On two control methods for smoothing the linear tubular switched reluctance stepping motor position

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Abstract This paper presents two control strategies proposed for the elimination of the oscillations of a linear tubular switched reluctance stepping motor. The first technique is the Bang Bang control mode which is an open loop control mode. The second solution is a fuzzy logic controller which has as inputs the back EMF voltages and its variations. So the major advantage of the designed FLC is that it does not use a position sensor which is cumbersome and very expensive.

Keywords Linear stepping motor, Bang Bang controller, Fuzzy Logic Controller (FLC)

1. Introduction

The Linear Tubular Switched Reluctance Stepping Motor (LTSRSM) position evolution presents some oscillations and a long settling time which can disturb some applications that require high positioning precision, figure.1. In addition, the oscillations can induce to an erratic working of the motor, at some control frequencies, [1,2,3].

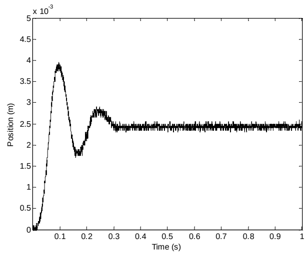


Figure 1: Natural one-step position evolution

There are two kinds of solutions which allow for the elimination of the stepping motor oscillations and which can be classified into mechanical solutions and solutions based on a specific control technique [1,2,3].

The basic principle of the mechanical solution is to introduce additional viscous friction to allow the elimination of the linear stepping motor oscillations. However, this solution gives to the motor some speed and acceleration limitations. Moreover, it reduces the nominal force value of the linear stepping motor.

The solutions based on a control technique are an alternative to such inconvenience. They can be classified into open-loop control mode and closed loop control one. The major advantage of the control solutions is that the latter can be applied to any stepping motor.

The studied LTSRSM is a linear stepping motor, that has a tubular mechanical geometry and four electrically identical phases denoted by A, B, C and D. The linear motor moving element is called forcer or plunger, and the stationary one is called stator. The stator and the plunger are equally teethed, figure.2. The studied motor has 0.2 mm air gap. The elementary step is about 2.54 mm for a total course length of 100 mm [4].

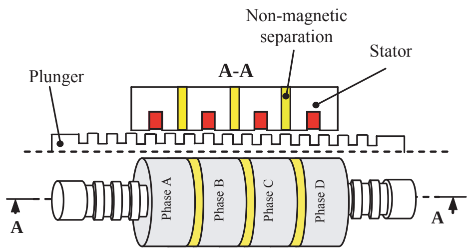


Figure 2: Linear stepping motor structure

In order to smooth the linear motor position evolution, two control approaches are proposed and compared in this paper: a Bang-Bang control technique which is an open loop control mode, and a FLC.

2. The mathematical model of the studied LTSRSM

The switching reluctance stepping motor mathematical model is given by the following system composed by five non linear differential equations:

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

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

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

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

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

using the following notation:

L_0 : phase inductance average

L_1 : phase inductance amplitude
F_m : electromagnetic force
F_0 : dray friction force
F_C : resistant force
v : linear speed
x : plunger position
m : plunger weight
ξ : dynamic viscosity coefficient
R : statoric resistance
U_n : nominal voltage
U_i : voltage applied to phase i=A,B,C and D
i_j : current of the phases j=A,B,C and D
I_n : nominal current

For this model, the proper winding inductances depend on the plunger position, and the mutual inductances are neglected because of the non-magnetic separation between the windings. The machine is also considered non saturated

The studied machine electrical and mechanical parameters are determined by practical tests. They are defined as follow: $m = 5$ Kg ; $\lambda = 10{,}16$ mm ; $\xi = 65$ Nm/s ; F_0=0.1N ; $L_0 = 225$ mH ; $L_1 = 50$ mH ; $R = 18\Omega$; $U_n = 18$ V .

3. Application of the Bang-Bang control technique to the LTSRSM

A stepping motor is a machine designed to be controlled in an open loop mode. The open loop control techniques have the merits of simplicity and consequent low cost. Thus, we propose, as first approach, to apply the Bang-Bang control technique allowing the elimination of the oscillations and the overshoot. It consists of the excitation of two of the motor windings. The first one is used as a pull winding. The second winding is used to break the kinetic energy developed by the pull winding [1].

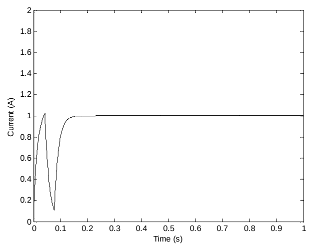
The commutation instants t_1 and t_2 for the case of a linear stepping motor can be approximated by the following expressions:

$$t_1 \approx \left(2 + 2\frac{\lambda F_C}{\pi L_1 I_n^2}\right)\sqrt{\frac{m\lambda^2}{2\pi^2 L_1 I_n^2}} \qquad (6)$$

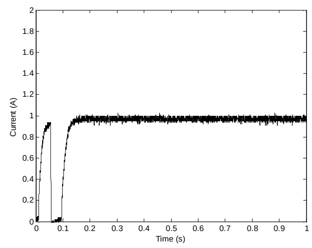
$$t_2 \approx 3\sqrt{\frac{m\lambda^2}{2\pi^2 L_1 I_n^2}} \qquad (7)$$

The Bang-Bang control was applied, in practice and by simulation, to the LTSRSM. The test bench has been built around a control board with a PIC 16F876 microcontroller, a power board with bipolar transistors, the linear stepping motor and a position linear sensor.

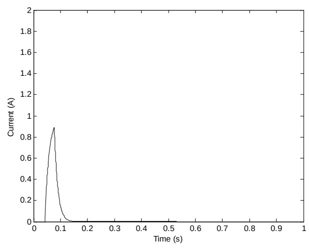
The Figure 3 shows a concordance between the experimental and the simulated results. We can notice also that the Bang-Bang control technique allows the elimination of the LTSRSM oscillations.



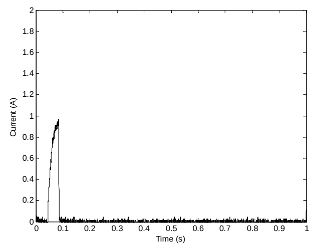
a) Simulated phase B current



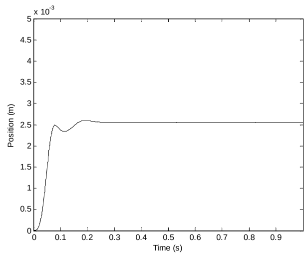
b) Experimental phase A current



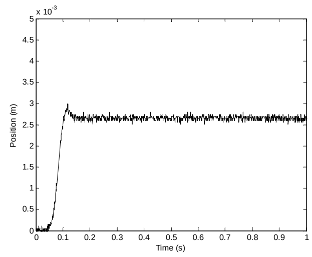
c) Simulated phase A current



d) Experimental phase A current



e) Simulated position



f) Experimental position

Figure 3: Simulated and experimental results obtained by application of the Bang Bang control strategy

The Bang-Bang control technique is a control technique easy to implement. However, the commutations instant between the pull and the breaking winding depend strongly on the motor mechanical and electrical parameters which are very difficult to estimate. As a consequence, the Bang-Bang control is inefficient for a small variation of any motor parameter [5,6].

Thus, we will propose in the next section a closed loop FLC as a robust control solution.

4. Proposed Fuzzy Logic Controller

The major disadvantage of closed loop schema is that some sensors must be used. In our case, the cost of a position sensor is equivalent to the price of the motor. This increases significantly the global cost of the motion control system. To avoid the use of a position sensor one solution is to use the back EMF voltage.

4.1. The back EMF voltage

The back EMF voltages depend on the motor position, speed and current. When the LTSRSM oscillates, the phase (i) EMF voltage U^{i}_{emf} presents also oscillations and it becomes zero when the plunger attends its equilibrium position, figure 4 and figure 5. Thus, the back EMF voltage gives information about the characteristic of the motor position [7].

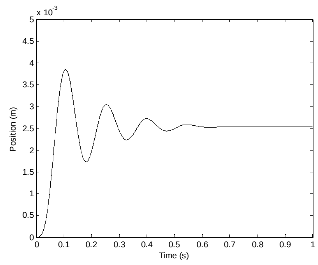


Figure 4: Position evolution

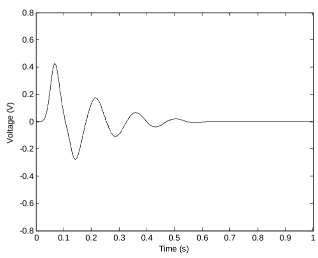


Figure 5: Phase B Back EMF voltage

4.2. Proposed fuzzy logic controller principle

FLC is useful when the operating procedure of the process can be well defined and the expertise well formulated, and is efficient even when the parameters of the system vary [8,9].

In order to smooth the studied linear stepping motor displacement, two successive phases (i) and (i+1) are excited. The phase (i+1), which corresponds to the pull winding (i+1), produces a positive force allowing to pull the plunger to its equilibrium position. However, the phase (i), corresponding to the brake winding, produces a negative force and drags the plunger in the negative direction.

The braking action, resulting from the force developed by the winding (i), allows the smoothing of the step position response by eliminating the oscillations.

The inputs of the proposed FLC are the phase (i+1) back EMF voltage, U_{emf}^{i+1} , and the back EMF voltage change ΔU_{emf}^{i+1} , figure 6.

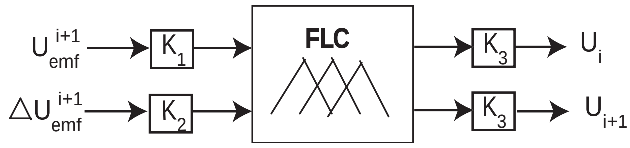


Figure 6: Structure of the proposed FLC

The output signals of the proposed FLC are U_i and U_{i+1} which correspond respectively to the pull and the breaking winding voltages. For each step, the excitation voltages U_{i+1} and U_i are defined in the Table 1.

Table 1: Definition of the pull and the braking winding for each step generation

Step order	1st step	2nd step	3rd step	4th step
Phase (i)	A	B	C	D
Phase (i+1)	B	C	D	A

For the studied motor, are used for the fuzzification procedure, five triangular or trapezoidal membership functions for the error, denoted by NB (Negative Big), NS (Negative Small), Z (Zero), PS (Positive Small), PB (Positive Big), and three ones for the error variation, denoted by N (Negative), Z (Zero) and P (Positive). These functions are normalized to the [-1, 1] interval by the use of the scaling factors k_1 and k_2, figure 7 and figure 8. For the output signals, only normalized singletons are used for the two output signals U_i and U_{i+1}, figure 9.

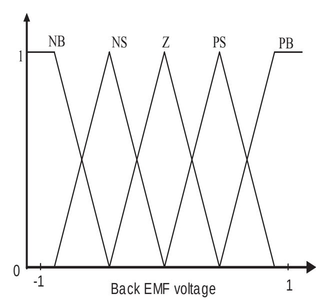


Figure 7: Membership functions of the Back EMF voltage

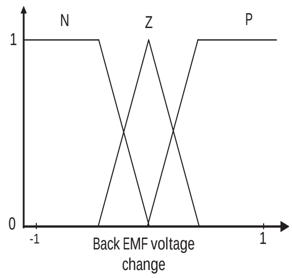


Figure 8: Membership functions of the Back EMF voltage variations

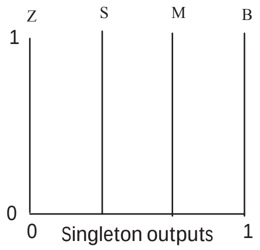


Figure 9: Output singletons

4.3. Simulation results

The simulation results, given by figure 10, show the natural one step position evolution and the position evolution obtained by application of the designed FLC.

We can notice that with the proposed FLC, the settling time is significantly reduced and the overshoot is less than 2%.

Figure 11 represents the single step position responses for two times the plunger weight. Those simulations, performed for natural step evolution and by application of the proposed FLC, show that the overshoot and the oscillations are reduced when the proposed FLC is used. The obtained results confirm the robustness of the proposed FLC.

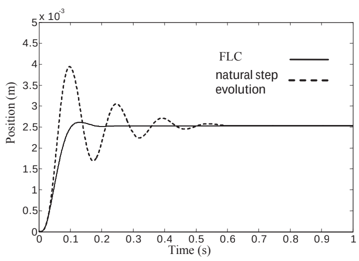


Figure 10: Position evolution by application of the FLC

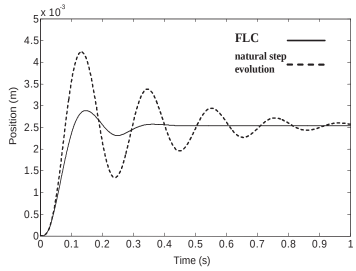


Figure 11: Position evolution by application of the FLC for two times plunger weight

Conclusion

In this paper, two control methods for smoothing the LTSRSM are presented.

A Bang-Bang control strategy is applied in practice and by simulation. The obtained results prove the efficiency of this method. However, this control solution is not robust if the LTSRSM parameters vary.

As a second solution, a FLC is proposed. It uses the motor back EMF voltages as inputs to avoid the use of position sensors which are expensive and cumbersome. The application of this robust controller has improved the dynamic behaviour of the studied motor by eliminating the oscillations even when the system inertia varies.

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