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VECTOR CONTROL FOR INDUCTION MOTOR WITH ROTOR FLUX ORIENTED USING XILINX SYSTEM GENERATOR

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ABSTRACT

The objective of this paper is to achieve the algorithm of a vector control for an induction motor with rotor flux oriented using Xilinx System Generator tools added to Matlab/Simulink. This tool allows generating automatically the VHDL file which can be implemented directly in FPGA hardware. This solves all the difficulties encountered in previous researches which require a great knowledge of the programming language VHDL.

Keywords: *FPGA, Induction Motor, Vector Control, Rotor Flux Oriented, Xilinx System Generator, Matlab & Simulink.*

1. INTRODUCTION

The Control structures for electrical machines have several loops of regulation nested. The inner loop of current is she who consumes more time for calculation, and only limited computational resources are dedicated to the outer loops. To do this, it is advantageous to use digital solutions with a large of computing capacity for the implementation of control algorithms. Digital solutions commonly used for the control of electrical machines are the microprocessors and the DSPs. However, the requirements of modern control in the field of control of electrical machines exceed the computing capabilities offered by these solutions, and although the new models of high performances of multiprocessors also those of the DSPs can solve this problem, they have the disadvantage of high cost.

The migration from the operation sequential mode of the software's solutions to operation parallel mode of hardware solutions is a new degree of freedom offered to designers which has proved beneficial in the field of control of the electric machines and which enabled to meet requirements modern control.

Among the new hardware solutions, FPGAs have been successfully used in various applications related to the control of electric machines. In fact, they were used for the control of power converters such as the three-phase voltage inverters, the rectifiers, the multi-level converters, the active filters… The FPGAs have also been used for the control of the induction machines, the synchronous machines and the variable reluctance machines...

Thus, thank to the characteristics of FPGAs, it is possible to:

- Implement complex algorithms: With technological advancement, the increasing integration of FPGAs is increasing. Nowadays, the ability of FPGAs can achieve the equivalent of 10 million logic gates with switching frequencies around 500 MHz. This allows the implementation of the complex control algorithms in their entirety with the least delay possible of computing time.
- Perform dynamic reconfigurations,
- Improve control performances: the rapid of calculation of FPGA allows for increase of bandwidth regulation loops and a better temporal resolution,
- Strengthen Confidentiality: the control architecture implemented on FPGA is not easily duplicable
- The best way to design an embedded system that can control our machine is the FPGAs,

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- The major advantage of an FPGA relative to DSP and more precisely the DSPACE and what prompted us to use them, is that they can hold a controller with an observer and give very good results with very good performance. What we have not managed to do in our research team on DSPACE 1104 [1],

This paper is organized as follows:

In the second section we will present the model of the induction machine with the rotor flux orientation on d axis, and then we will try to calculate the various parameters of the PI controllers.

In the third section we will try to realize the vector control algorithm using Xilinx System Generator (XSG)

Finally we will present the simulation results and we will compare them to those obtained using Simulink.

2. INDUCTION MOTOR VECTOR CONTROL

2.1. Machine with rotor flux oriented equations

Starting from the equations for the functioning of the induction motor presented in a reference rotating frame (d-q) and by considering the flux orientation φ_r on the d-axis: $\varphi_{rq} = 0 \, and \, \dot{\varphi}_{rq} = 0$, we obtain these equations :

$$\begin{cases} v_{sd} = \sigma L_s.\dfrac{di_{sd}}{dt} + (R_s + R_r.\dfrac{M^2}{L_r^2})i_{sd} \\ \qquad - \sigma L_s \omega_s i_{sq} - \dfrac{M}{L_r^2}.R_r \varphi_r \\ v_{sq} = \sigma L_s.\dfrac{di_{sq}}{dt} + (R_s + R_r.\dfrac{M^2}{L_r^2})i_{sq} \\ \qquad - \sigma L_s \omega_s i_{sd} - \dfrac{M}{L_r}.\omega \varphi_r \\ T_r \dfrac{d\varphi_r}{dt} + \varphi_r = M.i_{sd} \\ \omega_s = \omega + \dfrac{M}{T_r.\varphi_r}.i_{sq} \\ C_{em} = \dfrac{3}{2} p.\dfrac{M}{L_r}.\varphi_r.i_{sq} \end{cases} \tag{1}$$

With:
***V_{sd}, V_{sq}*:** Direct and quadrature axis stator voltage.
***i_{sd}, i_{sq}*:** Direct and quadrature axis stator currents.
d, q: d- and q-axis rotating reference frame.
α,β: α- and β-axis stationary reference frame
ω: Rotation's speed electric.
***w_s*:** Electrical synchronous speed.
p: Number of pairs of poles.
J : Total moment of inertia.
f : Coefficient of viscous friction.
C_r: Resistive torque.
M: Mutual inductance.
σ: Leakage coefficient.
φ_{rd}: d axis stator magnetic flux.
***φ_{rq}*:** q axis stator magnetic flux.
L_s: Stator leakage inductance.
L_r: Rotor leakage inductance.
R_s: Stator resistance.
T_r: rotor time constant
C_{em}: Eectromagnetic torque.

2.2. Decoupling with compensation

From the first two equations of the system (1) we can define two new control variables v_{sd1} and v_{sq1} such as:

$$\begin{cases} v_{sd} = v_{sd1} - e_{sd} \\ v_{sq} = v_{sq1} - e_{sq} \end{cases} \tag{2}$$

Voltages v_{sd1} and v_{sq1} are given by:

$$\begin{cases} v_{sd1} = \sigma.L_s.\dfrac{di_{sd}}{dt} + R_s.i_{sd} = v_{sd} - e_{sd} \\ v_{sq1} = \sigma.L_s.\dfrac{di_{sq}}{dt} + R_s.i_{sq} = v_{sq} - e_{sq} \end{cases} \tag{3}$$

Assuming that the modulus of the rotor flux varies only very slowly compared to i_{sd} and i_{sq}, the voltages e_{sd} and e_{sq} can be written as:

$$\cdot\begin{cases} e_{sd} = \sigma.L_s.\omega_s.i_{sq} \\ e_{sq} = -\sigma.L_s.\omega_s.i_{sd} - \dfrac{M}{L_r}.\omega_s.\varphi_r \end{cases} \tag{4}$$

Actions on the d and q axes are then decoupled.
After decoupling, the block diagram of vector control becomes:

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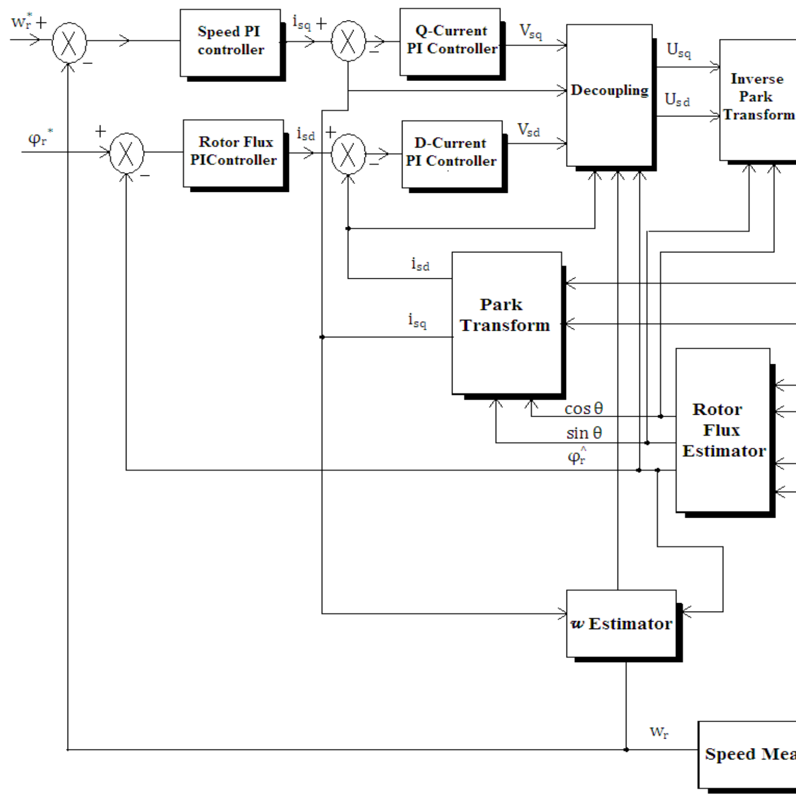

Fig.1. Block Diagram Of Vector Control

2.3. Calculation of controllers

The Vector control with rotor flux oriented is simulated using four regulation loops: regulation loop speed, regulation loop current i_{sq}, flux regulation loop and finally a current regulation loop i_{sd}. We adopted for the different regulation loops of conventional type controllers, (proportional integral: PI) having the following operational form:

$$R_x(p) = \frac{k_x}{T_x.p}.(1+T_x.p) \qquad (5)$$

The model used for the simulation is given in *Fig.2*. x may be the rotor flux, the speed w, the current i_{sq}, the current i_{sd}.

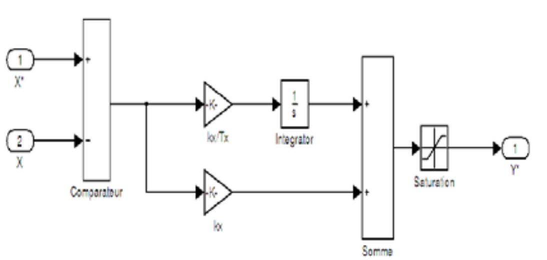

Fig.2.Block Diagram Of A PI Controller Followed By Saturation

A saturation block is essential having regard to the increasing behavior in the output of an integrator.

The *PI* controller has a proportional action is used to adjust the speed at which regulation should take place and an integral action is used to increase the class of subsystem and eliminate the static error between the controlled variable and the desired value.

In determining the parameters, we denote by $H_o(p)$ the transfer function of open-loop and $H_F(p)$ the transfer function of closed loop obtained by the formula of BLACK. For the synthesis of these parameters, we adopt the method of compensation the poles by zeros.

a. Regulation of the rotor flux:

The block diagram of the regulation loop of rotor flux is given by *Fig.3*. The output of the flux controller is used to generate the direct stator current of reference i_{sd}^*.

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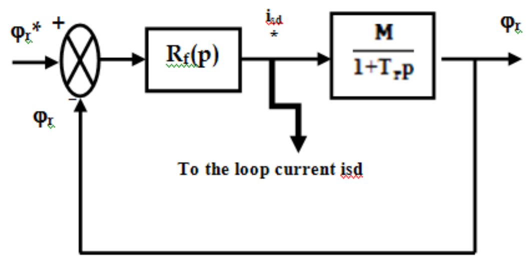

Fig 3: Block Diagram Of The Regulation Loop Of Rotor Flux

The controller is of the form:

$$R_f(p) = \frac{k_f}{T_f.p}.(1 + T_f.p) \tag{6}$$

The transfer function in open loop is:

$$H_0(p) = \frac{k_f.M}{T_f.p}.\frac{1 + T_f.p}{1 + T_r.p} \tag{7}$$

The Compensation of the rotor time constant by that of the regulator can lead to:

$$\begin{aligned} &H_0(p) = \frac{k_f.M}{T_f.p} \\ &H_p(p) = \frac{H_0(p)}{1 + H_0(p)} = \frac{1}{1 + \tau_f.p} \\ &\text{With} \quad \tau_f = \frac{T_f}{k_f.M} \end{aligned} \tag{8}$$

This is a first order system; the choice of response time to 5% (denoted by t_{rf}) fixes the value of the time constant τ_f ($t_{rf}=3.\tau_f$).

The parameters of the PI regulator in the regulation loop of the rotor flux are then:

$$\begin{cases} k_f = \dfrac{3.T_f}{r_{rf}.M} \\ T_f = T_r \end{cases} \tag{9}$$

b. *Regulation of the current i_{sd}:*

The block diagram of the regulation loop of the current i_{sd} is given by *Fig.4*. The output of the current controller is :

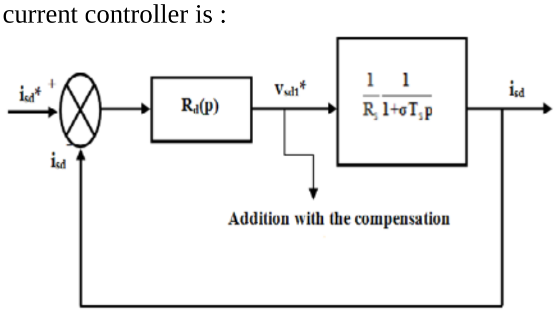

Fig.4.Block Diagram Of The Regulation Loop Of The Current I_{sd}

The controller is of the form:

$$R_d(p) = \frac{k_d}{T_d.p}.(1 + T_d.p) \tag{10}$$

The transfer function in open loop is:

$$H_0(p) = \frac{k_d}{R_s.T_d.p}.\frac{1 + T_d.p}{1 + \sigma T_s.p} \tag{11}$$

The Compensation of the time constant σT_s by that of the regulator can lead to;

$$\begin{aligned} &H_0(p) = \frac{k_d.M}{R_s.T_d.p} \\ &H_F(p) = \frac{H_0(p)}{1 + H_0(p)} = \frac{1}{1 + \tau_d.p} \\ &\text{With} \quad \tau_f = \frac{R_s}{k_f.M} \end{aligned} \tag{12}$$

This is a first order system, the choice of response time to 5% (denoted by t_{rd}) fixes the value of the time constant τ_d ($t_{rd}=3.\tau_d$).

The parameters of the *PI* controller in the regulation loop of the current i_{sd} are then:

$$\begin{cases} k_d = \dfrac{3.\sigma L_s}{t_{rd}} \\ T_d = \sigma.T_s \end{cases} \tag{13}$$

c. *Regulation of the rotationnel speed W:*

The block diagram of the regulation of speed is given by *Fig.5*. The output of the speed controller is used to generate the torque of reference C_{em}^*. From this equation we calculate the quadrature current of refence i_{sq}*.

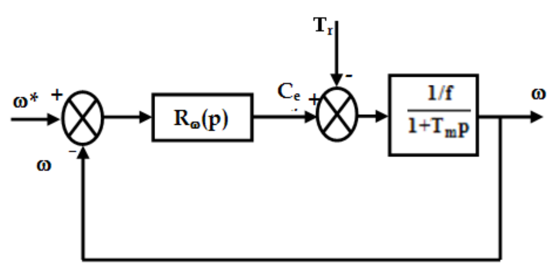

Fig.5.Block Diagram Of The Regulation Of Speed

The controller is of the form:

$$R_\omega(p) = \frac{k_\omega}{T_\omega.p}.(1 + T_\omega.p) \tag{14}$$

The transfer function in open loop is:

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$$H_0(p)=\frac{k_\omega}{f.T_\omega.p}.\frac{1+T_d.p}{1+T_m.p} \quad (15)$$

The Compensation of the mechanical time constant by that of the controller can lead to;

$$H_0(p)=\frac{k_\omega}{f.T_\omega.p}$$

$$H_F(p)=\frac{H_0(p)}{1+H_0(p)}=\frac{1}{1+\tau_\omega.p} \quad (16)$$

$$With \quad \tau_\omega=\frac{f.T_\omega}{k_\omega}$$

This is again a system of first order; we proceed in the same way as before.

The parameters of the PI regulator in the regulation loop of the speed W are then:

$$\begin{cases} k_\omega = \dfrac{3.f.T_\omega}{t_{r\omega}} \\ T_\omega = T_m \end{cases} \quad (17)$$

d. Regulation of stator current i_{sq}:

The block diagram of the regulation of current i_{sq} is given by *Fig.6*. The output of the current controller is used to generate the stator voltage in quadrature $V_{sq}{}^*$.

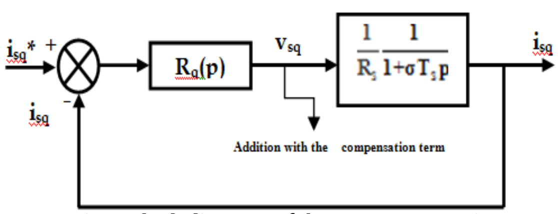

Fig.6.Block diagram of the stator current i_{sq}

The controller is of the form:

$$R_q(p)=\frac{k_q}{T_q.p}.(1+T_q.p) \quad (18)$$

This is the same loop and the same parameters described for regulating the current i_{sd}. Except that in this case, the reference of current i_{sq}* is obtained from this relationship:

$$C_{em}^*=p.\frac{M}{L_s}.\varphi_r.i_{sq}^*\Rightarrow i_{sq}^*=\frac{C_{em}^*}{p.\frac{M}{L_s}.\varphi_r} \quad (19)$$

The parameters of the *PI* controller in the regulation loop of the speed *w* are then:

2.4. Estimation of rotor flux:

$$i_{sdr}=\frac{M}{T_r s+1}.\hat{\varphi}_r \quad (20)$$

2.5. Estimation of speed:

$$\omega_s=\omega+\frac{M}{T_r}.\frac{i_{sq}}{\hat{\varphi}_r} \quad (21)$$

3. REALIZATION OF VECTOR CONTROL USING XILINX SYSTEM GENERATOR

3.1. Structure

It is a toolbox developed by *Xilinx* to be integrated into the environment Matlab/Simulink and lets the user creates highly parallel systems for *FPGA*. The models created are displayed in the form of block and they can be connected to other blocks and to all the others toolboxes of Matlab / Simulink. Once the system is completed, the *VHDL* code generated by the tool XSG exactly reproduces the behavior observed in Matlab. It is much easier to analyze the results with Matlab that with the tools usually associated with VHDL as Modelsim.

Then the model can be coupled to virtual engines. The XSG tool is used to produce a model that will immediately operate on the hardware once completed and validated.

The functional model consists of four main blocks:

- A control block: the block contains also other sub-blocks:
  - Estimation block of rotor flux,
  - Speed estimation block,
  - The blocks of coordinate's transformation: the transformation of Park Inverse (dq to αβ),
  - 4 blocks of PI control,
- A block of the induction motor in the alpha-beta coordinates,
- 2 Blocks for the Park transformation (αβ to dq)

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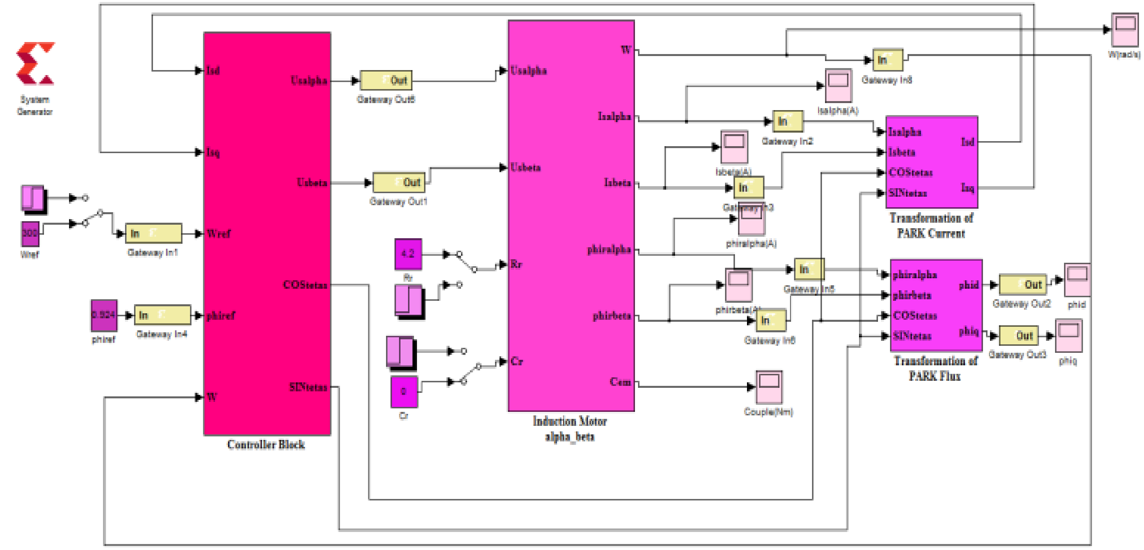

Fig.7.External View Of The Diagram With XSG

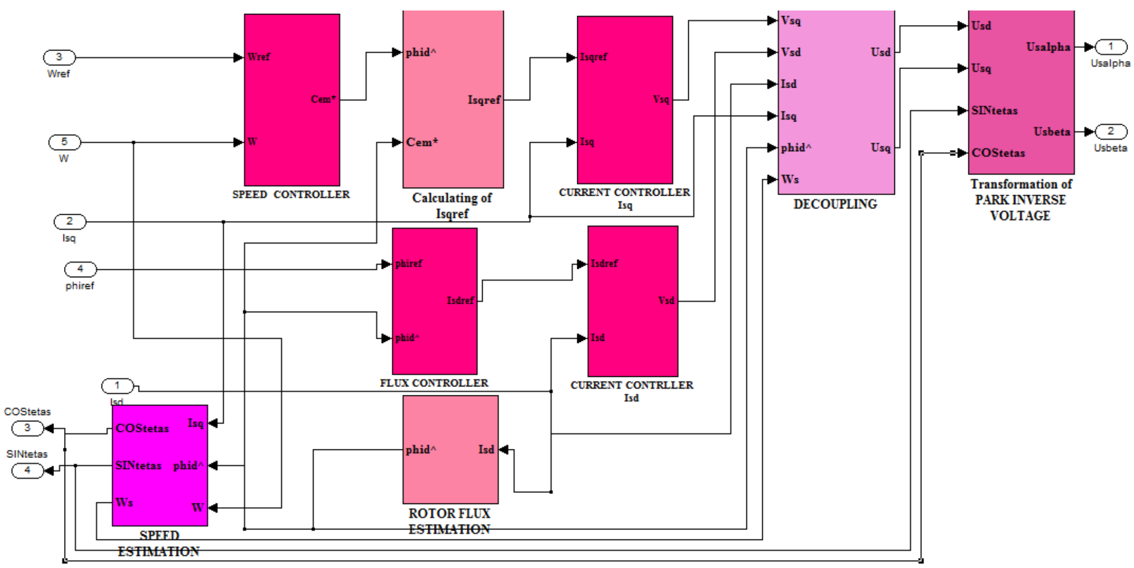

Fig 8: Internal View Of The Diagram With XSG

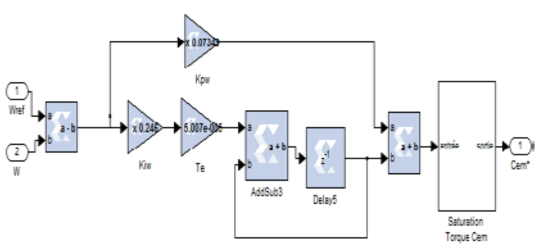

Fig .9.Internal View Of The Subsystem PI Speed Controller With XSG

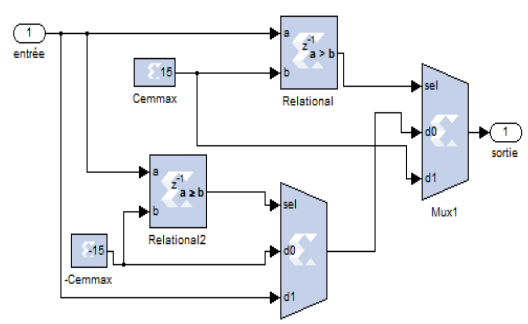

Fig 10: Internal View Of The Subsystem Saturation Of The Torque With XSG

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For example to realize the block of rotor flux estimation w must do this:

$$= \frac{M}{T_r s + 1} . i_{sdr} \qquad (22)$$

We develop this relation and we obtain:

$$\hat{\varphi}_r . T_r . s + \hat{\varphi}_r = M . i_{sdr} \Rightarrow \frac{d\hat{\varphi}_r}{dt} = \frac{M}{T_r} . i_{sdr}$$
$$\Rightarrow \hat{\varphi}_r = \int (\frac{M}{T_r} . i_{sdr}) dt \qquad (23)$$

Then we realize this function with XSG as follows:

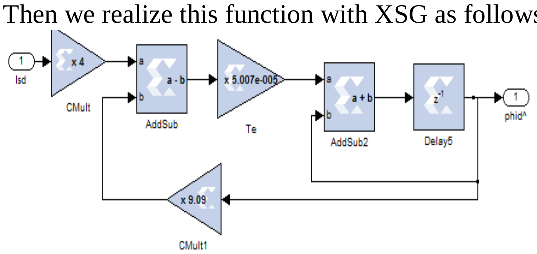

Fig 11: Internal View Of The Subsystem Of The Rotor Flux Estimation Block With XSG

3.2. Simulation Results:

We present in this section a comparison between simulation results using XSG and simulation results using Simulink that is to say a comparison between discrete and continuous results.

We suppose:

- Period of sampling; $T_e = 50\mu s$
- Rotor flux reference: $\varphi_r^* = 0.924Wb$.
- Rotor speed reference: Wr^* an echelon of speed which start at $t=0.1s$ and and a setpoint equal to *300(rad/s))*.

a. *Simulation results using XSG:*

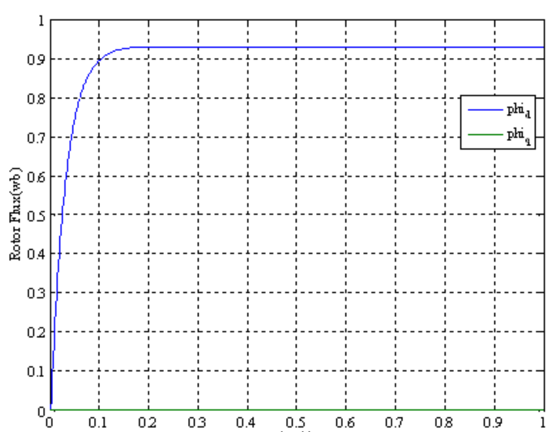

Fig.12.Dq Axis Rotor Flux

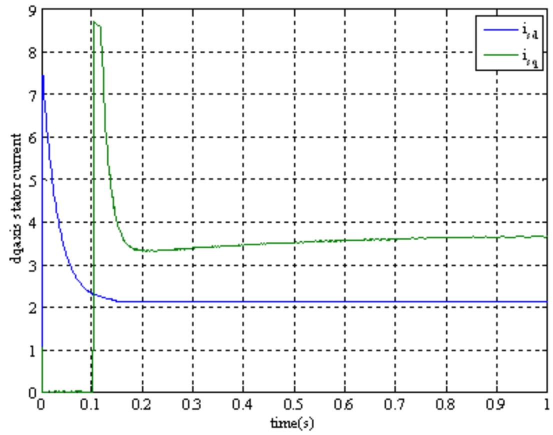

Fig.13.D-Q Axis Stator Current

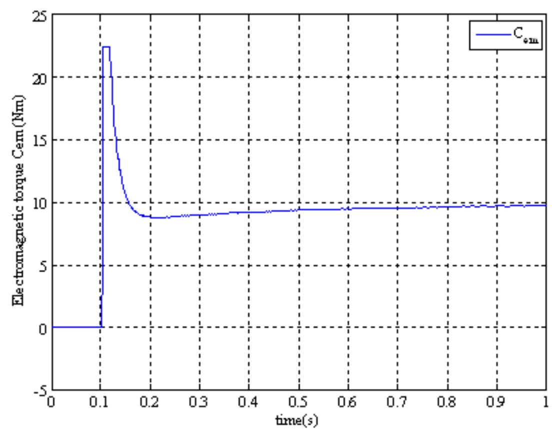

Fig.14.Electromagnetic Torque (C_{em})

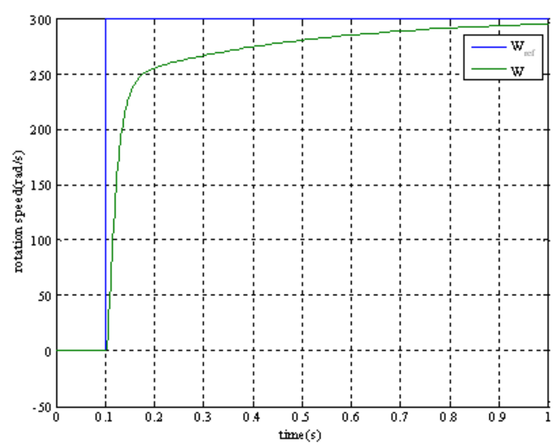

Fig.15.Response Of Rotation Speed

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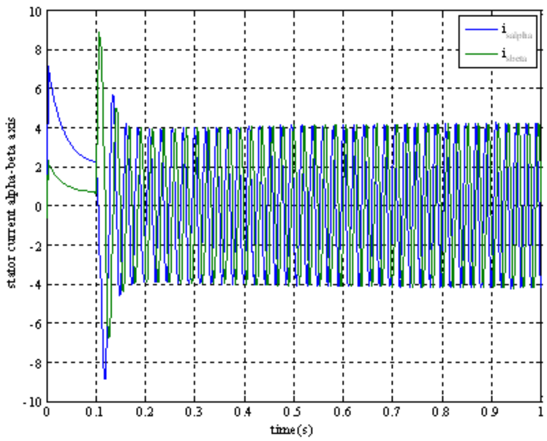

Fig.16.A-B Axis Stator Current

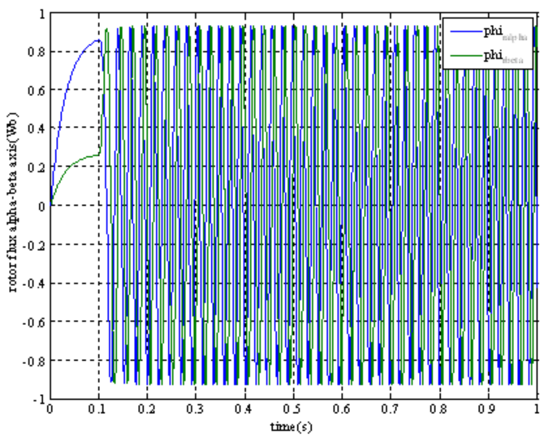

Fig.17.A-B Axis Rotor Flux

b. ***Simulation results using Matlab/Simulink:***

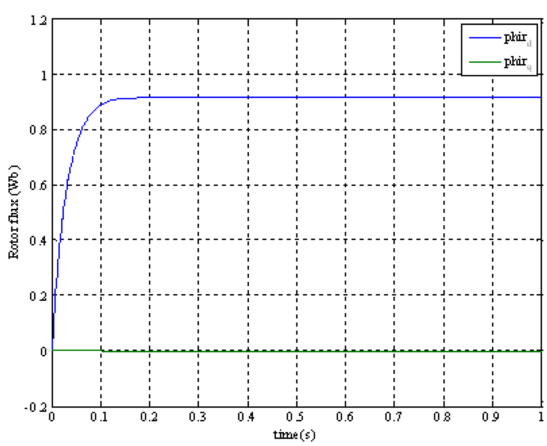

Fig.18.Dq Axis Rotor Flux

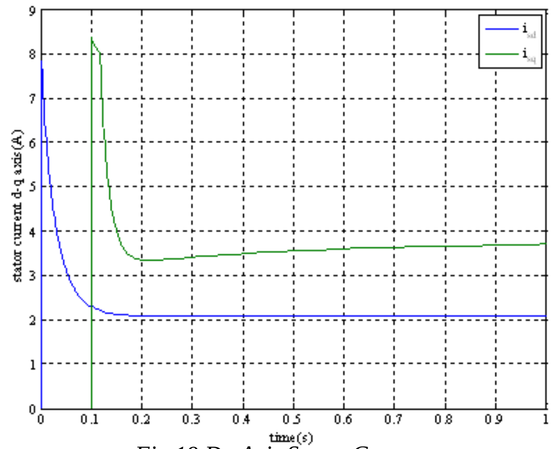

Fig.19.Dq Axis Stator Current

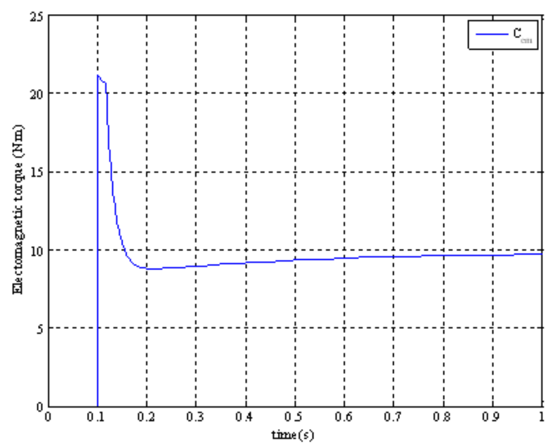

Fig.20.Electromagnetic Torque (Cem)

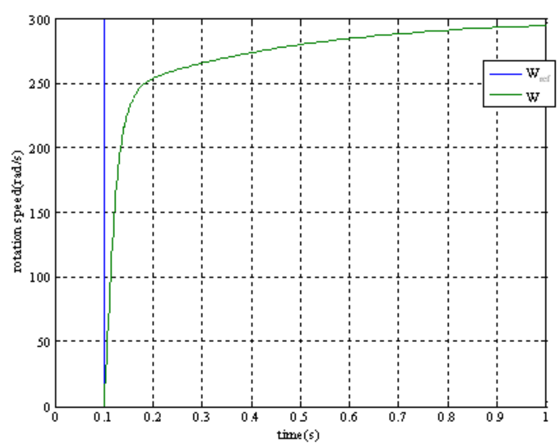

Fig.21.Response Of Rotation Speed

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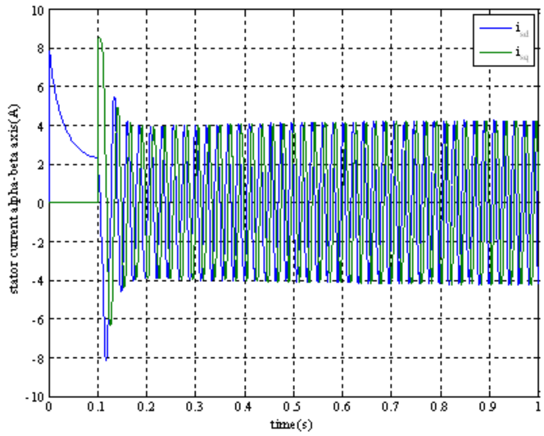

Fig.22.A-B Axis Stator Current

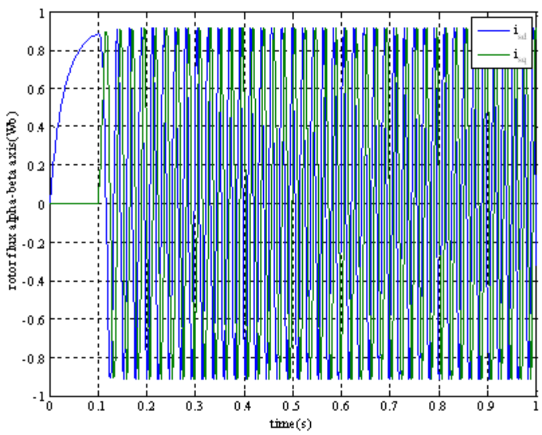

Fig.23.A-B Axis Rotor Flux

By comparing the simulation results obtained for the two cases by using XSG or by using Simulink we see we have the same results with the 2 methods that is to say with the digital or analog approach we find identical results. Therefore our XSG algorithm is correct and just press generate to generate the *VHDL* code that will be implemented in our FPGA to control the induction motor.

CONCLUSION

In this paper we have succeeded in presenting a new technique (XSG) to get the VHDL code of vector control of an induction motor without being forced to make a difficult programming mainly in our case. Also, we can control the good operation of our algorithm and even curves before implementing it on our motor. This technique is very interesting because we can test the functioning of subsystems one by one. For the next work we will try to implement it and see the experimental results.

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