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Direct Torque Control of Induction Motor Based on Space Vector Modulation Using a Fuzzy Logic Speed Controller

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Abstract

In the present paper, the proposed direct torque control using space vector modulation is based on a fuzzy logic technique to replace proportional integral regulator PI anti-windup of the speed of induction motor. In order to reduce torque, flux ripples and gets a swifter response velocity in comparison with the conventional DTC based on SVM. The MATLAB SIMULINK programming environment is used as a simulation tool. The results obtained show the importance of this control method.

Keywords: *Induction Motor IM, Direct Torque Control DTC, Space Vector Modulation SVM Proportional Integral PI, Fuzzy Logic Controller FLC*

Nomenclature

DTC: Direct torque control.
SVM: Space vector modulation.
PI: Proportional integral.
FLC: Fuzzy logic controller.
FDTC: Fuzzy direct torque control
IM: Induction motor.

1. Introduction

High dynamic performance of induction motor drives is indispensable in many applications of today’s automatically controlled machines. Induction motor control has attracted much attention recently in the power electronics field. Vector control based in rotor flux orientation presents a major disadvantage to be relatively sensible to the machine parameters variation. For such reasons, the direct torque control (DTC) methods of the induction machines have been developed during the nineties [1]. The basic concept is to control both stator flux and electromagnetic torque of the machine simultaneously. Its simple structure is due to the use of two hysteresis comparators and switching vector tables for both flux and torque control. The hysteresis controller is usually a two-value bang-bang controller, which results in taking the same action for the big torque error and small torque error [2]. Thus, it may produce a big torque ripple. To overcome the above problems, a few researchers have so far presented the DTC scheme using the space vector modulation (SVM) techniques.

To control the speed of an induction motor driven by the DTC-SVM. The Proportional-Integral controller is always the preferred choice. This is because the implementation of the PI controller requires minimal information about the motor, where the controller gains are tuned until a satisfactory response is obtained [3].

As the induction motor is naturally a non-linear system and is subject to parameter variations, external disturbances, and non-linear loads, PI controller may not give a satisfactory performance when subjected to these conditions as shown by [4].

Nowadays, fuzzy logic is considered an interesting alternative approach for its advantages: analysis close to that of man-operator, ability of nonlinear systems control, best dynamic performances and the inherent quality of robustness.

The objective of this paper is, first, to solve the problems of torque ripple and inconstant switch frequency of inverter in the conventional direct torque control, a new DTC-SVM method for a speed control of AC motor drive is proposed. Second, to control the speed of AC motor driven by DTC-SVM using fuzzy controller in order to improve the speed of the response, small overshooting and fine precision in high and low speed.

2. Principle

Using the vectorial expressions, the machine in the reference frame binds to the stator is defined by:

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$$\begin{cases} \overline{V}s = Rs\overline{I}_s = \dfrac{d\overline{\Phi}_s}{dt} \\ \overline{V}_r = 0 = Rr\overline{I}r + \dfrac{d\overline{\Phi}_r}{dt} - j\omega\overline{\Phi}_r \end{cases} \quad (1)$$

From the flux expressions, the rotor current can be written:

$$\overline{I}_r = \frac{1}{\sigma}\left(\frac{\overline{\Phi}_r}{L_r} - \frac{L_m}{L_r L_s}\overline{\Phi}_s\right) \quad (2)$$

With: $\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$ (variability (scatter) factor)

The equations become:

$$\begin{cases} \overline{V}_s = Rs\overline{I}s + \dfrac{d\overline{\Phi}_s}{dt} \\ \dfrac{d\overline{\Phi}_r}{dt} + \left(\dfrac{1}{\sigma\tau_r} - j\omega\right)\overline{\Phi}_r = \dfrac{L_m}{L_s}\dfrac{1}{\sigma\tau_r}\overline{\Phi}_s \end{cases} \quad (3)$$

These relations show that:

- It can possibly control the $\overline{\Phi}_s$ vector starting from the $\overline{V}_s$ vector, with the voltage drop $R_s\overline{I}_s$
- The flux $\overline{\Phi}_r$ follows the variation of $\overline{\Phi}_s$ with time constant $\sigma\tau_r$.
- The electromagnetic torque is proportional to the vectorial product of the stator and rotor flux vectors.

$$\Gamma_{elm} = p\frac{L_m}{\sigma L_s L_r}\Phi_s\Phi_r \sin\gamma \quad (4)$$

With : $\gamma = (\overline{\Phi}_s \overline{\Phi}_r)$

- Thus the torque depends on the amplitude and the relative position of the two vectors $\overline{\Phi}_s$ and $\overline{\Phi}_r$.
- If we manage to perfectly control the flux $\overline{\Phi}_s$ (starting from $\overline{V}_s$) in module and position, we can thus control the amplitude and the relative position of $\overline{\Phi}_s$ and $\overline{\Phi}_r$, consequently the torque. This can be possible only when the control period T_e of the voltage V_s is such as $T_e << \sigma\tau_r$ With: $\sigma = 1 - \dfrac{M^2}{L_s L_r}$: The coefficient of dispersion [5].

3. Fuzzy Direct Torque Control Based on Space Vector Modulation FDTC SVM

The structure of the DTC space vector modulation with fuzzy controller speed is as shown in figure 1 :

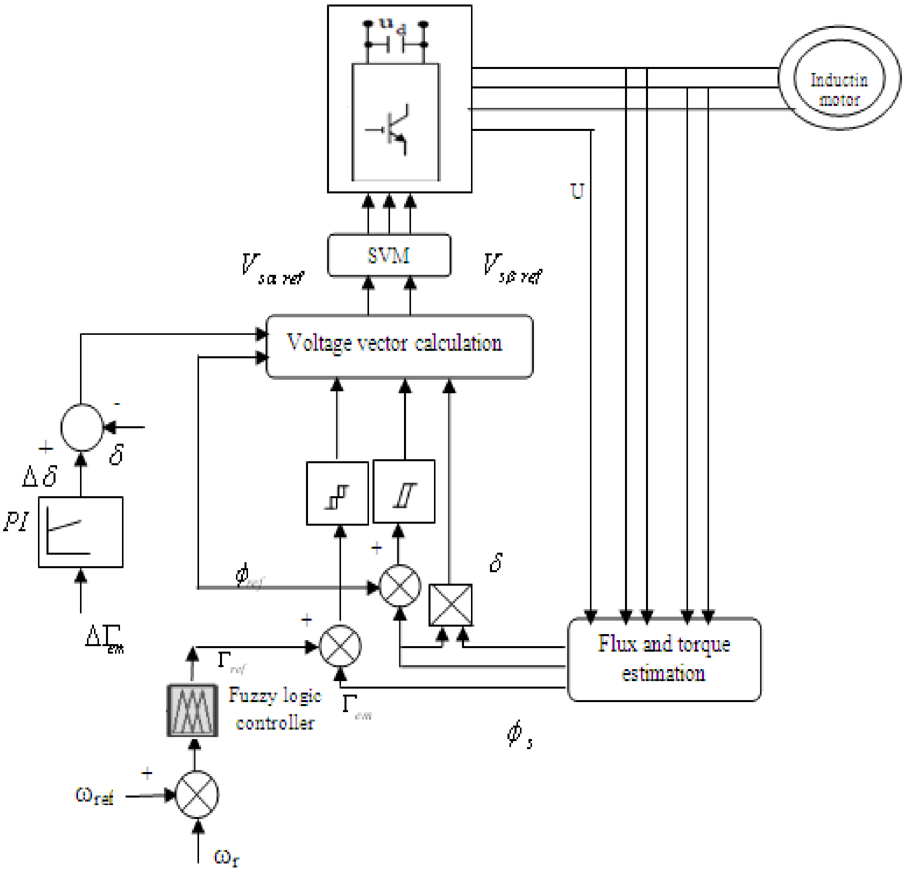


Figure 1. The block scheme DTC space vector modulation with fuzzy controller speed

In the DTC system, the same active voltage vectors are applied during the whole sample period, and possibly several consecutive samples give rise to relatively high ripple levels in stator current, flux linkage and torque. One of the proposals to minimise these problems is to introduce Space Vector Modulation (SVM), which is a pulse width modulation technique that is capable of synthesising any voltage vector lying inside the sextant spanned by the six PWM voltage vectors.

In this method, DTC–SVM has proved to generate very low torque and flux ripples while showing almost as good dynamic performance as the DTC system. The DTC-SVM systems, though being a good performer, do introduce extra complexity [6].

The fluctuation of the IM torque has a closed relationship to the deviation from an ideal rotation stator flux vector Φ_{sref} which has a constant rotational speed and a constant length. The difference between Φ_{sref} and Φ_s, which is generated in a three-phase PWM inverter, causes torque pulsation. The relationship between torque pulsation $\Delta\Gamma_e$ and the deviation of Φ_s from Φ_{sref} has been deduced as:

$$\frac{\Delta\Gamma_e}{\Gamma_{e\,ref}} = k_s \frac{|\Delta\Phi_s|}{|\Phi_{s\,ref}|} + k_\delta \Delta\delta \quad (5)$$

Where Γe ref is the steady state torque $\Delta\Phi s$ and $\Delta\delta$ are respectively the deviations from $|\Delta\Phi_s|$ and δ which are defined by:

$$\Delta\Phi_s = |\Phi_{s\,ref}| - |\Phi_s| \quad (6)$$

$$\Delta\delta = \angle\Phi_{sref} - \angle\Phi_s$$

Where k_δ and k_s are the constants derived from the IM specifications.

The torque ripple is actually caused by $\Delta\Phi s$ and $\Delta\delta$ and the influence of the $\Delta\Phi s$ is considerably smaller than that of $\Delta\delta$. As a consequence, the torque ripple can be almost removed if $\Delta\delta$ is kept close to zero.

In Figure1, one can notice that the torque error $\Delta\Gamma e$ and the reference stator flux amplitude $|\Phi_{sref}|$ are delivered to voltage vector calculation, which, in its input, gives the deviation of reference stator flux angle.

From the α, β axes components of the stator reference voltage $V_{s\,ref}$, are calculated as:

$$V_{s\alpha\,ref} = \frac{\Phi_{s\,ref}\cos(\delta+\Delta\delta) - \Phi_{s\,ref}\cos(\delta)}{T_s} + R_s I_{s\alpha} \quad (7)$$

$$V_{s\beta\,ref} = \frac{\Phi_{s\,ref}\sin(\delta+\Delta\delta) - \Phi_{s\,ref}\sin(\delta)}{T_s} + R_s I_{s\beta} \quad (8)$$

Where the vector magnitude and angle are given as,

$$V_{s\,ref} = \sqrt{V_{s\alpha\,ref}^{\;2} + V_{s\beta\,ref}^{\;2}} \quad (9)$$

$$\delta = \arctan\left(\frac{V_{s\beta\,ref}}{V_{s\alpha\,ref}}\right) \quad (10)$$

Where, T_s is the sample time of system.

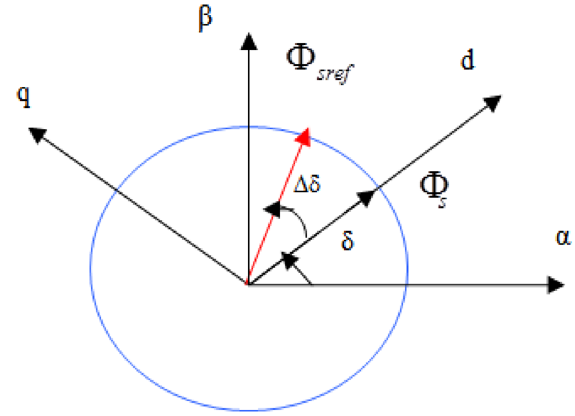


Figure 2. Representation of stator flux vectors Φ_s and $\Phi_{s\,ref}$

The voltage vectors, produced by a 3-phase inverter, divide the space vector plane into six sectors as shown in Figure3. In every sector, the arbitrary voltage vector is synthesised by a basic space voltage vector of the two sides of the sector and the one zero vector. For example, in the first sector, V_s is synthesised by the voltage space vector equations (10) and (11),

$$\overline{V}_{sref}\, T_s = \overline{V}_0 T_0 + \overline{V}_1 T_1 + V_2 T_2 \quad (11)$$

$$T_s = T_0 + T_1 + T_2 \quad (12)$$

Where, T_s is the sample time of system, T_0, T_1 and T_2 are the work times of the basic space voltage vector V_0, V_1 and V_2, respectively (Figure 4); with T_1 and T_2 are given by simple projections:

$$\begin{cases} T_1 = \dfrac{T_S}{2E}\left(\sqrt{6}\, V_{s\beta\,ref} - \sqrt{2}\, V_{s\alpha\,ref}\right) \\ T_2 = \sqrt{2}\,\dfrac{T_S}{E} V_{s\beta\,ref} \end{cases} \quad (13)$$

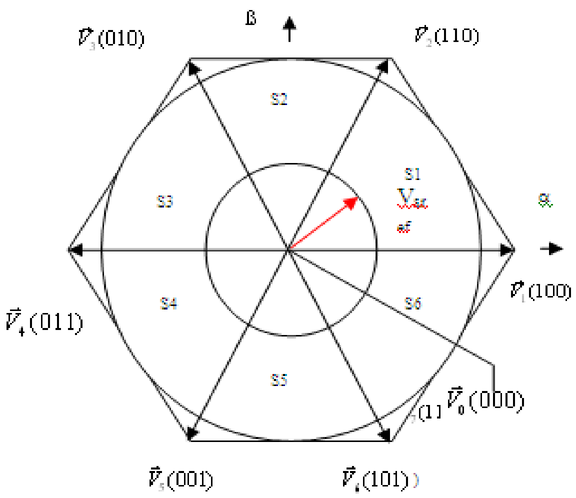


Figure 3. Diagram of the inverter exported voltage space vector

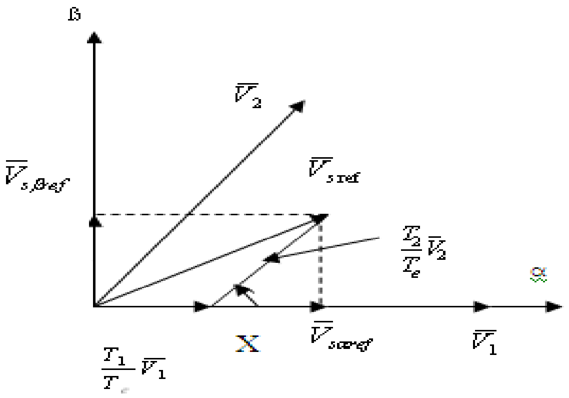


Figure 4. Projection of the reference voltage vector

The rest of the period is spent in applying the null-vector. For every sector, the commutation period is calculated. The amount of the times of vector application can all be related to the following variables: [7].

$$\begin{cases} X = \dfrac{T_S}{E}\sqrt{2}V_{s\beta\,\mathrm{ref}} \\ Y = \dfrac{T_s}{E}\left(\dfrac{\sqrt{2}}{2}V_{s\beta\,\mathrm{ref}} + \dfrac{\sqrt{6}}{2}V_{s\alpha\,\mathrm{ref}}\right) \\ Z = \dfrac{T_s}{E}\left(\dfrac{\sqrt{2}}{2}V_{s\beta\,\mathrm{ref}} - \dfrac{\sqrt{6}}{2}V_{s\alpha\,\mathrm{ref}}\right) \end{cases} \quad (14)$$

Table 1 . Applications durations of the sectors boundary

Sectors	T1	T2
1	Z	Y
2	Y	-X
3	-Z	X
4	-X	Z
5	X	-Y
6	-Y	-Z

The third step is to compute the three necessary duty cycles as:

$$\begin{cases} T_{aon} = \dfrac{T_S - T_1 - T_2}{2} \\ T_{bon} = T_{aon} + T_1 \\ T_{con} = T_{bon} + T_2 \end{cases} \quad (15)$$

The last step is to assign the right duty cycle (T_{xon}) to the right motor phase according to the sector.

Table 2. Assigned duty cycle to the PWM outputs

Sector	1	2	3	4	5	6
Sa	Tbon	Taon	Taon	Tcon	Tbon	Tcon
Sb	Taon	Tcon	Tbon	Tbon	Tcon	Taon
Sc	Tcon	Tbon	Tcon	Taon	Taon	Tbon

4. Fuzzy Logic Speed Controller

In the objective to cancel the static error and to reduce the time response while preserving the system stability, the proportional integral corrector PI used is replaced with a fuzzy logic controller.

4.1. Fuzzy Logic Controller

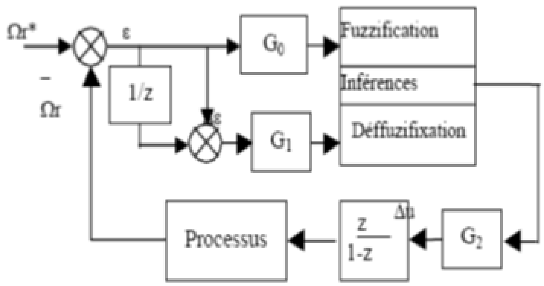


Figure 5. Fuzzy logic controller topology

The block diagram of the loop is made up mainly of the process to control, fuzzification blocks, inference and defuzzification where we define the membership functions of ε, Δε, and Δu for the first, fuzzy rules and their deduction for the second and the conversion of fuzzy variable into deterministic value for the third, of standardization factors (G0, G1 and G2), respectively associated at the input $\varepsilon = \omega_{ref} - \omega_r$, also its variation Δε and the control variation Δu [8].

4.2. Fuzzification

It rests on a positioning of the fields of possibilities in fuzzy subsets. For our case, the regulator has two inputs ε, Δε and for the fuzzified outputs Δu as follow: for ε et Δu, we have seven linguistic terms (NS,NM,NB,EZ,PS,PM,PB) and for Δε only three which are (N,EZ,P), each one of them is defined by a membership function of the triangular type according to Figures 6 and 7.

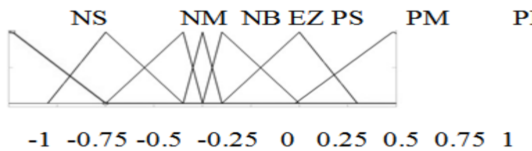


Figure 6. Fuzzy subset ε and Δu

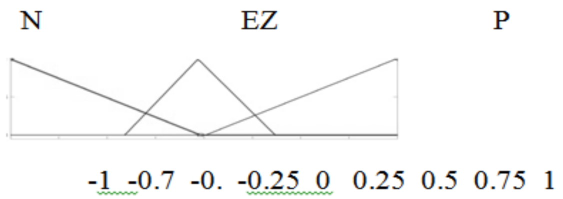


Figure 7. Fuzzy subset Δε

4.3. Rules

The set of rules is described according to the decision table of Mac Vicar [9] with the format If-Thus under the fuzzy rules table with two inputs variables according to:

Table 3. Decision table Mac Vicar

ε / Δu Δε	NB	NM	NS	EZ	PS	PM	PB
N	NM	NS	EZ	PS	PM	PB	PB
EZ	NB	NM	NS	EZ	PS	PM	PB
P	NB	NB	NM	NS	EZ	PS	PM

4.4. Interfacing

The choice of the inference method depends upon the static and dynamic behavior of the system to regulate, the control unit, and, especially, on the advantages of adjustment taken into account.

We have adopted the inference method Max-Min because it has the advantage of being easy to implement on the one hand and gives better results on the other hand [9].

4.5. Defuzzification

The most used defuzzification method is that of the center of attraction of balanced heights, our choice is based on the latter owing to the fact that it is easy to implement and does not require much calculation [10].

5. Simulations Results

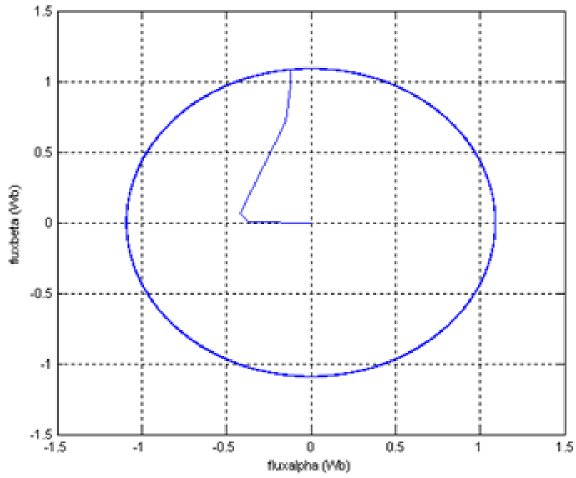
In order to illustrate the improvements that offer a fuzzy regulator with regards to a classic PI for the static and dynamic performances of the control of the asynchronous machine with DTC using space vector modulation, we led a study of simulation with the same test conditions such as the three transitory modes: a no load starting, an introduction of a load torque and the inversion of the direction of speed rotation, and to test the control robustness with respect to the parametric variations.

5.1. Introduction of Load Torque

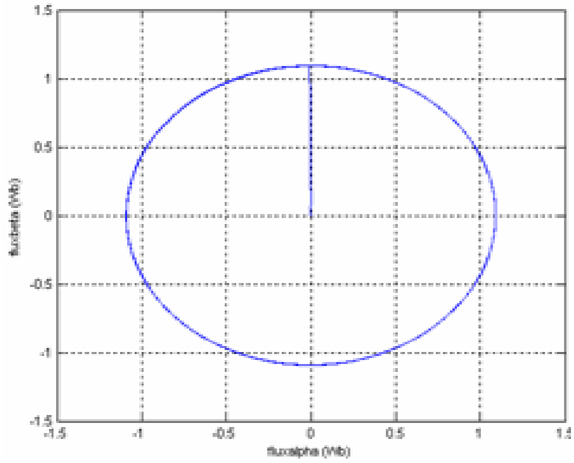
To test the adjustment robustness of the induction machine with fuzzy logic controller, we have introduced a load torque of 25N.m at t=0.5s ; to examine this test further, we used a step of instruction of 25N.m at t=0.5s, see Figure 8. It is noted that the speed reaches its reference ω_{ref} = 100rad/s without going beyond and that the disturbance rejections due to the applied instructions of loads at the various above mentioned moments are eliminated in contrast to those observed during the adjustment by classic PI, see Figure 7. It is also noted that the regulation effect always persists; indeed the electromagnetic torque acts very quickly to follow the instructions of the introduced loads and presents a remarkable reduction in the harmonics.

5.2. Inversion of Speed Direction of Rotation

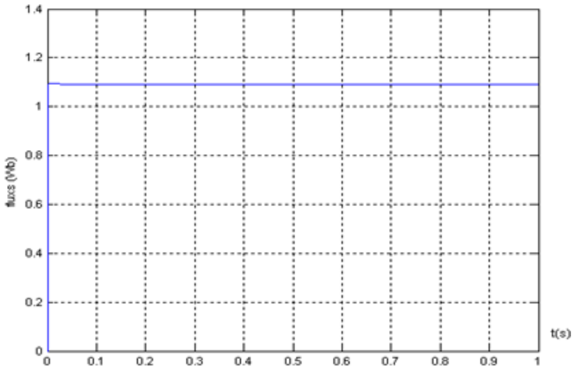
Figure 8 clearly illustrates the robustness of the fuzzy regulator, particularly the speed response with regards to a significant inversion of its reference from 100 rad/s to -100 rad/s. and for low speed for 20 rad/s to -20 rad/s, it is clearly noted that the speed is established without going beyond and converges quickly to its reference. However, the electromagnetic torque marks a peak at starting and another reverse at the change of the speed direction of the rotation, but the braking time at starting, in the reverse direction, is relatively shorter than that obtained by a classic PI .



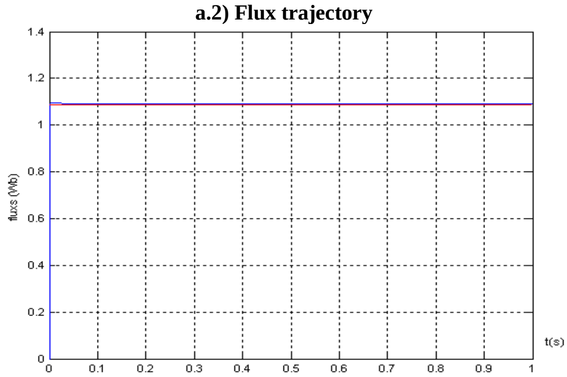
a.1) Flux trajectory



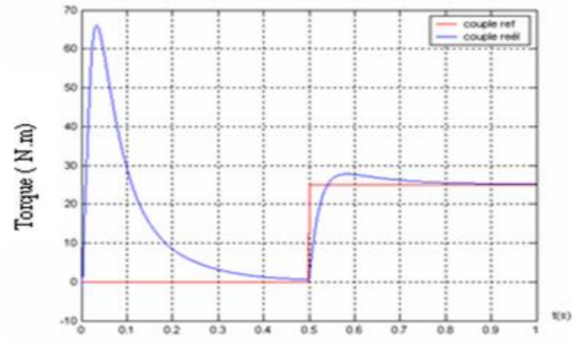
a.2) Flux trajectory



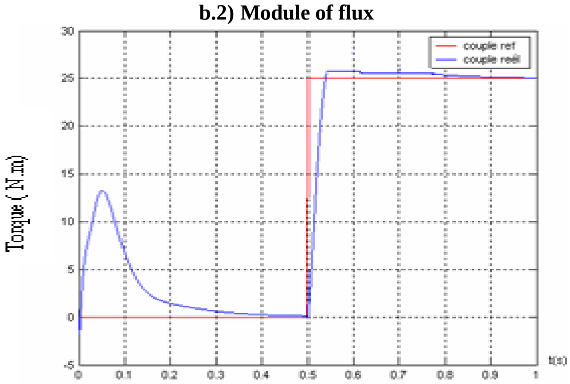
b.1) Module of flux



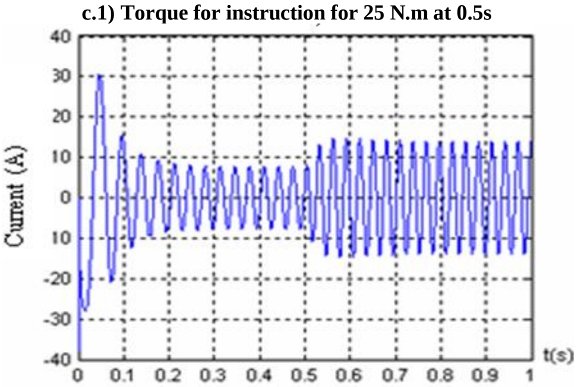
b.2) Module of flux



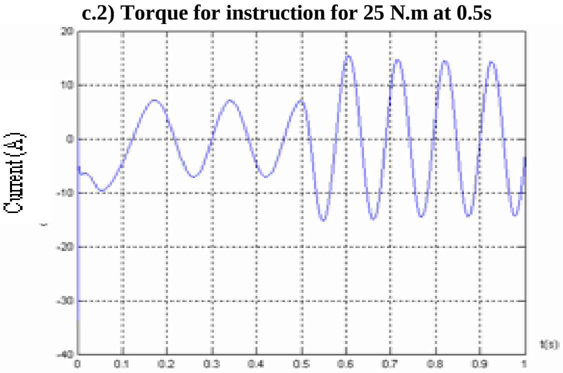
c.1) Torque for instruction for 25 N.m at 0.5s



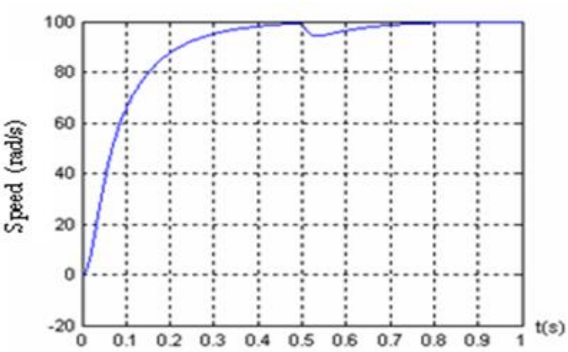
c.2) Torque for instruction for 25 N.m at 0.5s



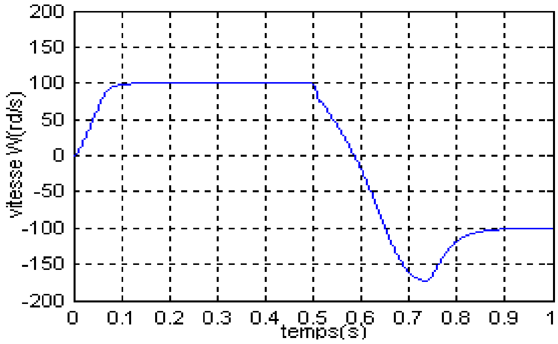
d.1) Current



d.2) Current

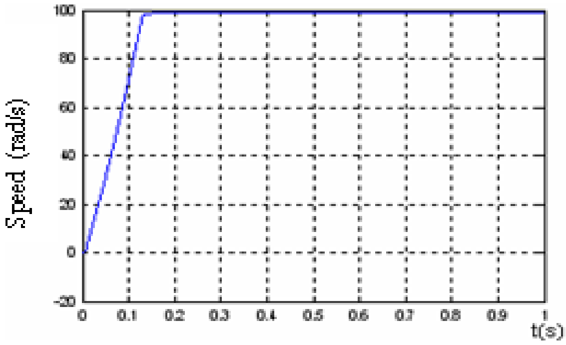


e.1) Speed

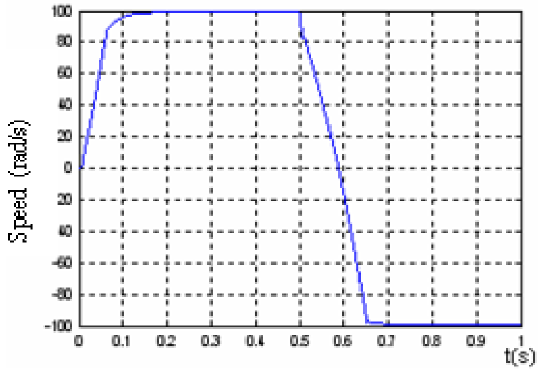


f.1) for speed inversion of – 100 rad/s at t=0.5s.

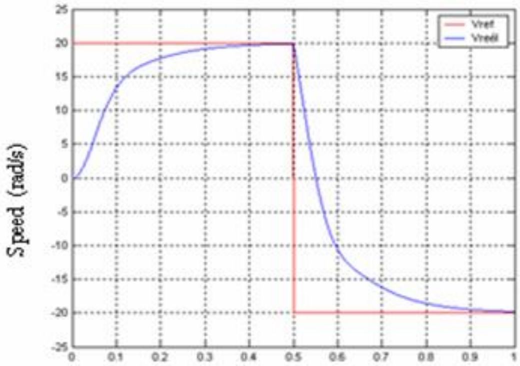
Figure 8. The system response with classic PI



e.2) Speed



f.2) for speed inversion of – 100 rad/s at t=0.5s.



g.2) for speed inversion of -20rad/s at t=0.5s.

Figure 9. The system response with fuzzy logic controller

Conclusion

In the present study, we have introduced the principles of the fuzzy logic control and have also justified our choice of this method for the control of asynchronous machines. After having chosen the method of Simulink simulation and having confirmed its effectiveness, we have used this simulation under several operating conditions in order to exploit, with exactness, the different results obtained. Thus, it was clearly shown that the fuzzy controller exceeds the classic regulator. But in spite of the robustness of FLC fuzzy logic controller for all the considered variations (load torque and inversion of the speed direction of rotation) with respect to classic PI, there are certain reserves on the characteristics of this new control technique when the operating conditions change in large band. In conclusion, it is believed that the DTC, using SVM principle, will continue to play a strategic role in the development of high performance drives [11].

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Appendix: Simulation Parameters

Stator resistance Rs = 1.2Ω.
Rotor resistance Rr = 1.8Ω.
Stator inductance Ls = 0.1554 H.
Rotor inductance Lr = 0.1568 H.
Rotor time constant Tr = 0.0871s.
Mutual inductance M = 0.15H.
Motor inertia j= 0.07 Kg.M^2.
Coefficient of friction f = 0.00 N.m/rad/s.
Number of pole pairs P=2.
Reference Flux Φ_{ref} = 1.1Wb.
Rated power Pn = 4 Kw.
Rated speed ω_n = 100 Rad/s.