

A Fuzzy Direct Torque Control of Induction Motor for FPGA Implementation

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Abstract: This paper resumes a Direct Torque Fuzzy Control (DTFC) of an Induction Motor (IM). The novel approach aims to ameliorate the performances of the conventional Direct Torque Control (DTC) by considerably reducing electromagnetic torque and stator flux ripples and improving the form of stator current. The proposed controller is based on fuzzy logic technique and it is developed in order to be implemented on Field Programmable Gate Array chip (FPGA) by using Matlab/Simulink package and Xilinx System Generator (XSG) toolbox. The efficiency of proposed technique is evaluated through simulative results that show its performance compared to conventional one.

Keywords: DTC, IM, DTFC, XSG, FPGA

1. Introduction

Different techniques of induction machine drive have been introduced in order to ensure speed control at variable frequency. Direct Torque Control (DTC) technique was proposed in the middle of the 1980s by I. Takahashi. It is considered as the most advanced AC drive technology; indeed, it presented many advantages compared to previous ones such as scalar control and vector control [1]-[2]. In fact, DTC has the advantages of a fast torque and flux response and no need for a modulator as used in Pulse Width Modulation (PWM) to control the frequency and the voltage since the inverter is controlled directly by the voltage vectors through a switching table indeed, DTC is essentially based on determining the sequence of control applied to the inverter switches at each switching time.. Besides, DTC's structure is simple without Park transformation in the electrical machine's model and the estimation of control variables that are stator flux and torque are estimated without tachometer or encoder to monitor motor shaft speed or position. [1] [3].

In spite of all the mentioned advantages of DTC compared with other control techniques, it has the disadvantage of having a variable switching frequency with fixed hysteresis bands; this is the main cause of undesired ripples generation. These ripples are the source of other problems such as audible noise. In order to overcome these disadvantages, many improvements have been realized in order to ameliorate conventional DTC dynamic performance while preserving the advantages of the conventional DTC structure.

In [4] and [5] a prediction technique is employed to improve the conventional DTC's torque and flux ripple performance; the proposed controllers predicts several/future switch transitions and choose the adequate sequence of inverter switch positions so that the switching frequency is reduced. And in [6] authors proposed a predictive direct torque control DTC algorithm for induction machine drives including a Sliding Horizon Prediction. In [7] an analytical approach to select the hysteresis bands of DTC to achieve constant switching frequency and lower Total Harmonic Distorsion (THD) in motor currents has been presented. In [8] authors presented a novel space vector modulation based on twelve 30° sectors of flux and voltage vectors within a circular locus of space vector for Induction motor control based DTC. The reference [9] detailed an improved DTC which is based on a Sliding Mode Direct Torque Control (SM-DTC) of IM drive and in [10] the Artificial Neural Networks ANN-based DTC of an IM was developed. While authors in [11] investigate the application of both ANN to Conventional DTC and SVM_ DTC to improve the performances of conventional

DTC. In [12] authors presented some variety of DTC combined with Field Oriented Control (FOC) structures: Hysteresis controllers and switching table are replaced by Proportional Integral PI controllers and space vector modulator(SVM). Three algorithms work in fixed switching frequency are developed: Direct Voltage Control (DVC) Direct Torque Control with Space Vector Modulation (DTC-SVM) and DTC-SVM with Closed – Loop Flux Control (DFC). In [13] authors combined the DTC-SVM structure with an observer for both torque/flux and speed sensorless control including flux weakening rang. In [14] a modified DTC approach which use a three-level inverter (Neutral Point Clamped (NPC) structure) instead of the two-level inverter and a PI fuzzy controller instead the classic PI controller was developed.

Some improvements based on artificial intelligence and specifically on fuzzy logic was realized: In [15] and [16], authors presented and discussed the efficiency of a Fuzzy Logic Controller (FLC) for the DTC of an IM for FPGA implementation. The proposed design is developed by a hardware description based on the VHSIC Hardware Description Language (VHDL) hardware description language. In [17] an improvement of the Conventional DTC of an induction motor is presented. The Fuzzy Logic is introduced at the PI controller of speed to be implemented on FPGA.

This paper describes a novel approach of DTC based on fuzzy logic. The fuzzy controller is developed by using XSG software packages to be implemented on FPGA. It's shown to be able to reduce electromagnetic torque and flux ripples by simulative results. This paper is organized as follows: section 2 presents the adequate model of IM designed for DTC, in section 3 the principle of conventional DTC is presented, section 4 contained the basic principle of Direct Torque Fuzzy Control (DTFC), section 5 is about presenting the DTFC approach using XSG, in section 6 simulation and interpretation results are developed and finally the procedure of FPGA implementation of the DTFC is given.

2. Modeling of Induction Motor for DTC

The IM can be modeled in terms of stator flux φ_s and stator current i_s in the reference (α,β) as shown in the following expression:

$$\begin{cases} \frac{d\bar{i}_s}{dt} = (j\omega - \frac{1}{\sigma\tau_s} - \frac{1}{\sigma\tau_r})\bar{i}_s + (\frac{1}{\tau_r} - j\omega)\frac{\bar{\varphi}_s}{\ell'_s} + \frac{\bar{V}_s}{\ell'_s} \\ \frac{d\bar{\varphi}_s}{dt} = -R_s\bar{i}_s + \bar{V}_s \end{cases} \quad (1)$$

Where l_s, l_r, l_m are respectively stator, rotor and mutual inductance, R_s, R_r denote stator and rotor resistance, $\ell'_s = \sigma l_s$ $\sigma = 1 - \frac{l_m^2}{l_s l_r}$ $\tau_s = \frac{l_s}{R_s}$ and $\tau_r = \frac{l_r}{R_r}$

Stator flux and stator current in the stationary reference frame (α, β) are considered as the state variables of the system while vector control consists of the components of stator voltage as mentioned below:

$$\begin{aligned} [x] &= [i_{s\alpha} \quad i_{s\beta} \quad \varphi_{s\alpha} \quad \varphi_{s\beta}]^T \\ [u] &= [V_{s\alpha} \quad V_{s\beta}] \end{aligned}$$

Equations system in (1) can be evaluated using the matrix vector form into the following state space representation:

$$\frac{d\bar{x}}{dt} = A\bar{x} + B\bar{u}$$

Where

$$A(\omega) = \begin{bmatrix} (j\omega - \frac{1}{\sigma\tau_s} - \frac{1}{\sigma\tau_r}) & (\frac{1}{\tau_r\ell'_s} - j\frac{\omega}{\ell'_s}) \\ -R_s & 0 \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{\ell'_s} \\ 1 \end{bmatrix} \quad (2)$$

3. Conventional DTC principle

DTC technique is based on choosing the optimum vector of the voltage. This makes the stator flux rotate and consequently produce the desired torque. The structure of DTC contains mainly two loops of the control variables: the electromagnetic torque and the stator flux. It's illustrated on figure.1. A two level hysteresis comparator has the role of comparing the estimated stator flux magnitude with its reference value while a three level hysteresis comparator calculates the error between the estimated torque and the reference torque. The error of Electromagnetic torque and stator flux's error and sector are the inputs of a switching table which generates the adequate sequence of inverter control [18]. The sequences of inverter control are given through a switching table which generates control commands taking as inputs the sector of stator flux vector and the errors of the torque and flux. The error signals are given by two hysteresis regulators whose role is to compare estimates with those of reference data in order to maintain their values within hysteresis bands. This requires the use of estimators of the control values. In the following paragraph we give the procedure of the determination of required values.

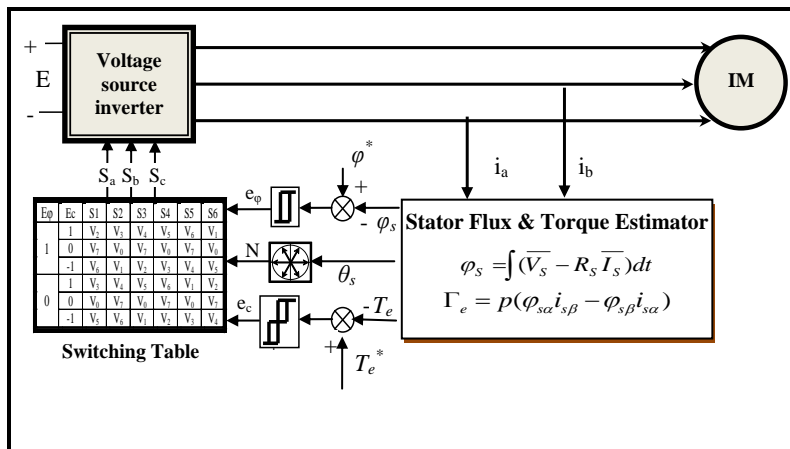


Figure 1. Block Diagram of Conventional Direct Torque Control

The choice of the control sequence applied to the switches of a three-phase voltage inverter is based essentially on the use of hysteresis comparators. Hysteresis bands allow avoiding unnecessary switching when the calculated error is very small. Thus, stator flux vector is kept in a circular crown. Control sequence of the inverter switches voltage is then defined by:

- The output value of the electromagnetic torque three levels hysteresis comparator
- The output value of the stator flux two levels hysteresis comparator
- The position of the stator flux vector in the reference (α, β)

These variables are used as inputs in the switching table of TAKASHI illustrated by Table 1 and which enables the determination of the voltage vector.

4. Stator flux estimation

Table 1. The switching Table for basis DTC

Sector		1	2	3	4	5	6
ef	ec						
1	1	V ₂	V ₃	V ₄	V ₅	V ₆	V ₁
	0	V ₇	V ₀	V ₇	V ₀	V ₇	V ₀
	-1	V ₆	V ₁	V ₂	V ₃	V ₄	V ₅
0	1	V ₃	V ₄	V ₅	V ₆	V ₁	V ₂
	0	V ₀	V ₇	V ₀	V ₇	V ₀	V ₇
	-1	V ₅	V ₆	V ₁	V ₂	V ₃	V ₄

A. Stator flux estimation

$$\varphi_{s\alpha} = \int_{t_0}^t (v_{s\alpha} - R_s \cdot i_{s\alpha}) dt \tag{3}$$

$$\varphi_{s\beta} = \int_{t_0}^t (v_{s\beta} - R_s \cdot i_{s\beta}) dt$$

Stator flux magnitude is the square root of the squared components: $\Phi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2}$

Where the components of stator voltage vector are defined in terms of switch control variables S_A, S_B and S_C in equation (4) and the components of stator current are established in equation (5) by applying Concordia form to currents components i_a and i_b

$$V_{s\alpha} = \sqrt{\frac{3}{2}} U_0 \left[S_A - \frac{1}{2}(S_B + S_C) \right]$$

$$V_{s\beta} = \sqrt{\frac{1}{2}} U_0 [(S_B - S_C)] \tag{4}$$

$$i_{s\alpha} = \sqrt{\frac{3}{2}} i_a \tag{5}$$

$$i_{s\beta} = 1/\sqrt{2} (i_b - i_c)$$

B. Electromagnetic torque estimation

Electromagnetic torque can be estimated from the components of the stator flux and current in the reference (α, β) using the equation (6):

$$\Gamma_e = p (\varphi_{s\alpha} \cdot i_{s\beta} - \varphi_{s\beta} \cdot i_{s\alpha}) \tag{6}$$

C. Position of the stator flux vector

The angle between stator flux vector and the axis α of the stationary reference is evaluated by the following expression:

$$\theta_s = \tan^{-1} \left(\frac{\varphi_{s\alpha}}{\varphi_{s\beta}} \right) \tag{7}$$

4. Direct Torque Fuzzy Control principle

In order to improve the conventional DTC principle, it's interesting to incorporate intelligent controllers as fuzzy logic, neuronal network neuro-fuzzy, etc. These controllers are known by their design that does not depend on accurate mathematical model of the system and thus it handles nonlinearity of arbitrary complexity [19].

They are used to ameliorate the conventional controller and particularly decrease torque and flux ripples. These ripples are due to hysteresis regulators' and which act directly on the variables control: stator flux and electromagnetic torque. It is noted that these ripples are the main disadvantage of the DTC since they can cause vibration and audible noise in the induction motor and eventually results the degradation of some components.

The Direct Torque fuzzy Control Scheme (DTFC) is given by Figure2 In fuzzy approach, the two hysteresis comparators and the switching table are substituted by a fuzzy controller [20] [21].

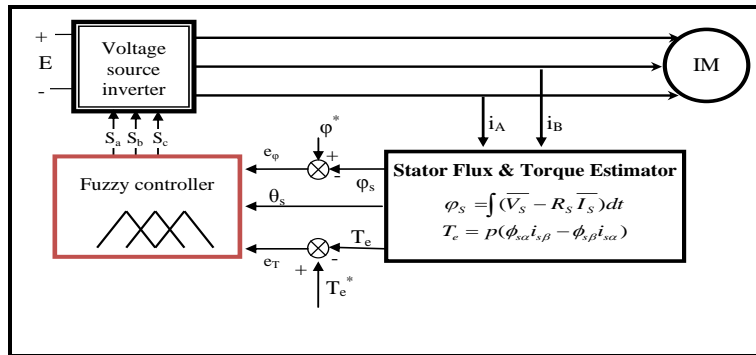


Figure 2. Block Diagram of Direct Torque Fuzzy Control

In the introduced approach, a Mamdani-type fuzzy logic controller (FLC) is used in order to adapt the torque hysteresis band, so undesired ripples can be reduced.

The FLC is designed to have torque error, flux error; stator flux angle as inputs and the output is the voltage vector which is applied at the end of the sample time.

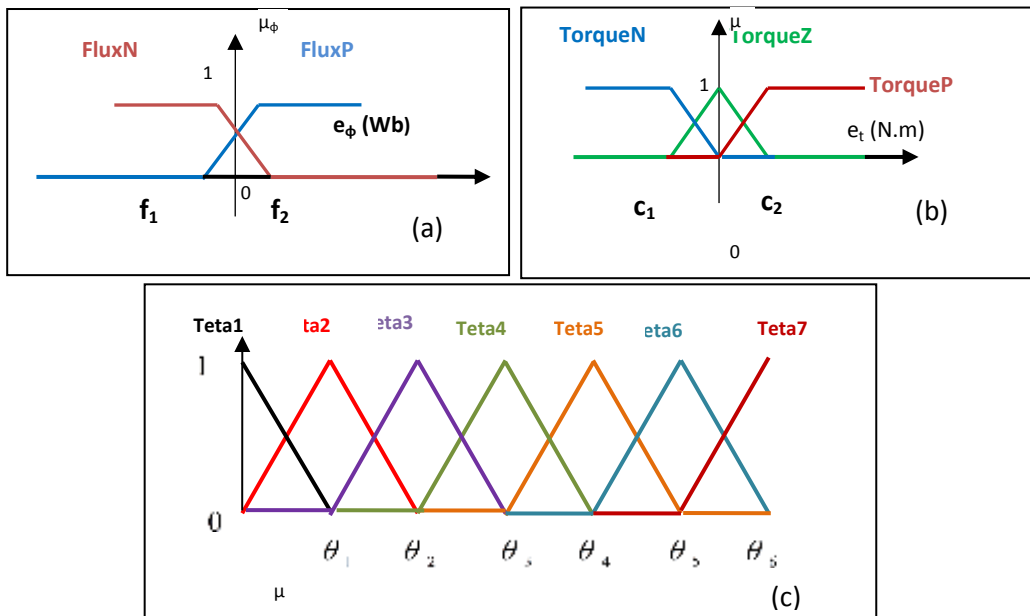


Figure 3. Membership functions for input/output variables of FLC. Stator flux error (b) Electromagnetic torque error (c) stator flux sector

The stator flux error can be negative (FluxN) or positive (FluxP) corresponding to 2 overlapping fuzzy sets. The flux error membership function is represented by two symmetric trapezoidal membership functions. The torque error membership function is represented by three fuzzy sets as shown in Figure 3.(b) with delta and trapezoidal shape. Its membership is named negative torque error (TorqueN), Zero torque error (TorqueZ) and Positive torque error (TorqueP). The flux angle has a universe of discourse equal 360 degrees ($[0, 2\pi]$). It is divided into six sectors. The universe of the discourse of this fuzzy variable is divided into six fuzzy sets denoted θ_1 to θ_7 with a width of $\pi/3$ as shown in Figure 3.c. The associated membership functions are defined by six equidistant isosceles triangular membership functions are used named as Teta1, Teta2, Teta3, Teta4, Teta5, Teta6 and Teta7.

The bases of rules for direct torque fuzzy control are developed by the use of TAKASHI table given in Table.2

Table. 2 Voltage vector fuzzy control table

Θ		Teta1	Teta2	Teta3	Teta4	Teta5	Teta6	Teta7
e_f	e_t							
FluxP	TorqueP	V2	V3	V4	V5	V6	V1	V2
	TorqueZ	V7	V0	V7	V0	V7	V0	V7
	TorqueN	V6	V1	V2	V3	V4	V5	V6
FluxN	TorqueP	V3	V4	V5	V6	V1	V2	V3
	TorqueZ	V0	V7	V0	V7	V0	V7	V0
	TorqueN	V5	V6	V1	V2	V3	V4	V5

Each control rule can be described using the input variables torque error e_t , flux error e_f , flux angle θ and the output variable V as:

If (e_f is A) AND (e_t is B) AND (θ is C) THEN (V is V_i) Where A, B and C are the fuzzy set of the input variables.

The developed FLC uses the method of SOM (the Smallest Of Maximum) in the defuzzification process .It returns the smallest output with the maximum membership function as the crisp value. [23]

The design of the developed controller is empirical and defined by the simulation of the system that enables the choice of adequate parameters for the defined application. Simulation is realized by using Matlab/Simulink environment in order to have the optimum level of torque ripples [22]. The performance of the FLC is mainly influenced by the shape of the membership function, the fuzzy reasoning rules and the defuzzification method.

5. DTFC based FPGA Design using XSG

XSG generates a synthesizable code VHDL to be used for Xilinx FPGA chip implementation. It's a toolbox developed for MATLAB/Simulink which enable an abstraction algorithm level while keeping traditional Simulink blocksets [24] - [26]. In this section the detailed XSG design of the FLC's different parts are presented.

A. Rules Design

The following figure illustrates an example of a rule established from Table2. It consists of the 3 memberships of inputs linked by an "AND" operator which is translated mathematically to the function "minimum".

Rule2: If (e_f is FluxP) AND (e_t is TorqueZ) AND (Teta is Teta2) then (V is V_0).

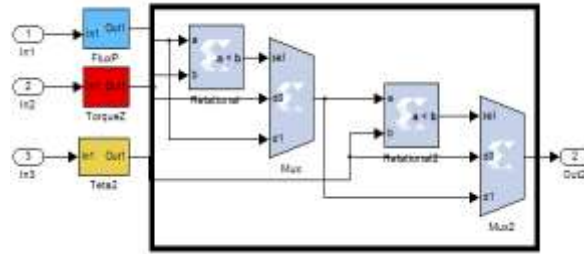


Figure 4. XSG design of Rule2

The detailed XSG design the different subsystems of the inputs memberships functions are illustrated by Figure 5.

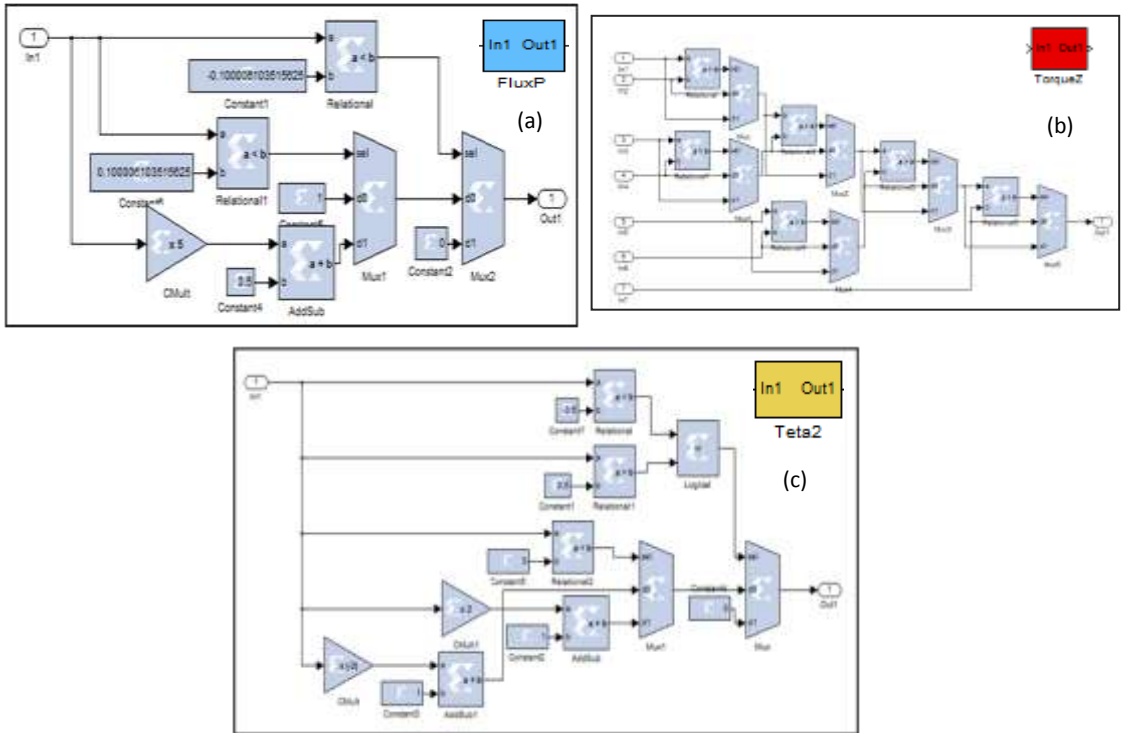


Figure 5. XSG Design of inputs memberships

- (a) XSG Design of stator flux membership function FLuxP,
- (b) XSG Design of Electromagnetic Torque membership function TorqueZ,
- (c) XSG Design of Stator flux angle Teta2

B. Rules interconnection and voltage vector control determination

Once the 42 rules are set, the basis of rules is established by linking the rules as follows:

If (e_f is P) AND (e_t is Z) AND (Teta is 2) Then (V is V0)

OR if (e_f is P) AND (e_t is P) AND (Teta is 2) Then (V is V7)

OR if

The OR operator of Mamdani fuzzy logic controller is presented by the MAX operator that connects the different rules and which outputs the maximum value calculated. Figure6 illustrates the maximum operator design in XSG.

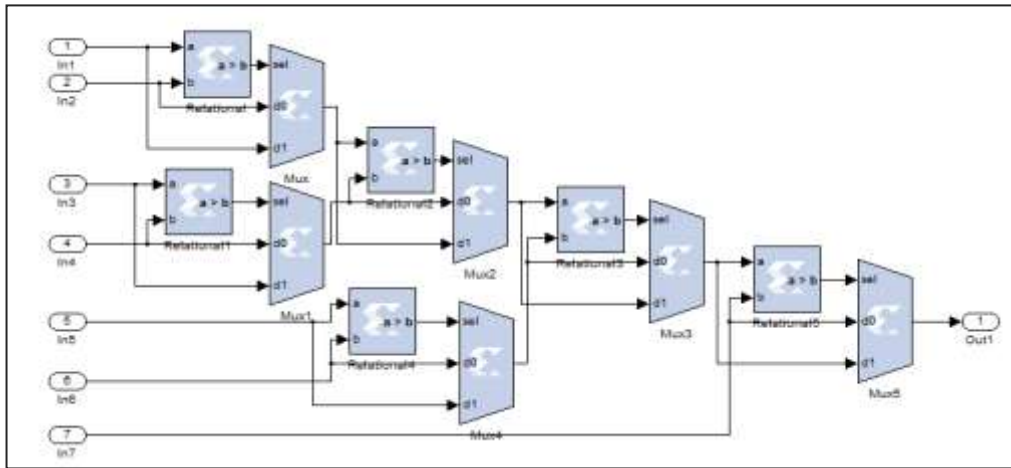


Figure 6. XSG Design of maximum operator linking the different rules

The determined rules are regrouped in accordance with the determined control vector and constitute the 8 inputs of the block designing the adequate control vector. Once control vector is determined, the sequence of logic variables associated is chosen. The detailed design of determining the inverter's switches is shown in Figure 7, Figure 8, and Figure 9

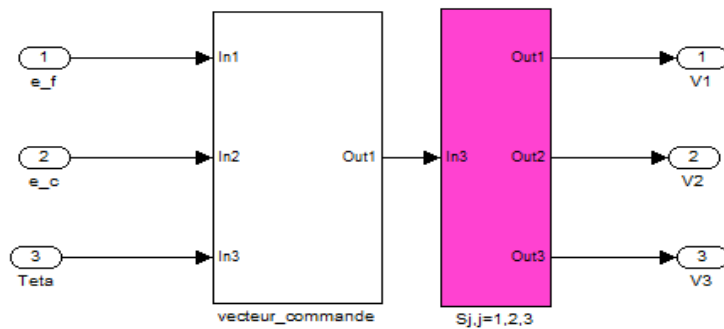


Figure 7. XSG Design of determining the inverter's switches

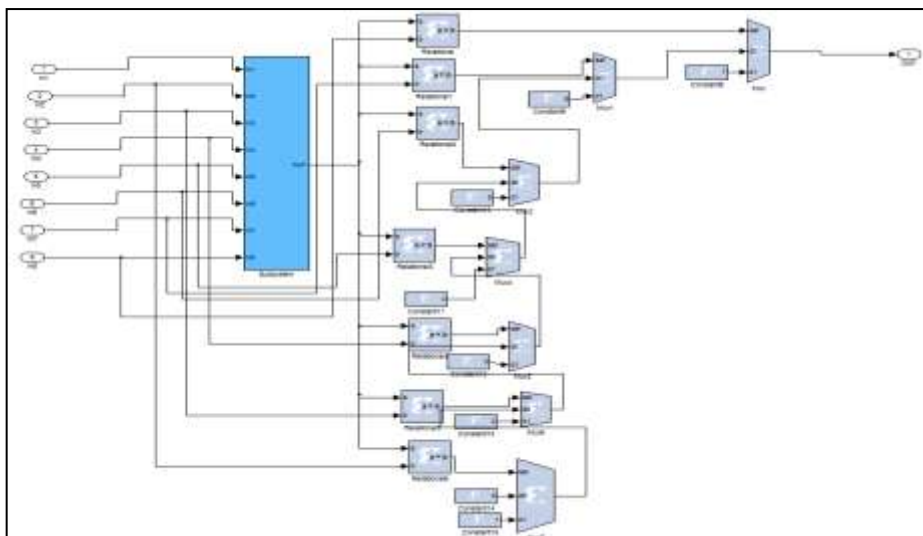


Figure 8. XSG Design of The Subsystem $S_{j,j=1,2,3}$ of Figure 12

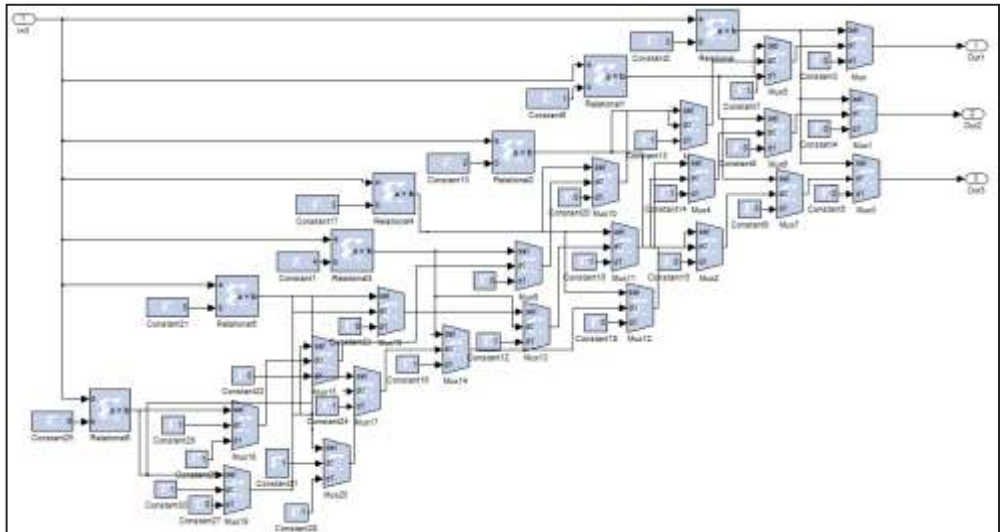


Figure 9. XSG Design of The Subsystem “Vecteur-commande” of Figure 12

6. Simulation results and Interpretation

The performance of the developed FLC is evaluated through a MATLAB/Simulink and XSG simulation. Indeed, DTC and DTFC scheme are simulated and the different results as well as interpretations are given in this section.

A. Simulation results

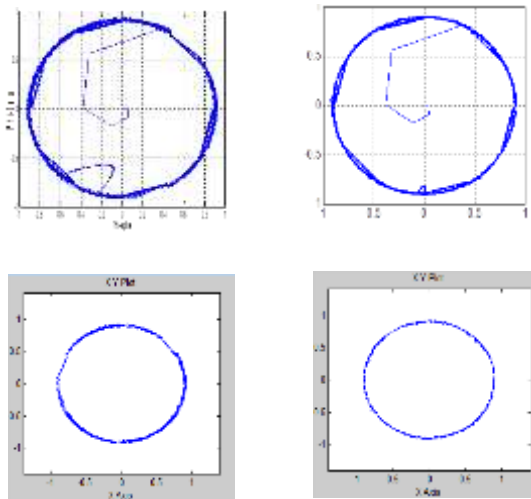


Figure 10. Stator Flux evolution and trajectory (a) DTC, (b) DTFC

Table 3. illustrates induction machine parameters used in the simulation.

Table 3. Parameters of induction machine

Nominal Power	1.5KW
Moment of Inertia	$J=0.049 \text{ kg.m}^2$
Stator resistance	$R_s=5.717\Omega$
Rotor resistance	$R_r=4.282\Omega$
Stator inductance	$l_s=0.464\text{H}$
Rotor inductance	$l_r=0.464\text{H}$
Mutual inductance	$M_{sr}=0.441\text{H}$
Viscous friction coefficient	$f= 0.0029 \text{ N.m.s/rad}$

The Electromagnetic torque and flux references used in the simulation are equal to 10 N.m and 0.91 wb respectively. The sampling period of the system is 50 μ s.

We obtain in Figure10, Fig .11, Figure12, the evolution of stator flux evolution and trajectory, electromagnetic torque and stator current in the cases of DTC and DTFC scheme respectively.

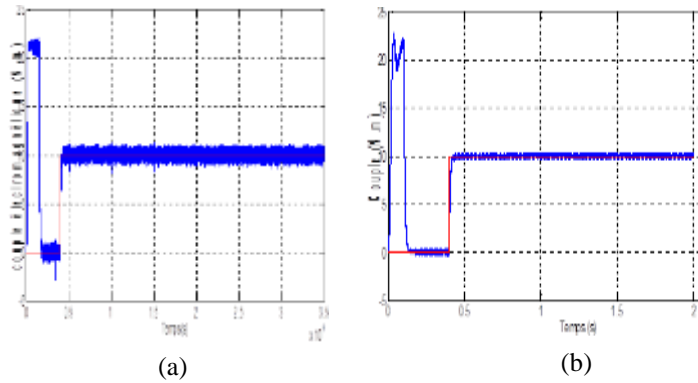


Figure 11. Electromagnetic Torque response (a) DTC, (b) DTFC

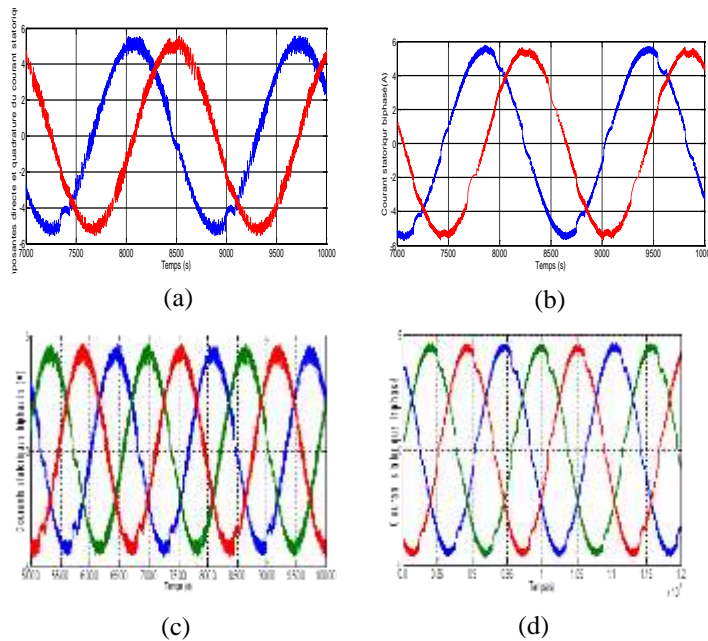


Figure 12. Stator currents (a) Three phases Stator currents in DTC, (b) Three phases Stator currents in DTFC, (c) Two phases Stator currents in DTC, (d) Two phases Stator currents in DTFC

B. Interpretation

From Figure 10 (a) and (b) we can notice that stator flux trajectory takes an almost circular shape form with a slight deviation at the border and its form is enhanced in the case of a DTFC compared with DTC.

Figure 11 illustrates the Electromagnetic Torque response. Its ripples are significantly reduced under DTFC compared with DTC. Furthermore, the quality of Stator current is improved; in Figure 12 we can notice a notable reduction on stator current distortion.

We can notice the improvement of the different simulations obtained previously in the DTFC compared to DTC and which are resumed in Table.4.

Table 4. Comparison of results observed in the torque ripples and flux in DTC and DTFC

	DTC		DTFC	
	In Wb/N.m	In %	In Wb/N.m	In %
Stator flux ripple	0.06	6.59	0.04	4.4
Torque ripple	2.25	22.5	0.7	7

The performance of the proposed controller are tested and simulated and highlighted by comparing to conventional DTC which is based on conventional hysteresis comparator and the switching table. These results prove the efficiency of the introduced DTFC scheme. FPGA implementation of the DTFC Algorithm

Hardware block of the FLC established in XSG can be synthesized and downloaded into the desirable FPGA chip. Table.5 show the implementation results for DTFC Utilization of the DTC and DTFC implementation on the Xilinx Virtex-V FPGA is shown in Table V. It presents the information concerning the number of required Input Output blocks, Slices, Flip Flops, and Multipliers. Figure13 presents the implementation result made by Xilinx ISE FPGA Editor.

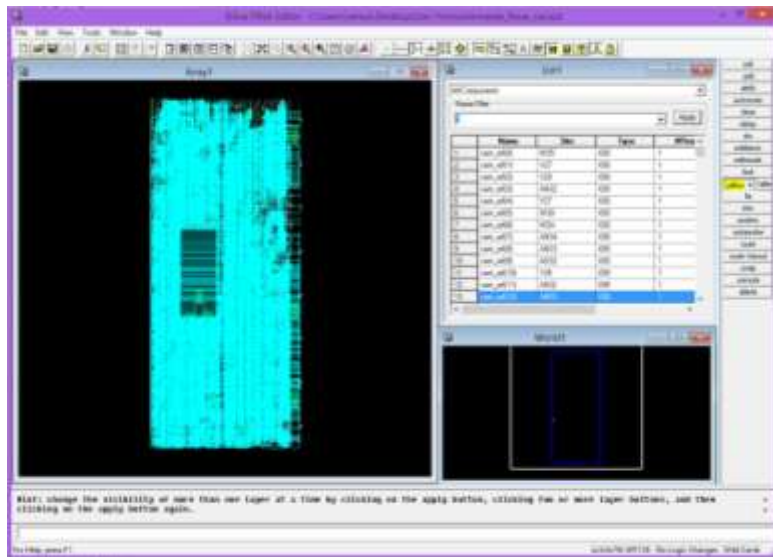


Figure 13. Graphical view of the implementation design on FPGA

Table 5. resources utilisation table

Resources	DTC	DTFC
Number of bonded IOBs	120	120
Number of BUFG/BUFGCTRLs	1	1
Number of Slice LUTs	1987	9156
Number of DSP48Es	12	14

7. Conclusion

In this paper, an improvement for DTC algorithm is proposed by using a fuzzy logic controller. It aims to reduce electromagnetic torque and stator flux ripples, as well as stator current distortion. The DTFC scheme presented in this paper has shown through the different simulations using MATLAB/Simulink and XSG its superior performance over conventional DTC. FLC developed is designed to be implemented on FPGA using XSG which is an interesting approach. In fact, its use is very practical since HDL knowledge is unnecessary so, implementation time is reduced. So that, the obtained design can be automatically translated into VHDL programming language and then embedded into the Xilinx FPGA application board.

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