INDUCTION MOTOR DIRECT TORQUE CONTROL – FUZZY LOGIC CONTRIBUTION

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Abstract: *In this article we present the simulation results of the induction motor speed regulation by the direct torque control with a classic PI regulator. The MATLAB SIMULINK programming environment is used as a simulation tool. The results obtained, using a fuzzy logic, shows the importance of this method in the improvement of the performance of such regulation*

Keywords: *DTC, Induction motor, PI, Fuzzy logic, FLR(Fuzzy logic regulator)*

1. Introduction

. Vector control based en rotor flux orientation presents a major disadvantage to be relatively sensible to the machine parameters variation, for such reason the direct torque control (DTC) methods of the induction machines have been developed during the nineties. In these control methods the stator flux and the electromagnetic torque are estimated from the unique electric parameters of stator that can be handled (accessible) without mechanical sensors. This control technique presents remarkable dynamic performances, also a good robustness with respect to the motor parameters variations.

Now a day's fuzzy logic is considered an interesting alternative approach for its advantages: analysis close to that of the man (operator), ability of nonlinear systems control, best dynamic performances and the inherent quality of robustness [1].

2. Principle

2.1 General principles of direct torque control

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

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

From the flux expressions, the rotor current can be written

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

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

The equations become:

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

These relations show that:

- Il can possibly control the $\bar{\Phi}_s$ vector starting from the $\bar{V}_s$ vector, with the voltage drop $R_s\bar{I}_s$

- The flux $\bar{\Phi}_r$ follows the variation of $\bar{\Phi}_s$ 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 $\gamma = (\bar{\Phi}_s \bar{\Phi}_r)$

- Thus the torque depends on the amplitude and the relative position of the two vectors $\bar{\Phi}_s$ and $\bar{\Phi}_r$.

- If we manage to control perfectly the flux $\bar{\Phi}_s$ (starting from $\bar{V}_s$) in module and position, we can thus control the amplitude and the relative position of $\bar{\Phi}_s$ and $\bar{\Phi}_r$, consequently the torque. This can be possible only when the control period T_e of the voltage V_s is such as $T_e << \sigma\tau_r$ [2].

3. Choise of voltage vector VS

The choice of the vector $\bar{V}_s$ depend on the position of $\bar{\Phi}_s$, the desired variation for the module of Φ_s , the desired variation for the torque , and the direction of rotation of $\bar{\Phi}_s$.

The steady complex plan (α,β) of the stator is subdivided into six sectors S_i with: i =1, …, 6 so that **:**

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$$(2i-3)\frac{\pi}{6} \leq S_i \leq (2i-1)\frac{\pi}{6} \quad (5)$$

Each sector S_i contains an active space voltage vector V_i of the inverter as shown on figure (1). Thus the flux rotate in the trigonometrically direction

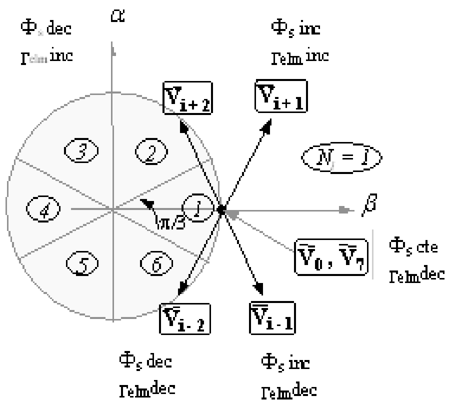

Fig. 1.Choice of the voltage vector.

These voltage vectors are selected from a commutation table according to the flux errors, torque and position of the stator flux vector. However, the position of the rotor is not needed for the choice the voltage vector. This particularity is an advantage of the (DTC) since the mechanical sensor is not necessary.

The voltage vector at the inverter output is deduced from the variations of torque and flux estimated relatively to their reference, as well as the position of vector $\overline{\Phi_s}$. An estimator of $\overline{\Phi_s}$ in module and position as well as an estimator of torque are therefore necessary.

4. Estimators

4.1. Estimation of the stator flux

The flux estimation can be obtained from the measurements of current and voltage of the machine stator parameters.

$$\overline{\Phi_S} = \Phi_{S\alpha} + j\Phi_{S\beta} \quad (6)$$

$$\begin{cases} \Phi_{S\alpha} = \int_0^t \left(V_S - R_S I_{S\alpha}\right)dt \\ \Phi_{S\beta} = \int_0^t \left(V_{S\beta} - R_S I_{S\beta}\right)dt \end{cases} \quad (7)$$

We obtain the voltages VS_α et $V_{S\beta}$ from controllers ($S_aS_bS_c$), of the measured voltage U_0.

4.2. Estimation of the electromagnetic torque

The torque Γ_{elm} can be only estimated from the stator parameters flux and current, from their components (α, β), the torque can be written:

$$\Gamma_{elm} = p\left[\Phi_{s\alpha} I_{s\beta} - \Phi_{s\beta} I_{s\alpha}\right] \quad (8)$$

5 Development of the control vector

5.1 The flux corrector

With this type of controller, the corrector output, represented by a Boolean variable (Cflx), indicate directly if the amplitude of flux must be increased (Cflx=1) or decreased (Cflx=0) in order to maintain the relationship:

$$\left| (\Phi_s)_{ref} - \Phi_s \right| \leq \Delta\Phi_s \quad (9)$$

with: $(\Phi_s)_{ref}$ is a reference flux, $\Delta\Phi_s$ is the hysteresis width of the corrector

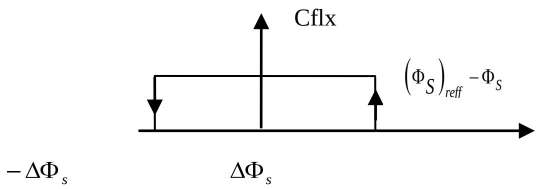

Fig. 2 Hysteresis flux corrector.

5.2 Electromagnetic torque corrector

The torque corrector maintains the torque within the following limits:

$$\left|(\Gamma_{elm})_{ref} - \Gamma_{elm}\right| \leq \Delta\Gamma_{elm} \quad (10)$$

with : $(\Gamma_{elm})_{ref}$: reference torque.

$\Delta\Gamma_{elm}$: The corrector hysteresis band.

5.3 Three levels comparator

The comparator allows the motor control in the two directions of rotation, either for positive or negative torque. It indicates directly if the torque amplitude must be increased in absolute value (ccpl=1), for a positive order and (Ccpl=-1), for a negative order, or decrease (Ccpl=0).

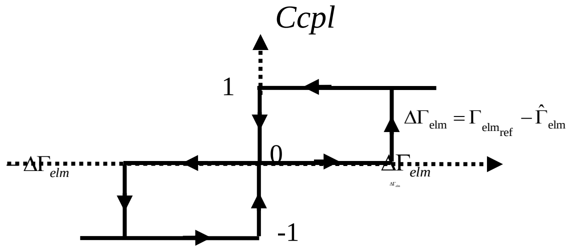

Fig. 3 three levels torque corrector

5.4 Takahashi DTC control strategy

The choice of the inverter state is carried out in a table of commutation built according to the variables state (cflx) , (ccpl) and the area of the flux position Φ_s. By selecting one of the vectors null, the rotation of stator flux is stopped and involves therefore a decrease of torque. We choose V_0 or V_7 in a manner to minimize the number of commutation of the same inverter switch [3].

Cflx	1	1	1	0	0	0
Ccpl	1	0	-1	1	0	-1
S1	V2	V7	V6	V3	V0	V5
S2	V3	V0	V1	V4	V7	V6
S3	V4	V7	V2	V5	V0	V1
S4	V5	V0	V3	V6	V7	V2
S5	V6	V7	V4	V7	V0	V3
S6	V1	V0	V5	V2	V7	V4

Table (1) DTC commutation Table

6. DTC General structure control

The structure of the torque direct control is represented as follows [4]:

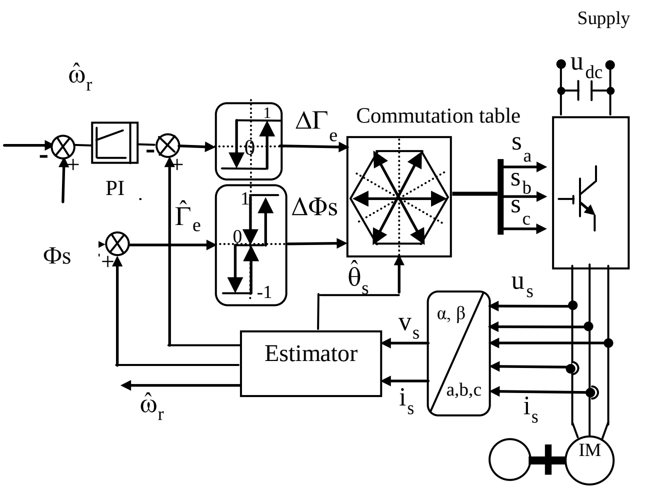

FIG. 4 General structure of DTC with a PI

7. Machine control with FLR

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 regulator.

7.1. Fuzzy logic regulator.

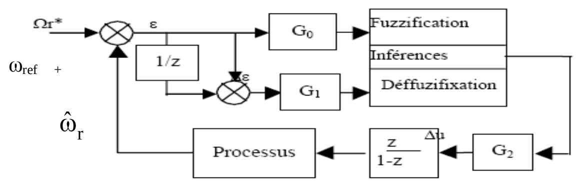

Fig. 5 Fuzzy logic regulator topology

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 [5].

7.2 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 fuzzyfied 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)

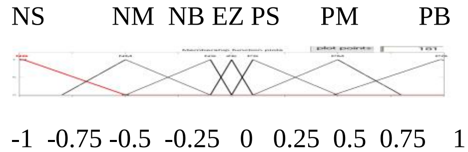

Fig (6) Fuzzy subset ε and Δu

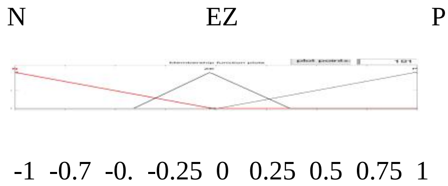

Fig (7) Fuzzy subset Δε

7.3 Rules

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

ε / Δε | Δu	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

Table (2) Decision table Mac Vicar

7.3 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 one hand and gives better results on the other hand [6].

7.4 Defuzzyfication

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 [7].

8. Simulation results

In order to illustrate the improvements that offers a fuzzy PI regulator with regards to a classic PI for the static and dynamic performances of the control of the asynchronous machine with DTC, we led a study of simulation with the same test conditions such as the three transitory modes : a load less 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 .

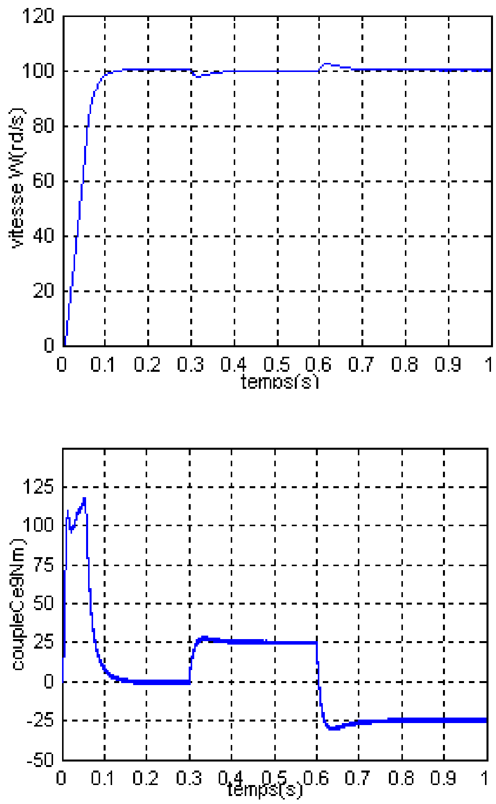

Fig (8) the system response with classic PI for two instructions for 25Nm and -25Nm at t=0.3s and 0.6s

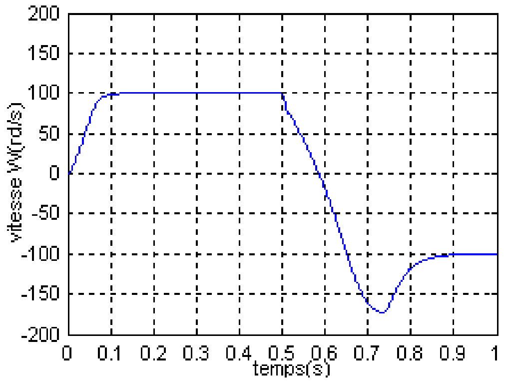

Fig (9) the system response with classic PI for speed inversion of -100rd/s at t=0.5s

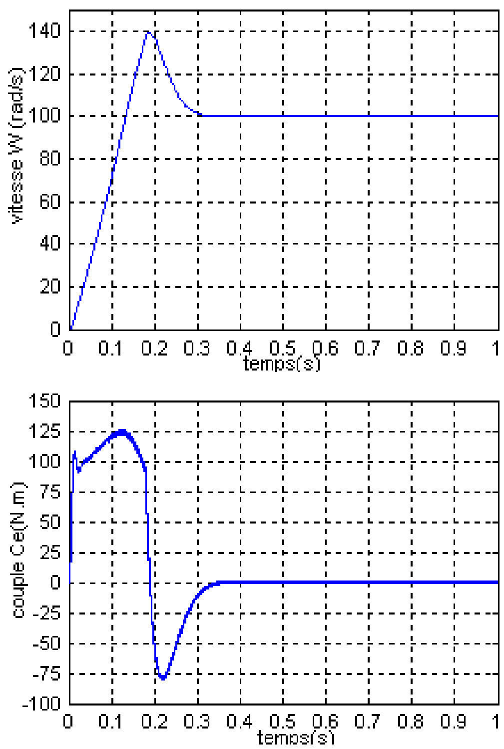

Fig (10) the system response with classic PI during variation of the moment of inertia by 100%

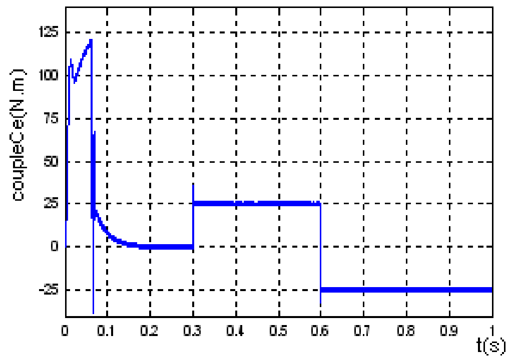

Fig (11) The system response with FLR for two instructions of 25Nm and -25Nm at t=0.3s and 0.6s

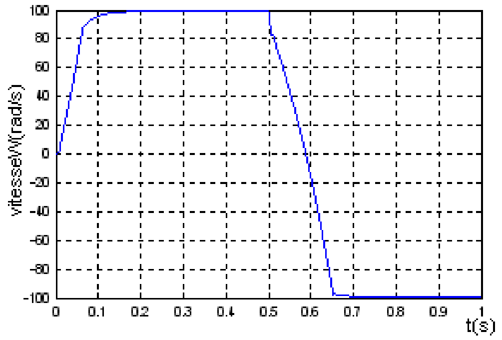

Fig (12) the system response with FLR for speed inversion of -100rd/s at t=0.5s

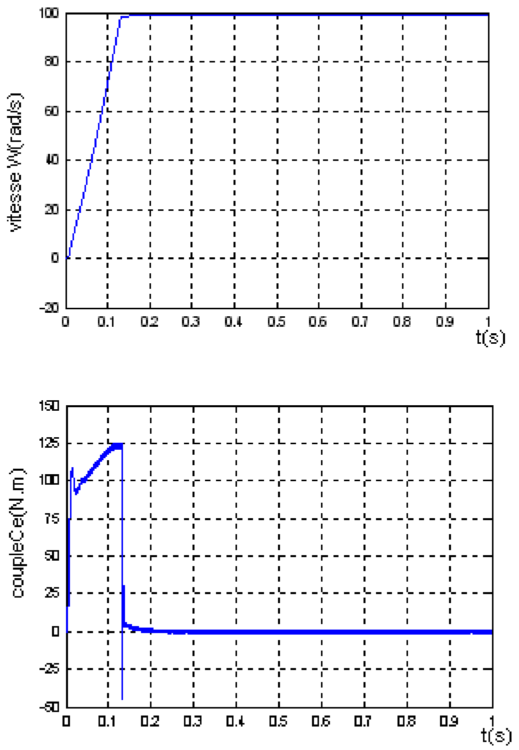

Fig (13) the system response with FLR during variation of the moment of inertia by 100%

A. Introduction of load torque

To test the adjustment robustness of the induction machine with fuzzy PI we have introduced a load torque of 25N.m at t=0.5s and to examine more this test we have used a step of instruction of 25N.m at t=0.3s and other of -25N.m at t=0.6s, see figure (11). 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 that observed during the adjustment by classic PI see figure (8) . It is also noted that the regulation effect persists always, indeed the electromagnetic torque acts very quickly to follow the instructions of introduced loads and presents a remarkable reduction in the harmonics

.

B. Inversion of speed direction of rotation

Figure (12) illustrates clearly the robustness of PI fuzzy regulator particularly the speed response with regards to a significant inversion of its reference from 100rad/s to -100rad/s. However the electromagnetic torque marks a peak at starting and another reverse at the change of the speed direction of rotation but the braking time at starting in the reverse direction is relatively shorter than that obtained by a classic PI see figure(9) .

C. Variation of the inertia moment

We observes in this case a clear improvement of the control robustness with respect to the adjustment by a classic PI see figures (10) and (13) especially for the variation of the moment of inertia where it is clearly noted that the speed is established without going beyond and converges quickly to its reference of 100rad/s whereas the electromagnetic torque reaches a peak and stabilizes with a practically null value in steady state mode.

9. Conclusion

In this article we have introduced the principles of the fuzzy logic control and justifying our choice of this method for the control of asynchronous machines. After having chosen the method of Simulink simulation and having confirmed his 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 fuzzy regulator exceeds classic PI regulator. But in spite of the robustness of PI fuzzy regulator for all the considered variations (load torque, inversion of the speed direction of rotation and inertia moment) with respect to classic PI , nevertheless there are certain reserves on the characteristics of this new control technique about its high performances when the operating conditions change in large band.

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Note:

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