# FUZZY SPEED CONTROL OF INDUCTION MOTOR WITH DTC-BASED NEURAL NETWORKS

**[1]Y. Sayouti, [1]A. Abbou, [2]M. Akherraz, [2]H. Mahmoudi**

[1]Student, Laboratoire LEEP, Dept. Electrique, EMI, Morocco

[2]Prof, Laboratoire LEEP, Dept. Electrique, EMI, Morocco

E-mail: sayouti@emi.ac.ma, abbou.a@yahoo.fr, Akherraz@emi.ac.ma, mahmoudi@emi.ac.ma

## ABSTRACT

In this paper, the authors present the induction motor speed control with DTC (direct torque control). The DTC in its conventional form uses algorithms to select the components of the voltage inverter. This paper proposes to replace the conventional selector switches statements of the voltage inverter by a selector based on neural networks ANN (Artificial Neural Network), which is able to manage in the same way the switches states, without resorting to complex programming. The speed loop regulation is carried out by a fuzzy controller giving exceeding performance in comparison with a classic PI regulator. The design of the controller is based on the experience without knowing the mathematical model of the Motor. The simulation results in Matlab/Simulink show that the speed static error and accelerating error is near zero, also the torque and flux ripples are respectively in the range of 2.5% and 5%.

**Keywords:** Induction Machine (IM), DTC, Neural Network, Fuzzy control.

## 1. INTRODUCTION

The direct torque control (DTC) has been developed by Takahashi and Depenbrock specifically for induction machines [1]-[2]. Recently, it has become more useful in the industry replacing the flux oriented Control strategy (FOC). The DTC is a control technique which exploits the possibility to impose the torque and the flux with decoupled manner.

Several studies have suggested the application of the techniques of artificial intelligence (AI) to select switches statements of the inverter [3]-[4]. The control loop of the motor speed, proposed in this article, is provided by a PI controller based on fuzzy logic.

This paper is organized as follows: first the dynamic model of induction motor is presented, and a Control strategy of DTC is described and implemented. In the second part, the neural network selector and the fuzzy PI speed controller are detailed. Finally, the simulation results on Matlab / Simulink are presented and discussed in the absence and presence of a speed loop PI Fuzzy control.

## 2. MODEL OF THE INDUCTION MOTOR

The model of the IM is presented as follows:

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX \end{cases} \tag{1}$$

Where:

$$X = \begin{bmatrix} \mathrm{i}_{s\alpha} & \mathrm{i}_{s\beta} & \psi_{r\alpha} & \psi_{r\beta} \end{bmatrix}^T \tag{2}$$

$$U = \begin{bmatrix} V_{s\alpha} & V_{s\beta} \end{bmatrix}^T \tag{3}$$

$$Y = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \end{bmatrix}^T \tag{4}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}^T \tag{5}$$

$$A = \begin{bmatrix} -\gamma & 0 & \frac{K}{T_r} & K\omega_r \\ 0 & -\gamma & -K\omega_r & \frac{K}{T_r} \\ \frac{M}{T_r} & 0 & -\frac{K}{T_r} & \omega_r \\ 0 & \frac{M}{T_r} & \omega_r & -\frac{K}{T_r} \end{bmatrix} \tag{6}$$

With:

$$K=\left[\frac{M}{\sigma L_s L_r}\right],\quad \gamma=\left[\frac{R_s}{\sigma L_s}+\frac{R_r M^2}{L_r^2 \sigma L_s}\right]$$

$$B=\begin{bmatrix}\frac{1}{\sigma L_s} & 0\\ 0 & \frac{1}{\sigma L_s}\\ 0 & 0\\ 0 & 0\end{bmatrix} \tag{7}$$

## 3. DTC PRINCIPLE

DTC of IM is based on the direct determination of command sequence applied to the voltage inverter switches. The command stator flux and torque magnitude are compared with the respective estimated values, and the errors are processed trough hysteresis-band controller.

The two levels voltage inverter has seven positions distinct in the phase plane, corresponding to the eight sequences of the output voltage vector.

In steady state, the stator flux can be easily estimated from $I_s$ and $V_s$. The values of flux and torque are then calculated without complex loop, independently of the rotor parameters.

Since the DTC orders the switches directly, it's clearly the dynamic performances improved of the drive compared to the vectorial control [8].

DTC can be schematized by the following figure:

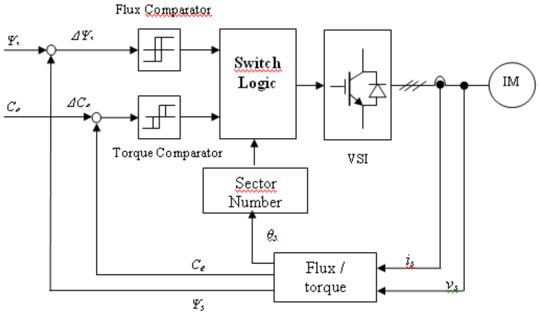

*Figure 1: DTC principle*

In the reference frame (α, β) the equation of flux is:

$$\overline{V}_s = R_s \overline{I}_s + \frac{d}{dt}\overline{\Psi}_s \tag{8}$$

The electromagnetic torque is proportional to the vector product of flux stator and rotor, it is expressed by [5]-[6]:

$$C_e = k(\overline{\Psi}_s \times \overline{\Psi}_r) = k|\Psi_s||\Psi_r|\sin(\delta) \tag{9}$$

Where: $K=\frac{3P}{2}\frac{L_m}{\sigma L_s L_r}$ and $\sigma = 1-\frac{M^2}{L_s L_r}$

$\delta$: Angle between the vector of stator and rotor flux.

## 4. CONTROL STRATEGY OF DTC

The choice of the vector $\overline{V}_s$ depends on:

- The position of $\overline{\Psi}_s$ in the reference frame (α, β),
- The variation desired for the module of $\overline{\Psi}_s$ (neglecting the stator resistance),
- The variation desired for the torque, and
- The direction of rotation of $\overline{\Psi}_s$.

When the flux is in a zone I, the control of flux and torque can be ensured by selecting one of the eight vectors tensions as following:

- If $V_{i+1}$ is selected, $\overline{\Psi}_s$ increase, and Ce increase.
- If $V_{i-1}$ is selected, $\overline{\Psi}_s$ increase, and Ce decrease.
- If $V_{i+2}$ is selected, $\overline{\Psi}_s$ decrease, and Ce increase.
- If $V_{i-2}$ is selected, $\overline{\Psi}_s$ decrease, and Ce decrease.
- If $V_0$ or $V_7$ is selected, the rotation of flux is stopped; the torque decreases whereas the module of flux remains unchanged.

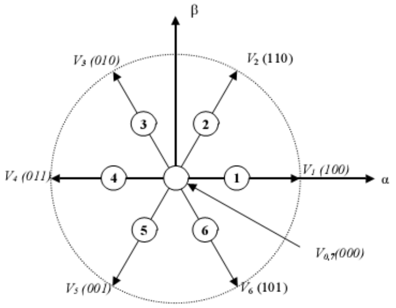

*Figure 2: stator vectors of tensions delivered by a two level voltage inverter.*

The voltage vector table in figure 1 receives the input signals $H_\Psi$, $H_{Ce}$, and S and generates the appropriate control voltage vector (switching states) for the inverter according to the Table 1.

| $\Delta\phi_s$ | $\Delta C_e$ | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 110 | 010 | 011 | 001 | 101 | 100 |
| | 0 | 000 | 000 | 000 | 000 | 000 | 000 |
| | -1 | 101 | 100 | 110 | 010 | 011 | 001 |
| 0 | 1 | 010 | 011 | 001 | 101 | 100 | 110 |
| | 0 | 000 | 000 | 000 | 000 | 000 | 000 |
| | -1 | 001 | 101 | 100 | 110 | 010 | 011 |

*Table 1: Status of switches*

The flux and torque are controlled by two hysteresis comparator illustrated in Figure. 3.

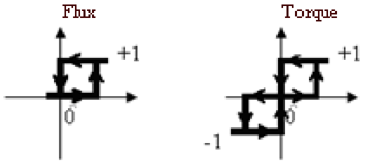

*Figure 3: hysteresis-band controllers*

The dynamic torque is generally faster than the flux. Therefore, the use of a comparator with two level hysteresis-band is justified in order to adjust the torque and minimize the frequency switching average [7].

## 5. ESTIMATED TORQUE AND FLUX

The estimated flux can be achieved from measurements of stator current and voltage of the motor.
Starting from the equation:

$$\overline{\Psi}_s = \int_0^t (\overline{V}_s - \overline{R}_s \overline{I}_s)dt \tag{10}$$

The (α, β) components of the vector $\overline{\Psi}_s$ are:

$$\Psi_{s\alpha} = \int_0^t (V_{s\alpha} - R_{s\alpha} I_{s\alpha})dt \tag{11}$$

$$\Psi_{s\beta} = \int_0^t (V_{s\beta} - R_{s\beta} I_{s\beta})dt \tag{12}$$

The module of the stator flux is:

$$\Psi_s = \sqrt{\Psi_{s\alpha}^2 + \Psi_{s\beta}^2} \tag{13}$$

The stator flux sector is determined by the components $\Psi_{s\alpha}$ and $\Psi_{s\beta}$. The angle between the referential and $\overline{\Psi}_s$ is equal to:

$$\delta_s = \tan^{-1}\left(\frac{\Psi_{s\alpha}}{\Psi_{s\beta}}\right) \tag{14}$$

The torque is written as follows:

$$C_e = \frac{3P}{2}\left(i_{s\beta}\Psi_{s\alpha} - i_{s\alpha}\Psi_{s\beta}\right) \tag{15}$$

## 6. THE NEURAL NETWORK SELECTOR

As the DTC uses algorithms to select a large number of statements inverter switches, neural networks can accomplish this task after a learning phase.

The neural network selector inputs proposed are the position of flux stator vector represented by the number of the corresponding sector, the error between its estimated value and the reference value, and the difference between the estimated electromagnetic torque and the torque reference.

The input layer consists of 3 neurones. The output layer is composed of three neurons, each representing the state Ei of one of the three pairs of switches Ti of the inverter connected to the positive DC bus. Figure 4 illustrates the Neural Network selector.

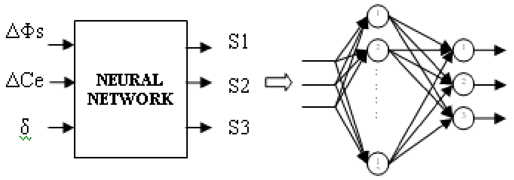

*Figure 4: Neural Network Selector*

After several tests the architecture 3-12-3 with a single hidden layer.

The function f (n) activation of the hidden layer is

Tansig: $a = \dfrac{e^n - e^{-n}}{e^n + e^{-n}}$ (16)

While the activation function of the output layer is
Purelin.: $a = n$ (17)

The learning of the neural network is done by using the algorithm LVM (levenberg Marquardt) with a number of epochs 500 and an error of 10-3.

## 7. FUZZY SPEED CONTROLLER

The motor speed can be controlled indirectly by controlling the torque with a fuzzy controller. Fuzzy logic is based on the theory of fuzzy sets developed by Zadeh [9]. This is an extension of the classical theory for the incorporation of fuzzy set. The proposed fuzzy controller has two inputs and one output as described in Figure 5.

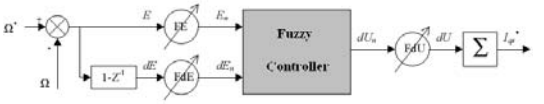

*Figure 5: structure of the fuzzy controller*

Where E is the error, expressed by:

$$E(k) = \Omega^*(k) - \Omega(k-1) \qquad (18)$$

dE is derived from the error approximated by:

$$dE(k) = \frac{E(k) - E(k-1)}{T_e} \qquad (19)$$

With: Te is the sampling period.

The output of the regulator is given by:

$$C_e^*(k) = C_e^*(k-1) + dU(k) \qquad (20)$$

FE, FdE, FdU are gains called "scale factor". They can change the sensitivity of the controller without changing its structure. The fuzzy controller is composed of three blocks: fuzzification, rule bases, and defuzzification. Figure 7 show the function of membership of each input signals (E, dE). The fuzzy subsets are as follows: NB (Negative Big), Nm (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big).

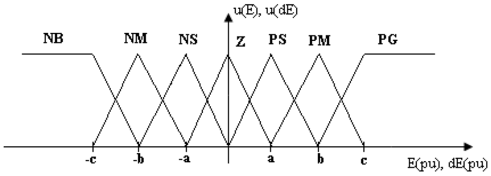

*Figure 6: Member functions*

There are 7 fuzzy subsets for each variable, which gives 7 * 7 = 49 possible rules, where a typical rule is: "If E(pu) is PS and dE(pu) is PM Then dU (pu) PB ".

← **En** →

| | | **NB** | **NM** | **NS** | **Z** | **PS** | **PM** | **PB** |
|---|---|---|---|---|---|---|---|---|
| | **PB** | **Z** | PS | PM | PB | PB | PB | PB |
| ↑ | **PM** | NS | **Z** | PS | PM | PB | PB | PB |
| | **PS** | NM | NS | **Z** | PS | PM | PB | PB |
| **dEn** | **Z** | NB | NM | NS | **Z** | PS | PM | PB |
| | **NS** | NB | NB | NM | NS | **Z** | PS | PM |
| ↓ | **NM** | NB | NB | NB | NM | NS | **Z** | PS |
| | **NB** | NB | NB | NB | NB | NM | NS | **Z** |

*Table 2: rules base*

Defuzzification is done by centroid method based on the inference method Takagi-Sugeno-Kang.

## 8. SIMULATION RESULTS

The parameters of the IM are as follows:

| **Rated power** | **7.5 KW** |
|---|---|
| **Voltage** | 380V Y |
| **Frequency** | 50 Hz |
| **Pair pole** | 2 |
| **Rated speed** | 1450 rpm |
| **Stator resistance** | 0.63 Ω |
| **Resistance Rotor** | 0.4 Ω |
| **Inductance stator** | 97 mH |
| **Inductance rotor** | 91 mH |
| **Mutual inductance** | 91 mH |
| **Moment of inertia** | 0.22 Kg.m ² |

The DTC simulation of the induction machine with a speed loop fuzzy controller is done using Matlab/ Simulink®.

Figure 7 presents the system's response to torque reference equals to 20N.m and stator flux reference to 0.8wb.

Figure 8 shows the results of speed control according to a profile 0,+100,-100,0 with a fixed charge of 20N.m. Speed, torque, current stator, stator flux are visualised.

Figure. 9 illustrates the response to a record speed with an application of a load of 40N.m.

## 9. DISCUSSION OF RESULTS

Figure 7 shows the flux and torque control. The stator flux and torque are applied as order respectively with 0.8Wb and 20N.m. It is clear that the system follows these references. The torque and the flux ripples are due to the hysteresis-band comparator. Note that the dynamics of torque is faster compared with other methods of control (FOC). In the (α,β) reference frame, the stator flux follow a circular trajectory with radius of 0.8Wb.

Figure 8 shows the fuzzy speed loop control with the drive system during positive and negative rotation according to a profile +100, 0, -100, 0 with a fixed charge of 20N.m. The proposed control reveals that the speed response tracks the speed command quickly and tightly with 1% speed overshoot. The stator current is sinusoidal with fluctuations order of 10% around the average value, due to the hysteresis-band comparator.

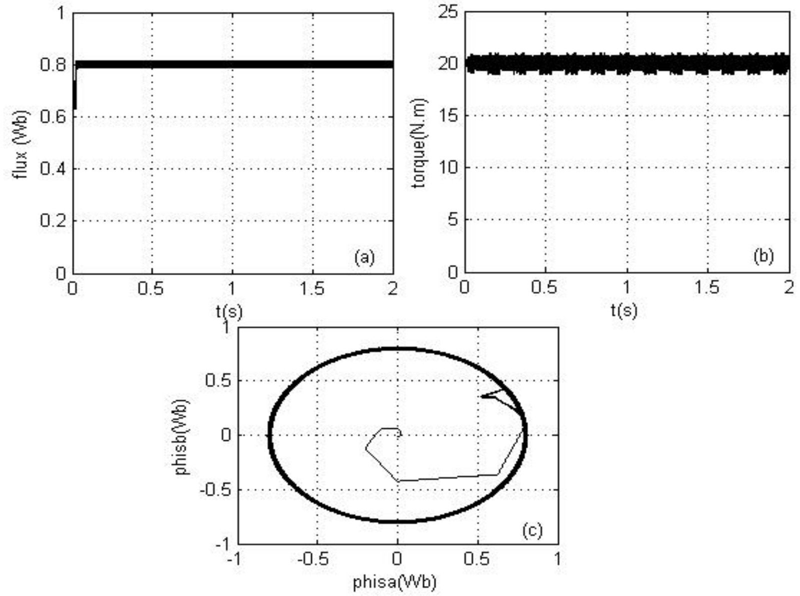

*Figure 7: direct flux and torque control (a) stator flux, (b) electromagnetic torque, (c) stator flux trajectory*

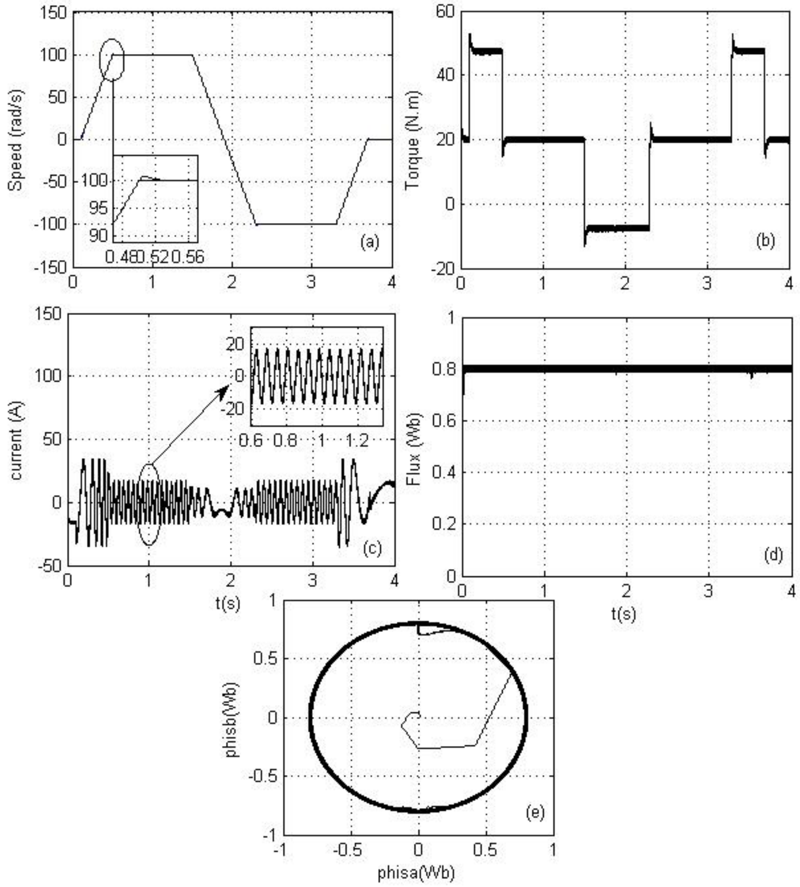

*Figure 8: Fuzzy speed controller. Speed (a) , (b) electromagnetic torque, (c) current isα., (d) the stator flux trajectory, ( e) stator flux.*

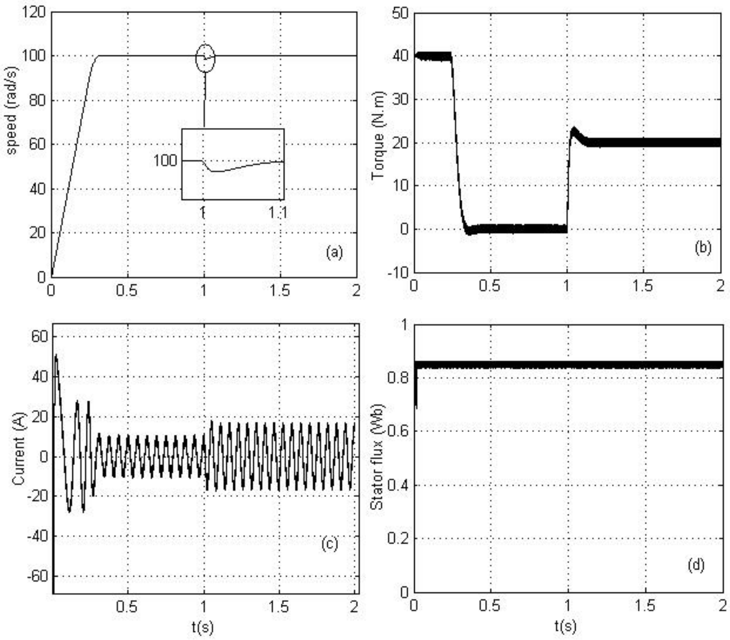

*Figure 9: fuzzy controller with load disturbance: (a) speed, (b) electromagnetic torque, (c) current isα, (d) stator flux*

In Figure 9, the motor starts under no load. The starting electromagnetic torque is 28 Nm, which drops to zero when speed is reached. At t = 0.8s, a 40 Nm load is applied. The controller rejects the disturbance with a maximum speed dip of 0.04%. Figure (9-d) clearly shows that the stator flux is not disrupted by the application of such load.

## 10. CONCLUSIONS

In this article a fuzzy speed controller of an induction motor with neural network based DTC has been proposed. The neural network with feedforward 3-12-3 architecture is applied to generate voltage inverter switches states according to the classical DTC table. The speed controller proposed is a fuzzy controller designed without the mathematical model of the induction motor. The excellent simulation results obtained show the effectiveness of this technique in the speed regulation of the induction motor.

## 11. REFERENCES

[1] I. Takahashi, Direct Y.Ohmori, "High-performance Torque Control of year Induction Motor", IEEE Transactions one Industry Applications, vol. 25, pp. 257-264, March/April 1989.

[2] M. Depenbrock, “Direct self-control (DSC) of inverter-fed induction machine”, IEEE Trans. Power Electron., vol.3, pp. 420-429, Oct. 1988.

[3] L Zhong, Mr. F Rahman, W.Y. Hu, K W Lim, M. A. Rahman, "A Direct Torque Controller for Permanent Magnet Synchronous Motor Drives", IEEE Transactions one Energy Conversion, vol. 14, pp. 637-642, September 1999.

[4] A. L Orille, G M. A. Sowilam, "Application of Neural Networks for Direct Torque Control", Computers & Industrial Engineering 37; pp.391-394, 1999.

[5] D. Casadei, F profum, G Serra, and A. Tani "JIB and DTC: two viable schemes for induction motors torque control ", Trans IEEE. Power Electronics, vol. 17, pp. 779-786, September 2002.

[6] F Khoucha, K Marouani, K Aliouane, and A. Experimental Kheloui "adaptive performance analysis of flux and direct speed observers for torque control of sensorless induction motor drives", Trans IEEE. Power Electronics Germany, pp. 2678-2683, 2004

[7] C Carlos, "Modeling Controls Vectorial and DTC, Asynchronous Engine control 1", Edition Hermes Science Europe 2000.

[8] P. A. Arias, "Improvement in Direct Torque Control of Motors induction", Ph.D Thesis, University of Catalunya, Spain, 2000.

[9] L. A. Zadeh, "Fuzzy Setes" Information and Control, vol. 8, pp.338-353, 1965.