM modulation technique ensuring a functioning to smooth plunger motion [5-6].

2. Proposed Control Method

2.1. Global Structure of the Studied Linear Stepping Motor

The electromagnetic structure of a four phases linear tubular stepping motor is composed of a toothed plunger structure and a four statoric stack with the same tooth and slot widths. Figure 1 represents, in the axial plane, the general structure of the considered motor. Also, non magnetic separations are set between the statoric modules, so that only one statoric phase can be aligned with plunger teeth when it is supplied.

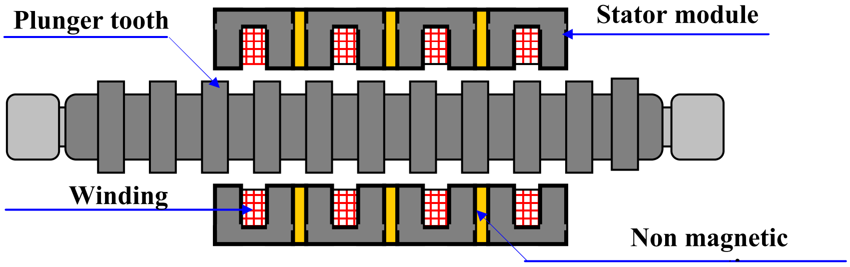


Figure 1. General structure of the linear tubular stepping motor

2.2. Principe of the Suggested Approach

The working in dynamic regime of this machine is governed by the following mathematical non linear differential equations system pattern [6-8]:

$$U_A = Ri_A + \left[L_0 + L_1\cos(\frac{2\pi x}{\lambda})\right]\frac{di_A}{dt} + \frac{2\pi}{\lambda}L_1\sin(\frac{2\pi x}{\lambda})Vi_A \quad (1)$$

$$U_B = Ri_B + \left[L_0 + L_1\cos(\frac{2\pi x}{\lambda} - \frac{\pi}{2})\right]\frac{di_B}{dt} + \frac{2\pi}{\lambda}L_1\sin(\frac{2\pi x}{\lambda} - \frac{\pi}{2})Vi_B \quad (2)$$

$$U_C = Ri_C + \left[L_0 + L_1\cos(\frac{2\pi x}{\lambda} - \pi)\right]\frac{di_C}{dt} + \frac{2\pi}{\lambda}L_1\sin(\frac{2\pi x}{\lambda} - \pi)Vi_C \quad (3)$$

$$U_D = Ri_D + \left[L_0 + L_1\cos(\frac{2\pi x}{\lambda} - \frac{3\pi}{2})\right]\frac{di_D}{dt} + \frac{2\pi}{\lambda}L_1\sin(\frac{2\pi x}{\lambda} - \frac{3\pi}{2})Vi_D \quad (4)$$

$$\frac{dv}{dt} = -\frac{\pi L_1}{m\lambda}\left[i_A^2\sin(\frac{2\pi x}{\lambda}) + i_B^2\sin(\frac{2\pi x}{\lambda} - \frac{\pi}{2}) + i_C^2\sin(\frac{2\pi x}{\lambda} - \pi) + i_D^2\sin(\frac{2\pi x}{\lambda} - \frac{3\pi}{2})\right] - \frac{F_0 \mathrm{signe}(v)}{m} - \frac{\xi}{m}v - \frac{F_r}{m} \quad (5)$$

This system is composed by a four electric equations and a one mechanical equation of movement. The solution of the last equation is described by the following oscillating response; Figure 2. These oscillations may induce dynamic instability problems and erratic functioning. In fact, this oscillation evolution varies between a maximum and a minimum displacements, respectively x_{Max} and x_{Min}. Assuming that the commutation of the following displacement is set at x_c where the plunger with the driven part, moving in a negative speed, have acquired kinetic energy W_c

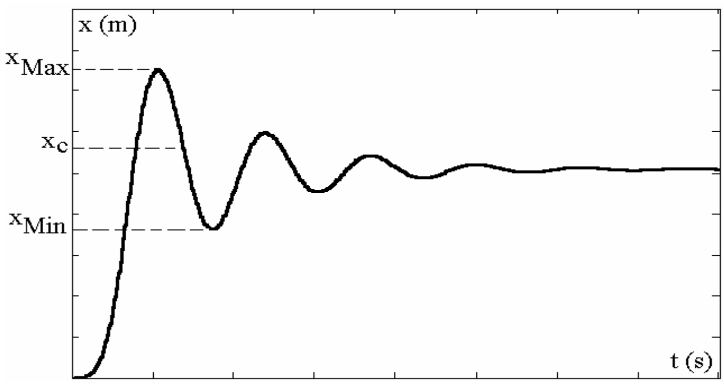


Figure 2. Linear displacement evolution on a one step

In the interval $[x_c\text{-}x_{Min}]$, the propulsive effort, resulting from the difference between the electromagnetic thrust force and the resisting force (F_r), must primarily reduce the effect of acquired W_c. The energy W_f needed to brake the system is expressed as:

$$W_f = \int_{x_{Min}}^{x_{Max}} (F_{em}(x) - F_r)\, dx \qquad (6)$$

and the condition of steady working is $W_f > W_c$

If this condition is not satisfied, the motor keeps its translation in the reverse direction and gets in domains of erratic behaviour. According to the importance of the static and the dynamic friction, stepping motors can evince one or several instability domains. These domains may emerge either when the step duration is adjoining the natural period of oscillations or their multiples, or when the control frequency is closely related to the natural frequency or its sub-multiples [9 -12].

In order to reduce these zones of resonance, it is necessary to attenuate the overshoot and deaden the oscillations of movement. This objective could be reaches by an adequate control of the kinetic energy of the mobile part. So, in order to limit the evolution of this energy, we solicit the plunger to two antagonistic forces. The first force provokes the advance of the mobile part in the positive sense. The second one brakes the movement of the plunger. Hence, the translation will be operated in fragmented steps.

In order to produce these two antagonistic axial forces, we inject simultaneously two current intensities in two adjacent statorics windings. However, when the excitation is maintained simultaneously on the winding A and on the winding B (for example), the equation of movement (5) could be reduced, in permanent regime, to the following expression:

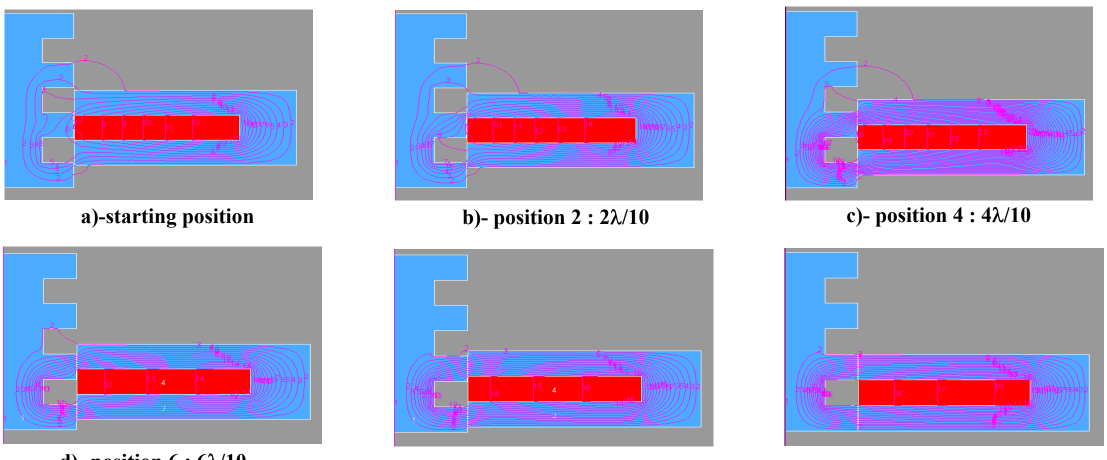
$$m\frac{dv}{dt} = -\frac{\pi L_1}{\lambda}\left[i_A^2 \sin(\frac{2\pi x}{\lambda}) + i_B^2 \sin(\frac{2\pi x}{\lambda} - \frac{\pi}{2}) \right] \qquad (7)$$

The compensation of these two forces shows, by the equation (8), that an adequate modulation of the statoric currents imposes to the plunger an artificial positioning in x such as :

$$x = \frac{\lambda}{2\pi} \operatorname{arctg}(\frac{i_B^2}{i_A^2}) \qquad (8)$$

However, in order to adjust independently the electromagnetic thrust forces, it is considerably important that the statoric modules are not magnetically coupled. Under this condition, it is possible of adjusting the axial forces produced by the statoric modules in order to nullify the resultant force in any desired position. Hence, the analysis of magnetic behavior of the considered motor was developed for the verification of this condition. This analysis is articulated the finite element by the utilization of the OPERA software. The obtained results are consigned in Figure 3.

This result illustrates the magnetic behaviour of the studied structure for a positioning spaced to the tenth of the pole pitch λ. The obtained distributions of the flux show the existence of negligible magnetic leakage between the statoric modules. Thus, the statoric modules could be considered non magnetically coupled.



a)-starting position **b)- position 2 : 2λ/10** **c)- position 4 : 4λ/10**

d)- position 6 : 6λ/10 **e)- position 8 : 8λ/10** **f)- Final position : 10λ/10**

Figure 3. Description of the magnetic behaviour of the considered machine

2.3. Development of the Suggested Approach

With the assumption, the control of antagonist axial forces of the two excited statoric modules can then be obtained by a finer control of statoric currents. In order to concretize the proposed control, we exploit a Pulse Width Modulation technique (PWM). However**,** for such linear variable reluctance stepping motor, the thrust force produced depends on the square of the phase current, and its direction is independent of the phase current direction. Thereby, a unipolar DC voltage (U) can be used to supply a phase current through a two-switch converter as shown in Figure 4, where the phases of the considered motor was replaced by their equivalents circuits.

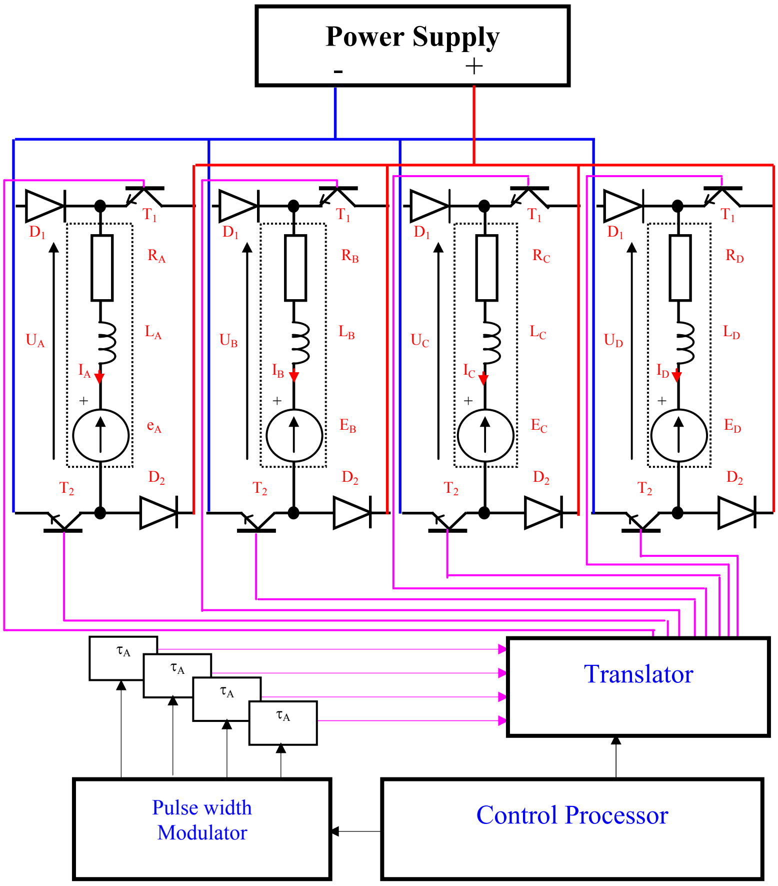


Figure 4. Block diagram of the proposed digital control

In order to subdivide the first mechanical step, the both phase windings (A) and (B) must be excited simultaneously. But the phase winding (B) is excited by a PWM signal having a cyclic ratio progressively increasing. However the phase winding (A) is excited by the complement of it signal which present an impulse width progressively decreasing. Consequently the first phase produces a positive force allowing pulling the plunger in the positive sense, (this is a pull winding); and the second phase produces a negative force and drags the rotor in the inverse sense (this is a brake winding). The global propulsive force resultant of these two partial forces allows to immobilize the plunger in an intermediate position. The gradual variations of the commutation times of the PWM control signal confers to the rotor a positioning by microsteps.

The control signal is synthesized by the PWM synthetisor using a programmable microprocessing control. The frequency of this signal is determined by the specific characteristics of the considered machine. The desired number of microsteps sets landings of the ratio cyclic. The PWM synthetisor is followed by an adequate logic control, which supervises the conduction and the commutation of the transistors. Thus, in order to ensure the positioning in four microsteps/steps along a one electric cycle containing four mechanic steps, the suggested control mode allows to apply to the statoric windings two complementary signals modulated in pulse width according to the cyclogram of Figure 5, [13-14]:

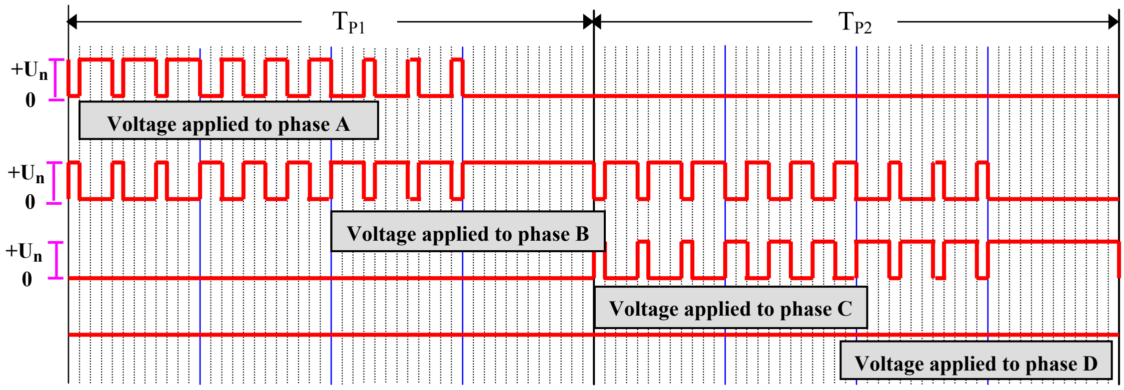


Figure 5. Cyclogram of voltages applied to statoric phases

In this case of the excitation mode, when to energize a phase, both T_1 and T_2, are turned on. This applies U to the phase winding and i_{ph} builds up. T_2 is kept closed so long as the phase is remain energized. When T_1 is on, U_{ph} = U and i_{ph} increases. When T_1 is turned off, i_{ph} circulates through (T_2, D_2) and decreases. When the phase is to be de-energised, both T_1 and T_2 are turned off. Now the phase current flows through diodes D_1 and D_2 and V_{ph}=-U. This causes the phase current to decrease rapidly to zero. The inductive energy is fed back to the DC supply.

An adequate choice of over-modulation frequency allows to establish the steady values of statoric currents during the control period Tc as shown in Figure 6:

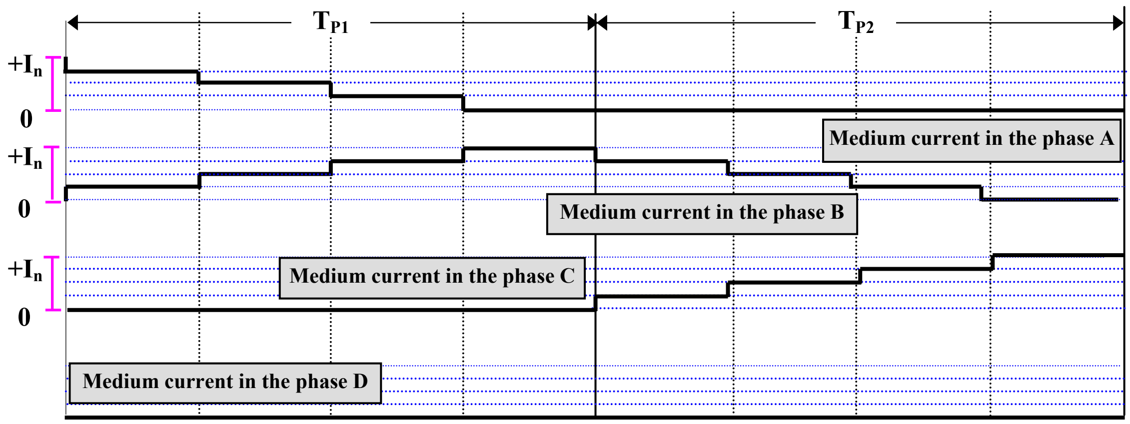


Figure 6. Medium currents in the statoric phases

Being a mechanical filter, the plunger of the considered machine takes its position according to the compensation of the two antagonists thrust forces, obtained by this precisely controlling pulse width of the control signal. Thereby, the evolution of the plunger position will be conduct in very small steps, as shown in Figure 7:

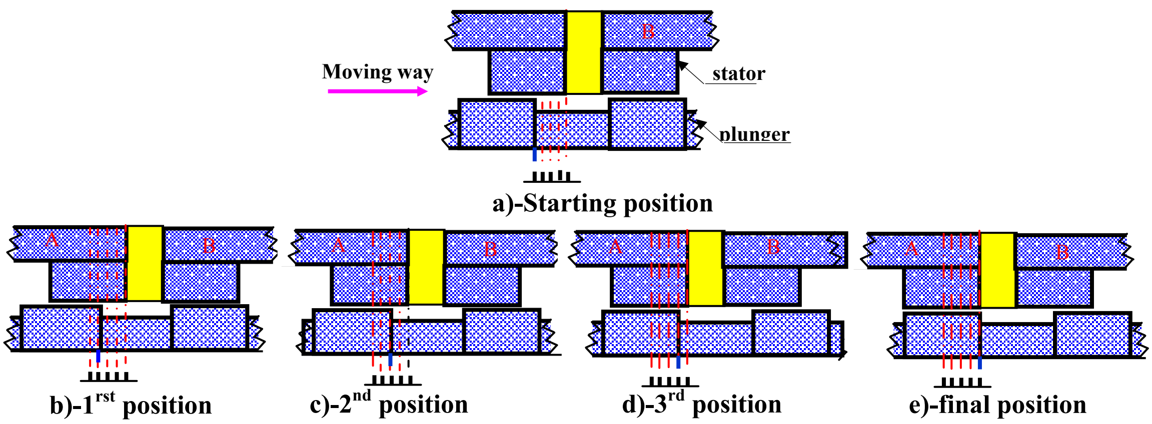


Figure 7. Displacement of the plunger on one mechanic step

2.4. Formulation of the Control Law

The mathematical formulation of the control law of this digital voltage mode control, consists in to formulate some equations defined by interval. Every interval contains two equations. The first one establishes the succession of the necessary periods for the excitation of the pull phase winding. The second one adjusts the excitation of the brake phase winding. Therefore, considering k_1 and k_2, to follow the contents of the periods counters T_c and T_m respectively, whose contents are respectively initiated with one and zero, we can easily deduce the equations describing the control law from the cyclogram of the Figure 4, [13 -15]:

1[rst] step: $0 < t \leq T_p$

Excitation of the phase B

$$((k_1-1)T_C + k_2T_m) < t \leq (k_2T_m + \tau_B T_m + (k_1-1)T_C) \quad (9)$$

$$U_B = U$$

Excitation of the phase A

$$((k_1-1)T_C + k_2T_m) < t \leq (k_2T_m + \tau_A T_m + (k_1-1)T_C) \quad (10)$$

$$U_A = U$$

2[nd] step: $T_p < t \leq 2T_p$

Excitation of the phase C

$$((k_1-1)T_C + k_2T_m + T_p) < t \leq (T_p + k_2T_m + \tau_C T_m + (k_1-1)T_C) \quad (11)$$

$$U_C = U$$

Excitation of the phase B

$$((k_1-1)T_C + k_2T_m + T_p) < t \leq (T_p + k_2T_m + \tau_B T_m + (k_1-1)T_C) \quad (12)$$

$$U_B = U$$

3[rd] step: $2T_p < t \leq 3T_p$

Excitation of the phase D

$$(2T_p + (k_1-1)T_C + k_2T_m + T_p) < t \leq (2T_p + k_2T_m + \tau_D T_m + (k_1-1)T_C) \quad (13)$$

$$U_D = U$$

Excitation of the phase C

$$(2T_p + (k_1-1)T_C + k_2T_m) < t \leq (2T_p + k_2T_m + \tau_C T_m + (k_1-1)T_C) \quad (14)$$

$$U_C = U$$

4[th] step: $3T_p < t \leq 4T_p$

Excitation of the phase A

$$(3T_p + (k_1-1)T_C + k_2T_m) < t \leq (3T_p + k_2T_m + \tau_A T_m + (k_1-1)T_C) \quad (15)$$

$$U_A = U$$

Excitation of the phase D

$$(3T_p + (k_1-1)T_C + k_2T_m) < t \leq (3T_p + k_2T_m + \tau_D T_m + (k_1-1)T_C) \quad (16)$$

$$U_D = U$$

3. Numerical Results and Simulations

In order to demonstrate the efficiency of these proposed digital control, we consider the four phases linear tubular stepping motor which is characterized by the following principal parameters: $m = 1kg$; $L_0 = 225mH$; $L_1 = 50mH$; $R = 18\Omega$; $U = 10V$; $\lambda = 10,16\,mm$.

The numerical simulation results show the relationship of the machine behaviour, between the statoric currents, the speed and the linear displacement of the plunger.

In this sense, Figure 7 illustrates a functioning to two full steps.

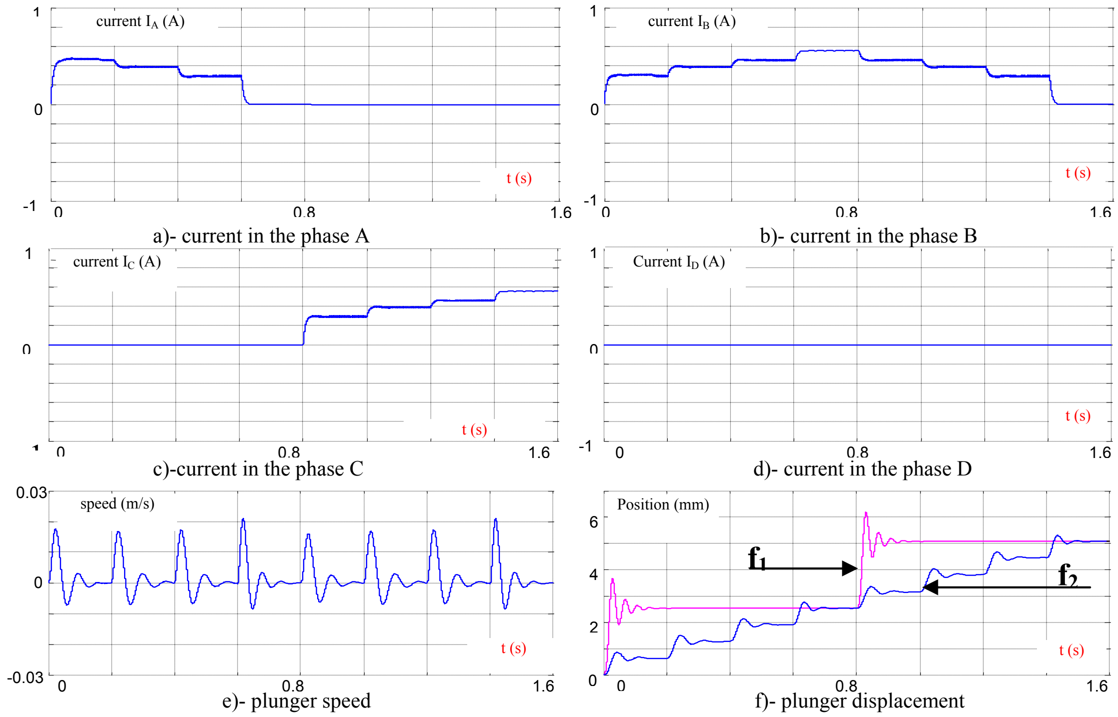


Figure 7. Reduction of the overshoot by segmentation in 4 microsteps/step

The response indicated by (f_1) is relative to the working without control kinetic energy. It shows that the movement of the considered motor is greatly oscillating and characterized by an overshoot equalizing about 30%. The evolution marked by (f_2) shows that a fragmentation in 4 microsteps/step reduced considerably this overshoot.

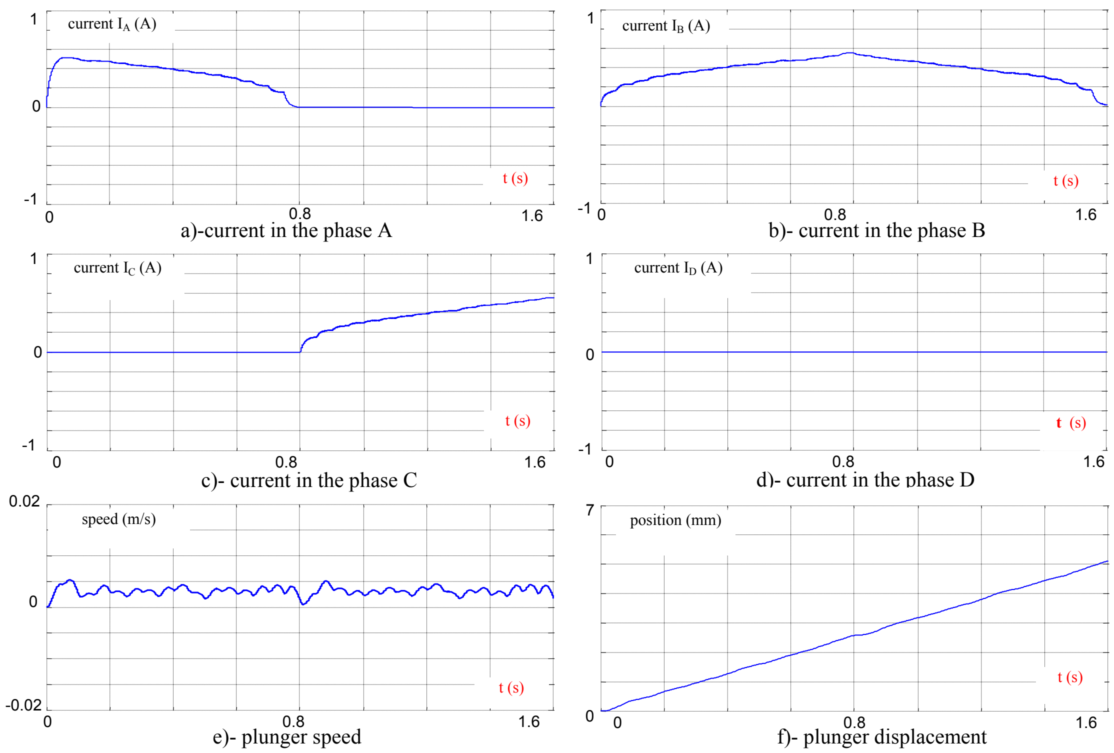


Figure 8. Smoothing of movement obtained by a segmentation in 16 microsteps/step

If the control of the linear tubular stepping motor is structured around of the suggested approach, the quality of its movement improves when the degree of fragmentation increases. In particular, Figure 8 shows a perfectly smooth movement obtained by a fragmentation in 16 microsteps/step.

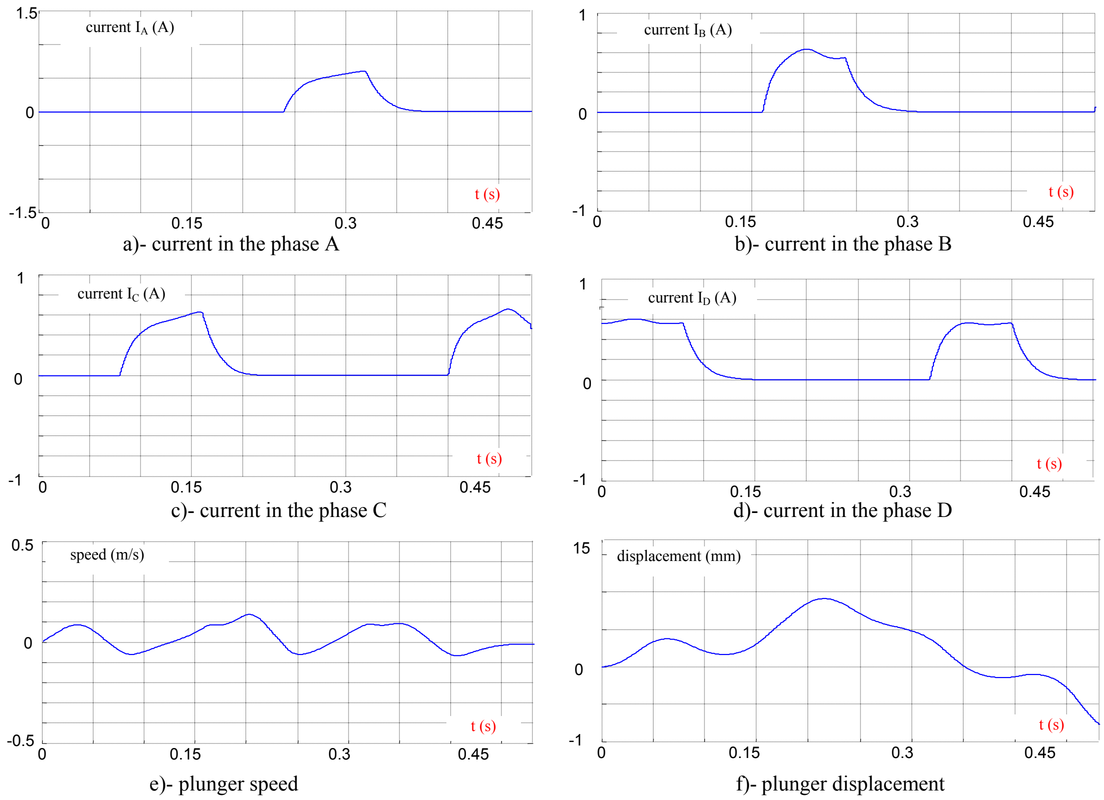


Figure 9. Erratic functioning obtained at 800 steps/min

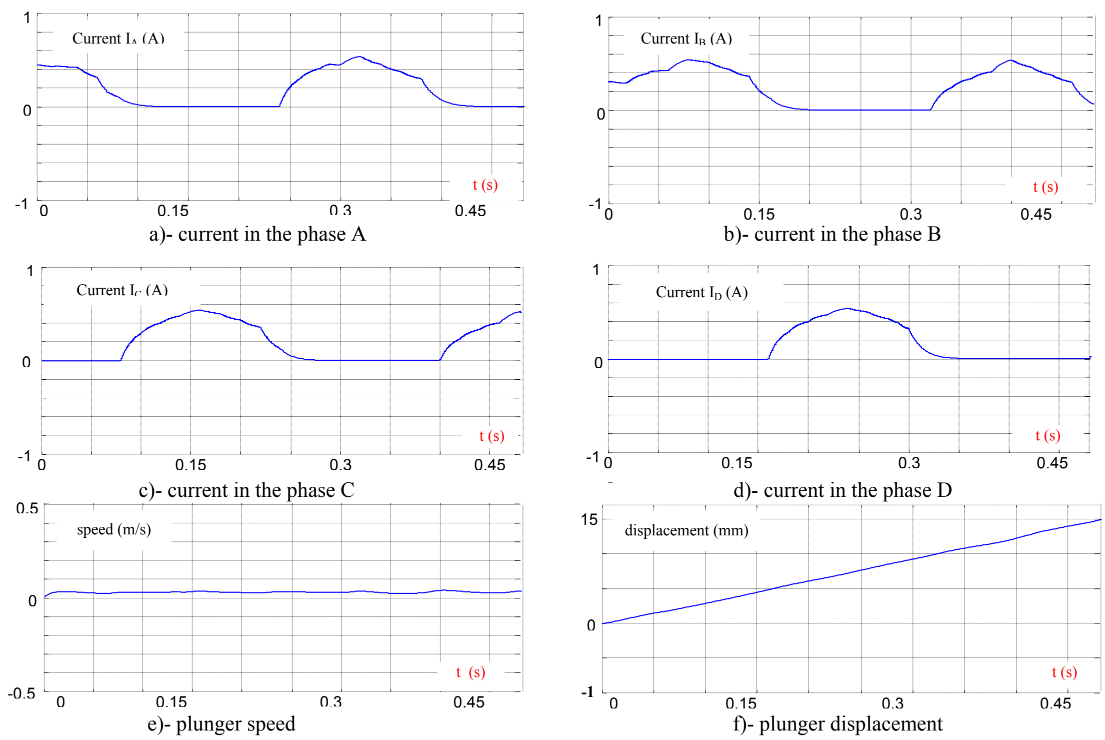


Figure 10. Steady functioning obtained at 800 steps/min with the proposed approach

The numerical simulation, to dynamic functioning of the considered motor under feeding to variable frequency, enabled us to identify the instability domain located at a control frequency equal to 800 steps/minute, Figure 9. For this excitation cadence, the motor starts with a very oscillating movement. Quickly, at the beginning of the third step, the motor is carried in an unexpected functioning mode and its motion becomes out of control.

The simulation results of figure 10 show that the application of the control strategy allows a normal functioning of the considered motor at the same control frequency of 800 steps/minute, a value at which unhooking was possible. In this particular case, a segmentation of the full step in 4 microsteps is extensively sufficient in order to re-establish the normal working for this feeding rhythm.

Nomenclature

UA,…,D,	:	phases voltage
iph= IA,,D	:	phases current
L_0	:	mean inductance term
L_1	:	First harmonic inductance term
L	:	step pitch
R	:	resistance phase
F_r	:	resistant force opposed by the load
F_o	:	friction coefficient
□	:	dynamic viscous coefficient
x	:	position of the moving part
m	:	mass of the moving part
v	:	linear instantaneous speed
T_c	:	control period;
T_m	:	over-modulation period;
T_p	:	step period;

4. Conclusion

In this paper, we have presented a new method of control using a PWM technique. This control approach attenuates the oscillations and eliminate the problems of overshoot and resonance. Hence, this method contribute to the improvement of the dynamic stability of stepper linear motors functioning in lower speed. Also, this method preserves the digital character of all the structure (control-power part-motor), what constitutes a considerable advantage in open-loop control.

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