International Journal of Sciences and Techniques of Automatic control & computer engineering
IJ-STA, Volume 9, N°1, December 2015, pp 2041–2048.

Sliding Mode Speed Controller Associated with the classical DTC: Hardware FPGA- Co-simulation

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Abstract*— the aim of this paper is to present a rapid prototyping of the Direct Torque Control (DTC) based Sliding Mode Speed Controller (SMSC) of an Induction Motor (IM). Conventionally, the IM speed is controlled with Proportional Integral (PI) regulator which is featured by its simplicity, but this controller is not able to support the variation of the motor parameters and the external disturbances as the load torque variation. The first objective of this study is to develop an SMSC in order to overcome the PI controller limitations. The rapid prototyping consists to implement the SMSC associated to the DTC on the Field Programmable Gate Array (FPGA) using Xilinx System Generator (XSG), that present the second aim of this paper. The algorithm of the proposed approaches has been developed, designed and verified by simulation utilizing the XSG tool. The VHDL code has been generated and synthesized. A comparative study under load torque variation between the PI and the SMSC has been carried out by simulation through the XSG tool. A hardware co-simulation has been carried out utilizing a Xilinx FPGA Virtex V.

***Index Terms*—Direct Torque Control, PI regulator, Sliding Mode Speed Controller, Xilinx System Generator, FPGA.**

I. INTRODUCTION

In 1984, the classical Direct Torque Control (DTC) of the AC motors was developed by Takahashi and Noguchi, which is known as a robust approach, thanks to its less dependence to the motor parameters [1]. In fact, the classical DTC utilizes only the stator resistance to estimate the stator flux. Furthermore, this approach is characterized by a good dynamic response [3, 4]. By comparison with the Field Oriented Control, the classical DTC is featured by a simple structure. In fact, the Pulse Width Modulation (PWM), the current and flux controllers used in the FOC are not required in the DTC structure, which increase complexity of the algorithm complexity and its sensitivity to parameters variations. In spite to its simple structure, the DTC is producing a fast torque in steady state and at a low speed with high load torque [5]. In the field of the Electric Vehicles (EV), it is important to produce a fast torque response, guarantee the robustness and a reasonable cost, the DTC is the best candidate which can be used for EV applications [6]. The main limitations of the DTC are the important ripples in electromagnetic torque and the stator flux which can be rectified using the fuzzy logic which is developed in paper [7], or the space vector modulation which is developed in papers [8, 9].

In spite to its simplicity, the conventional PI regulator is the most commonly used to regulate the speed of electrical motors [10, 11]. However, the PI parameters are strongly linked to the Induction Motor (IM) parameters; therefore tuning the parameters of the PI is difficult. Furthermore, the conventional PI is sensitive to the external disturbances which consequently decrease the performances of the system. Another method developed in paper [12] which consists to use the fuzzy logic in order to optimize the conventional PI performances. In this work, a Sliding Mode Speed Controller (SMSC) is developed. The proposed SMSC is a modern controller used to solve the problems of speed tracking for the DTC of IMs. This controller is featured by its robustness overlooked of the load torque disturbances and the parameter variations. The SMSC is a promising approach for solving the parameters problem of the conventional PI regulator.

Nowadays, the software solutions like the microcontrollers (STM32...) and the Digital Signal processors (DSPs) become a secondary choice for several industrial applications. Due to their sequential processing, the DSPs and STM32 become not able to meet the need of the market. Among novel digital devices, the Field Programmable Gate Array (FPGA) is the first candidate which must be used, due to its important hardware resources and its parallel processing. These available resources are utilized to increase the calculation speed.

Recently, the FPGAs devices are used by several researchers to control the electrical motors [12, 14]. The advantages of the hardware implementation on the FPGAs are multiple: (1) The execution time is reduced thanks to its parallel processing, (2) rapid prototyping, (3) the possibility of implementing complex algorithms and reducing the execution time [15].

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This paper was recommended for publication in revised form by the Editor Staff.
Edition: CPU of Tunis, Tunisia, ISSN: 1737-7749

To configure an FPGA the VHDL code must be used. However, this method requires huge knowledge and a lot of time. Another method named Xilinx System Generator (XSG) which can be utilized to design the suggested algorithm under Simulink Environment and lets the user to generate the VHDL code [15]. In this paper, the XSG is chosen thanks to its simplicity and rapid prototyping.

This paper is ordered as follows, a briefly reviews of the IM model and the classical DTC approach are represented in section 2. In section 3, a theoretical study of the SMSC is described. In sections 4, the DTC-SMSC architecture from XSG is presented. The digital simulation, the VHDL code generation and the hardware co-simulation are illustrated and discussed in section 5.

II. IM MOTOR MODEL AND DTC PRINCIPLE

A. IM modeling

The three-phase IM model is described by the following equation [17]:

$$\frac{dX}{dt} = [A]X + [B]U \tag{1}$$

where:

$$[A] = \begin{pmatrix} \dfrac{\frac{Rs}{Ls}+\frac{Rr}{Lr}}{\text{sigma}} & -\omega & \dfrac{Rr}{\text{sigma } LrLs} & \dfrac{\omega}{\text{sigma } Ls} \\ -\omega & \dfrac{\frac{Rs}{Ls}+\frac{Rr}{Lr}}{\text{sigma}} & -\dfrac{\omega}{\text{sigma } Ls} & \dfrac{R_r}{\text{sigma } LrLs} \\ -Rs & 0 & 0 & 0 \\ 0 & Rs & 0 & 0 \end{pmatrix}$$

$$U = \begin{pmatrix} v_{S\alpha} \\ v_{S\beta} \end{pmatrix}, \quad [B] = \begin{pmatrix} \dfrac{1}{\text{sigma } Ls} & 0 \\ 0 & \dfrac{1}{\text{sigma } Ls} \\ 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$X = [i_{S\alpha}\ i_{S\beta}\ \varphi_{S\alpha}\ \varphi_{S\beta}]^T$$

where ($i_{\alpha s}$, $i_{\beta s}$), ($v_{\alpha s}$, $v_{\beta s}$) and ($\varphi_{\alpha s}$, $\varphi_{\beta s}$), are the stator current, the stator voltage, the stator flux respectively in (α, β) reference. ω (rd/s), is the electric speed. The IM parameters are presented in the appendix.

B. DTC principle

In the classical DTC, the stator flux and the electromagnetic are the both controlled using two hysteresis controllers, which are shown in figure 2. In fact, the stator flux is controlled by hysteresis controller with two levels, in order to limit the variation of the flux module within its reference value. Similarly, the electromagnetic torque is controlled by a hysteresis controller with three levels in order to develop the desired torque and controlling the machine in both directions of rotation [18].

Equation (2) presents the relation between the voltage vector V_S and states of the inverter switches (S_A, S_B, S_C).

- If S_j= 1 (j= A B or C): the high switch of the inverter be closed, the low switch must be opened.

$$V_S = \sqrt{\frac{2}{3}} E\,(S_A + S_B e^{j\frac{2\pi}{3}} + S_C e^{j\frac{4\pi}{3}}) \tag{2}$$

Using the equation (2), the combination of the variables (S_A, S_B, S_C) generates eight positions of the voltage vector V_S, with two inactive vectors as shown in figure 1.

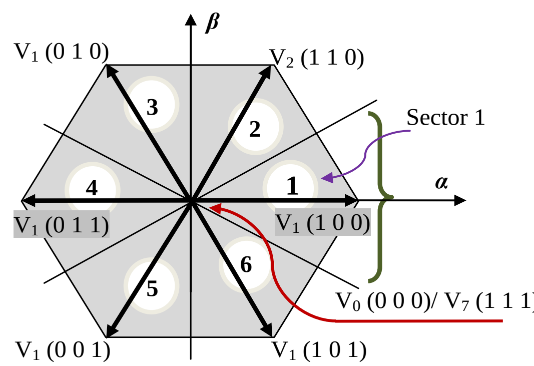

Fig. 1. Evolution of voltage vector V_S (S_A S_B S_C)

The estimated flux is given by equation (3), be seen that the flux estimation requires the measurement of the voltage, the current and the stator resistance, as shown in equation (3):

$$\varphi_S = \int (V_S - R_S i_S)dt \tag{3}$$

The flux magnitude is calculated as follows:

$$|\varphi_S| = \sqrt{\varphi_{S\alpha}^2 + \varphi_{S\beta}^2} \tag{4}$$

In the DTC to estimate the torque, equation (5) must be used:

$$T_{em} = \frac{3}{2} p(\varphi_{S\alpha} i_{S\beta} - \varphi_{S\beta} i_{S\alpha}) \tag{5}$$

The hysteresis controllers are featured by their independence of the induction motor parameters and their simplicity. These hysteresis controllers' structures are presented in figure 2.

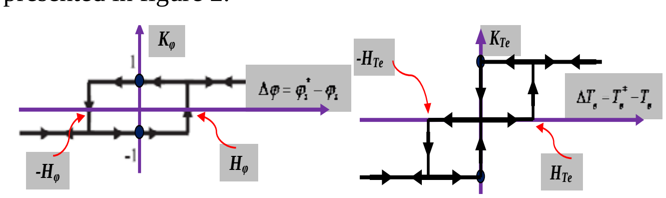

Fig. 2. Hysteresis controllers used for: (a). Flux, (b) Torque

Hysteresis comparators outputs noted (K_φ, K_C) and the number of the sector noted (N) (when the flux vector is located) present the switching table (Table I) inputs [2]. Utilizing the combination of these three inputs, a voltage vector V_i can be selected for each sampling period.

The stator voltage vector is the output of the switching table. Then, using the equation (2) the variables (S_A, S_B, S_C) of the inverter can be calculated.

Table 1. Control or Switching Table

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

Figure 3 illustrates the DTC diagram.

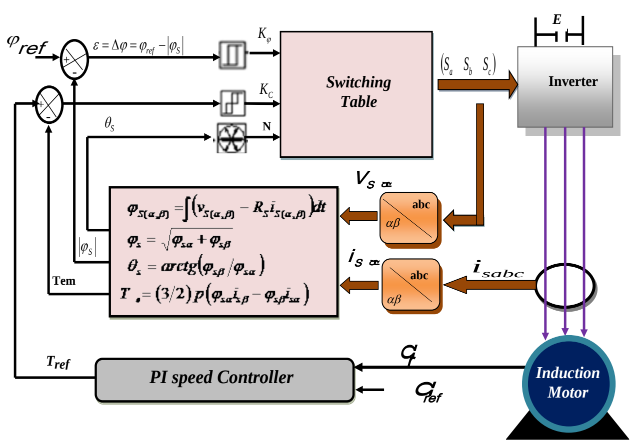

Fig. 3. DTC Diagram of an IM

C. *Development of the SMSC of speed*

In order to overcome the PI regulator limitations, an SMSC is proposed and developed. The proposed controller is known as a robust speed controller thanks to its robustness under the external disturbances, like the variations of the load torque and the motor parameters. The development of this controller is based on the electromechanical equation represented by (6).

$$J\frac{d\Omega}{dt} = T_{em} - T_L - f\Omega \tag{6}$$

with:
*f: T*he viscous friction coefficient.
J: Motor inertia.
T_L: Load torque.
T_{em}: Electromagnetic torque.
Ω: Mechanical rotor speed in rd/s.
The electromagnetic torque can be defined as follows:

$$T_{em} = \frac{3}{2}p(\varphi_{S\alpha} i_{S\beta} - \varphi_{S\beta} i_{S\alpha}) \tag{7}$$

The electromechanical equation of the motor can be rewritten as [19]:

$$\dot\Omega + a\Omega + d = bT_{em} \tag{8}$$

where: $a = \frac{f}{J}, b = \frac{1}{J}, d = \frac{T_L}{J}$

If uncertainties introduced, the equation (8) becomes:

$$\dot\Omega = -(a+\Delta a)\Omega - (d+\Delta d) + (b+\Delta b)T_{em} \tag{9}$$

These uncertainties are based on machine parameters like J, f and T_L.

The speed error is chosen as follows:

$$e(t) = \Omega(t) - \Omega^*(t) \tag{10}$$

with $\Omega^*(t)$ is the mechanical speed reference. The derivate of the equation (10) is written as:

$$\begin{cases} \dot e(t) = \dot\Omega(t) - \dot\Omega^*(t) \\ \quad = -(a+\Delta a)\Omega - (d+\Delta d) + (b+\Delta b)T_{em} - \dot\Omega^*(t) \\ \quad = -ae(t) + f(t) + x(t) \end{cases} \tag{11}$$

with

$$\begin{cases} f(t) = bT_{em}(t) - a\Omega^*(t) - d(t) - \dot\Omega^*(t) \\ x(t) = bT_{em}(t) - \Delta a\Omega - \Delta d(t) + \Delta bT_{em}(t) \end{cases} \tag{12}$$

Now, the sliding variable is expressed as [19]:

$$s(t) = e(t) - \int_0^t (h-a)e(\tau)d\tau \tag{13}$$

with h is a constant.

Assumption**:** To choose the gain h, (h-a) should be negative, hence h< 0. Equation (14) describes the sliding surface:

$$s(t) = e(t) - \int_0^t (h-a)e(\tau)d\tau = 0 \tag{14}$$

A speed control law can be illustrated as:

$$f(t) = he(t) - \beta\,\mathrm{sgn}(s(t)) \tag{15}$$

where:

- β: Switching gain.
- *S(t)*: Sliding surface.
- *sign(s(t))* : Sign function, which is written as follows:

$$\text{Sign (S)} = \begin{cases} 1 & \text{if } S \succ 0 \\ -1 & \text{if } S \prec 0 \end{cases} \tag{16}$$

For all time the gain value β must be chosen from this condition $\beta \geq |x(t)|$.

The major drawback of the sign function used in equation (16) is chattering phenomenon. In order to avoid this phenomenon a saturation function is used as given by equation 17 [20]. Then equation (16) is replaced by equation (17).

$$Sat(S)=\begin{cases}1 & if \quad S>\lambda \\ -1 & if \quad S<-\lambda \\ \dfrac{S}{\lambda} & if \quad |S|<\lambda\end{cases} \tag{17}$$

where λ is a positive constant.

Finally, the electromagnetic torque reference can be rewritten as:

$$T^*_{em}=\frac{1}{b}((he) - \beta\times \mathrm{sign}(S) + a\Omega^* + \dot{\Omega}^* + d) \tag{18}$$

The DTC-SMSC is presented in figure 4.

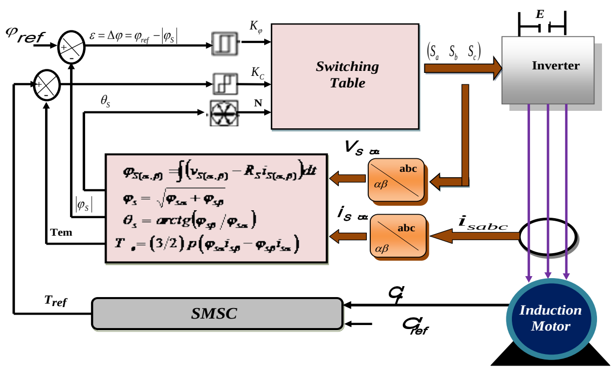

Fig. 4. Structural diagram of DTC-SMSC of an induction motor

III. FPGA Implementation Methodology, Digital Simulation and VHDL Code Generation

A. Design of the proposed approach from the XSG

The XSG is a high-level tool which can be used to design a control algorithm with high performances that uses the Matlab/simulink and the Xilinx Integrated Synthesis Environment (ISE). This study consists to represent the algorithm by a graphical view using the XSG blocks. To program the FPGA the knowledge of the Hardware Description Language (HDL) is not necessary, because of its automatic generation using the XSG tool. Once the functionality of the system is verified by digital simulation, the XSG offers the possibility to generate the VHDL code, and then the bitstream file to configure the FPGA. The XSG Design flow is shown as follows:

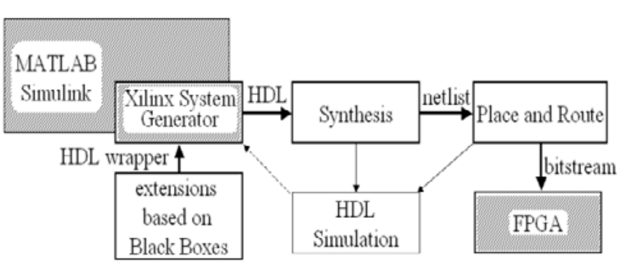

Fig. 5. Design Flow using the Xilinx System Generator

The classical DTC diagram based SMSC contains several blocks. The internal architecture of some blocks are presented using the XSG, like the internal architecture of sign function which is presented in figure 6, the sliding Surface is which illustrated by figure 7, the internal architecture of the block of the reference of the electromagnetic torque which is presented by figure 8.

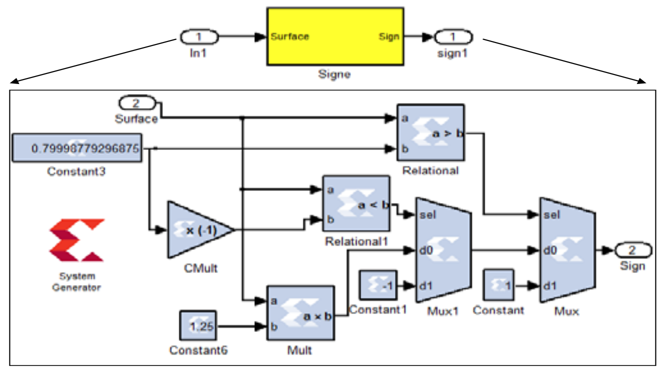

Fig. 6. Design of the sign function from the XSG

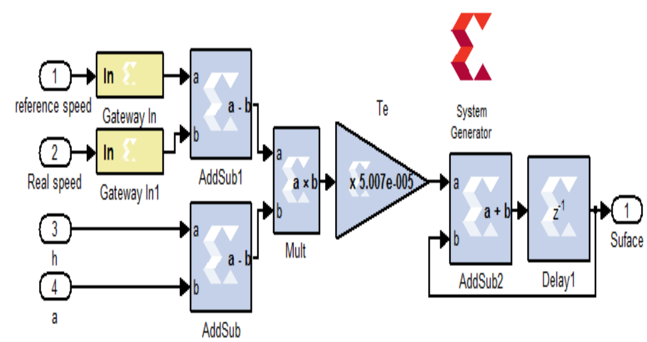

Fig. 7. Design of the sliding Surface from the XSG

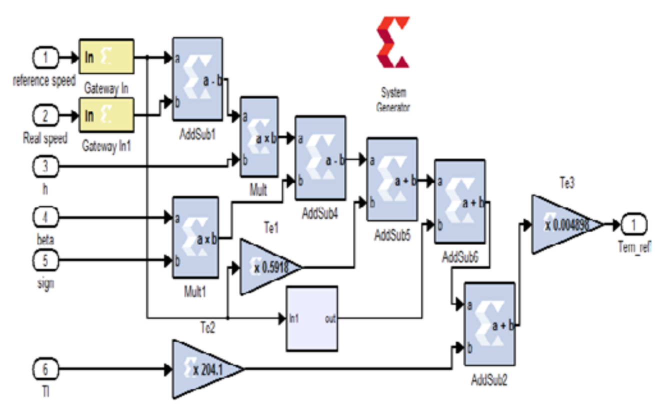

Fig. 8. Design of the reference torque from the XSG

B. Digital simulation of classical DTC based PI regulator utilizing the XSG tool

The classical DTC based PI regulator has been designed and simulated utilizing the XSG tool. The stator flux reference is φ_{ref}=0.91wb. The motor is started with a reference speed equal to 75 rd/s, at t=0.8s the reference speed increase two time. At t= 0.5s, a load torque equal to 5 Nm is applied, at t=1 the load torque increase two time.

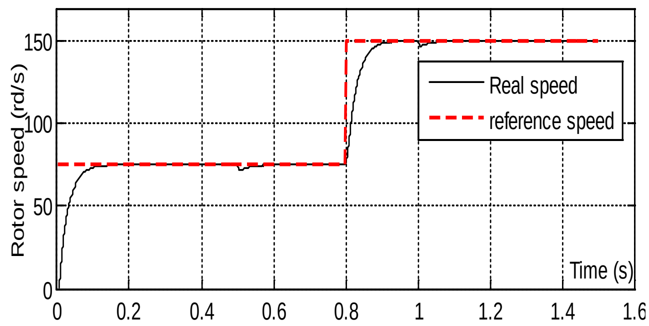

Fig. 9. Mechanical speed response of the classical DTC based PI regulator using the XSG

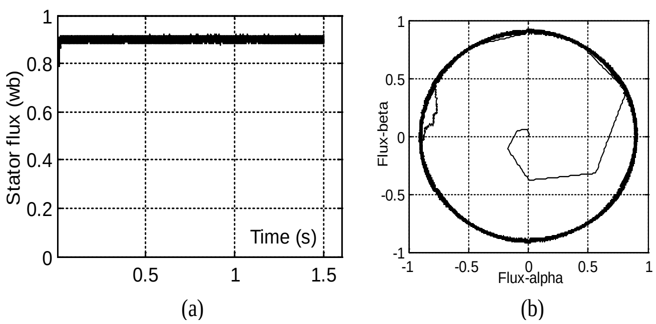

Fig. 10. Evolution of the real stator flux: (a):Stator flux module, (b): stator flux vector trajectory using the XSG

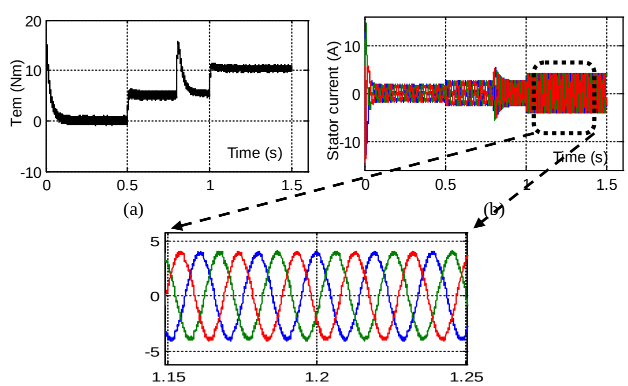

Fig. 11. (a) Motor Torque (Nm): (b): stator current for DTC with PI regulator using the XSG

Referring to the figure 9, the rotor speed reached quickly its reference value that demonstrates the fast dynamic of the DTC. As shown in figure 10, the stator flux rapidly converges to its reference value, with significant ripples because of the variation of the switching frequency which is uncontrolled in the classical DTC. Referring to the figure 11, the DTC offer a good torque response, with significant ripples in the torque and distortions in the stator current wave form, this due to the variation of the switching frequency.

C. PI regulator *and SMSC: A comparative study*

In order to test the performances of the SMSC relative to the PI regulator, a variation of the load torque and the rotor speed are applied as external disturbances. The comparative study is described by a digital simulation utilizing the toolbox XSG. The reference flux is equal to 0.91 wb. The load torque is equal to 10 Nm.

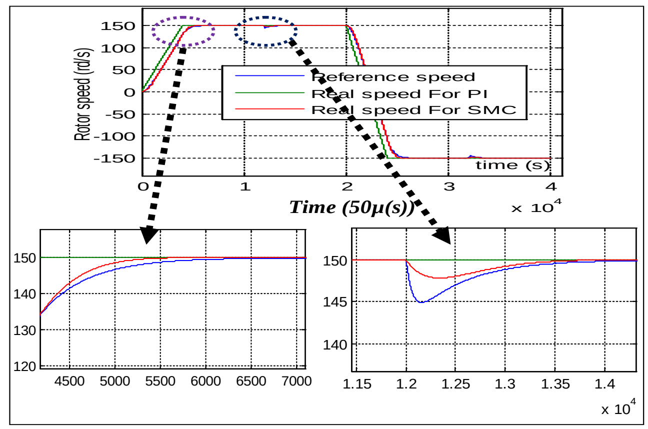

Fig. 12. First test: Mechanical speed for the DTC based PI regulator and the DTC-SMSC with inversion of the rotor speed

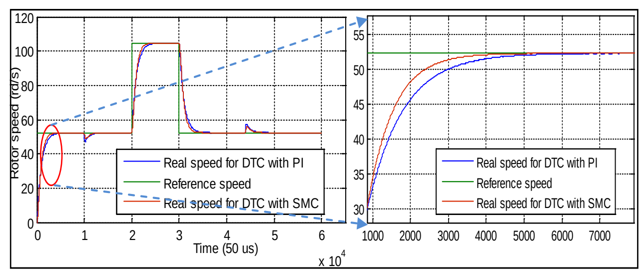

Fig. 13. Second test Mechanical speed for the DTC based PI regulator and the DTC-SMSC with positive rotor speed

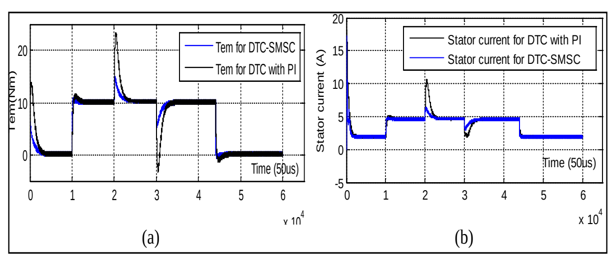

Fig. 14. (a) Torque Variations : DTC with PI regulator and the DTC-SMSC, (b) Current Module Evolution: DTC with PI and the DTC-SMSC

In this part, a comparative study between the SMSC and the PI regulator has been carried out. In this digital simulation the IM is started and operates with a variable reference speed, as shown in figure 12. The reference speed is described by an acceleration ramp with rotation reversal. Referring to this figure, the reference speed has reached quickly its reference value in the case of the SMSC. At t=0.6 s a nominal load torque is applied and removed at t=1.6s, as presented in figure 12, the SMSC offer a best performances in terms deviation which demonstrate its robustness under the external disturbances. As shown also in figure 13, the SMSC offer a better performance in terms of rapidity relative to PI regulator. Referring to the figure 13, the motor speed presents a variation at t=2s and at t=3s, in the case of the PI controller, this variation creates a high deviation in the stator current and the electromagnetic torque, which is enormously reduced in the case of the SMSC, as presented in figure 14. As a consequence, after an extended operation the high deviation of the stator current affects the motor winding and reduces its service life. The comparative study is summarized in Table 2.

Table 2. A Comparative Study

	DTC with PI regulator	DTC-SMSC
Behavior under speed variation	bad	good
Behavior during startup	good	excellent
Behavior under load torque variation	good	excellent

D. VHDL code generation of the DTC-SMSC and hardware Co-simulation

The DTC-SMSC has been verified by simulation, which gives to the user the possibility to generate the VHDL code utilizing the tool Xilinx ISE 12.4 [21]. The Implementation result using the Xilinx FPGA Virtex 5 ML507 is presented in figure 15. The resources utilization and timing performances are archived in table 3.

Fig. 15. Synthesis result of DTC-SMSC speed controller using Xilinx ISE 12.4

Table 3. Synthesis results and Execution Time for the FPGA based DTC-SMSC Controller

DTC with SMC speed controller	
Number of bonded IOBs	68
Number of Slices	259
Number of Slice LUTs	1344
Number of MULT18X18s	16
Execution Time (µs)	
Concordia transformation	0,12
Torque and flux Estimators	0,16
Sector and hysteresis controllers	0,16
SMSC	0,12
Execution Time (µs) :	*0,56*
Total Execution Time (µs) :	*0,56 +t_{ADC}*
t_{ADC} : Analogue to digital conversion time	

The estimated processing time is 0.56 +t_{ADC} µs using a Xilinx Virtex-5 FPGA ML507 with an xc5vfx70t-3ff1136 package. In paper [22] the total execution time is not less than the 100µs, due to the serial treatment of the software solutions. However, the execution time using the FPGA does not exceed 5µs.

Before moving to the experimental validation it is possible to test the control algorithm functionality by co-simulation [23]. The co-simulation consists firstly, to generate the JTAG block and the bitstream file. Secondly, The DTC design in Simulink must be replaced by the generated JTAG block, then connect the FPGA to PC computer through JTAG cable and click start simulation, in this step the FPGA board executes the algorithm. In fact, the FPGA receive the stator current, the real speed and the reference speed, and then send the inverter switching states through JTAG cable. The Hardware co-simulation environment based on the personal computer, Xilinx FPGA Virtex V ML507 is represented in figure 16.

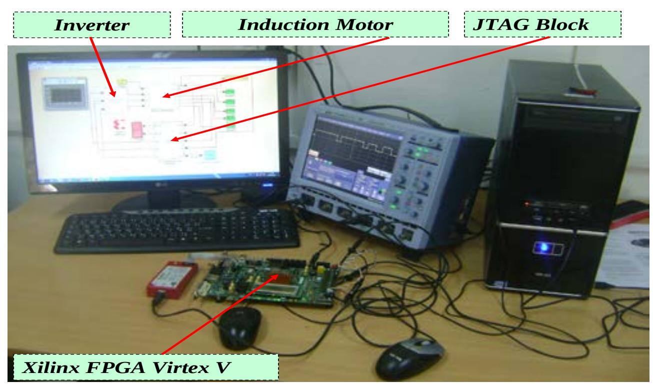

Fig. 16. Hardware Co-simulation environment

The hardware Co-simulation results are presented by the following figure:

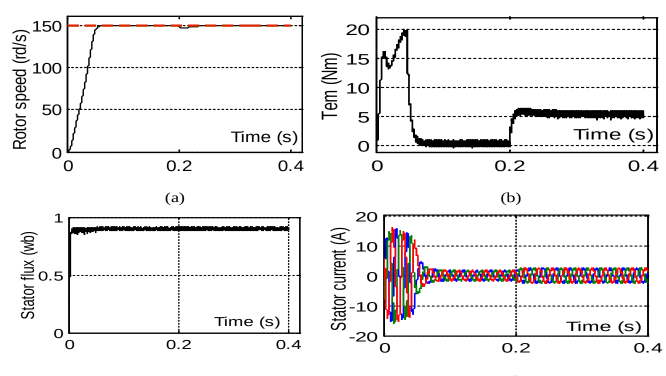

Fig. 17. Hardware co-simulation results

Figure 17, shows the IM motor response in the hardware Co-simulation step. In this figure the evolution of the rotor speed, the electromagnetic torque, the stator flux and the stator current are presented. It has been noticed that the obtained results are similar to that obtained by digital simulation.

IV. Conclusion

This researches work proposes a rapid prototyping of the classical DTC based PI regulator and the DTC based SMSC of the rotor speed. The proposed approaches have been investigated, developed, designed from the XSG tool. The robustness of the proposed controllers has been tested by simulation under load torque variation and show the robustness of the SMSC relative to the PI regulator. The VHDL code has been generated and synthesized. The obtained computation time of the FPGA is too weak relative to that obtained utilizing the software solutions like the DSPs. In the next work we will present real experimental results using the test bench.

V. Appendix

Table 4. Induction machine parameters

number of pairs of poles P= 2	L_s= 464mH
F= 50 Hz	L_r= 464mH
V/U: 230/400 V	M_{sr}= 441,7mH
R_s=5,717 Ω,	*J*= 0.0049 kg.m²
R_r=4.282 Ω	*f*= 0.0029 kg.m²/s
R_r =4,282 Ω	

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