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# Induction Motor Direct Torque Control with Fuzzy Logic Method

**Abdessalem Chikhi* and Khaled Chikhi***

**Abstract** – In this article we present the simulation results of induction motor speed regulation by 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

## 1. Introduction

Vectorial control based on rotor flux orientation presents a major disadvantage relative to the variations of a machine's parameters It was for this reason that direct torque control (DTC) methods of induction machines were developed during the nineties. With these control methods, stator flux and electromagnetic torque are estimated from the unique electric parameters of the stator that can be handled (accessible) without mechanical sensors. This control technique presents remarkable dynamic performances, as well as a good robustness with respect to motor parameter variations.

Today, fuzzy logic is considered an interesting alternative approach due to its advantages: analysis close at hand for the operator, the ability to control nonlinear systems, excellent 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 and is defined by:

$$\begin{cases} \overline{V}_s = R_s\overline{I}_s + \dfrac{d\overline{\Phi}_s}{dt} \\ \overline{V}_r = 0 = Rr\overline{I}r + \dfrac{d\overline{\Phi}_r}{dt} - j\omega\overline{\Phi}_r \end{cases} \tag{1}$$

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

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

With $\sigma = 1 - \frac{L_m^2}{L_sL_r}$ (variability (scatter) factor)

The equations become:

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

These relations show that:

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

$$\Gamma_{elm} = p\frac{L_m}{\sigma L_sL_r}\Phi_s\Phi_r\sin\gamma \tag{4}$$

With $\gamma = \left(\overline{\Phi}_s, \overline{\Phi}_r\right)$

- 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 control perfectly 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 is possible only when the control period $T_e$ of the voltage $V_s$ is such as $T_e << \sigma\tau_r$ [2].

## 3. Choice of voltage vector VS

The choice of the vector $\overline{V}_s$ depends on the position of $\overline{\Phi}_s$, the desired variation for the module of $\Phi_s$, the desired variation for the torque, and the direction of rotation of $\overline{\Phi}_s$. The steady complex plan $(\alpha,\beta)$ of the stator is subdivided into six sectors $S_i$ with: i =1… 6 so that:

$$(2i-3)\frac{\pi}{6} \le S_i \le (2i-1)\frac{\pi}{6}$$

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* Department of Electrical Engineering, Batna University Algeria, (Email: k_chikhi@lycos.com)

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Each sector $S_i$ contains an active space voltage vector $V_i$ of the inverter as shown in Fig. (1). Thus the flux rotates in the trigonometrical direction.

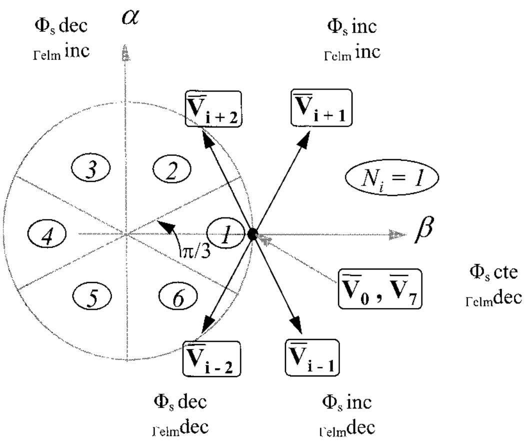

**Fig. 1.** Choice of voltage vector

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 of 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 the current and voltage of the machine stator parameters.

$$\overline{\Phi_S} = \Phi_{S\alpha} + j\Phi_{S\beta} \tag{6}$$

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

We obtain the voltages $VS_\alpha$ 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 $\Gamma_{elm}$ can only be estimated from the stator parameter's flux and current, and from their components $(\alpha,\beta)$ the torque can be written:

$$\Gamma_{elm} = p\left[\Phi_{s\alpha} I_{s\beta} - \Phi_{s\beta} I_{s\alpha}\right] \tag{5}$$

## 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), indicates directly if the amplitude of flux must be increased (Cflx=1) or decreased (Cflx=0) in order to maintain the relationship:

$$\left| (\Phi_s)_{ref} - \Phi_s \right| \le \Delta\Phi_s$$

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

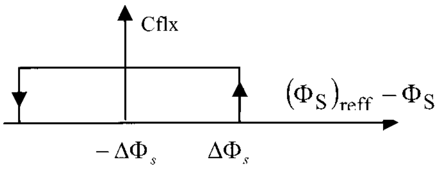

**Fig. 2.** Hysteresis flux corrector

### 5.2 Electromagnetic torque corrector

The torque corrector maintains the torque within the following limits:

$$\left| (\Gamma_{elm})_{ref} - \Gamma_{elm} \right| \le \Delta\Gamma_{elm} \tag{7}$$

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).

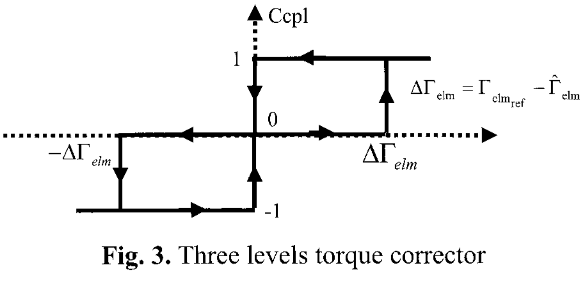

**Fig. 3.** Three levels torque corrector

## 6. Takahashi DTC control strategy

The choice of 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 $\Phi_s$. By selecting one of the vectors null, the rotation of stator flux is stopped and therefore involves a decrease of torque. We chose $V_0$ or $V_7$ to minimize the number of commutations of the same inverter switch [3].

**Table 1.** DTC commutation Table

| 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 |

### 6.1 DTC General structure control

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

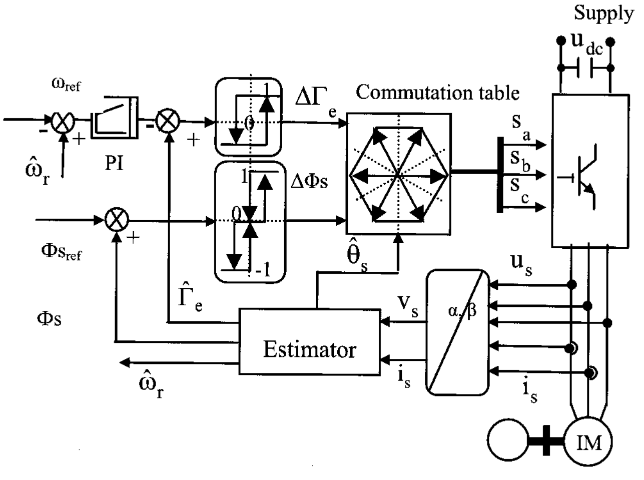

**Fig. 4.** General Structure of DTC with a PI

## 7. Machine control with RLF

With the objective of canceling the static error and to reduce the time response while preserving system stability, the proportional integral corrector PI used is replaced with a fuzzy logic regulator.

### 7.1. Fuzzy logic regulator

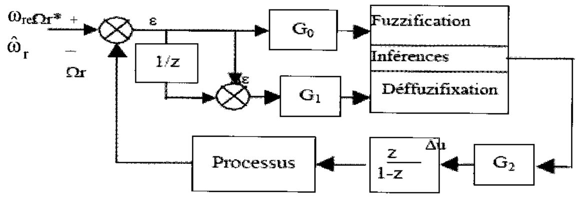

**Fig. 5.** Fuzzy logic regulator topology

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 variables into deterministic values 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. F our case the regulator has two inputs ε, Δε and for the fuzzyfied outputs Δu as follows: 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 defined by a membership function of the triangular type according to figures' (6) and (7).

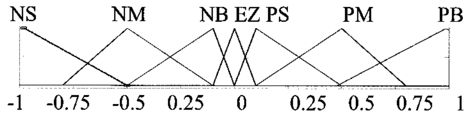

**Fig. 6.** Fuzzy subset ε and Δu

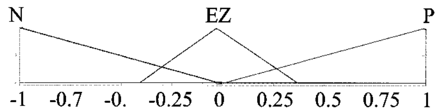

**Fig. 7.** Fuzzy subset Δε

### 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:

**Table 2.** Decision table Mac Vicar

| Δε \ ε<br>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 |

### 7.4 Interfacing

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

We have adopted the inference method Max-Min because it has the advantage of being easy to implement and provides better results, [6].

### 7.5 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 [5].

## 8. Simulation results

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

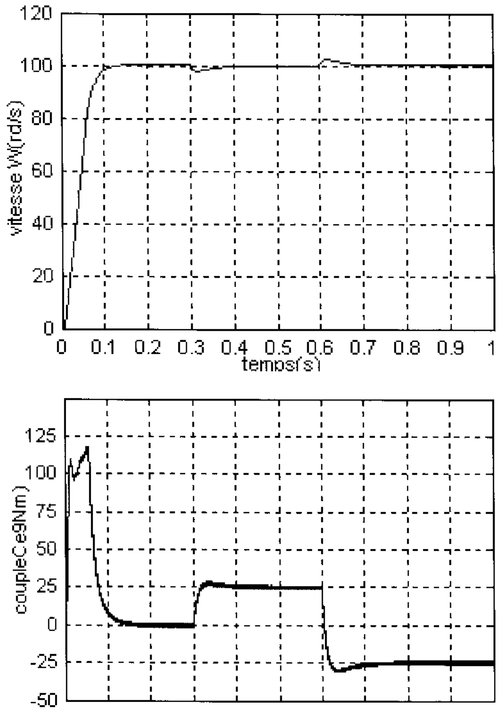

**Fig. 8.** The system response with classic PI for two instructions for 25Nm and -25Nm at t=0.3s and 0.6s

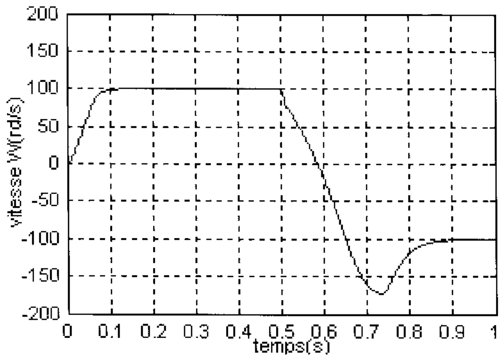

**Fig. 9.** The system response with classic PI for speed inversion of -100rd/s at t=0.5s

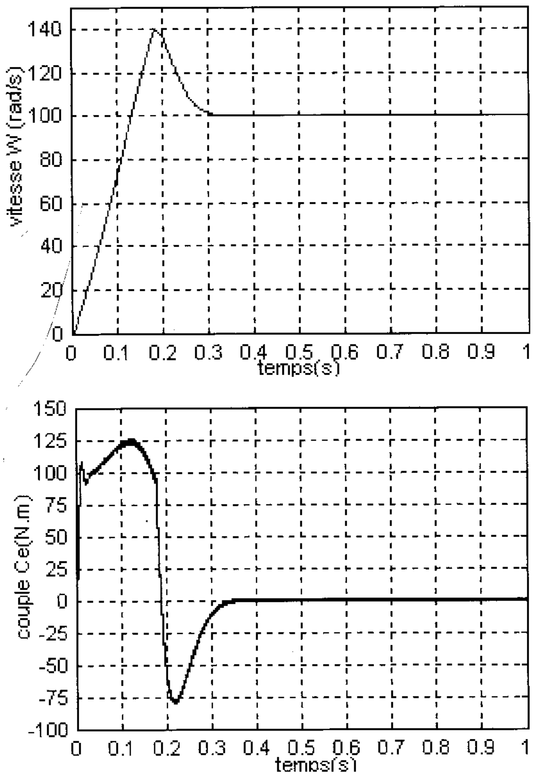

**Fig. 10.** The system response with classic PI during variation of the moment of inertia by 100%

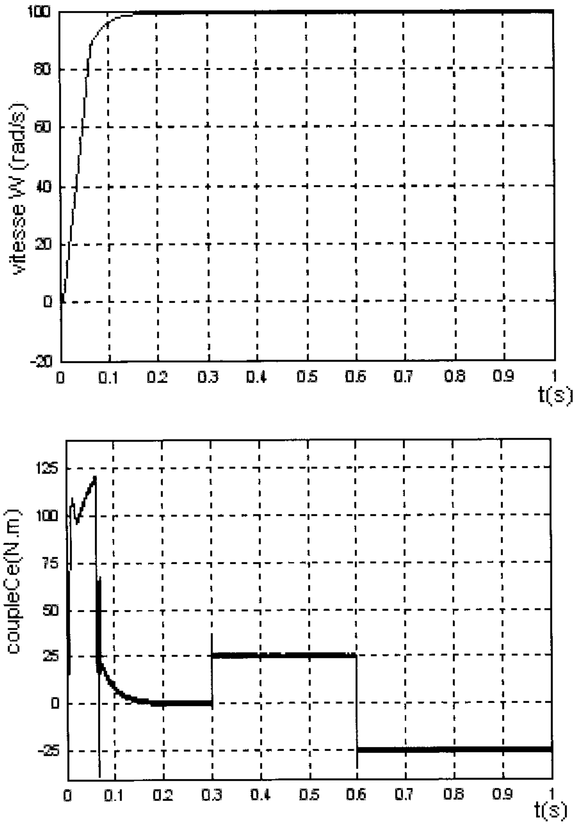

**Fig. 11.** The system response with RLF for two instructions of 25Nm and -25Nm at t=0.3s and 0.6s

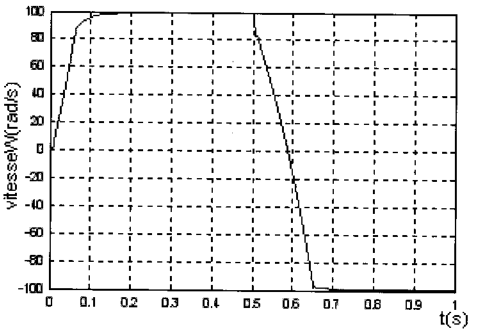

Fig. 12. The system response with RLF for speed inversion of -100rd/s at t=0.5s

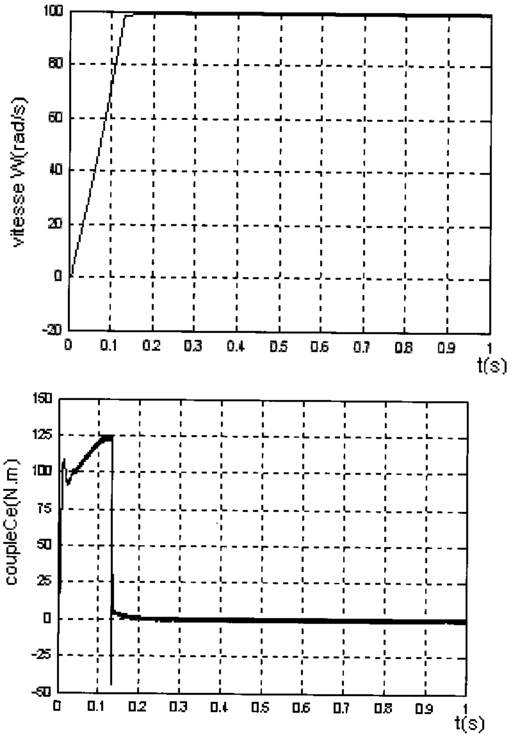

Fig. 13. The system response with RLF during variation of the moment of inertia by 100%

### 8.1 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. To further examine this test we have used a step of instruction of 25N.m at t=0.3s and another of -25N.m at t=0.6s (see Fig. 11). It is noted that the speed reaches its reference $\omega_{ref}$ = 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 adjustment by classic PI (see Fig. 8). It is also noted that the regulation effect always persists. Indeed, the electromagnetic torque acts very quickly to follow the instructions of introduced loads and presents a remarkable reduction in harmonics.

### 8.2 Inversion of speed direction of rotation

Fig. 12 clearly illustrates the robustness of the PI fuzzy regulator, particularly its 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 speed and direction of rotation, but the braking time after starting in the reverse direction is relatively short compared to that obtained by a classic PI (see Fig. 9).

### 8.3 Variation of the inertia moment

We observed in this case a clear improvement of control robustness with respect to adjustment by a classic PI (see Fig. 10 and 13). This was especially noticeable for variations in the moment of inertia where it is clearly noted that 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 a steady state mode.

## 9. Conclusion

In this article we have introduced the principles of fuzzy logic control and justify our choice of this method for the control of asynchronous machines. After having chosen the Simulink method of simulation and having confirmed its effectiveness, we used this simulation under several operating conditions in order to exploit with precision the different results obtained. Thus it was clearly shown that the fuzzy regulator exceeds the classic PI regulator. But in spite of the robustness of PI fuzzy regulators for all considered variations (load torque, inversion of the speed and direction of rotation and the moment of inertia) with respect to classic PI. Nevertheless, there are certain reservations relating to the characteristics of this new control technique regarding its high performance when operating conditions change in large band.

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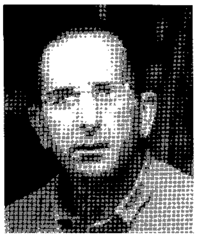
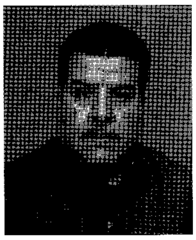


**Abdesselem Chikhi**
Was born in Batna (Algeria) in 1960. He received his Engineering degree from Batna University Center in 1986 and his Magister degree from the University of Batna in 2008. His research interests are power electronics, power quality and electrical drives control.



**Khaled Chikhi**
Has a Doctoral degree in Electrical engineering and has been a teacher since 1986 at the University of Batna (Algeria) and is Head of the Department of Electrical Engineering. His Research area interests are Energy quality, power systems, electrical drives control and electrical networks.