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# Fuzzy Inference System Based Direct Torque Control

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*Abstract*: - In this paper, two controllers are designed for a direct torque control of an induction machine and validated on a voltage-source pulse width modulation inverter-fed induction motor drive. Basically, it is a task of replacing the classical Direct Torque Control strategy (DTC) by a Direct Torque Fuzzy Control strategy (DTFC) based fuzzy controller. The aim of this work is to reduce the torque and the flux ripples caused by the hysteresis controllers and the selection table in the classical DTC and to require low current in the start-up by fluxing the machine when the torque is maintained zero. In this manner, the proposed method is incorporated in the classical DTC scheme in order to replace both hysteresis controllers and the selection table. In this context, an evaluation study is carried out to demonstrate the effect of the stator resistance variation on the torque and flux ripples, the robustness of these controllers in the transients at the start-up of the machine or when changing its rotary direction and the behaviour of the flux response when the torque is zero. In this context, this case study is carried out to justify the benefits of the fuzzy controller and its advantages over the classical one. In effect, computer simulations validate the proposed method, support its ability to follow desired dynamics and show good performance even in the low speed range, where the stator resistance influence becomes critical.

*Key-words*: - Direct torque control, induction motor control, fuzzy control.

## 1 Introduction

The apparition of the vector or field-oriented control made the induction machine drives a challenge in high performance control applications [1-2]. However, this technique yields some disadvantages such as imprecise and low torque response. Thus, many experiments have been done, to discover solutions resolving these problems. One of these solutions is the direct torque control (DTC) found by Takahashi [3] and that responds to the above requirements.

Conversely, in the literature, there are many references that deal with such control techniques [4-5]. It's principal, as is shown in [Fig. 1] is that the electromagnetic torque and flux are kept in prescribed levels through two respective hysteresis-band comparators based on the errors between reel and references values of the torque and the flux. In addition, both voltages and currents of the machine are supposed to determine the estimated torque and flux vectors, which provide information about the flux rms value location in one of six sectors.

A switching table selects the accurate voltage vector between six active vectors and two zero vectors to perform torque and flux requirements. Accordingly, this table generates pulses Sa, Sb and Sc to control the voltage-source pulse width modulation in order to supply the induction machine with voltages [6].

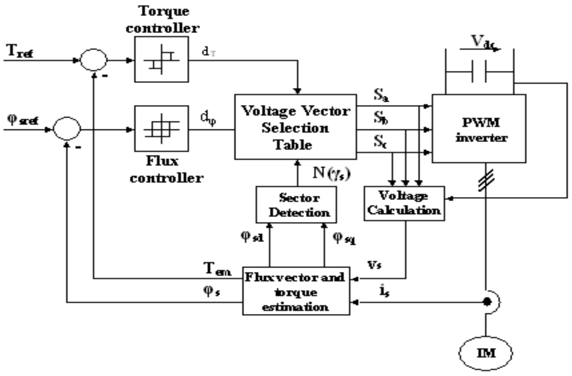


Fig.1 Classical DTC scheme of an induction machine

However, the presence of hysteresis controllers leads to a variable switching frequency, and the existence of torque and flux ripple due to the sector changes and problems caused at low speed. Based on these two negative aspects, researchers continue to find solutions that seam to be much valuable than those obtained. Currently, research has reached artificial intelligent techniques. These techniques, such as neural networks [7], fuzzy logic [8-9] and neuro-fuzzy systems [10-11] have recently shown promise in the application of power electronic systems and have become one of the most favorable areas of research for nonlinear systems. Thus, in this context, a fuzzy controller as is shown in [Fig. 2] is designed to replace both hysteresis comparators and selection table as it was suggested in [12]. The difference in this work is that the selection table used is the classical one based on six sectors as was proposed by Takahashi. Basically, this technique improves the performance of the DTC scheme in terms of torque and flux distortion, especially at low speed even where the stator resistance influence becomes critical and demonstrates the production of a flux when applying to the machine zero torque in order to require less current than with hysteresis controllers.

The paper is organized as follows. Section **2** presents the classical DTC technique based on hysteresis controllers. Section **3** offers the DTC technique based on fuzzy controller. Section **4** illustrates the simulation results. Section **5** shows discussion and comparisons. Section **6** is devoted to the conclusion.

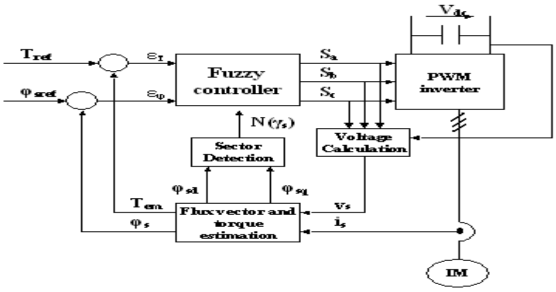


Fig.2. DTC based on fuzzy controller (DTFC).

## 2 Classical DTC Technique

The fundamental of the DTC is the direct flux and torque control. The inputs, voltage (vs) and current (is), on the stationary reference frame are given by the subsequent equations:

$$\boldsymbol{V_s} = \boldsymbol{V}_{s\alpha} + \boldsymbol{jV}_{s\beta} \tag{1}$$

$$\boldsymbol{i_s} = \boldsymbol{i}_{s\alpha} + \boldsymbol{ji}_{s\beta} \tag{2}$$

The stator flux and torque can be estimated from the equivalent circuit of the motor as follows:

$$\varphi_{sd} = \int (V_{sd} - R_s i_{sd}) dt \tag{3}$$

$$\varphi_{sq} = \int (V_{sq} - R_s i_{sq}) dt \tag{4}$$

$$\varphi_s = \sqrt{\varphi_{sd}^2 + \varphi_{sq}^2} \tag{5}$$

$$T_{em} = p(\varphi_{sd} i_{sq} - \varphi_{sq} i_{sd}) \tag{6}$$

Where $\varphi_{sd}$ and $\varphi_{sq}$ are stator flux vectors in the d and q reference frame respectively, $\varphi_s$ is the rms value of the flux vector, $T_{em}$ is the electromagnetic torque, and $R_s$ is the stator resistance.

The stator flux position is determined by the angle $\theta$ between stator flux and reference axis by this equation:

$$\theta = -\tan^{-1}\left(\frac{\varphi_{ds}}{\varphi_{qs}}\right) \tag{7}$$

Two hysteresis controllers are used for torque and flux control based on the errors $\varepsilon_\varphi$ and $\varepsilon_T$ between both of them and their references.

| | $N_s$ | $\Theta_1$ | $\Theta_2$ | $\Theta_3$ | $\Theta_4$ | $\Theta_5$ | $\Theta_6$ |
|---|---|---|---|---|---|---|---|
| $d_\varphi=1$ | $d_T=1$ | 110 | 010 | 011 | 001 | 101 | 100 |
| | $d_T=0$ | 111 | 000 | 111 | 000 | 111 | 000 |
| | $d_T=-1$ | 101 | 100 | 110 | 010 | 011 | 001 |
| $d_\varphi=0$ | $d_T=1$ | 010 | 011 | 001 | 101 | 100 | 110 |
| | $d_T=0$ | 000 | 111 | 000 | 111 | 000 | 111 |
| | $d_T=-1$ | 001 | 101 | 100 | 110 | 010 | 011 |

Table 1: Takahashi selection table

Thus keeping the flux and the torque amplitude errors within the specified limits set by the hysteresis bands of widths $H_\varphi$ and $H_T$. By this way, the controlling signals of the inverter are delivered by the selection table shown in [Table 1], in which $N_s$ define the stator flux position over six regions. $d_\varphi$ and $d_T$ are the flux and the torque coefficients and the digital number define the selection algorithm in which digits from right to left give values of $S_a$, $S_b$, and $S_c$ and constitutes the voltage vector to be selected controlling the inverter. At least, no more than eight possible voltage vectors can be selected. Accordingly, with the consideration of the position of the vector flux, the selection table generates the voltage vector based on the desired action (increase/decrease) on the flux and the torque. The digitised output signals of the torque controller are defined as:

$$\text{If } \varepsilon_T > H_T \text{ , then } d_T = 1 \tag{8}$$

$$\text{If } -H_T < \varepsilon_T < H_T \text{ , then } d_T = 0 \tag{9}$$

$$\text{If } \varepsilon_T < -H_T \text{ , then } d_T = -1 \tag{10}$$

And those of the flux controller as

$$\text{If } \varepsilon\varphi > H\varphi \text{ , then } d\varphi = 1 \tag{11}$$

$$\text{If } \varepsilon\varphi <- H\varphi \text{ , then } d\varphi = 0 \tag{12}$$

The stator voltage vector $V_{s,}$ in the other hand can be determined directly by this equation:

$$V_s = V_{sd} + jV_{sq} = \sqrt{\frac{2}{3}}\, V_{dc}\left(S_a + S_b\, e^{j(2\pi/3)} + S_c\, e^{-j(2\pi/3)}\right) \tag{13}$$

Where $V_{dc}$ is the dc link voltage of the inverter and $V_{sd}$ and $V_{sq}$ are supply voltages of the induction machine.

## 3 DTC technique based on fuzzy controller ( DTFC)

Contrarily to the other conventional controllers, fuzzy logic presents many advantages, particularly when the system to be controlled is uncertain or imprecise. In fact, fuzzy logic is a methodology that leads to an approximate solution where the problems are ill defined or subject to imprecise description [13-14]. Its major concept is the use of linguistic variables whose values are words expressed in natural language and also the use of fuzzy if-then rules, in which antecedents and a consequence contains linguistic variables. The essential of conventional fuzzy control consists in developing a rule base using linguistic descriptions of control protocols. The rule base consists of a set of if-then rules relating fuzzy quantities, which represent process response (output) and control inputs. The block fuzzy controller represented in the closed-loop control scheme [Fig. 2] consists of a fuzzification step, fuzzy inference and a defuzzification step. Fuzzification involves transforming, inputs from real values to fuzzy variables. Fuzzy inference is the process of applying fuzzy rules to the fuzzified input values and calculating the fuzzy outputs. In the last step, a defuzzifier transforms the fuzzy outputs back to the real values.

In this case study, the classical DTC presented in the previous section is replaced by another design controller based on a fuzzy controller DTFC in this manner: the error signals $\varepsilon_\varphi$ and $\varepsilon_c$ between flux, torque and their references are fed into the fuzzy controller as well as the information on the stator flux position sector $\theta$, in order to generate the pulses $S_a$, $S_b$, and $S_c$ to control the inverter. The fuzzy logic controller adapted in our application is a Mamdani type [15-16].

The membership functions of these fuzzy sets have triangular shape described by the following equation:

$$\mu_T(x)=\begin{cases} \frac{x-a}{b-a}, & \text{if } a\le x<b \\ \frac{c-x}{c-b}, & \text{if } b\le x<c \\ 0, & \text{otherwise} \end{cases} \qquad (14)$$

With a, b and c are basic parameters defining the shapes of the fuzzy sets associated to the membership functions.

Two fuzzy sets described by two linguistic variables {N, P} are designed for the flux-error, three linguistic variables {N, Z, P} for the torque-error, six linguistic variables for the stator flux position sector and eight membership functions for the output commanding the inverter. The forms of these membership functions are singleton. [Fig. 3] represents the membership functions related to each fuzzy set. In addition, [Table 2] represents the inference system that contains thirty-six fuzzy rules used for the design of the fuzzy logic controller.

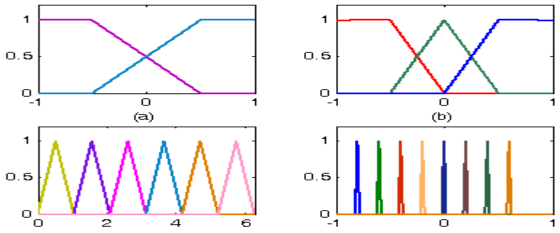


Fig.3. Fuzzy membership functions. (a):flux-error, (b): torque error, (c):stator flux position sector, (d):pulses controlling the PWM inverter.

Each rule takes three inputs and produces one output, which is a voltage vector represented by a digital number specifying the pulses controlling the inverter.

| $N_s$ | $\Theta_1$ | | | $\Theta_2$ | | | $\Theta_3$ | | |
|---|---|---|---|---|---|---|---|---|---|
| $d_T$ $d\varphi$ | N | Z | N | N | Z | P | N | Z | P |
| N | $V_2$ | $V_7$ | $V_4$ | $V_4$ | $V_7$ | $V_6$ | $V_1$ | $V_0$ | $V_5$ |
| P | $V_3$ | $V_0$ | $V_5$ | $V_5$ | $V_0$ | $V_1$ | $V_2$ | $V_7$ | $V_4$ |
| $N_s$ | $\Theta_4$ | | | $\Theta_5$ | | | $\Theta_6$ | | |
| $d_T$ $d\varphi$ | N | Z | P | N | Z | P | N | Z | P |
| N | $V_5$ | $V_0$ | $V_3$ | $V_6$ | $V_7$ | $V_4$ | $V_1$ | $V_0$ | $V_5$ |
| P | $V_6$ | $V_7$ | $V_2$ | $V_1$ | $V_0$ | $V_3$ | $V_2$ | $V_7$ | $V_4$ |

Table 2 : Fuzzy selection table

The control rule can be described in terms of the input variables $d_T$, $d_\varphi$ and $\theta$, and the output variable V. the $i^{th}$ rule can be written as:

$R_i$ : If $d_T$ is $A_i$ and $d_\varphi$ is $B_i$ and $\theta$ is $C_i$ then V is $D_i$ where $A_i$, $B_i$, $C_i$, and $D_i$ are the fuzzy sets of $d_T$, $d_\varphi$, $\theta$ and V, respectively.

The fuzzy output obtained after the inference must be defuzzified to get the real one. The Mean of Maxima (MOM) method is used for the defuzzification. According to this method the output in a discrete universe is given by:

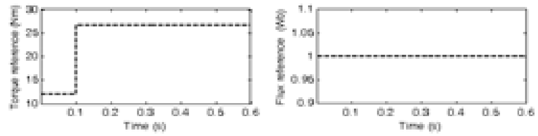
$$V=\frac{\sum_{i=1}^{36}\mu_{C_i\alpha}(V_i)\times V_i}{\sum_{i=1}^{36}\mu_{C_i\alpha}(V_i)} \qquad (15)$$

Where $\mu_{C_i\alpha}(V_i)$ are the $\mu_{C_i}(V_i)$ maximum values.

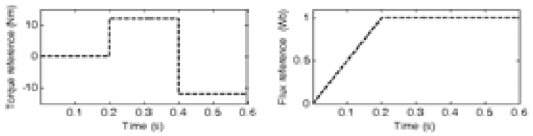
## 4 Simulation Results

The training design of the classical and the fuzzy controller is done with the environment of Matlab/Simulink and a comparative study is made based on the variation of the stator resistance $R_s$ from 1.6 Ω to 3.2 Ω. Simulation results are obtained with constant sampling frequency of 25µs. The control strategy has covered two cases:

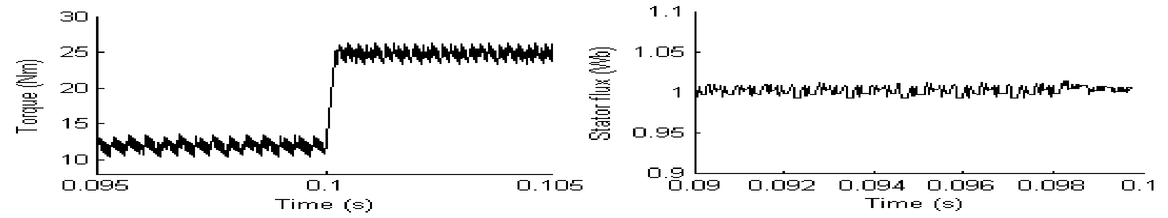
The first case reference is considered for both control techniques:



The second case references is applied in order to demonstrate the controllers robustness in the transient and when the torque value is zero:

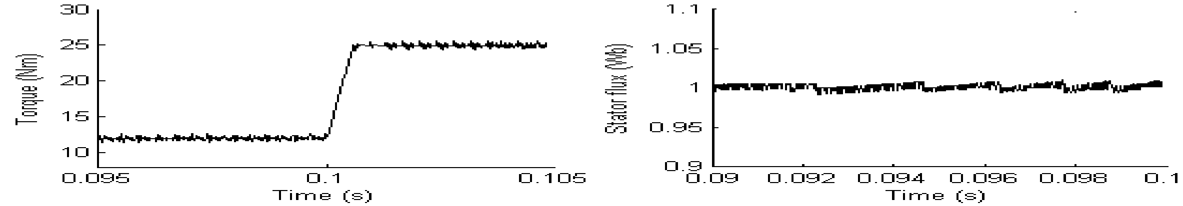


The results of the first case are presented in [Fig.4] to [Fig. 7]. Those of the second case are shown in [Fig. 8] and [Fig. 9]



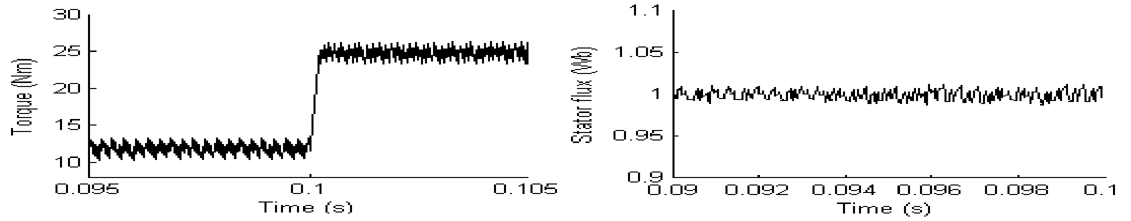
*a)* *b)*

Fig. 4 Simulation results with DTC : $R_s$=1.6Ω. (a) Step Torque response (Nm), (b) Flux response (Wb).



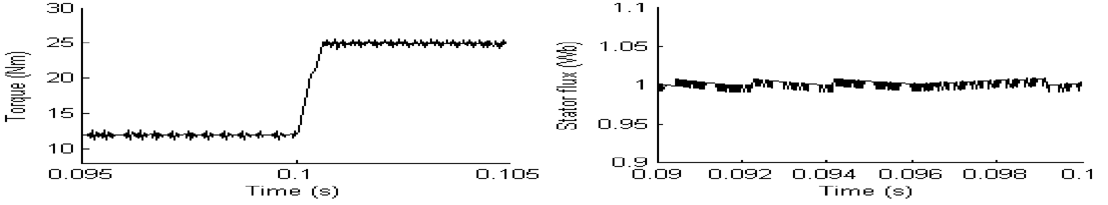
*a)* *b)*

Fig.5 Simulation results with DTFC: $R_s$=1.6Ω. (a) Step Torque response (Nm), (b) Flux response (Wb).



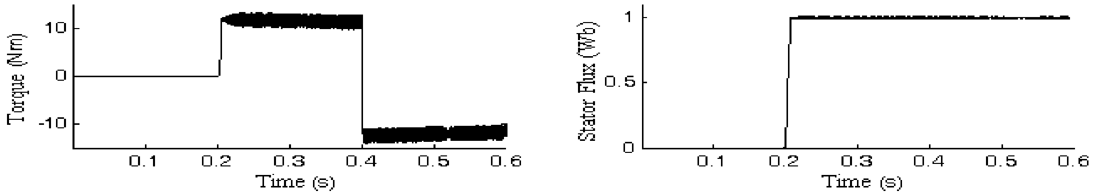
*a)* *b)*

Fig. 6. Simulation results with basic DTC: $R_s$=3.2Ω. (a) Step torque response (Nm), (b) Flux response (Wb).



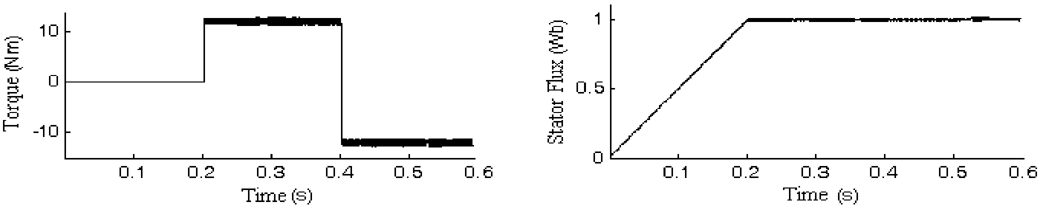
*a)* *b)*

Fig. 7. Simulation results with DTFC: $R_s$=3.2Ω. (a) Step torque response (Nm), (b) Flux response (Wb).



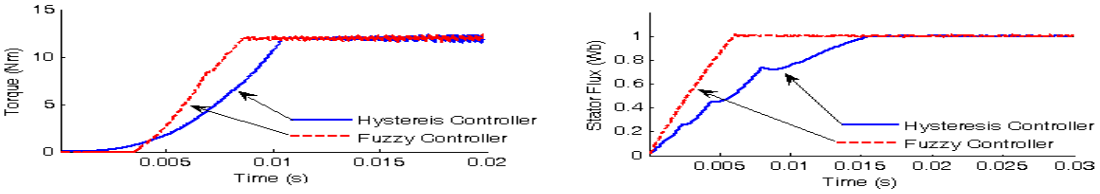
*a)* *b)*

Fig.8. Simulation results with classical DTC: (a) Torque (Nm), (b) Flux (Wb) transient responses



*a)* *b)*

Fig.9. Simulation results with classical DTFC: (a) Torque (Nm), (b)Flux (Wb) transient responses



*a)* *b)*

Fig.10.Simulation results with DTC and DTFC at the start-up of the machine: (a) Torque(Nm), (b)Flux (Wb)

## 5 Discussion and analyses

From the figures represented in the previous section, we can observe that with the hysteresis controller in [Fig. 4] and [Fig. 6], that corresponds to different stator resistance values, both electromagnetic torque and flux are subject to high ripples. Moreover, an increase of the stator resistance value causes an increase of the torque and the flux distortions. In addition, from [Fig. 8], we can see that the machine can't be fluxed when the torque is zero. However, this figure demonstrates that in terms of tracking, the system follows its desired dynamics imposed to each output variable and there are no problems at the transient of the machine especially when changing the rotary direction of the machine. Conversely, fuzzy controller acts as a minimization strategy that minimises torque and flux ripples. In fact, [Fig. 5] demonstrates that the distortions of the electromagnetic torque and the flux are reduced from those of the hysteresis controller. Besides, it is clear that the torque and the flux follows their desired trajectories and the variation of the stator resistance value has no effect on them in terms of ripples such as is seen in [Fig. 7]. This controller presents good transient responses that are shown in [Fig. 9], and the machine is fluxed when the torque is zero. Accordingly, it is clear that such controller improves dynamical performances of the machine. Moreover, this controller robustness is proved especially at low speed, when changing the rotary direction of the machine and when the system is subject to an increase of the stator resistance value. Furthermore, [Table3] and [Table4] indicates the percentage of torque minimization ripples magnitude in comparison with those allowed by the hysteresis controller based on the change of the stator resistance value.

For the first case torque and flux references, [Fig. 10] shows that the fuzzy controller provides faster torque and flux responses at the start-up in comparison with the ones supplied by the classical strategy.

| | Low speed | High speed |
|---|---|---|
| $R_{s1}$=1.6 Ω | 52.0442 % | 52.7126% |
| $R_{s2}$=3.2 Ω | 54.769 % | 53.037 % |

Table 3 : Minimization of torque ripple

| | Low speed | High speed |
|---|---|---|
| $R_{s1}$=1.6 Ω | 18.5028 % | 19.2356 % |
| $R_{s2}$=3.2 Ω | 18.9875 % | 19.7623 % |

Table 4 : Minimization of flux ripple

## 6 Conclusion

In this paper, two control methods using hysteresis and fuzzy controllers for DTC induction motor drive are presented.

The hysteresis controllers are fed with two input signals, which are the errors between the flux and the torque and their references. At their output, this controller provides desired actions on both torque and flux to the selection table. This later uses in addition the information on the stator flux position sector to generate pulses controlling the PWM inverter. Besides, the fuzzy controller replaces both hysteresis controllers and the selection table. So it has three inputs that are errors between torque and flux and their references in addition to the stator flux position sector.

From figures, we can see that fuzzy controller provides better results than those of hysteresis controllers. In fact, it proposes the above compensations and advantages:

- Minimization of torque and flux ripples;
- No ripple problems at low speed even with the stator resistance variation;
- The machine can be fluxed when the torque is zero;
- Faster torque and flux responses;
- No problems in the transients at the start-up and when changing the machine rotary direction.

By the same way, it must be noted that this case study was a difficult control problem because of the complex, non-linear and time-varying dynamics of the machine. However, the fuzzy control technique gives good results because of its ability to follow desired dynamics. In contrast, it is necessary to deal with the negative aspects of this technique in the charge of building the fuzzy controller. The difficulties are due to the shapes of all the membership functions that must be changed and adjusted. In fact, from the principle that we have no idea about the “optimal” shapes of these fuzzy functions that allow best responses, we could change the initial forms randomly and manually. In one hand, that was time consuming. In the other hand, it was a very hard task especially when the number of the membership functions is equal to 19. In addition to the scaling factors that inputs and outputs the controller and that could also be fine-tuned trough several tests. The procedure results are shown in [Fig.11]. Nevertheless, in spite of fuzzy controller implementation difficulties, simulation results validate this proposed method, show its effectiveness and robustness, and support its ability to follow desired dynamics.

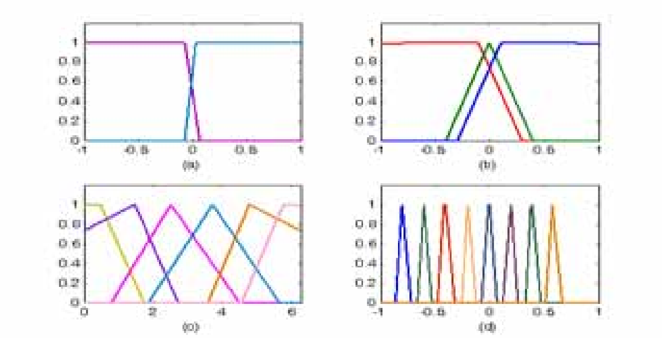


Fig.11. Final fuzzy membership functions. (a) flux-error, (b) torque-error, (c) stator flux position sector, (d) pulses controlling PWM inverter

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