A Comparison of Robustness: Conventional PI and Fuzzy Logic Control for a Linear Induction Motor

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Abstract: In order to increase the robustness of the implemented control relative to a linear induction motor (LIM), two control approaches are developed in this paper. Those approaches, adopted to control the velocity of the mover system, are based on the use of the vector control technique associated successively to analogical PI controllers and fuzzy logic controllers. The implantation of those control techniques is leaded by numeric simulations. The results are furthermore presented and compared.

Keywords: Linear Induction Motor (LIM), analytical model, vector control, analogical controller, fuzzy logic controller, robustness.

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1. Introduction

During the last decades, vector control technique has started to be applied in numerous applications in diverse industrial fields. It can cope with the control issues of linear induction actuator drives. Hence, the thrust force is controlled by the q-axis secondary current provided that the flux is well oriented along the d-axis of the synchronous (d, q) frame. On the other hand, vector control is extremely related to motor parameter and mechanical velocity. The parameter variation causes degradation of performances in a vector- controlled system [1]-[2].

To avoid the weakness of parametric perturbations in several manufacturing systems, fuzzy logic control is currently used. In fact, the fuzzy logic control is naturally nonlinear and adaptive, giving robust performance below parameter variation and load troubles [1]. The advance of fuzzy logic controllers is simple to study and does not require skilled personnel than the advance of conventional controllers. From the time when Fuzzy logic controller is based on uncertainty, it needs less mathematical operations than the analogical controllers. Its implantation does not require a computationally complicated system [1]-[3].

In this paper, to insure a high transient behaviour of the LIM drive and to increase the robustness of the implemented control, the conventional control and fuzzy logic control techniques are successively applied in the control of the velocity of linear induction motor [4-18].

2. Analytical Model

The Analytical model of the LIM is modified from the traditional model of a three-phase rotating induction motor. It can be expressed in the synchronously rotating dq-frame by the following equations [6]:

$$\frac{di_{qs}}{dt} = -\frac{\pi}{\tau} v_e i_{ds} - \left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{qs} - \frac{n_p L_m \pi}{\sigma L_s L_r \tau} v \lambda_{dr} + \frac{L_m}{\sigma L_s L_r T_r} \lambda_{qr} + \frac{1}{\sigma L_s} V_{qs} \tag{1}$$

$$\frac{di_{ds}}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right) i_{ds} + \frac{\pi}{\tau} v_e i_{qs} + \frac{L_m}{\sigma L_s L_r T_r} \lambda_{dr} + \frac{n_p L_m \pi}{\sigma L_s L_r \tau} v \lambda_{qr} + \frac{1}{\sigma L_s} V_{ds} \tag{2}$$

$$\frac{d\lambda_{qr}}{dt} = \frac{L_m}{T_r} i_{qs} - \left(\frac{\pi}{\tau} v_e - n_p \frac{\pi}{\tau} v\right) \lambda_{dr} - \frac{1}{T_r} \lambda_{qr} \tag{3}$$

$$\frac{d\lambda_{dr}}{dt} = \frac{L_m}{T_r} i_{ds} - \frac{1}{T_r} \lambda_{dr} + \left(\frac{\pi}{\tau} v_e - n_p \frac{\pi}{\tau} v\right) \lambda_{qr} \tag{4}$$

$$F_e = k_f (\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}) = M \frac{dv}{dt} + D v + F_L \tag{5}$$

with $k_f = \frac{3 n_p \pi L_m}{2 \tau L_r}$ and $\sigma = 1 - \left(\frac{L_m^2}{L_s L_r}\right)$.

3. The LIM vector control

The oriented field control consists of the orientation of the secondary flux axis along the d-axis, which can be expressed by considering:

$$\lambda_{qr} = 0 \quad \text{and} \quad \frac{d\lambda_{qr}}{dt} = 0 \tag{6}$$

Using equations (3) and (6), we can determine the slip velocity of the motor:

$$v_{sl} = \frac{\tau}{\pi} \frac{L_m}{T_r \lambda_{dr}} i_{qs} \tag{7}$$

Considering constant the d-axis secondary flux and using equations (4), (6) and (7), the slip velocity can be written:

$$v_{sl} = \frac{\tau}{\pi} \frac{1}{T_r i_{ds}} i_{qs} \tag{8}$$

After some mathematical manipulation of the machine equations, the desired total electromagnetic thrust force developed by the motor is obtained:

$$F_e = K_F \, i_{qs} \tag{9}$$

where

$$K_F = \frac{3}{2} n_p \frac{\pi L_m^2}{\tau L_r} i_{ds} \tag{10}$$

From equation (5), we can deduce the transfer function of the mover system as

$$H(s) = \frac{1}{Ms + D} \tag{11}$$

where s is the Laplace operator.

Considering i_{qs} as a first output of the studied system and $(V_{qs}+e_q)$ as a first input, we can obtain from equations (1) and (6) the first transfer function F_q as:

$$F_q = \frac{i_{qs}}{V_{qs} + e_q} = \frac{1}{\sigma L_S s + R_S + L_S \frac{1-\sigma}{T_r}} \tag{12}$$

where:

$$e_q = -\left(\sigma L_S \frac{\pi}{\tau} V_e \frac{1}{L_m} + \frac{n_p L_m \pi}{L_r \tau} v \right) \lambda_{dr} \tag{13}$$

In addition, considering λ_{dr} as a second output of the considered system and as (V_{ds}+e_d) the second input, we can determine in the same way from equations (2) and (6) the second function transfer F_λ as:

$$F_\lambda = \frac{\lambda_{dr}}{V_{ds} + e_d} = \frac{L_m / R_s}{1 + (T_S + T_r)s + \sigma T_S T_r s^2} \tag{14}$$

where:

$$e_d = \sigma L_S \frac{\pi}{\tau} V_e \, i_{qs} \tag{15}$$

The non linear terms e_d and e_q, appeared in the expressions of primary voltages, show that thrust force and the secondary flux are coupled. Those terms are considered as system perturbation voltages that require compensation.

4. Thrust force control for LIM

In order to control the thrust force for a Liner induction motor, the conventional vector control technique is used. The Bloc diagram of the proposed vector control for the considered linear induction motor is given in Figure 1.

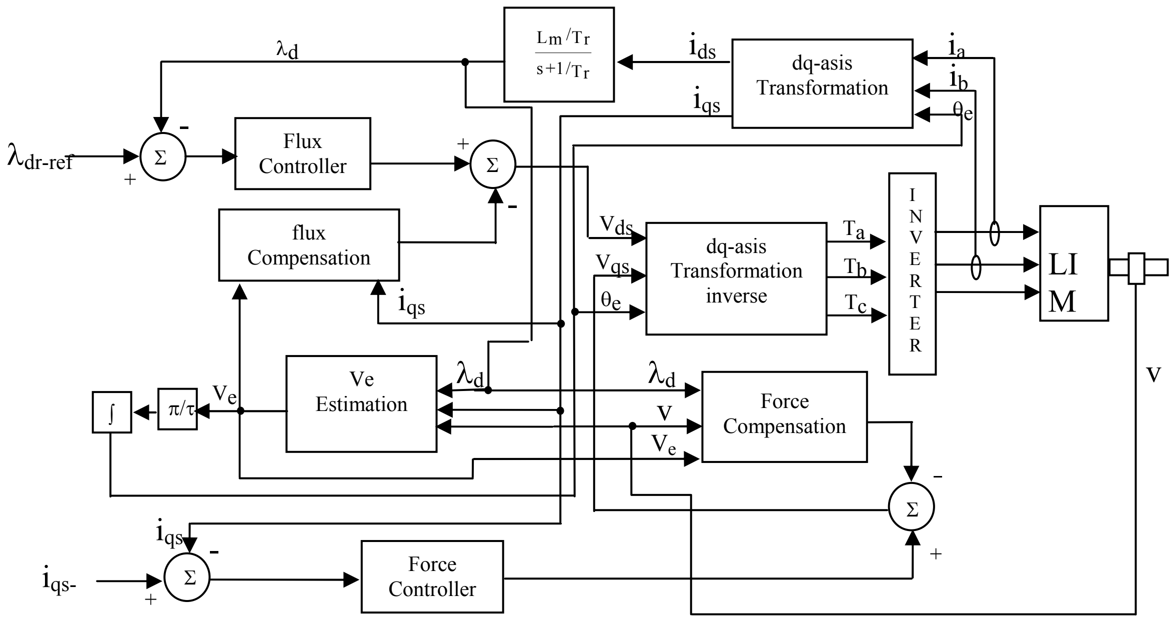


Figure. 1. Bloc diagram of the proposed vector control algorithm

The LIM characteristics used are borrowed from [7]. This motor presents the parameters listed in table I: For the simulation of the LIM vector control, the interface Simulink of the Matlab environment is used. The general diagram of this vector control consists of the LIM dynamic model connected to an indirect field-oriented mechanism constituted by a force loop controller and a secondary d-axis flux loop controller. The inputs of the system are the primary q-axis current reference and the secondary d-axis flux reference but the system outputs are the thrust fore, the velocity, the d-q primary currents and the d-q secondary flux.

The Parameters of studied machine

parameters	Values
Primary resistance per phase Rs	2.5 Ω
Secondary Resistance per phase Rr	1Ω
magnetizing inductance per phase L_m	0.118 H
primary inductance per phase Ls	0.15 H
Secondary inductance per phase Lr	0.1 H
pole pitch τ	0.15 m
d-axis and q-axis primary current i_{ds}	7.88 A
number of pole pairs n_p	1
Force constant K_F	34.48 N/A
total mass of the moving element M	10 Kg
viscous and iron-loss coefficient D	0.1 N.s /m

The non linear terms related to the magnetic coupling between the thrust force and the flux are compensated and only the force and the flux controllers are calculated. An analogical PI controller is chosen to regulate each component.

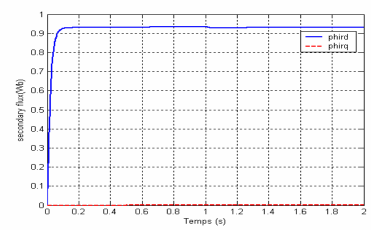
During the simulation, the secondary d-axis reference flux is maintained constant and equal to its nominal value of 0.93 Wb, however the primary q-axis current reference has changed, as follows: between 0 and 0.5 second, the reference is null, from 0.5 to 1 second, the reference is equal to 8.7 A, which is the nominal value of current, and after 1 second, the reference is stationary and equal to 4 A

The machine behaviour for the vector control is illustrated by Figure 2.

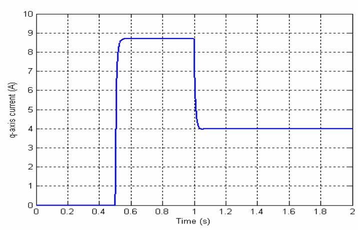
The d-axis secondary flux response is maintained constant and well oriented on its reference and the q-axis secondary flux is constantly null, Figure 2-a. This result confirms the adequate vector control obtained.

Figures 2-b presents the primary q-axis current characteristic. One can observe that the response of current follows effectively the reference's one.

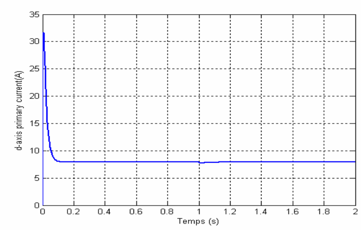
When the vector control is applied by using the secondary d-axis flux and q-axis current references that have been presented before, we note that the thrust force is proportional to the primary q-axis current, Figure 2-f.



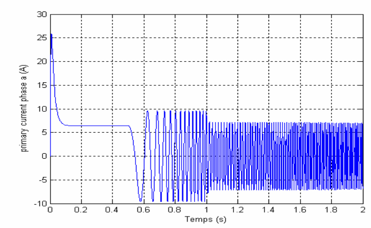
a. Secondary dq-axis flux



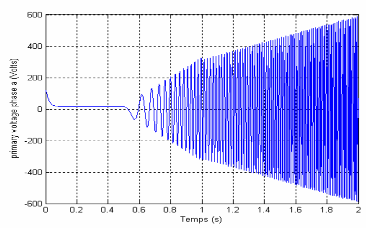
b. Primary q-axis current



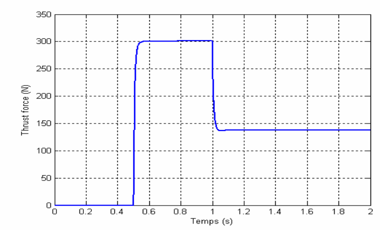
c. Primary d-axis current



d. Primary current phase a



e. Primary voltage phase a



f. Thrust force Fe

Figure 2. Dynamic behavior of the vector control of studied LIM

5. Analogical velocity control for LIM

After controlling the thrust force, we will deal in this section with the regulation of the considered linear induction motor. Considering equation (11), the LIM with its drive system can be rationally represented by the simplified control system block diagram, Figure 3, in which the velocity controller is chosen as an analogical PI controller.

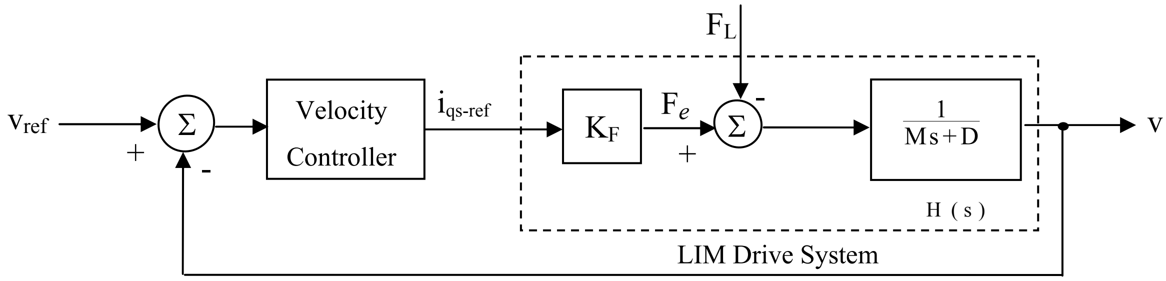
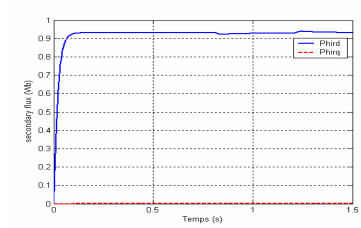


Figure 3. Block diagram of LIM velocity control

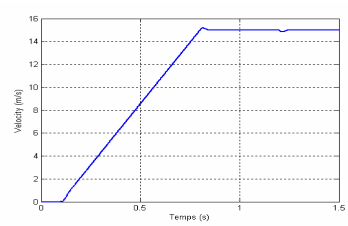
In order to simulate the control velocity of the studied linear induction motor, the interface Simulink is used. The simulation diagram consists of a LIM dynamic model connected to an indirect vector control mechanism which is constituted by a q-axis current loop controller, a velocity loop controller and a secondary d-axis flux loop controller. The inputs of the system are the linear velocity reference and the secondary d-axis flux reference but the outputs of the system are the d-q secondary flux, the d-q primary currents the linear velocity and the thrust fore.

During the simulation, the secondary d-axis reference flux is maintained constant and equal to 0.93 Wb, however the velocity reference has changed as follows: from 0 to 0.1 second, the reference is null, between 0.1 and 0.8 second, we applied a linear velocity ramp command from 0 to the synchronous linear velocity equal to 15 m/s. After 0.8 second, the reference is maintained equal to the synchronous linear velocity

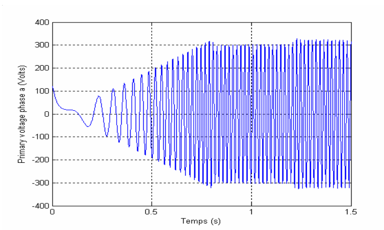
The external force disturbance F_L is maintained null during the [0,1] second interval and at time equal to 1.2 seconds, we apply abruptly an external force equal to 200 N.



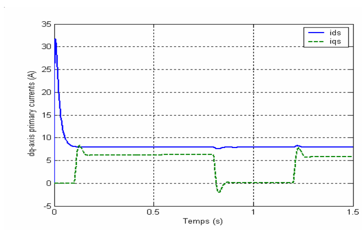
a. Secondary dq-axis flux



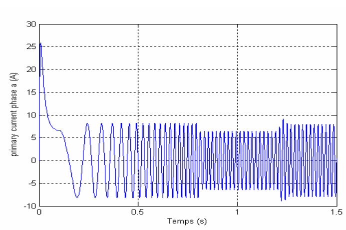
b. LIM Velocity



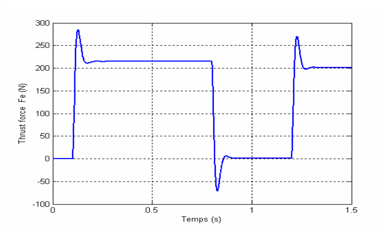
c. Primary voltage phase a



d. d-q axis primary



e. Primary current phase a



f. Thrust force Fe

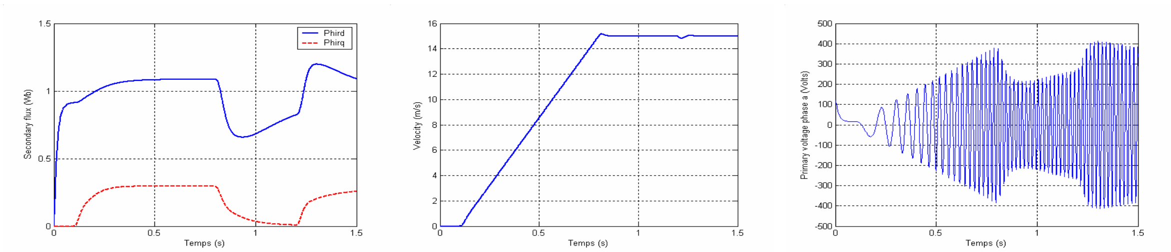
Figure 4. Response of conventional velocity control without secondary and primary resistance variations

The machine behaviour which is commanded according to its sequence of driving is illustrated by Figure 4 for the velocity control without secondary and primary resistance variations, Figure 5, for the same control with 50% secondary resistance variation and Figure 6, for the same control with 50% primary resistance variation.

For the case of velocity control without secondary and primary resistance variations, the d-axis response of the secondary dq-axis flux is well oriented on its reference, Figure 4-a. It reaches its reference after 90 ms and maintains constant. The q-axis secondary flux is constantly null. This result affirms the adequate vector control obtained.

The velocity of the studied LIM is presented in Figure 4-b. One can observe that the response of velocity follows effectively the reference's one. Furthermore, one can note a velocity drop of 1 % when the external force disturbance F_L is applied. The velocity returns to his permanent regime after 50 ms.

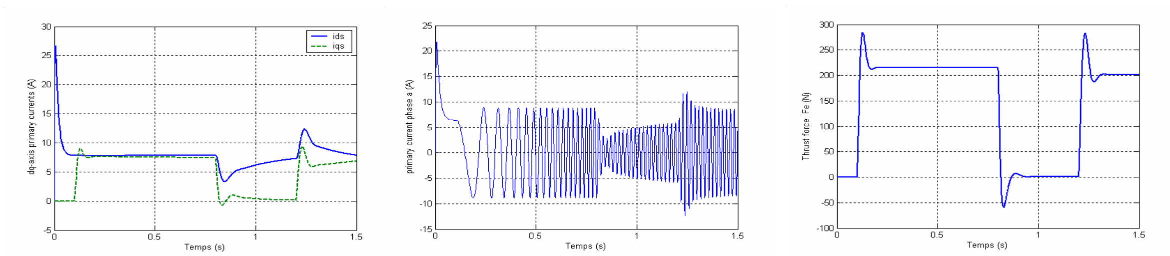
Figure 5.f gives the LIM thrust force characteristic. When the vector control is applied by using the secondary d-axis flux and velocity references that have been presented before, we note that the thrust is proportional to the primary q-axis current, Figure 5-d. In addition, one can note an increase of 33.5 % of the developed thrust when the external force disturbance F_L is applied. The equilibrium between the developed force and the imposed one is reached after 70 ms.



a. Secondary dq-axis flux

b. LIM Velocity

c. Primary voltage phase a



d. d-q axis primary

e. Primary current phase a

f. Thrust force Fe

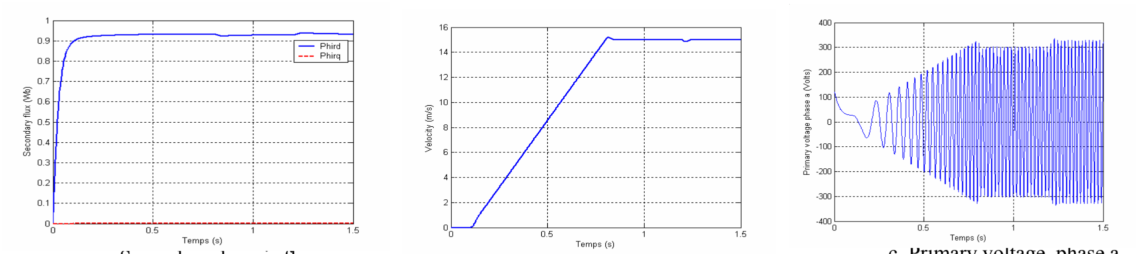
Figure 5. Conventional velocity control for the considered LIM with secondary resistance variation

With secondary resistance variation, the secondary flux response does not hold constant and it is not oriented on its reference, Figure 5-a. This result proves that secondary resistance has a fatal impact on the decoupling.

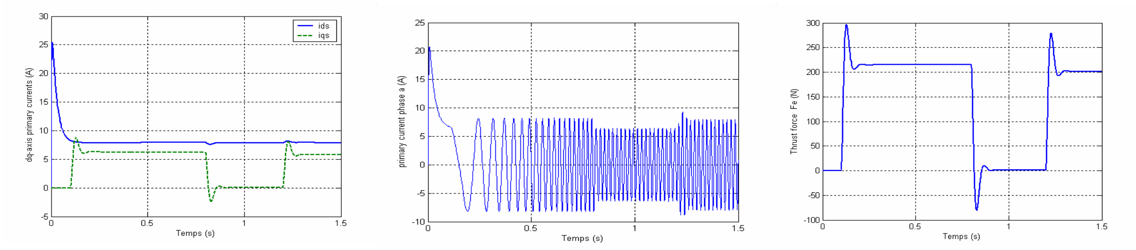
Although the velocity response of the considered machine follows its reference, Figure 5-b, one can note an increase in velocity drop value of 20 % when the external force disturbance F_L is applied. The velocity returns to its study state after 100 ms.

The thrust force graph, Figure 5-f, shows degradation in its evolution due to the bad orientation of the secondary flux. In fact, the thrust force presents an over-load of 40 % of the developed thrust when the external force disturbance F_L is applied. It joins its permanent regime 100 ms later.

Compared with the results obtained without resistance variations, Figure 4, the responses of the system obtained with primary resistance variation appeared similar. The secondary flux is also oriented to its reference, Figure 6-a, and the velocity evolution maintains its dynamic behaviour, 6-b. However, one can note a small increase of thrust force over-loads not exceeding 5%, Figure 6-f. Those results prove that the primary resistance variation hasn't any effect on the robustness of the velocity LIM control.



a. Secondary dq-axis flux b. LIM Velocity c. Primary voltage phase a



d. d-q axis primary current e. Primary current phase a f. Thrust force Fe

Figure 6. Conventional velocity control for the considered LIM with primary resistance variation

6. Fuzzy Logic control technique for ameloration of robustness

To ameliorate performances of the LIM mover system and particularly the control robustness in front of parametric perturbations, the fuzzy logic control technique is used, where the fuzzy logic controllers substitute for the PI analogical controllers of the conventional control.

The proposed technique is to regulate the secondary flux, the thrust force and the velocity of the mover system, according to chosen performances such as the secondary flux has to be constant and maintained equal to its reference. Three fuzzy logic controllers are considered for the control of the studied motor. The fuzzy logic controller design is presented in Figure 7.

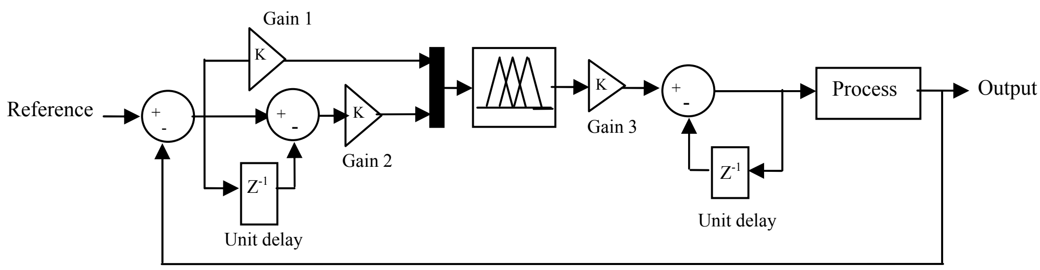


Figure7. Functional graph of the fuzzy logic controller

Each used fuzzy logic controller has two inputs and one output, [8]:

the first input is the error :

$$\varepsilon(k) = (x)_{ref}(k) - x(k-1) \quad (16)$$

and the second input is the error variation :

$$\Delta(\varepsilon) = \varepsilon(k) - \varepsilon(k-1) \quad (17)$$

$$x = \lambda_{dr}, i_{qs}, v.$$

where k is the sampling time.

The designed fuzzy logic controller is a system transferring numerical data in a symbolic form through a data base (fuzzification), [9-11]. Logic of decision-making (rules base) is implemented. Hence, it's possible to give a symbolic answer; which should be converted into a numerical data (defuzzification), [12-14]. The selected method of inference is the Mamdani method, known as the max-min method:

- The minimum of implication: for each rule, the system takes as conclusion the smallest value of premises,

- The maximum of aggregation: the maximum of the minimum is taken for a same output characteristic.

The method of defuzzification is the classical method of centre of gravity.

The two inputs and the output of each fuzzy controller are defined with five membership functions, where NB denoted (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), PB (Positive Big), Figure 8 and according to rules base, table I.

The output is converted on numerical value (defuzzification) and applied on the studied process.

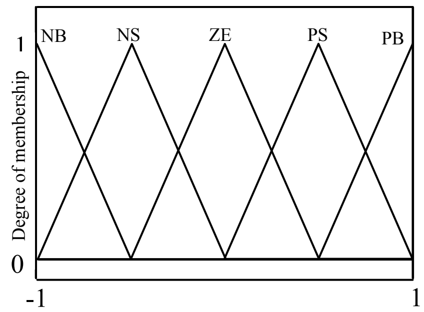


Figure 8. Membership Function plots

TABLE I
RULES BASE

ε \ Δε	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	ZE	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PB	PB	PB

7. Thrust force Fuzzy Logic control

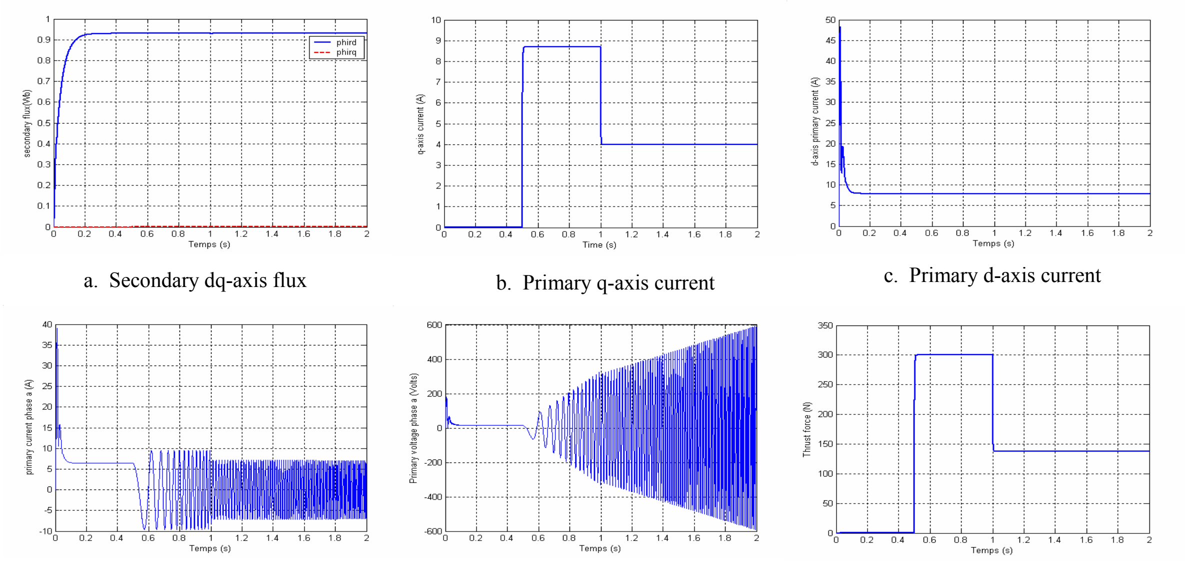
Identically to the previous simulation, the secondary d-axis reference flux is maintained constant and equal to 0.93 Wb, however the primary q-axis current reference has changed, as follows: between 0 and 0.5 second, the reference is null, from 0.5 to 1 second, the reference is equal to 8.7 A, which is the nominal value of current, and after 1 second, the reference is stationary and equal to 4 A. The machine behaviour of the thrust force fuzzy logic control is illustrated by Figure 9.

To show the efficiency of the proposed control, we compared the simulation results obtained with fuzzy logic and analogical PI controllers.

The d-axis secondary flux response is maintained constant and well oriented on its reference and the q-axis secondary flux is constantly null for the two kinds of controller, Figure 2-a and Figure 9-a. This result confirms the adequate vector control obtained.

Figures 2-b and 9-b present the primary q-axis current characteristic. One can observe that the response of current follows effectively the reference's one.

The thrust force response has a better dynamic behaviour with fuzzy logic controllers method than with analogical PI controllers one, Figure 2-c and Figure 9-f.



a. Secondary dq-axis flux

b. Primary q-axis current

c. Primary d-axis current

d. Primary current phase a

e. Primary voltage phase a

f. Thrust force Fe

Figure 9. Dynamic behaviour of the Fuzzy logic control of the considered machine

8. Velocity fuzzy logic control

In order to pass up to limitation of the conventional velocity control for the studied linear induction motor, the fuzzy logic control technique is developed, where the analogical PI controllers are replaced by fuzzy logic controllers.

For the period of the simulation, the secondary d-axis reference flux is also maintained constant and equal to its nominal value of 0.93 Wb, on the other hand the velocity reference has changed as follows: from 0 to 0.1 second, the reference is null, between 0.1 and 0.8 second, we applied a linear velocity ramp command from 0 to the synchronous linear velocity equal to 15 m/s. After 0.8 second, the reference is maintained equal to the synchronous linear velocity.

The external force disturbance F_L is maintained null from zero to one second interval and at time equal to 1.2 seconds, we apply suddenly an external force equal to 200 N.

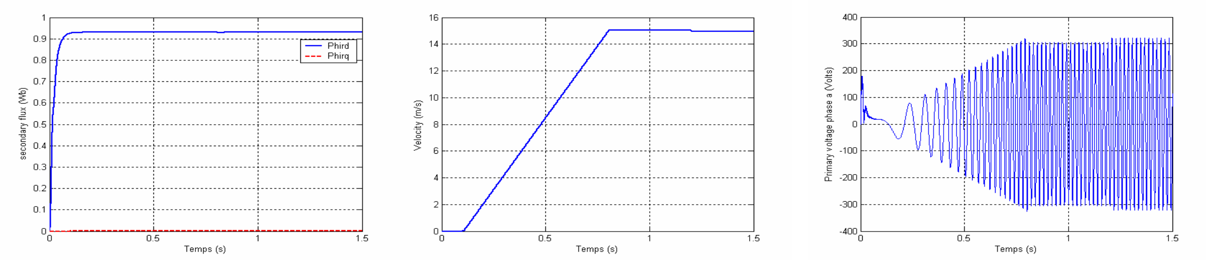
The dynamic behaviour of the system, which is controlled according to its sequence of driving, is given by Figure 10 for the velocity fuzzy logic control without secondary resistance variation, and Figure 11, for the same control with 50% secondary resistance variation.

To illustrate the efficiency of the proposed control, we compared the simulation results obtained with fuzzy logic and analogical PI controllers.

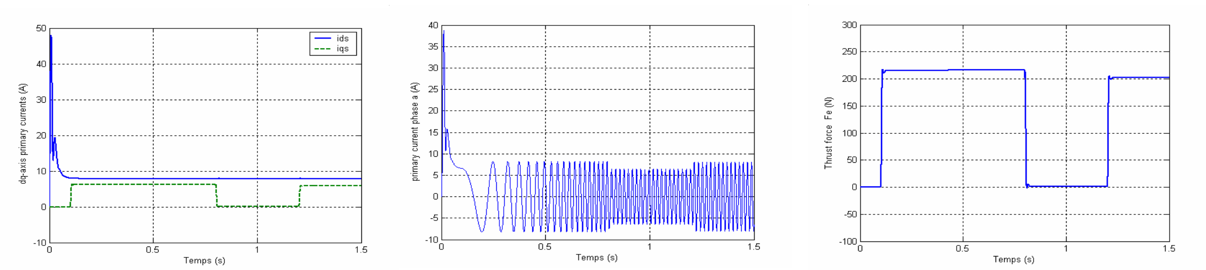
In the case without secondary and primary resistance variations, one can note that for the two kinds of controller, Figure 4-a and Figure 10-a, the d-axis secondary flux is maintained constant and well oriented on its reference. In addition, the q-axis secondary flux is maintained null. So we obtain an adequate vector control.

Using fuzzy logic controllers, the velocity response attains its reference with a good dynamic behaviour and without over-load. This response is insensitive to the external force disturbance applied at t = 1.2 s. Those performances are not satisfied by PI controllers' method, Figure 4-b and Figure 10-b.

The thrust force response with fuzzy logic controllers method has a better dynamic behaviour and less over-load than with PI controllers one as shown in Figure 4-f and Figure 10-f.



a. Secondary dq-axis flux b. LIM Velocity c. Primary voltage phase a

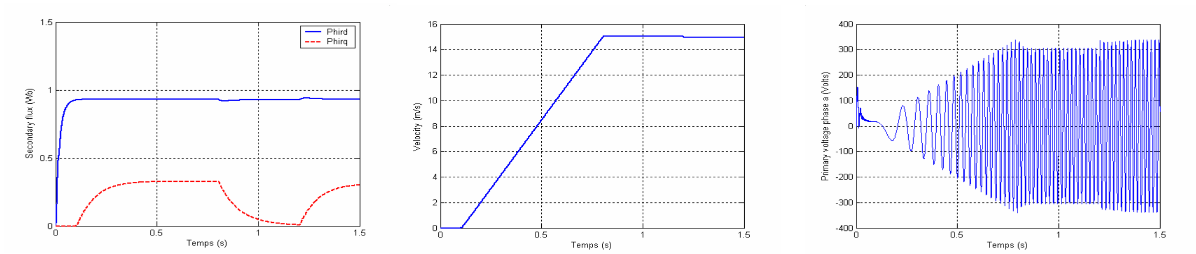


d. d-q axis primary e. Primary current phase a f. Thrust force Fe

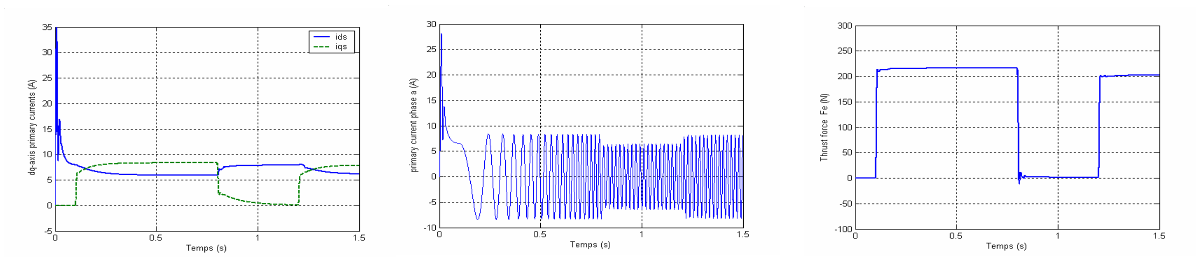
Figure 10. Velocity Fuzzy logic control for the considered LIM without secondary resistance variation

With secondary resistance variation, the secondary flux response does not hold constant and it is not oriented on its reference for the two kinds of controller, Figure 5-a and Figure 11-a.

Figure 11-b gives the velocity evolution of the mover system when the fuzzy logic method is applied with LIM secondary resistance variation. We can deduce that the velocity is practically insensitive to the parametric variation. These dynamics performances are not satisfied with the conventional control method as shown in Figure 5-b.



a. Secondary dq-axis flux b. LIM Velocity c. Primary voltage phase a



d. d-q axis primary e. Primary current phase a f. Thrust force Fe

Figure 11: Velocity Fuzzy logic control for the considered LIM with secondary resistance variation

The primary dq-axis current responses are dynamically better with fuzzy logic controller than when PI controllers' method is applied, Figure 5-d and Figure 11-d.

In spite of the bad orientation of the secondary flux, we note that with fuzzy logic controllers' method, the thrust force response evolution is dynamically better than when the PI controllers' one is used, Figure 5-f and Figure 11-f.

Nomenclature

R_s : primary resistance per phase
R_r : secondary resistance per phase
L_m: magnetizing inductance per phase
L_s : primary inductance per phase
L_r : secondary inductance per phase
T_r : secondary time constant
σ : leakage coefficient
v_e : synchronous linear velocity
v : linear velocity
i_{ds}, i_{qs}: d-axis and q-axis primary current
V_{ds}, V_{qs} : d-axis and q-axis primary voltage
λ_{dr}, λ_{qr} : d-axis and q-axis secondary flux
τ : pole pitch
n_p : number of pole pairs
F_e : total electromagnetic thrust force
F_L : external force disturbance
k_f : force constant
M : total mass of the moving element
D : viscous and iron-loss coefficient

9. Conclusion

In order to ameliorate the robustness of the implanted control for a linear induction motor, two control approaches are developed in this paper. Those approaches, adopted to control the velocity of the mover system, are based on the use of the oriented flux control technique associated successively to analogical PI controllers and fuzzy logic controllers.

The simulation results of thrust and velocity control have shown that the fuzzy logic controllers' technique led to better performances in both study state and dynamical behaviour of the considered system.

Furthermore, considering the parametric perturbations of motor system due to the saturation and the temperature variation, we tested the performances of the mover system with secondary resistance variation for the two kinds of controllers. In the case of analogical PI controller's method, those performances are reduced; in fact, the controller's parameters are related to the motor ones. However, with the fuzzy logic controllers, the obtained simulation results are better than those obtained with the analogical PI controllers and confer to this type of control certain robustness.

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