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Hardware in Loop Methodologies for the Control of Dual-PMSM Connected in Parallel: FPGA Implementation and Experimentation.

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Keywords

Real time simulation, Multi-Machine System, Vector Control, Pulse Width Modulation (PWM).

Abstract

The focus of this article is to study the Hardware In the Hoop (HIL) generic methodology for the design of a universal real-time control. FPGAs (Field Programmable Gate Arrays) are used to control a DPMSM (Dual Permanent Magnet Synchronous Machine) variable speed drive supplied by a Dual-PWM Voltage Source Inverters (VSIs). The load of the two PMSMs can be either separated or in common and are controlled by individual vector controls associated with a PWM modulator in a first step. In a second step we will realize a comparative study between the responses of the mathematical model and the real system.

The implementation of the different control configurations is done using the dSPACE DS52030D digital platform containing DSP and Xilinx FPGA. An efficient solution is proposed in which the software part is managed by a Matlab-Simulink layer. This method allows a material library to be built which can be used for other control systems based on a PMSM.

Introduction

Recently we have observed very important developments of variable speed and/or torque drives. More often than not they are now constituted of a combination of multi-converter /multi-machine systems. These drives are present in several embedded systems such as vehicles, aircraft, ships, trains and other industrial applications where weight and volume reduction are critical.

The multi-PMSM system is widely used because of the following characteristics: high performances, high power density and low inertia. In addition, the static converter used in this system drive is less cumbersome because it provides only load current. In this paper the authors are interested in the implementation of an FPGA target of speed control of DPMSM system supplied by two level PWM Voltage Source Inverters (PWM-VSI).

In this study we chose a “d,q” vector control strategy based on cascaded PI controllers for each PMSM. So, the q axis is formed by two control loops; the outer loop is the speed control and the inner loop is the i_q current control. The “d” axis is formed by an inner loop for the regulation of the i_d current. The aim of the d,q vector control strategy is to maintain zero i_d current. Consequently, to control the PMSM torque, it is necessary to control the stator current i_q which is its image. This is obtained by controlling its amplitude and its phase shift ψ , the angle between EMF, E , and the current vector I as it is shown in Figure1. Another possibility concerns the individual control of current components following the direct axis i_d and quadrature axis i_q or the three real stator phase currents.

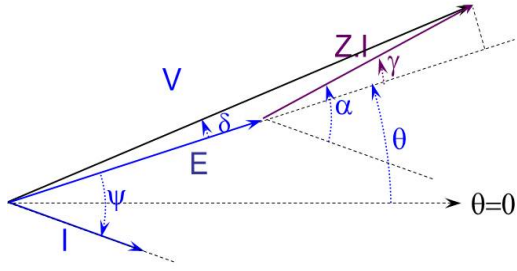


Figure 1: Vector diagram for a smooth PMSM.

System presentation

PMSM modeling hypotheses

In modeling of the PMSM, we assumed that:

- The stator is not saturated.
- The PMSM losses are disregarded.
- The rotor permanent magnet field has sinusoidal distribution in the air gap space.
- The damper windings are disregarded.
- Separation mode is applied to this PMSM, i.e. the dynamics of the stator currents are very fast compared to the rotation speed dynamics of the system.
- The rotation speed ω is considered as a parameter.

PMSM Modeling

The electrical equation expressed in Park frame can be written as follows [5]:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_s + L_d \cdot s & -\omega \cdot L_q \\ \omega \cdot L_d & R_s + L_d \cdot s \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \cdot \phi_f \end{bmatrix} \quad (1)$$

1) Current mode transfer functions

The two current modes are described by two corresponding transfer functions expressed from (1) as below:

$$V_d(s) + \omega L_q i_q = \frac{1}{1 + \frac{L_s}{R_s} s} \quad (2)$$

$$V_q(s) - \omega L_d i_d - \omega \phi_f = \frac{1}{1 + \frac{L_s}{R_s} s} \quad (3)$$

The expressions of the two transfer functions show the coupling terms between the d and q axes. These terms are respectively formulated thus:

$$V_d^c = \omega \cdot L_q \cdot i_q \quad (4)$$

$$V_q^c = \omega \cdot L_d \cdot i_d + \omega \cdot \phi_f \quad (5)$$

It can be noted that the dynamics of terms (4) and (5) depend on the rotation speed defining by the mechanical mode of this system. Their dynamics are very slow and consequently, they can be compensated.

2) Mechanical mode transfer function

The mechanical equation of PMSM is defined as below:

$$J \frac{d\omega}{dt} + f\omega = T_{em} - T_L \quad (6)$$

Thereby, the transfer function of the mechanical mode can be written as follows:

$$T_{em} - T_L = \frac{1}{1 + \frac{f}{f_s}} \quad (7)$$

Where T_{em} is the PMSM electromagnetic torque and T_L represents the load torque.

3) Electromagnetic torque calculation

In order to control PMSM power, it is essential to know its electromagnetic torque T_{em} . So, to determine the torque expression, we introduce the power definitions. In the d,q reference frame, the stator instantaneous active power $p(t)$ can be expressed as follows:

$$p(t) = V_d \cdot i_d + V_q \cdot i_q \quad (8)$$

The electrical power consumption is expressed as:

$$p(t) = R_s \cdot (i_d^2 + i_q^2) + L_d i_d \frac{di_d}{dt} + L_q i_q \frac{di_q}{dt} + \omega \cdot (L_q - L_d) i_d \cdot i_q + \omega \cdot \Phi_f i_q \quad (9)$$

Consequently, we can deduce the expression of the electromagnetic torque.

$$T_{em} = P \cdot ((L_q - L_d) i_d \cdot i_q + \Phi_f i_q) \quad (10)$$

4) PMSM with smooth poles

When the PMSM has smooth poles, $L_d = L_q$ and the torque expression (3) can be reduced to:

$$T_{em} = P \cdot \Phi_f \cdot i_q \quad (11)$$

The electromagnetic torque T_{em} depends only on the stator quadrature current component i_q . Consequently, the maximal value of T_{em} is obtained when the stator direct current is equal to zero, $i_d=0$. In this case, the angle ψ between the current vector I and the ElectroMotive Force (EMF), E , is equal to zero. Therefore, the resulting torque T_{em} is proportional to the i_q current of the PMSM as in the case of a DC machine with permanent magnets or with separated excitation.

5) Decoupled current control

The principal difficulty of a d,q PMSM vector control design is the coupling between the d and q axes presented in the expression (2). This inconvenience can be canceled by introducing a conventional compensation method. When the signs of the coupling terms in the PMSM model have been identified, we introduce the same terms with opposite signs to the controller outputs as shown in the figure 2. Finally, for the PI current controller synthesis, one ignore the coupling terms. So after compensation, we obtain the d and q voltage references which will be transformed into three phase voltages. So, the output of the regulators are V_d^r and V_q^r . The reference voltages are expressed as below:

$$V_d^* = V_d^r + V_d^c \quad (12)$$

$$V_q^* = V_q^r - V_q^c \quad (13)$$

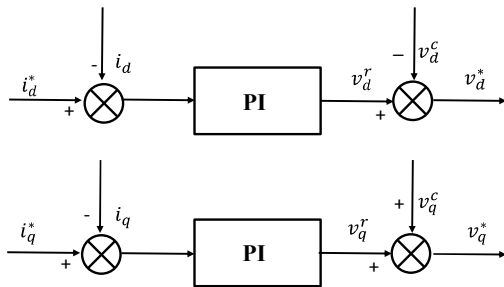


Figure 2: Current diagram with compensation term strategy.

Figure 3 represents the global diagram of this vector control used for one PMSM speed drive. This control will be applied to Multi-PWM VSI / Multi-PMSM system. For this study we limit the number of PMSM and PWM VSI to two.

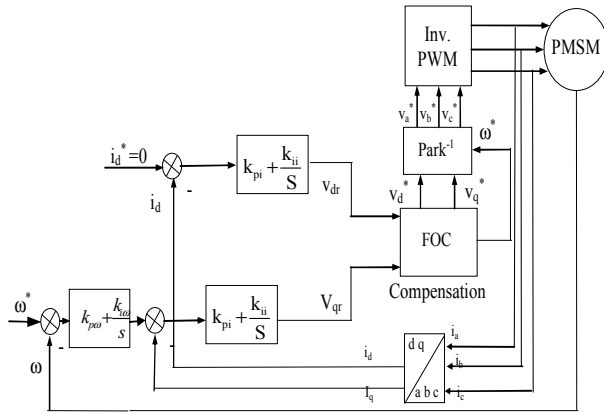


Figure 3: General diagram of PMSM vector control with compensation coupling terms.

Simulation

The system generator is a Xilinx Toolbox in a Simulink environment (XSG: Xilinx System Generator). The first phase is described in section (c), the multi PMSM system model is simulated in a Simulink environment. This simulation works with a floating point. In this way, we can evaluate an order of variable magnitudes and analyze output results which are used in the Xilinx environment operating with a fixed point. Thus we realize the necessary conversion from floating to fixed point. After this analysis of the system performances in the Simulink environment, the system is simulated using equivalent Xilinx blocks supported in the Simulink environment.

Simulation Results

In this section we present a comparison between the simulation results using XSG and those using Simulink only.

The parameters of the studied PMSM are as follows:

Stator resistance	$R_s=2.281\Omega$.
Direct and quadrature inductance	$L_d=L_q=23.173\text{mH}$.
Magnetic Flux	$\Phi=0.241\text{Wb}$.
Number of pairs of poles	$P=4$.
PMSM inertia	$J=0.00221\text{Kg.m}^2$.
Viscous friction coefficient	$f=0.0001\text{Nms/rad}$.

Simulation results using Simulink

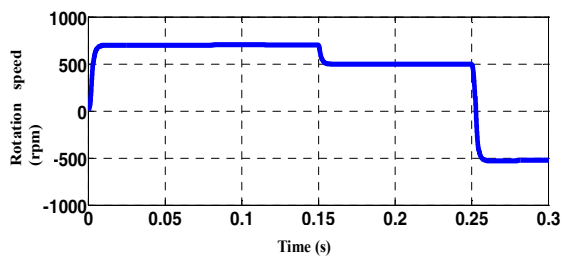


Figure 4: PMSM rotation speed response.

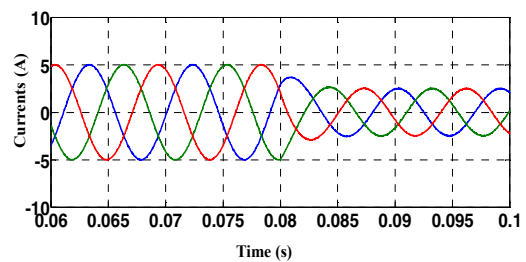


Figure 5: PMSM stator currents

Simulation results using XSG

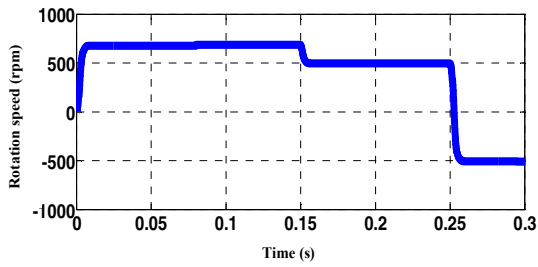


Figure 6: Rotation speed response.

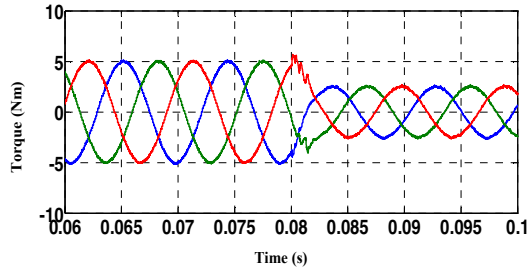


Figure 7: Currents of machine.

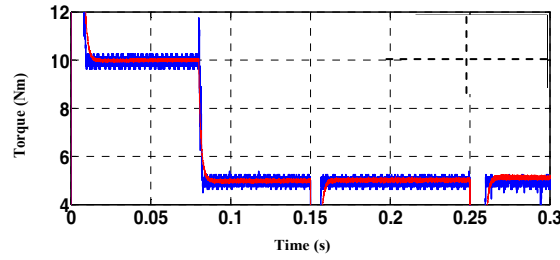


Figure 8: Electromagnetic torque (T_{em}) using Simulink and XSG model.

FPGA implementation

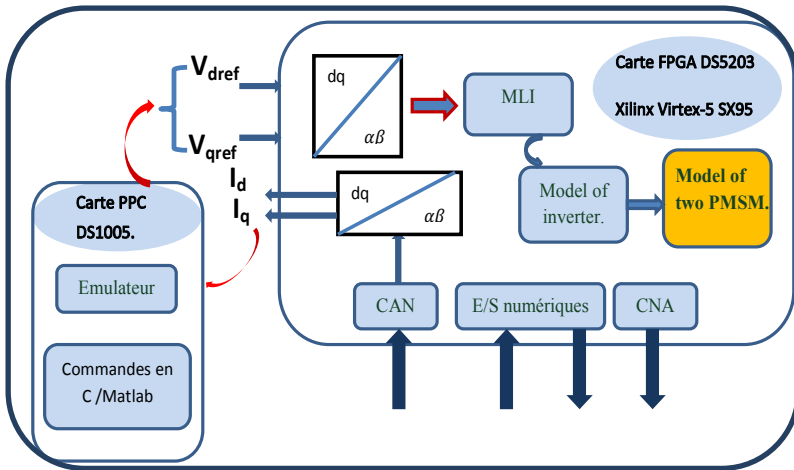


Fig. 9: The different system parts implemented in FPGA.

The different parts implemented in FPGA target are shown in figure 9. Hardware utilization on target device is shown in table I. The implementation results are shown in programming results.

Table I: Hardware Utilization

Device parameter	No Usage	No Available	% Utilization
No of Slice Register	19,251	58,880	32%
No of Slice LUTs	18,958	58,880	32%
No of bonded IOB	393	640	61%
No of BUFG	2	32	6%

Implementation results:

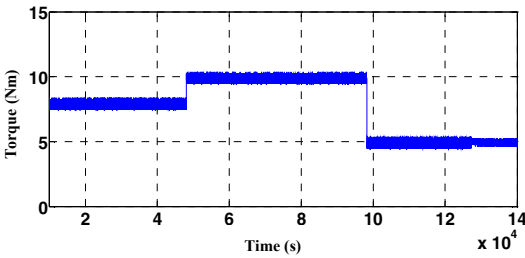


Figure. 10: Electromagnetic torque (T_{em}) of PMSM1.

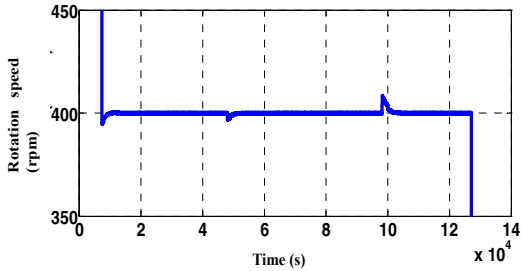


Figure. 11: Rotation speed response of PMSM1.

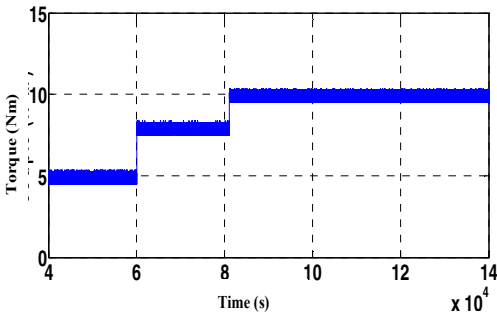


Figure 12: Electromagnetic torque (T_{em}) of PMSM2.

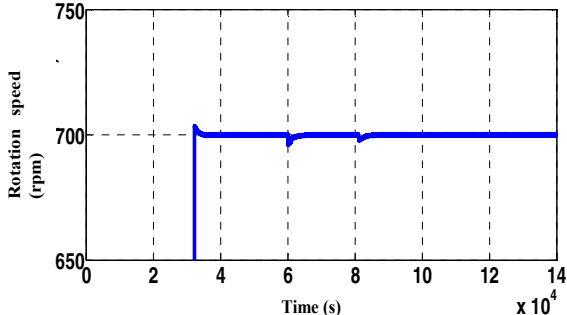


Fig. 13: Response of rotation speed of PMSM2.

Prototyping platform

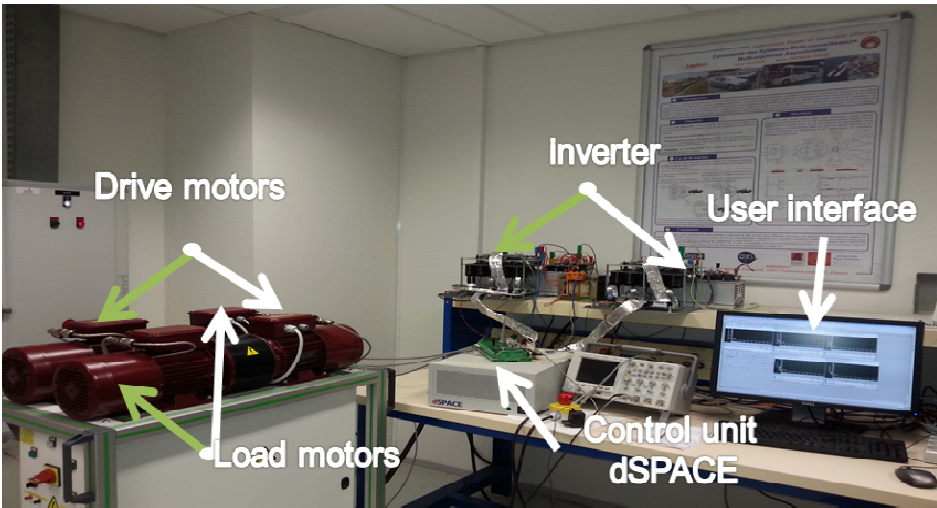


Figure 14: The experimental bench.

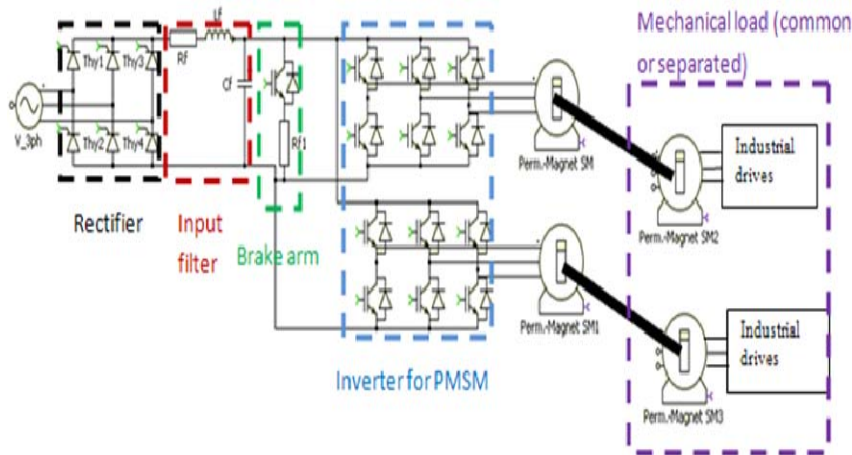


Figure 15: General diagram of the experimental platform.

The common or separated load torque is generated by the industrial PMSM controlled torque drives. In this case the reference of desired torque is imposed by the PPC DS1005 processor. In the FPGA target, the following parts have been implemented:

- Interface ADC, DAC and the two incremental encoders.
- PWM modulation.
- $dq/\alpha\beta$ transformations for the two PMSM.
- $123/\alpha\beta$ and $\alpha\beta/dq$ transformations.

All the parts implemented are resumed in figure 16.

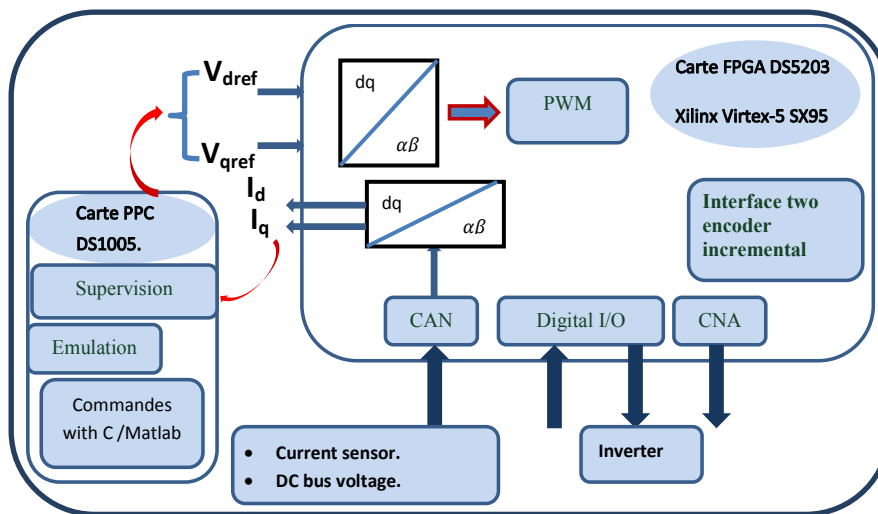


Figure 16: The different parts implemented in FPGA.

Experimental results

The performance of the speed control is shown in Figure.17, we observe two rotation speeds which slave their reference values correctly. The figure 18 shows the currents I_d (red) and I_q ; the first one is equal to zero, as required in the control, therefore the second current is exactly image of the electromagnetic torque. The figure 19 shows the stator PMSM phase current responses.

We can observe that the tested control guarantees the good behavior of the system when the reference value of the rotation speed is changed. The system operation is also satisfactory with the load torque modification.

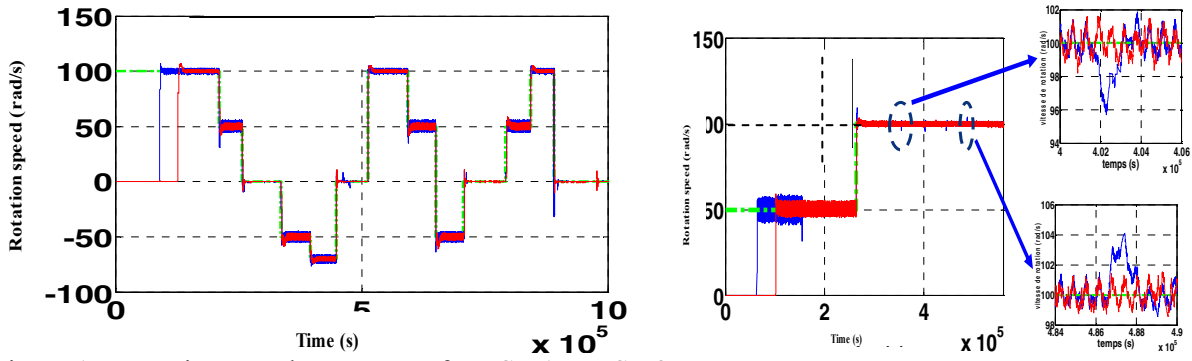


Figure 17: Rotation speed responses of PMSM1, PMSM2.

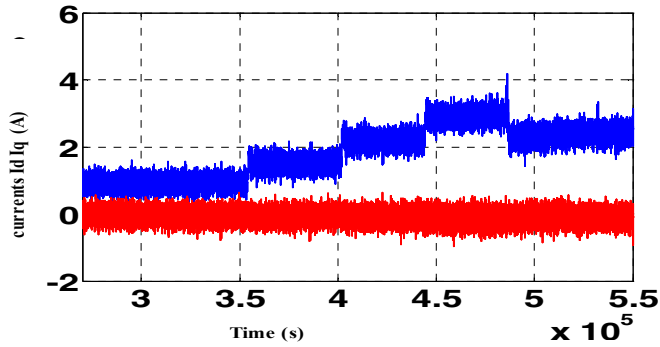


Figure 18: Currents I_d (red) and I_q (blue) of PMSM1.

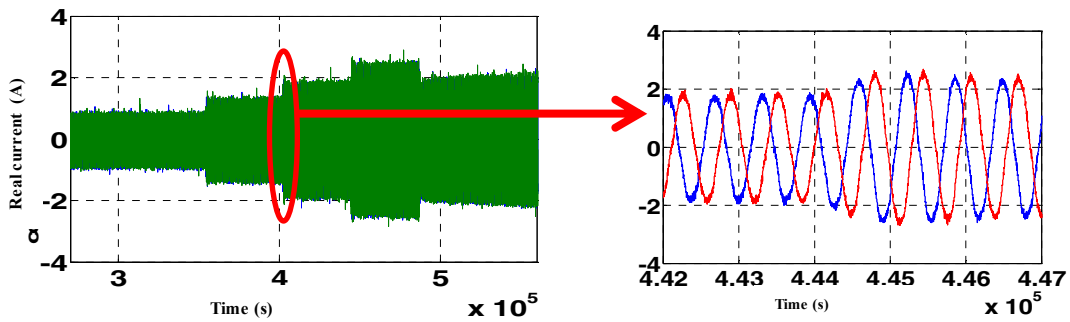


Figure 19: Stator currents of PMSM1

Comparing responses of the mathematical model and the real system.

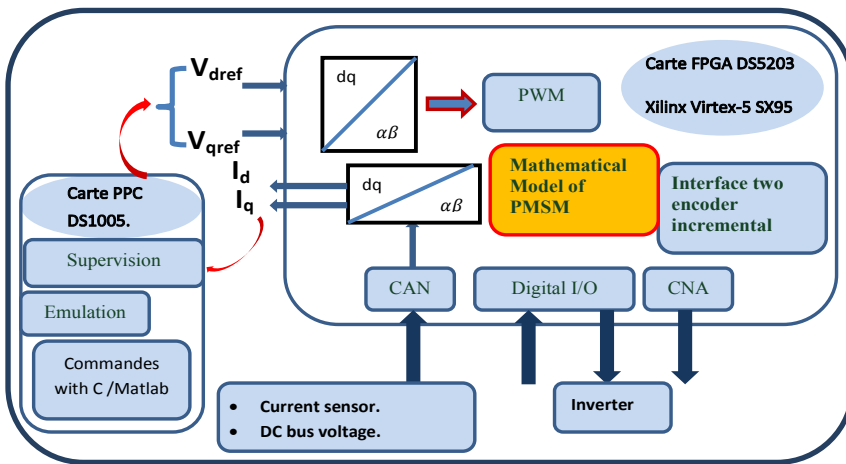


Fig. 20: The different parts implemented in FPGA.

In the FPGA target, the following parts have been implemented:

- Interface ADC, DAC and the two incremental encoders.
- PWM Modulation.
- Transformation $dq/\alpha\beta$ for the two PMSM.
- **Mathematical model of the PMSM.**
- Transformation $123/\alpha\beta$ and $\alpha\beta/dq$.

All the parts implemented are resumed in Fig.20.

Experimental results:

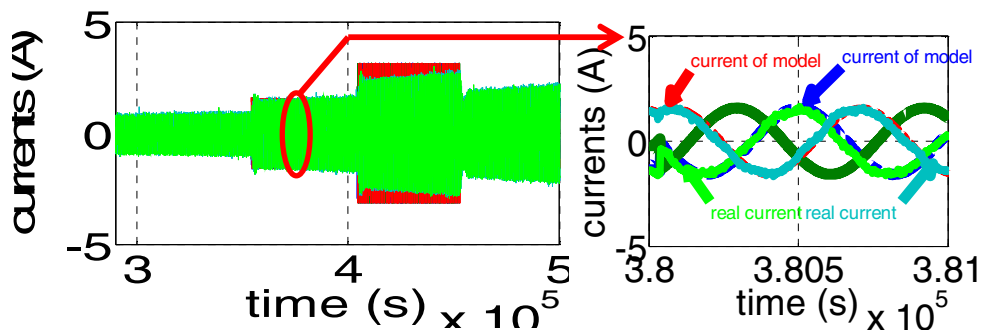


Figure 21: Current responses of PMSM 1 and of its Emulator.

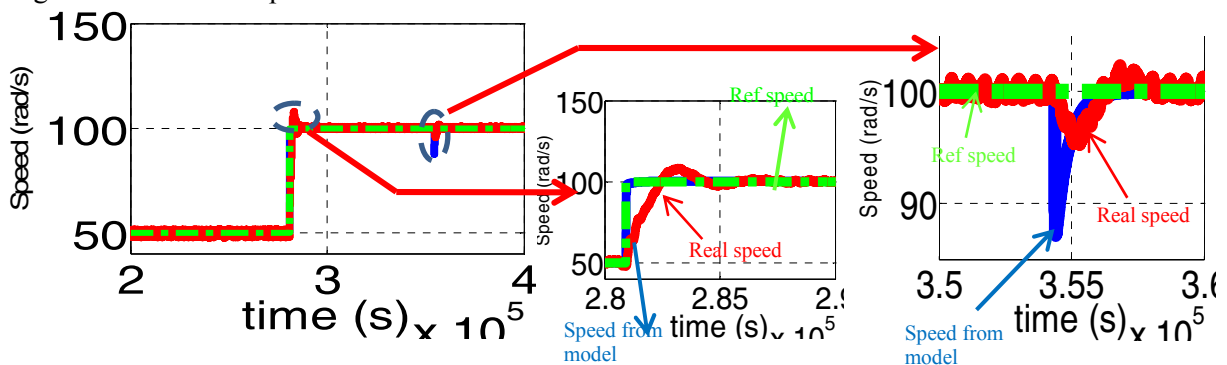


Figure 22: Rotation speed responses of PMSM1 and of its Emulator.

The model of the PMSM machine has been implemented on the FPGA target in order to validate it in real time operation. Firstly, the vector control law used for the controls was implemented on the card PPC DS1005 with PWM modulator and calibrated inputs / outputs. The results presented in Figures 21 and 22 allow comparison of measurable quantities of the PMSM machine, i.e the stator currents and rotation speed with that of the model operating in real time on the FPGA. This approach validates the proper functioning of the model and parameter identification of PMSM motor and the vector control of the machine.

Note: To obtain the real time operation we must be multiplied the base time by the scale factor equal to 10^{-4} s

Conclusion

FPGA was used for the control of two parallel connected PMSMs operating at variable rotation speeds and with variable load torques. The results show that speed controls with an FPGA have a good static and dynamic performances in terms of response time and precision, with the advantage of flexibility in the implementation of the control system.

The objective of this work was to validate the performance of the real time Dual-PMSM drive by using the vector control law, and comparing the reference system (which is the real physical system) with the co-simulated system implemented on FPGA. Also, we want to demonstrate the ability of the Hardware-In-the Loop Emulation in real time in health or fault conditions. We will prepare some scenarios of the system anomalies and we will introduce the corresponding faults such as: DC voltage reduction, open supplying phase, inverter IGBT short-circuit, loss of information from speed sensor or current sensor in the PMSM drive system emulator.

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