Hardware Implementation of a Neuro Fuzzy Based DTC-SVM of an Induction Motor on the FPGA.

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*Abstract:-*The implementation of Direct Torque Control (DTC) in Induction Motor (IM) drives suffers from complex tuning and overshoots problems. One of the various methods to tackle this problem is the use of intelligent controllers like Neuro Fuzzy Controller (NFC). This paper suggests a new approach, NFC based space vector modulation (SVM), on the direct torque controlled IM and aim of the approach is to overcome high torque ripple disadvantages of conventional DTC. The objective of this paper is to present a new method to implement the algorithm of NEURO FUZZY based SVM-DTC on Field Programmable Gate Array (FPGA). The hardware implementation method is based on Xilinx System Generator (XSG) which a modeling tool developed by Xilinx. This tool can automatically generate the VHDL code without resorting to a painful programming without being obliged to do approximations and more we can visualize the behavior of the machine before implementation which is very important for not damage our machine. The simulation results showed that a significant improvement in the dynamic torque and speed responses when compared to the conventional direct torque control method.

Key-Words: - Neuro Fuzzy Controller (NFC), Xilinx System Generator (XSG), Direct Torque Control (DTC), Field Programmable Gate Array (FPGA).

1 Introduction

In practice, the vector control algorithm for IM is implemented using Digital Signal Processor (DSP).The DSP control procedure is performed sequentially; this may result in a slower cycling period if complex algorithms are involved. Employing FPGA in implementing vector control strategies provides advantages such as simpler hardware and software design, rapid prototyping, hence fast switching frequency and high speed computation [1] [2].

For the control of the variable speed electrical machines, various control algorithms are used. In recent years, many efforts have been made to improve the performance of DTC, especially by fixing the inverter commutation frequency and by reducing the torque ripples. Several studies investigated the possibility to associate Space-Vector Modulation (SVM) techniques with DTC strategies in order to control the switching frequency [3]- [6].

On the other hand, intelligent control methods like Neuro Fuzzy Logic have been explored by several researchers for its potential to incorporate human intuition in the design process. The Neuro Fuzzy has gained great attention in the every area of electromechanical device control due to no need. In general the use of fuzzy systems does not require the accurate mathematical model of the process to be controlled. Instead, it uses the experience and knowledge of the involved professionals to construct its control rule base. The NFC has proved powerful in the power electronics area and control of electric machines as shown in various articles in the literature [7]-[9]. In our case we use the NEURO FUZZY based DTC- SVM that contains a speed control loop, stator flux regulator, electromagnetic torque regulator and fuzzy logic controller.

During the past few years several researchers use the FPGA for controlling electrical system [10]-[15]. Most of them develop the algorithm on a VHDL hardware description language. For the hardware implementation of the NEURO FUZZY based DTC- SVM of an IM on the FPGA, we use XSG toolbox developed by Xilinx and added to Matlab/Simulink. The XSG advantages are the rapid time to market, real time and portability. Once the design and simulation of the proposed algorithm is completed we can automatically generate the VHDL code in Xilinx ISE.

This paper is organized as follows. In section 1 the general structure of the control DTC is presented. In section 2 and 3 the proposed NFC is described in details, mentioning different aspects of its design. Section 4 presents the simulations results using XSG, Matlab/Simulink software packages and the implementation on FPGA controller .In the section 5 we present the FPGA simulation results of NEURO FUZZY based DTC-SVM. In the end, the conclusion is given in Section 6.

2 Direct Torque Control of an Induction Motor

In conventional DTC scheme, the control of an IM involves the direct control of stator flux vector by applying optimum voltage switching vectors of the inverter. The structure of the conventional DTC was shown in Fig.1 which consists of two hysteresis comparator, torque and flux estimators, voltage vector selector and voltage source inverter (VSI). The basic idea of the DTC concept is to choose the best vector of the voltage, which makes the flux at its rated value and produce the desired torque. During this regime, the amplitude of the flux rests in a pre-defined band.

In the basic form , the stator flux φ_s is estimated with :

$$\varphi_s = \int_0^t (V_s - R i_s) dt \qquad (1)$$

The stator voltage and stator current are calculated from the state of three phase (Sa ,Sb ,Sc) and measured currents (ia, ib, ic).

$$V_s(S_a, S_b, S_c) = \sqrt{\frac{2}{3}} E_0 (S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}}) \qquad (2)$$

$$i_s(i_a, i_b, i_c) = \frac{2}{3}(i_a + i_b e^{j\frac{2\pi}{3}} + i_c e^{j\frac{4\pi}{3}})$$

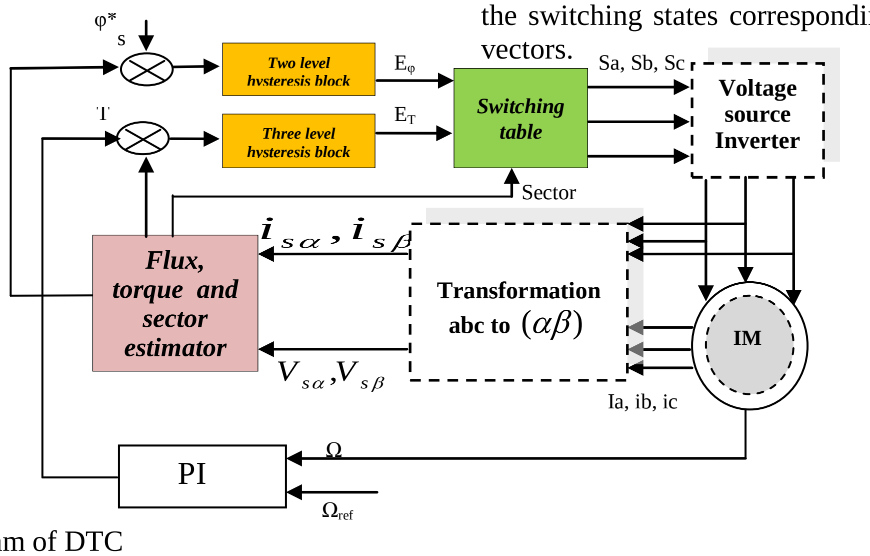

Fig.1. Block diagram of DTC

Phase angle and stator flux amplitude are calculated in expression (3)

$$\theta_s = arctg(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}})$$

$$\varphi_s = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \qquad (3)$$

The developed electromagnetic torque T of the machine can be evaluated by equation (4):

$$T = \frac{3}{2} p (i_{s\beta} \phi_{s\alpha} - i_{s\alpha} \phi_{s\beta}) \qquad (4)$$

The estimated values of the stator flux and electromagnetic torque are compared with their reference values φ_{ref}, T_{ref} respectively. Switching states are selected by the switching table, where E_φ is the error of the stator flux and E_T is the error of the electromagnetic torque after hysteresis block. S_i (1:6) means the sector (Table 1).

Table 1. Switching table for DTC

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

3 The Neuro Fuzzy based DTC-SVM

3.1 Principle of DTC-SVM

The objective of space vector pulse width modulation technique is to obtain the demanded output voltage, by instantaneously combination of the switching states corresponding the basic space vectors.

The principle of vector MLI is to project the desired stator voltage vector V_s on the two adjacent vectors corresponding to two switching states of the inverter. The values of these projections provide the desired commutation times.

Expressing the voltage vector in the graduation (α, β) we have:

$$\overrightarrow{V_s} = V_{s\alpha} + jV_{s\beta} = \frac{T_1}{T_{\text{mod}}}\overrightarrow{V_1} + \frac{T_2}{T_{\text{mod}}}\overrightarrow{V_2} \qquad (5)$$

The key step of the SVM technique is the determination of T_i and T_{i+1} during every modulation period T_{mod}. Expanding this equation it is possible to express the time T_1 and T_2 in terms of $V_{s\alpha}$ and $V_{s\beta}$. The conduction time will be expressed as follows:

$$T_1 = \left(\sqrt{\frac{3}{2}}V_{s\alpha} - \sqrt{\frac{1}{2}}V_{s\beta}\right).\frac{T_{\text{mod}}}{E} \qquad (6)$$

$$T_2 = \sqrt{2}V_{s\beta}.\frac{T_{\text{mod}}}{E}$$

To facilitate the calculations, we normalize the voltages $V_{s\alpha}$ and $V_{s\beta}$ by posing:

$$\hat{V}_{s\alpha} = \frac{V_{s\alpha}}{E}\sqrt{2} \qquad (7)$$

$$\hat{V}_{s\beta} = \frac{V_{s\beta}}{E}\sqrt{2} \qquad (8)$$

Consequently, the duties expressions are given as follows:

$$D_0 = 1 - D_1 - D_2 \qquad (9)$$

$$D_1 = \frac{\sqrt{3}}{2}.\hat{V}_{s\alpha} - \frac{1}{2}.\hat{V}_{s\beta} \qquad (10)$$

$$D_2 = \hat{V}_{s\beta} \qquad (11)$$

The duties of each phase of the inverter are presented as follows:

$$S_a = 0.5(1 + D_1 + D_2) \qquad (12)$$

$$S_b = 0.5(1 - D_1 + D_2) \qquad (13)$$

$$S_c = 0.5(1 - D_1 - D_2) \qquad (14)$$

3.2 Principle of Neuro Fuzzy based DTC-SVM

The main idea of Neuro Fuzzy based DTC –SVM is to recover the reduction of the ripples of torque and flux, and to have superior dynamic performances.

The NFC is a system formed by the learning algorithm inspired by neural network theory to determine its parameters (fuzzy rules, fuzzy sets). The Adaptive Neuro-Fuzzy Inference Systems (ANFIS) structure is one of the proposed methods to combine artificial neural networks and fuzzy logic. An NF inference system contains fuzzification, rule base, defuzzification unit as well as a decision making unit. The structure proposed contains 5 network layers:

First layer (Fuzzification): The first layer gives the degrees of membership of the input variables (x_1, x_2) to the fuzzy sets (A_i, B_{i-2}).

$$O_i^1 = \mu_{Ai}(x_1) \quad for \quad i = 1,2,3 \qquad (15)$$

$$O_i^1 = \mu_{Bi-2}(x_2) \quad for \quad i = 4,5,6 \qquad (16)$$

Where:

- x_1, x2: the inputs of the respective nodes (1, 2,3) and (4,5,6);
- A_i: a linguistic term associated to the membership function μ_{Ai};
- B_{i-2}: a linguistic term associated to the membership μ_{Bi-2} function.

Second layer (fuzzy rules): each node is associated to generate the synaptic weights .The node output represents the degree of membership of each rule:

$$O_i^2 = w_i = \prod_{i=1}^{m} \mu_{Ai}(x) \qquad (17)$$

Third layer (Normalization): The nodes of this layer realize the normalization of weights of fuzzy rules using the following equation:

$$\overline{w_i} = \frac{w_i}{\sum_{i=1}^{m} w_i} \qquad (18)$$

Fourth layer (Défuzzification): Each node in this layer calculates the outputs of the rules by using this function:

$$O_i^4 = y_i = \overline{w_i}(p_i x_1 + q_i x_2 + r_i) \qquad (19)$$

Fifth layer (Summation): The fifth layer provides the output by calculating the sum of the outputs of the previous layer:

$$O_i^5 = \sum_{i=1}^{m} y_i \qquad (20)$$

Fig. 2 presents a possible schematic of Neuro Fuzzy based DTC-SVM. There are two different loops corresponding to the magnitudes of the stator flux and torque. The error between the estimated stator flux magnitude φ_s and the reference stator flux magnitude φ_s^* and the error between the estimated torque T and the reference torque T^* are the input of Neuro Fuzzy logic controller. The outputs of the regulator are used as inputs of SVM bloc.

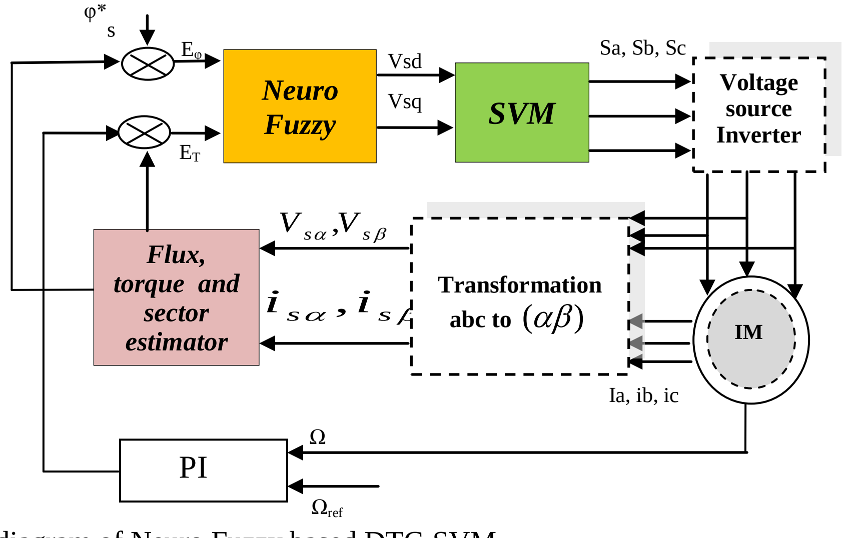

Fig.2. Block diagram of Neuro Fuzzy based DTC-SVM

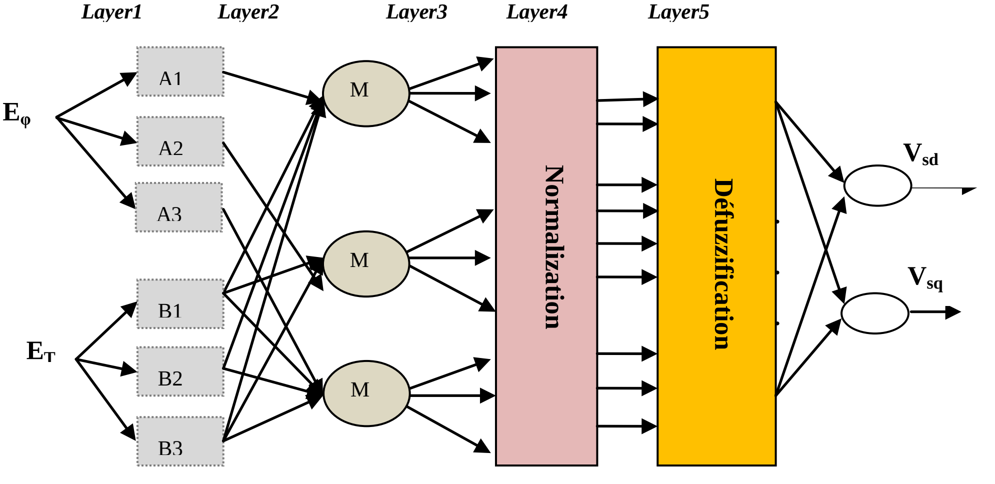

Fig. 3. Proposed Neuro-Fuzzy Controller scheme.

The ANFIS controller have two variables input, the electromagnetic torque error and stator flux error, the outputs are the voltage vector V_{sd} and V_{sq}. The ANFIS network was programmed using the toolbox provided by Matlab. The internal structure of the NFC is shown in Fig 3.

In the first layer of the NF structure, the stator flux error and the electromagnetic torque error are multiplied by weights which are introduced through the fuzzy membership functions. These functions are chosen to be Trapezoidal and Triangular shaped. The second layer calculates the minimum of the input signals. The output values are normalized in the third layer. The torque fuzzy logic regulator variables memberships is representing in Fig 4.

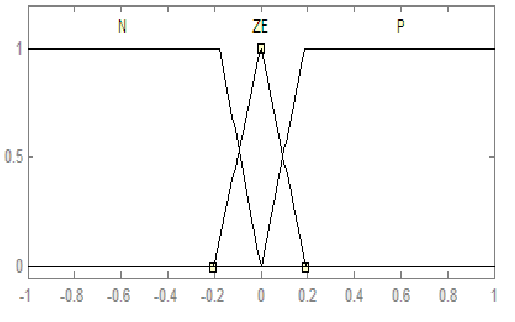

Fig . 4 .Torque regulator variables membership

Fig. 5 shows the Flux fuzzy logic regulator variables memberships.

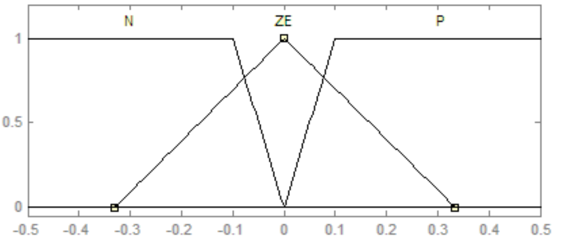

Fig .5 Flux regulator variables membership

The direct component of the stator voltage V_{sd} is determined by the rule of the form:

R_x: if E_φ is Fe and E_T is Te then $V_{sd}= a E\varphi + b E_T$

However, the quadrature component of the stator voltage V_{sq} is determined by the rules of the form:

R_y: if E_φ is Fe and E_T is Te then $V_{sq}= -b E\varphi + a E_T$

Where Fe = Te = {N, ZE, P} are the fuzzy sets of the inputs and, a and b are coefficients of the first order polynomial function typically present in the consequent part of the firs-order Takagi-Sugeno fuzzy controllers.

The rule base to calculate Vsd and Vsq is shown in Table 2. The product is the conjunction operator and the weighted average (wtaver) is the defuzzification method used to set the controller in the MATLAB fuzzy editor.

Table.2. Fuzzy rules for computation of V_{sd} and V_{sq}

E_φ / E_T	**N**	**ZE**	**P**
N	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe
ZE	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe
P	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe	V_{sd}=aFe+bTe V_{sq}=-bFe+aTe

4 Use of Xilinx System Generator (XSG) in the controller design.

4.1 Description of Xilinx System Generator

The design developed in this paper was performed according to an appropriate methodology. This new methodology consists of a set of steps and roles that offer considerable hardware design advantages see Fig.6.

A low cost Xilinx Virtex 5 XC5VFX50T-1FFG1136 (ML506) FPGA, that contains a matrix of 7200 Slices and includes a 50 MHz oscillator (Clock period equal to 20 ns), was used as a target for the implementation of the controller. The designed architecture wasn't coded using the VHDL (Very high speed integrated Hardware Description Language) hardware description language but in this paper, it resorts to use XSG.

XSG is a modeling tool developed by Xilinx for the design of implemented systems on FPGA. It has a library of varied blocks, which can be automatically compiled into an FPGA. In this work, XSG is used to implement the architecture of the Neuro Fuzzy based DTC-SVM on FPGA. In the first step, we begin by implementing of the proposed architectures using the XSG blocks available on the Simulink library. Once the Design of the system is completed and gives the desired simulation results, the VHDL code can be generated by the XSG tool. After generation of VHDL code and the synthesis, we can generate the bit stream file. Then we can move this configuration file to program the FPGA.

System Generator provides hardware co-simulation, making it possible to incorporate a design running on an FPGA directly into a Simulink simulation. Hardware Co-Simulation compilation targets automatically create a bit stream and associate it to a block. Hardware in the loop (HIL), or FPGA in the loop, is a concept that as revealed by the name uses the hardware in the simulation loop. This leads to easy testing and the possibility to see how the actual plant is behaving in hardware. By having the stimuli in software on the PC, implementing a part of the loop in hardware and then receiving the response from hardware back in the software.

4.2. Design of the Neuro Fuzzy based DTC-SVM using XSG

In MATLAB, the ANFIS editor graphics user interface is available in Fuzzy Logic Toolbox. Using a given input/ output data set, the toolbox constructs a fuzzy inference system (FIS) whose membership function parameters are adjusted using either a back propagation algorithm alone, or in a combination with a least squares method. The switching frequency of PWM inverter was set to be 10kHz, the stator reference flux considered was 0.92 Wb and the coefficients considered were a = 90 and b = 2.

For Neuro Fuzzy based DTC-SVM modeling, the blocks used are mostly multipliers, adders, Mcode, etc.

The Design of the SVM introduced into the equations system (5), (6), (7), (8) and (9) as shown in Fig. 8.

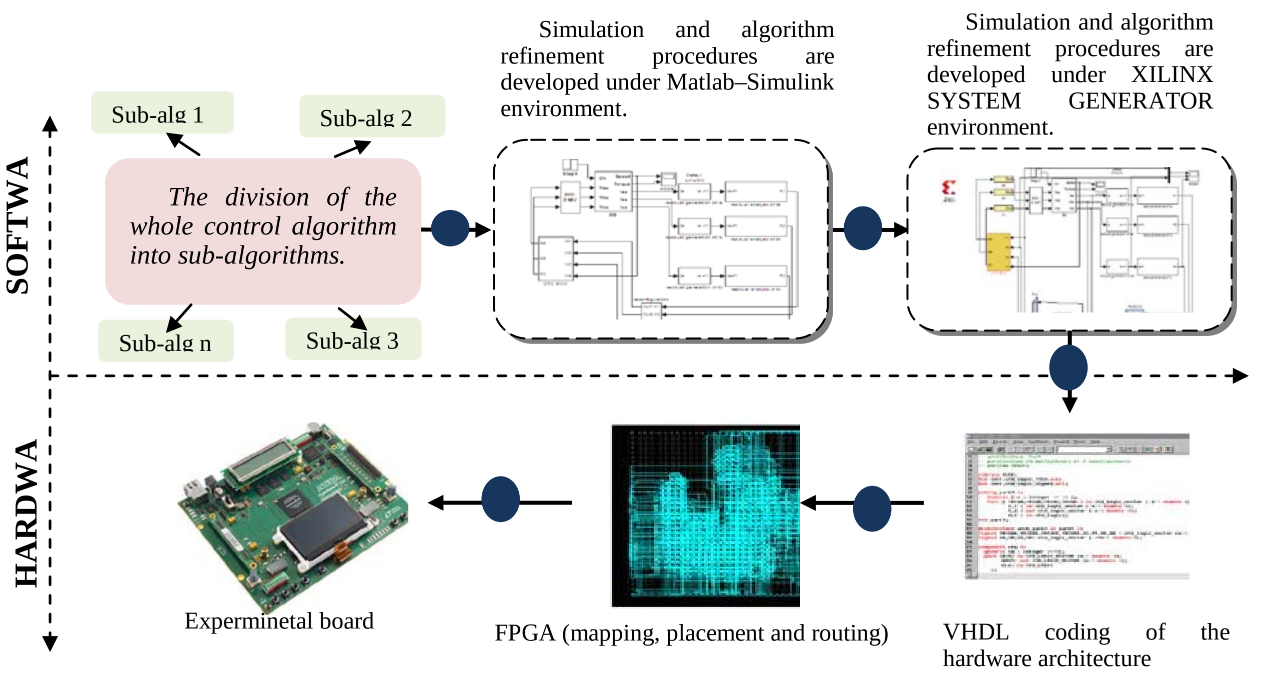

Fig.6. Steps of hardware design

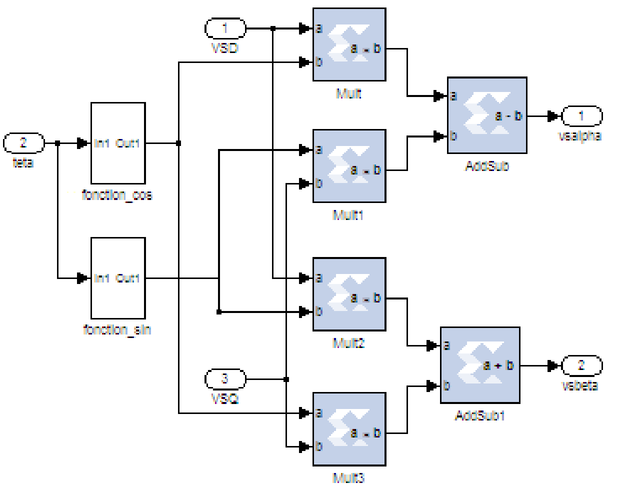

Fig. 1 . Calcul of $V_{s\alpha}$ and $V_{s\beta}$

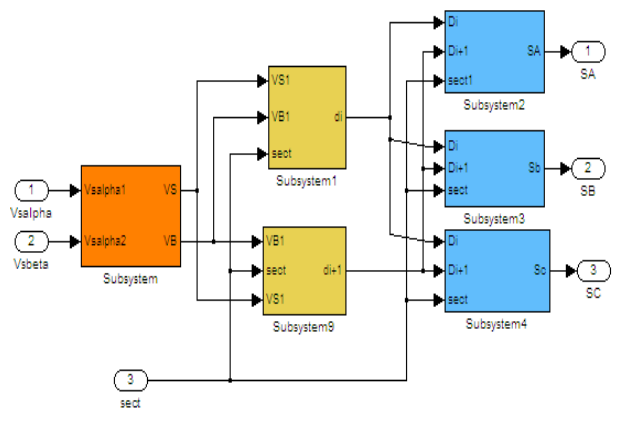

Fig.8. Calcul of Sa, Sb, Sc

4.3 Simulation Results using Xilinx System Generator and Discussions

The structure of the Neuro Fuzzy based DTC-SVM of an IM is shown in Fig.9. The simulation of the conventional DTC and the Neuro Fuzzy based DTC-SVM is achieved using the XSG. The speed, torque and flux references, used in the simulation results of the DTC strategy are Ω_{ref}=300rad/s and φ_{ref} = 0.91 Wb, respectively.

The performance of the IM under different operating conditions was also investigated in order to verify the robustness of the proposed control scheme. The steady state behaviors of IM with the different controller are illustrated in Fig 10-11-12.

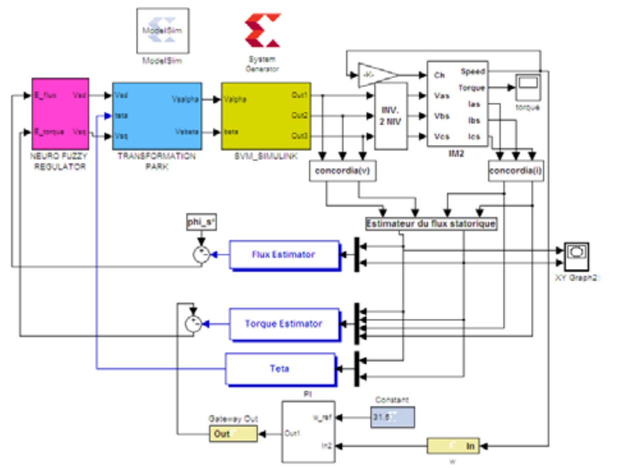

Fig.9. Schematic of the Neuro Fuzzy based DTC-SVM

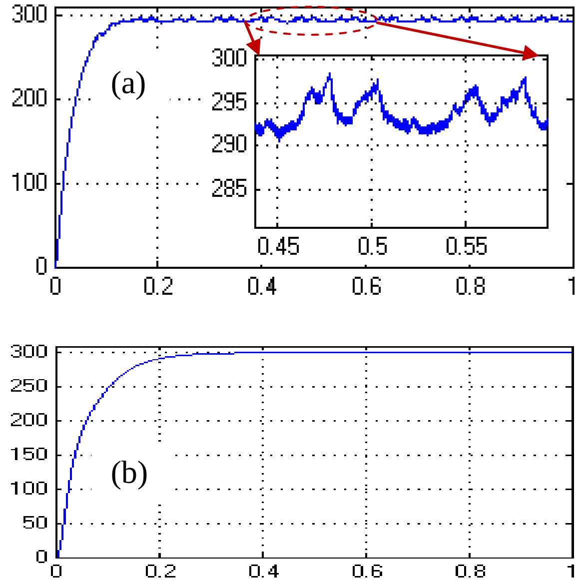

Fig.10. Evolution rotor speed for: (a) Conventional DTC (b) NEURO FUZZY DTC-SVM

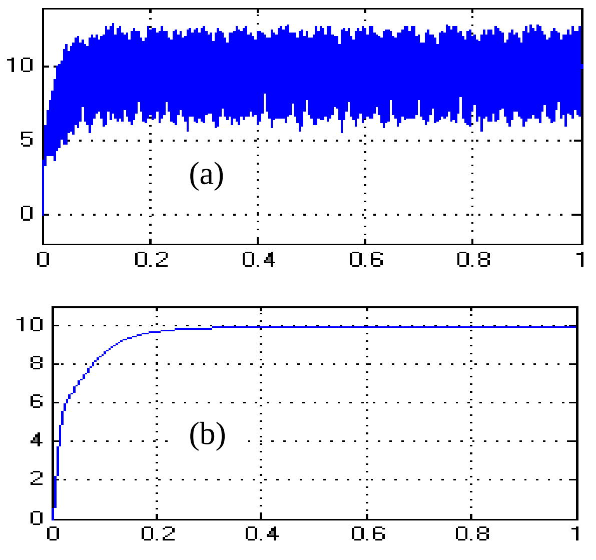

Fig.11. Evolution torque for: (a) Conventional DTC (b) NEURO FUZZY DTC-SVM

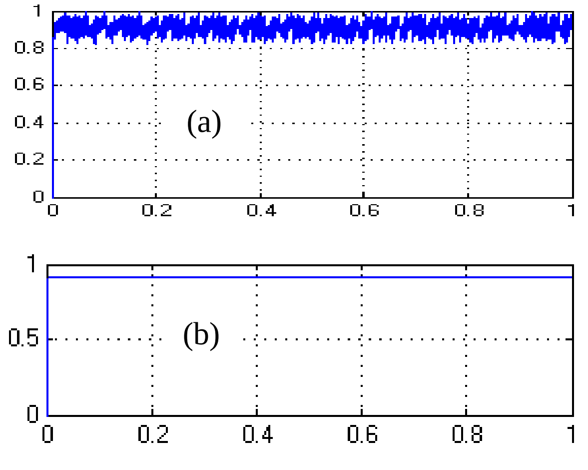

Fig.12. Evolution flux for: (a) Conventional DTC (b) NEURO FUZZY DTC-SVM

Fig.11 shows the electromagnetic torque response when the step change in the motor load is applied. However, the main differences have appeared at torque responses of both control methods at steady state conditions. It can be seen that, with the Neuro Fuzzy DTC SVM torque ripples of the motor are reduced significantly.

We can notice in Fig. 12 that the stator flux reached immediately its reference value with a small overshoot equal to 0.02 using XSG.

These results show the effectiveness of the Neuro Fuzzy DTC-SVM control relative to the conventional DTC control in terms of ripples in the stator flux and electromagnetic torque.

Using ANFIS control provides the system with minimum ripple for both torque and flux. If we need to compare of steady state conditions of the motor for both control method, it must be pointed out that the Neuro Fuzzy DTC SVM controlled motor has better performance as lesser torque ripples and speed fluctuations.

5 Implementation Results

The register transfer level (RTL) schematic of the Neuro Fuzzy DTC-SVM in the Xilinx Integrated Synthesis Environment (ISE) 12.4 is given in Fig. 13. The performance of the hardware solution based on the FPGA in terms of execution time is shown Table 3.

Using the dSPACE, the sampling time is to 100µs, due to the sequential processing of the dspace [16] [17].

Using the FPGA the execution time of the control algorithm of IM is (1 to 2µs). Therefore, the obtained execution time using the FPGA is far lower compared to the software solutions. In this paper the execution time of the Neuro Fuzzy DTC-SVM is 0.99µs using the Xilinx Virtex-V FPGA with an xc5vfx70t-3ff1136 package.

Table 3. Execution time T

Module	*Execution time*
Concordia	0.17
Neuro Fuzzy	0.52
SVM	0.14
PI controller	0.16

Total Time:

$T_{total} = T_{Neuro\ Fuzzy\ DTC\text{-}SVM} + T_{ADC}$

T_{ADC} : Analogue to digital conversion time.

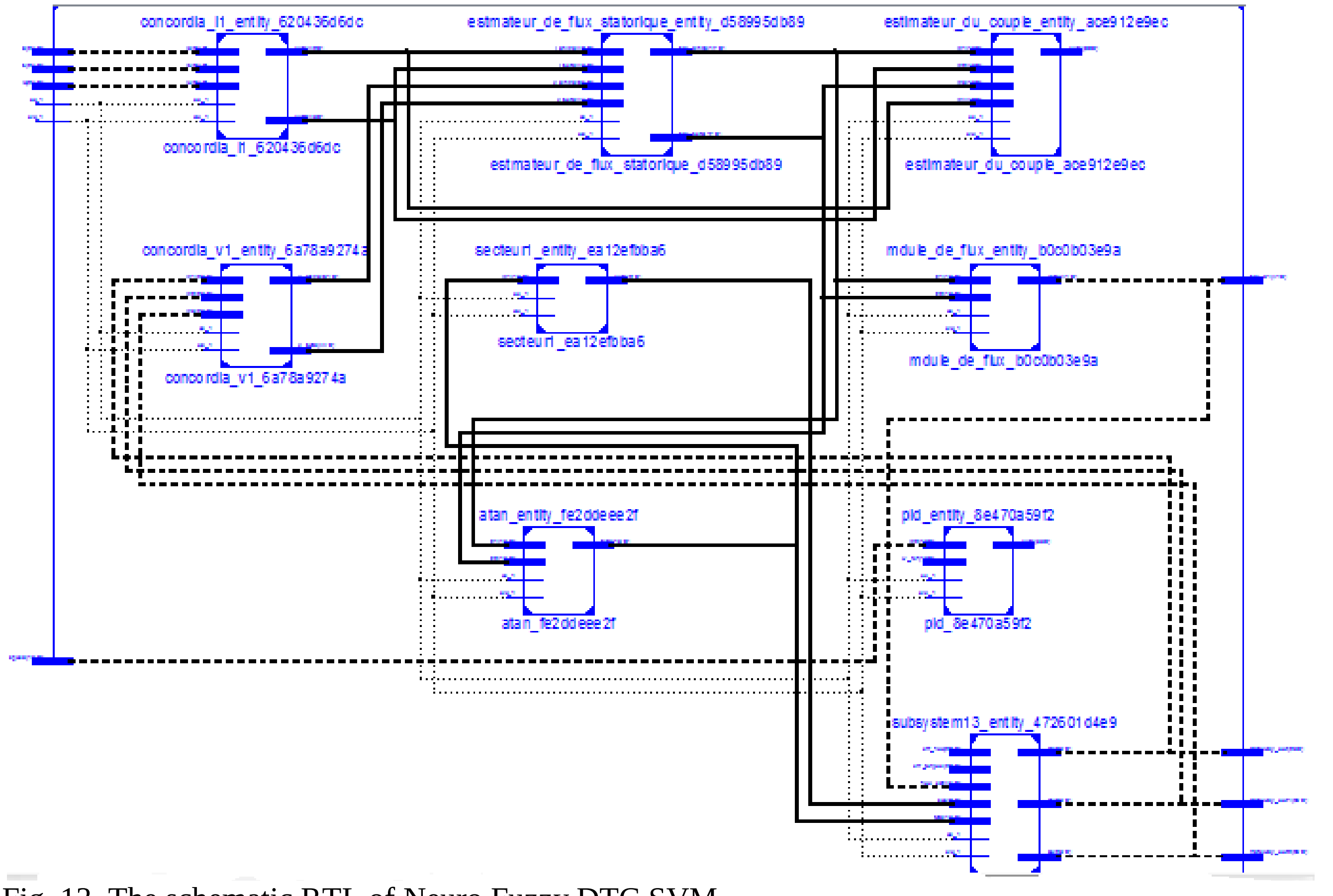

Fig. 13. The schematic RTL of Neuro Fuzzy DTC SVM

6 Conclusions

In this paper Neuro Fuzzy DTC-SVM controller of IM has been proposed. The low torque and flux ripple and constant switching frequency were obtained using space vector modulation technique. Numerical simulations results at different operating conditions verify that the proposed Neuro Fuzzy DTC-SVM controller achieved good performance measure. These results validate the proposed scheme. The proposed high performance scheme is designed using XSG. The VHDL code is generated and synthesized. The implementation results show the performances of the hardware implementation in terms of design time which is reduced, minimal resources utilization, and low execution time.

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