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# Sensorless Tolerant Fault Control for Dual Permanent Magnet Synchronous Motor Drive with Global FPGA Emulator

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## Abstract

This paper proposes sensorless tolerant fault control of Dual Permanent Magnet Synchronous Motors (DPMSM), fed by PWM Inverters with separated or coupled loads. The analytical redundancy is realized by FPGA Emulator of global system. This Hardware In Loop (HIL) emulation guarantees system monitoring and its successful operation without any sensor in health end fault conditions.

## 1. Introduction

Nowadays, Multi-PMSM (MPMSM) and Multi-Voltage Source Inverters (MVSI) systems operate with independent or coupled loads and are applied in different embedded systems such as: avionic, railway, vehicular and also ships. In these systems the operation reliability and volume and weight minimization of drives presents their important design criteria. These actuators can operate simultaneously or with sequential order imposed by the special system monitoring. In this paper the authors dedicate this study to several distributed actuators where each PMSM is fed by own PWM Inverter and has individual control operating with physical, electrical and mechanical sensors. These inverters are connected in parallel to DC bus and create an “input electrical coupling”. In the same way the common load associated to several actuators introduces an “output mechanical coupling”. These couplings can introduce the active disturbance propagations between the actuators and also between the input and output of the system.

In this paper the authors focus their study on a Dual PMSM and Dual VSI system, DPMSM/DVSI, which operates with independent or common loads. Two individual real time vector controls are applied to drive this global system. To respect its tolerant fault operating two Xilinx FPGA Emulators are introduced to increase the system reliability and to admit total physical measure suppression. Certainly, the natural and structural redundancy exists in the DPMSM/DVSI system permitting to switch the speed sensor from first PMSM to second one, or vice versa, when a fault occurs (offset, gain, etc.). In the case of current sensor fault its time sharing operation is impossible and it is necessary to dispose three sensors for each PMSM to choose two of them in vector control strategy. The emulator concept with load torque definition, with “virtual mechanical coupling” in the case of common loads, corresponds to an introduction of analytical redundancy in parallel to real system. In this way the virtual reconstituted variables replace the real physical measures in the control of this system. So, the permanent monitoring detects the sensor failure and generates the decision signal to replace the real measure by corresponding virtual one. The experimental validation of this tolerant sensor fault vector control is made on Laplace DPMSM/DVSI experimental bench and confirms its successful operation and its satisfactory reliability.

## 2. System presentation

The real system studied in this paper corresponds to the test bench conceived in LAPLACE laboratory in Toulouse (see Appendix). There is a small scale experimental realization of a bogie of distributed synchronous railway traction (Figure 1) or a flight control actuators of aircraft.

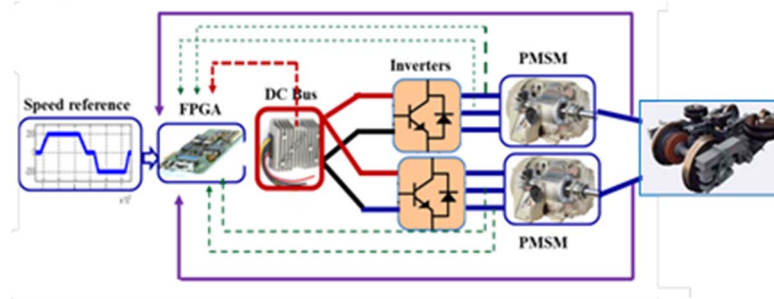


Fig. 1: General DSPSM/DVSI system scheme

### Parameters of Leroy Somer PMSM

Power	P=3kW
Nominal speed	N=1500rpm
Voltage	U=380V
Stator phase resistance	$R_s=25 \text{ m}\Omega$
Cyclic inductances	$L_d=L_q=L_s=5,17\text{mH}$
Magnetic flux	$\Phi=0,5\text{Wb}$
Number of pairs of poles	P=4
PMSM inertia	$J=0.00361\text{Kg.m}^2$
Viscous friction	$f=0.0001\text{Nms/rad}$

## 3. PMSM Modelling

We define the PMSM control laws in d,q Park reference frame, so the electrical equations of the machine are expressed as below:

$$V_d = RI_d + \frac{d\phi_d}{dt} - \omega_r \phi_q \quad (1)$$

with

$$\phi_d = L_d I_d + \phi_f$$

$$V_q = RI_q + \frac{d\phi_q}{dt} + \omega_r \phi_d \quad (2)$$

and

$$\phi_q = L_q I_q$$

Where :  $I_d$  and  $I_q$  are direct and quadrature components of stator current vector,  
 $V_d$  and  $V_q$  correspond to direct and quadrature components of voltage vector  
 $\omega_r$  is PMSM rotation speed  
 $\phi_f$  is the PMSM rotor magnetic flux

For smooth air gap PMSM  $L_d = L_q = L_s$  and equations (1) and (2) can be written as follows:

$$V_d = RI_d + L_s \frac{dI_d}{dt} - \omega_r L_s I_q \quad (3)$$

$$V_q = RI_q + \frac{dI_q}{dt} + \omega_r L_s I_d + \omega_r \phi_f \quad (4)$$

The mechanical equation is expressed by:

$$J \frac{d\omega_r}{dt} + f \omega_r = T_{em} - T_l \quad (5)$$

With:  $J$  - motor and load inertia,  $f$  - viscous friction coefficient,  $T_{em}$  - electromagnetic torque,  $T_l$  - load torque

The electromagnetic torque  $T_{em}$  can be expressed by (6) and in the case of smooth air gap PMSM it is directly proportional to quadrature component of stator current  $I_q$ .

$$T_{em} = \frac{3}{2} p (\phi_d I_q - \phi_q I_d) = \frac{3}{2} p (\phi_f + (L_d - L_q) I_d) I_q = \frac{3}{2} p \phi_f I_q \quad (6)$$

As announced and shown in the Figure 2 we chose arbitrary a d,q vector control strategy with a PI cascade structure for each PMSM. So, the q axis control is composed of two feedbacks. The outer imposes the PMSM rotation speed and the inner controls the  $I_q$  current. The d axis control has only one feedback allowing the direct current regulation  $I_d$ .

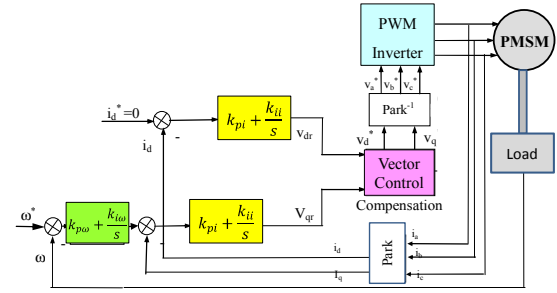


Fig. 2: Diagram of Vector Control of each PMSM

#### 4. Sensorless control operation of DPMSM system

This section presents the design, implementation, and experimental validation of a Real-Time Hardware-in-the-Loop Emulator of a DPMSM system. The two PMSM are modelled using a flexible piecewise linear state space approach and are simulated in hardware with 10 ns time step, which guarantees the high modelling fidelity of PMSM dynamics.

The validation of this Real-Time DPMSM Emulator is made by Real-Time comparison with a reference hardware model of a DPMSM drive. In this way we want analyze experimentally the operation of the HIL- DPMSM drive emulation under different operating scenarios, in health and faulty conditions.

The implementation of several control configurations is made using the dSPACE DS52030D digital platform containing the Power PC DS1005 and the Xilinx FPGA DS520. The task dispatching between PPC and FPGA can be modified during the final optimized implementation of global DPMSM drive system and also its load in common or separated configurations.

In the FPGA target, the following parts have been implemented, as shown in the Figure 3.

- ADC, DAC and the two rotation speed interfaces to adapt temporal signals obtained from two incremental encoders.
- $123/\alpha\beta$  and  $\alpha\beta/dq$  transformations for input signals obtained from DPMSM
- d,q / $\alpha\beta$  and  $\alpha\beta/123$  transformations for output signals sending to PWM modulators of VSIs.
- Calculating estimated voltages from the cyclic ratio and the DC bus voltage.
- Mathematical model of the DPMSM system, i.e. more complex and voluminous model implemented in FPGA target in comparison to one PMSM.

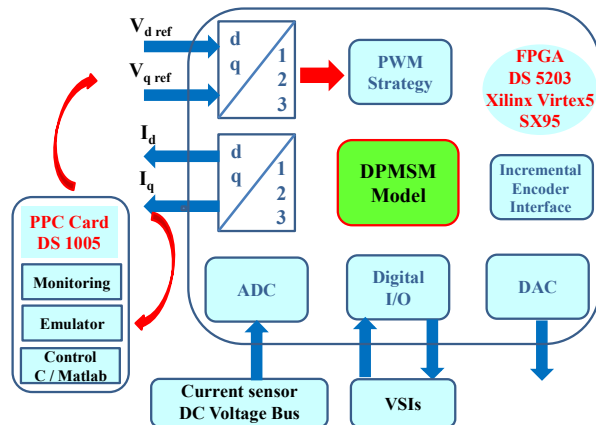


Fig. 3: Task repartition of Real Time Control implemented on FPGA and PPC board.

The Figure 3 shows the task dispatching between Power PC and FPGA board. So, the control laws and observer have been implemented on PPC 752 Processor. To manage effectively all tasks and also to organize the monitoring function, the PMSM emulator has been implemented on FPGA and on the processor.

#### 5. FPGA PMSM Emulator

The model of the PMSM machine is implemented on the FPGA target in order to validate this PMSM emulator, in real time conditions. This validation procedure is verified in following steps.

Firstly, the control laws, SVPWM strategy and calibration of inputs/outputs are realized on the PPC DS1005 card. The results presented in Figures 4.a, 4.b, 4.c, 4.d allow the comparison between the physical PMSM variables, such as stator currents and rotation speed, with the same variables obtained from the PMSM-FPGA and PPC emulator, all working in real time. This approach validates the

satisfactory functioning of the system model, its parameters identification and the vector control of the PMSM.

Next, this model is implemented in the FPGA, in order to use the emulated model for the control of the real system. We validate the real-time emulation in the steady state and transient operations and we compare them with the real PMSM working. Consequently, we confirm the ability of the real-time PMSM emulation, as Hardware In the Loop prototyping platform, to control the real system in a wide rotation speed range, from low to high speeds. The main advantage of this proposed HIL platform is the piecewise linear state space modelling approach which enables comprehensive modelling of PMSM, including the dynamics that occur on the control.

For the design and validation of applied methodology we precede as described below:

- **Algorithm design:** there is an important step and all the control algorithms will be realized under the Simulink Matlab environment with all necessary operations for the algorithm discretization and the fixed point simulation.
- **Architectural design and Modular verification:** in this part we proceed to the synthesis, emplacement and routing of the vector control algorithms of the real system and of the PMSM mathematical model with a temporal analysis for each programmed part.
- **Real time work:** in this phase a global check of the programming procedure is made after the implementation of the different algorithms on the FPGA target and the PPC card.

All these parts are presented in the following diagram:

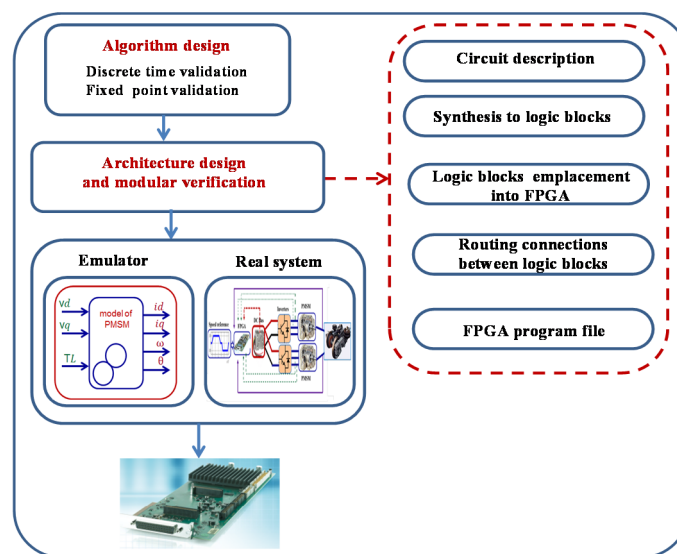


Fig. 4 : Design and validation methodologies

## 5.1 Description of the emulator

The complexity of the DPMSM makes the reproduction on a small scale in the laboratory is a very delicate operation. The validation of the various control strategies can be done through a specific simulation methodology.

Thus, an alternative based on the HIL simulation is proposed and tested in this study. The entire modelling part described in Section 3, starting from the electrical quantities to the dynamics of the machine, is replaced by an emulator implemented on the DS1005 and on the FPGA boards. The emulator reproduces in particular the same dynamics of the real system drive.

This emulator implemented on a real-time target offers the possibility to validate the different scenarios of failures. In this way, it is possible to study the machine behavior during a short circuit,

open phase, etc. The structure of this emulator is given in Figure 5. The voltages  $V_d$  and  $V_q$  necessary for the operation of this emulator can be obtained either from a closed-loop vector control of the mathematical model or from the real voltages that feed the machine. The problem persists when a fault that affects the physical sensors of the machine and these voltages will be affected by the fault and therefore the emulator becomes unstable and we cannot reproduce the real electrical and mechanical quantities of the machine.

Finally, the proposed solution consists to obtain the voltages  $V_d$  and  $V_q$  from the closed-loop vector control of the mathematical model, for a good stability of the emulator (observer). Concerning the load torque  $T_L$ , this quantity is very important in order to reconstruct the real electrical and mechanical variables of the machine. This quantity has been observed from the machine which has not yet failed (in our case we have two PMSMs, i.e. structural redundancy).

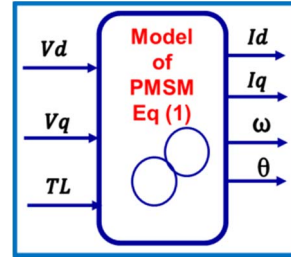


Fig. 5: Diagram of system model.

## 5.2. Experimental results

We present here some experimental results confirming the emulator operation in comparison with real system. So, when we impose the rotation speed cycle for this DPMSM we observe good performances of real rotation speeds  $\omega_{rM1}$  and  $\omega_{rM2}$  controlled with emulated one. The load torque modification don't change the system precision, the zooms shown in the figure 6.a proves the satisfying behavior of this DPMSM system.

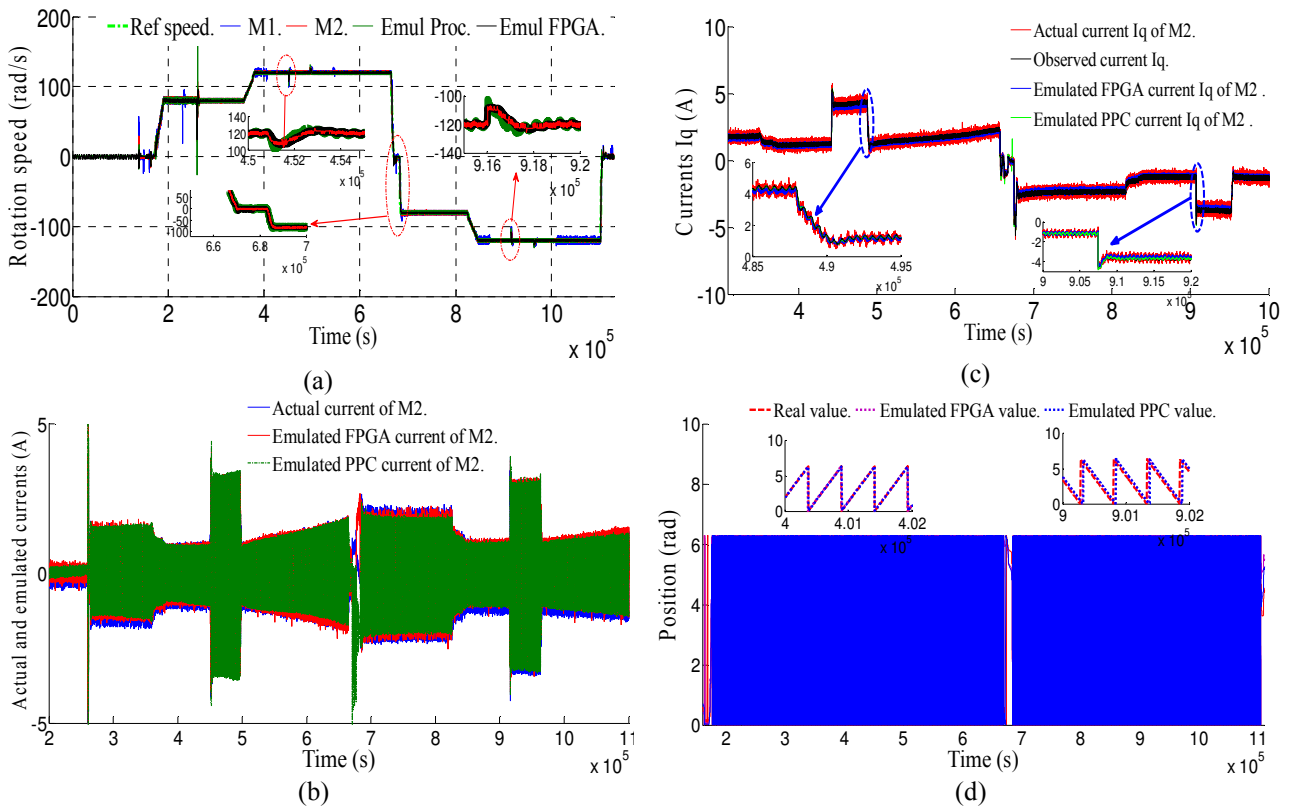


Fig. 6: Comparison of DPMSM real system and its FPGA emulator behaviors: (a) - PMSM rotation speed responses, (b) - PMSM current responses, (c) -  $I_q$  current of PMSM-M2 response and (d) - PMSM-M2 rotor position

It can be noted that this more precise validation is realized for PMSM-M2 (Figure 6.b, 6.c and 6.d) and the satisfactory behavior of virtual system corresponds perfectly to the dynamic operation of real PMSM system. The FPGA emulator reconstitutes successfully all electrical and mechanical system variables. We had also tested the real system and emulator concordance when this last was implemented on PPC card (with discretization). Also, we can remark in the figure 6.c the good emulation fidelity ( $I_q$  response), but for this PPC solution an important execution time constrains especially the emulation of several PMSMs simultaneously.

## 6. Sensorless tolerant fault control experimental validation

The validation of this control dedicated to DPMSM was also made in faulty operation conditions. In this paper we discuss the failed operation which concerns the rotation speed sensor fault. So, when the monitoring function detects incorrect physical measure in one PMSM speed sensor, immediately it can be replaced by virtual corresponding variable obtained from the global emulator.

To achieve this goal a decision organ is introduced (Figure 7) to accomplish this task. So without fault, the signal "Select" takes the value of "0" and when the first rotation speed sensor is failed, the signal "Select" changes to "1", it becomes "2" when a fault occurs in the second speed sensor. In our case the decision on faulty rotation speed sensor is confirmed if the sensor gives a value of 80% for the reference speed.

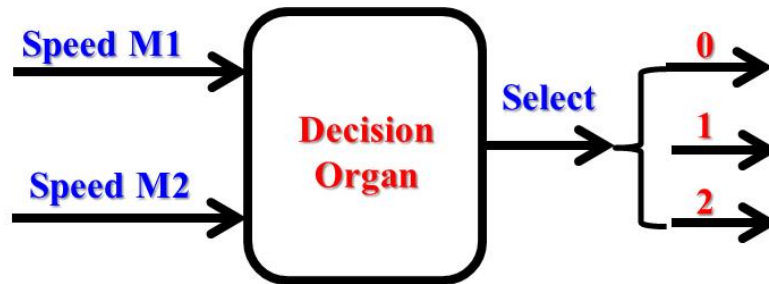


Fig. 7 : Decision organ operation

This decision organ operates according to the following implemented algorithms which introduces an analytic redundancy vs rotation speed physical sensor.

$$\text{select} = \begin{cases} = 1 & \text{if speed M1} \leq 80\% \text{ of reference speed} \\ = 2 & \text{if speed M2} \leq 80\% \text{ of reference speed} \end{cases}$$

This analytic redundancy allows also the sensorless control operation of the system and in our case it leads to sensorless tolerant fault control of DPMSM. The Figure 8 shows the DPMSM system rotation speed control in presence of faults occurring on speed sensor of PMSM-M2.

After fault detection by the monitoring device, an order is sent to replace the physical measure by corresponding virtual variable obtained from emulator. As this emulator is implemented on FPGA target, this operation is very fast and the system service continuity is guaranteed. Finally, the system behavior is the same as in health operating conditions.

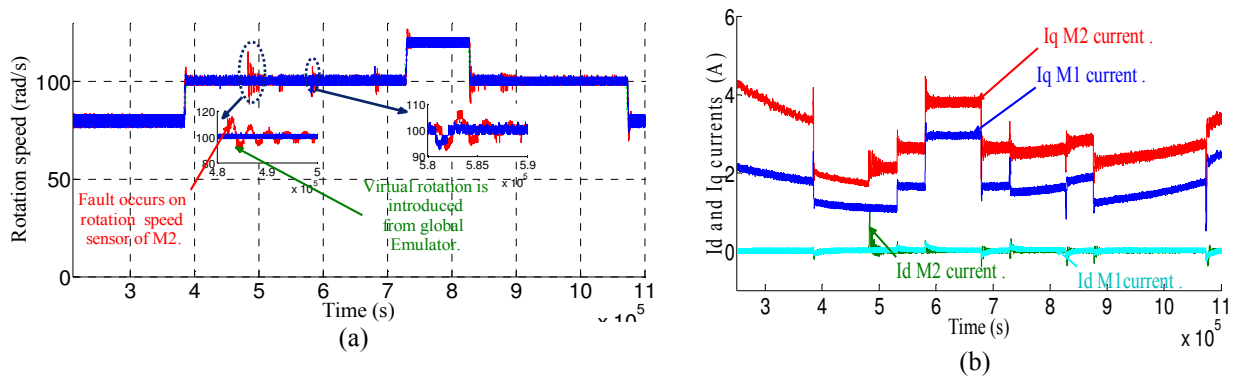


Fig. 8: Healthy and faulty system behaviors: (a) rotation speed response in presence of speed sensor fault, (b)  $I_q$  and  $I_d$  responses for DPMSM drive corresponding to realize rotation speed profile.

To continue the satisfactory operation with the emulated rotation speed, this substitution variable must be commuted in a very short time; otherwise the correct closed loop operation of the system using this one is compromised by instability due to this connection delay. In the Figure 8 it can be seen that the sensorless operation is ensured perfectly by the emulated speed variable. The electrical and mechanical variables can be compared with closed-loop operation with a physical sensor and without sensor which is replaced by corresponding emulated variable. In this study when a speed sensor fault occurs in the DPMSM drive system, this one continues its closed-loop operation with one PMSM working with physical rotation speed measure and another PMSM can operate thanks to analytic redundancy using this substituting variable.

It can be seen that the same rotation speed and electrical current are obtained, but low oscillation are observed during the transient for the PMSM controlled with the emulated rotation speed.

## 7. Conclusion

In this study the concept of a tolerant fault control dedicated to Dual PMSM system driving separated or common load is presented. This system is fed by dual SVPWM VSI. The main idea to guarantee the high static and dynamic performances consists to associate to the DPMSM controls a Global Real-Time Emulator. This global emulator includes two sub-emulators, each associated to one PMSM fed by its VS-PWM VSI and controlled by its own vector control. The great complexity of this emulation requires the rigorous programming on FPGA target and also on PPC. Furthermore an excellent management of all dispatched tasks between PPC and FPGA is necessary. Finally, the novel methodology which associates the real-time global system emulation with real time control allows the high level flexibility to replace any physical measure by its virtual corresponding variable. This global emulator guarantees the different diagnostic functions, i.e. detection, isolation and reconfiguration. This study concerns the health and faulty operation of the system according to the sensor possible failures. The obtained experimental results encourage us and offer the new research possibilities for the tolerant fault controls of complex embedded systems.

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## 9. Appendix

### LAPLACE Laboratory Test Bench Presentation

