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FPGA Field Oriented Control of an Axial Flux Motor-in-Wheel

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***Abstract*—This paper presents the design and the prototype implementation of a three-phase power inverter developed to drive a motor-in-wheel. The control system is implemented in a FPGA (Field Programmable Gate Array) device. The paper describes the Field Oriented Control (FOC) algorithm and the Space Vector Modulation (SVM) technique that were implemented. The control platform uses a *Spartan-3E* FPGA board, programmed with Verilog language. Simulation and experimental results are presented to validate the developed system operation under different load conditions. Finally are presented conclusions based on the experimental results.**

Keywords—Axial Flux Motor-in-Wheel; Field Oriented Control (FOC); Field Programmable Gate Array (FPGA); Space Vector Modulation (SVM)

I. INTRODUCTION

It is estimated that within 50 years the oil resources are virtually exhausted. While it is also expected that the overall number of vehicles will increase from 700 million to 2.5 billion, as consequence of the world population increase. Therefore, alternative energy sources and storage systems are needed. Electric mobility is growing as response to this need of reducing vehicles´ dependence on fossil fuels [1], [2].

Electric motors manufacturers are sensible to this change of the mobility paradigm, and new motors, specially designed for electric vehicles (EVs) are being developed. The axial flux motors are one of the most promising technologies due to its high power density. They can be mounted inside the vehicle's wheels, reducing, or even eliminating mechanical components. This concept is known as motor-in-wheel.

Electric motors can be used in electric vehicles to drive the vehicle, or in hybrid electric vehicles to assist the internal combustion engine (ICE). When assisting the ICE, the electric motor only produces the peak power required by the vehicle, reducing the ICE power, and consequently reducing fuel consumption, and therefore improving vehicle's efficiency. Another advantage of using electric motors in the powertrain is its ability to work as motor or generator. This characteristic allows regenerative braking, that increases the efficiency and autonomy of the vehicle.

This paper presents the power converter and the control algorithms design, simulation and experimental results of a motor-in-wheel controller. The proposed solution uses Field Oriented Control (FOC), and a Space Vector Modulation (SVM) techniques. The control platform uses a *Spartan-3E* FPGA Starter Kit Board from *Xilinx*.

II. FIELD ORIENTED CONTROL

With the Field Oriented Control (FOC) the motor torque and magnetization flux are, directly and separately, controlled. Using the FOC the motor is controlled as it is a DC motor, with all the arising advantages, namely instantaneous torque and flux control, which improves the motor performance both in transient and steady state operation [3]-[5].

Fig. 1 depicts the FOC with a Space Vector Modulation (SVM) technique. The Clarke transform is used to represent the motor currents in a two axes orthogonal α-β coordinate system. These currents are called i_α and i_β. With the Park transform the α-β components are translated to a two axes orthogonal *d*-*q* coordinate system synchronous with the rotor position. In this system the motor currents are called I_d and I_q Each of these current components is then compared with the correspondent reference current, I_d^* (flux reference) and I_q^* (torque reference). The I_d^* reference is set to zero in order to be obtained the maximum torque. The I_q^* reference is generated by the speed regulator. Using two PI controllers the *d*-*q* axis motor reference voltages (V_d and V_q) are obtained. The inverse Park transform translates the voltage references in two α-β reference voltage components, v_α and v_β, which are used as inputs for the SVM technique.

The motor was modeled using the *d*-*q* axis mathematical model. So, the main equations of the motor are expressed under a *d*-*q* coordinate system, as shown in equations (1) to (4). It was assumed that the rotor flux is constant and the motor losses were neglected [6], [7].

$$v_q = R_s\, i_q + L_q \frac{di_q}{dt} + \omega_e \left(\phi_m + L_d\, i_d\right) \tag{1}$$

$$v_d = R_s\, i_d + L_d \frac{di_d}{dt} - \omega_e \left(L_q\, i_q\right) \tag{2}$$

$$\omega_e = \frac{p}{2}\, \omega \tag{3}$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(i_q\, \phi_m + \left(L_d - L_q\right) i_q\, i_d\right) \tag{4}$$

Where, v_d and v_q, are the stator voltages, i_d and i_q are the stator currents, L_d and L_q are the motor inductances, R_s is the stator resistance, ω_e is the electrical rotor speed, ω is the rotor angular speed, ϕ_m is the rotor permanent magnets flux, and p is the number of poles.

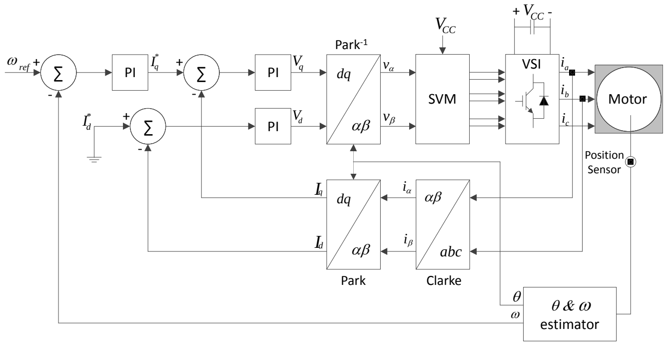

Fig. 1. Field Oriented Control (FOC) block diagram.

III. SPACE VECTOR MODULATION

As it can be seen in Fig. 1 the FOC produces two α-β reference voltage components, v_α and v_β, which represent the voltages that should be applied to the motor. The translation of these reference voltages in gate pulses for the inverter semiconductors is done by a pulse width modulation technique. Since the reference voltage is a vector, and considering the advantages of the Space Vector Modulation (SVM) technique, it was the natural choice. In comparison with other modulation techniques, SVM does a more efficient use of the DC-link voltage, generates voltages with lower total harmonic distortion and reduces the power semiconductors switching losses, improving efficiency [8], [9]. The SVM has good performance in applications where it is necessary a variable frequency, as it is the case of motors control. Nevertheless, it should be mentioned that it consumes more computational resources [8].

The working principle of the SVM is depicted in Fig. 2. It consists in representing the reference voltage (V_{ref}) in a α-β coordinate system, that is divided in eight different sectors defined by the voltage vectors, V_0 to V_7 [8].

The procedure to obtain the modulation duty cycles can be divided into three steps [10]:

1) Determination of the Sector of V_{ref}

With equations (5) and (6), and Table I, is identified the sector where vector V_{ref} is placed.

$$\begin{cases} If\ \ v_\beta > 0 & Then\ A = 1,\quad Else\ A = 0 \\ If\ \ (v_\alpha\sqrt{3} - v_\beta) > 0 & Then\ B = 1,\quad Else\ B = 0 \\ If\ \ (-v_\alpha\sqrt{3} - v_\beta) > 0 & Then\ C = 1,\quad Else\ C = 0 \end{cases} \tag{5}$$

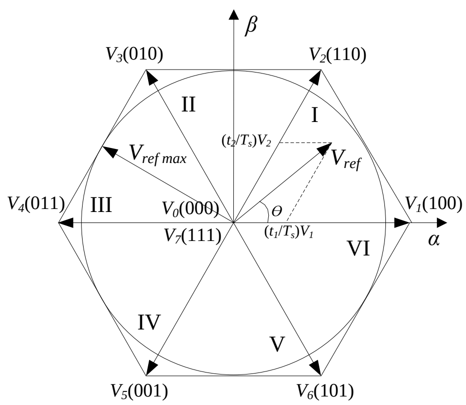

Fig. 2. SVM sectors and voltage reference (V_{ref}) in the α-β coordinate system.

TABLE I. V_{REF} SECTORS

N	1	2	3	4	5	6
Sector	II	VI	I	IV	III	V

$$N = A + 2\,B + 4\,C \tag{6}$$

2) Calculation of the Dwell Times t1 and t2

With equations (7) to (9) the auxiliary variables X, Y and Z are calculated. These auxiliary variables are used to define the dwell times, t_1 and t_2, according to Table II.

$$X = \frac{\sqrt{3}\,u_\beta}{V_{CC}} T_s \tag{7}$$

$$Y = \frac{1}{2\,\mathrm{V_{CC}}}\left(\sqrt{3}\,u_\beta + 3\,u_\alpha\right)T_s \tag{8}$$

$$Z = \frac{1}{2\,V_{CC}}\left(\sqrt{3}\,u_\beta - 3\,u_\alpha\right)T_s \tag{9}$$

Where, V_{cc} is the DC-link voltage and T_s is the switching period.

3) Determination of the Duty Cycles T_a, T_b and T_c

The next equations show the calculation of the duty cycles. Table III organizes the duty cycles according to V_{ref} sector.

$$t_{aON} = \frac{(T_s - t_1 - t_2)}{4} \tag{10}$$

$$t_{bON} = t_{aON} + \frac{t_1}{2} \tag{11}$$

$$t_{cON} = t_{bON} + \frac{t_2}{2} \tag{12}$$

IV. SIMULATION RESULTS

Before implementing the system a set of simulations were performed, in order to assess the system behavior and to improve design specifications. The simulation software used was *PSIM 9.1* from *Powersimtech*.

Many times electric motors manufactures do not provide all the parameters needed for its proper simulation Therefore, a set of experimental tests are needed in order to obtain them [11]. Table IV presents the main parameters of the motor-in-wheel that was used.

A. No-Load Simulations

Fig. 4 shows the motor speed along the time and its reference when the motor is operating without any mechanical load. It is

TABLE II. DWELL TIMES OF THE SWITCHING STATE VECTORS

Sector	I	II	III	IV	V	VI
t_1	$-Z$	Z	X	$-X$	$-Y$	Y
t_2	X	Y	$-Y$	Z	$-Z$	$-X$

TABLE III. DUTY CYCLES FOR EACH SECTOR

Sector	I	II	III	IV	V	VI
T_a	t_{aON}	t_{bON}	t_{cON}	t_{cON}	t_{bON}	t_{aON}
T_b	t_{bON}	t_{aON}	t_{aON}	t_{bON}	t_{cON}	t_{cON}
T_c	t_{cON}	t_{cON}	t_{bON}	t_{aON}	t_{aON}	t_{bON}

TABLE IV. MOTOR-IN-WHELL CHARACTERISTICS

Characteristic	Value	Unit
Nominal Power	1.8	kW
Speed	520	rpm
Nominal Voltage	33.2	V
Nominal Current	40.8	A
Torque	33	Nm
Number of Poles	32	-
Nominal Frequency	139	Hz
Stator Resistance	58	mΩ
d-axis Stator Inductance	205	µH
q-axis Stator Inductance	221	µH
Voltage constant	86.8	V/1000 rpm

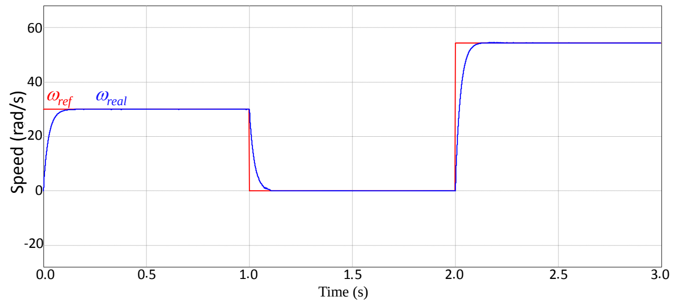

Fig. 4. Motor speed (ω_{real}) and its reference (ω_{ref}) without mechanical load.

possible to observe the speed following the reference. It is also visible that the system has a fast response to reference variations.

In Fig. 3 is shown the motor voltages (v_a, v_b and v_c) and currents (i_a, i_b and i_c) at nominal speed without mechanical load. The voltages were measured between each motor phase and the middle point of the DC-link, it was also used a low-pass filter set with a 500 Hz cutoff frequency.

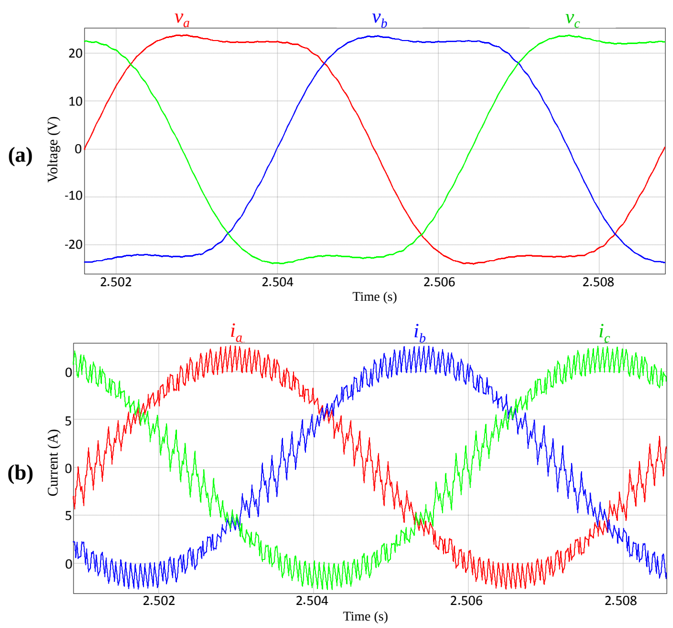

Fig. 3. Voltages and currents of the motor without nominal mechanical load: (a) v_a, v_b and v_c; (b) i_a, i_b and i_c.

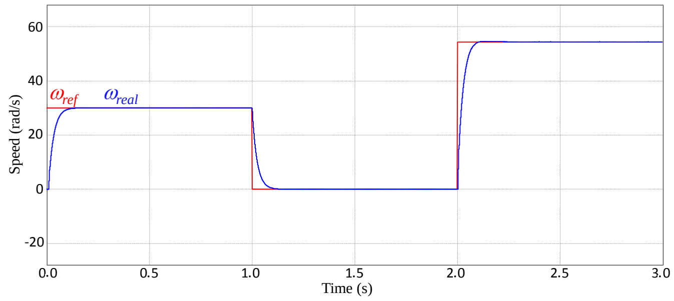

Fig. 5. Motor speed (ω_{real}) and its reference (ω_{ref}) with nominal mechanical load.

B. Full-Load Simulations

The system was simulated with a mechanical load of 33 Nm. Fig. 5 shows the motor speed and its reference when the motor runs at nominal load. It is possible to observe the speed following its reference. It is also visible that the system has a fast response to reference variations, and that it has not changed with the load.

Fig. 6 shows the motor voltages (v_a, v_b, v_c, v_{ab}, v_{bc} and v_{ca}) and currents (i_a, i_b and i_c) at nominal speed. Like in the no-load simulations, v_a, v_b, and v_c voltages were obtained between the motor phase and the middle point of the DC-link, while v_{ab}, v_{bc}, and v_{ca} voltages are the phase-to-phase motor voltages. It is

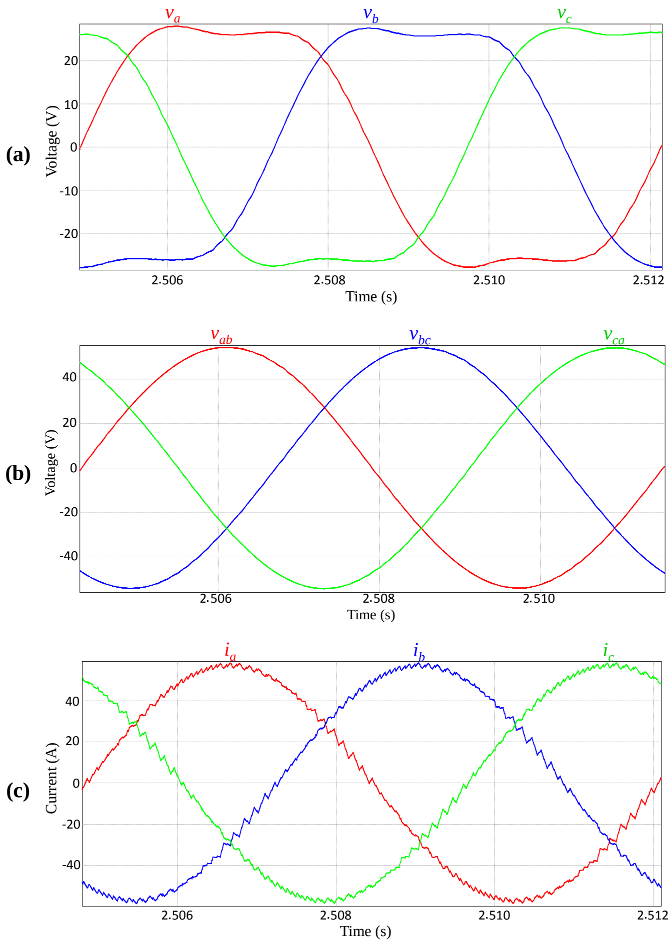

Fig. 6. Voltages and currents of the motor at nominal speed and with nominal mechanical load: (a) v_a, v_b and v_c; (b) v_{ab}, v_{bc} and v_{ca}; (c) i_a, i_b and i_c.

visible that the currents ripple is lower than with no-load operation, due to the higher RMS currents values.

V. System Implementation

As shown in Fig. 7, it was developed a three-phase power inverter to drive the motor. This inverter is composed by three IGBT legs, and three driver boards from *SEMIKRON*.

The control platform uses the FPGA *Spartan-3E Starter Kit Board* from *Xilinx* (Fig. 8).

This board uses the *Xilinx XC3S1600E Spartan-3E* with 232 I/O ports and around 10 000 logic cells. This board also has other features such as: a 50 MHz oscillator, a 16 Mb flash memory with SPI communication, two RS-232 ports, and support for a LCD [12]. The code was programmed in Verilog language to be achieved a faster system response.

The FOC process implementation follows the state machine presented in Fig. 9. In each state sequentially or parallel tasks can coexist. The sequence and parallelization of the tasks

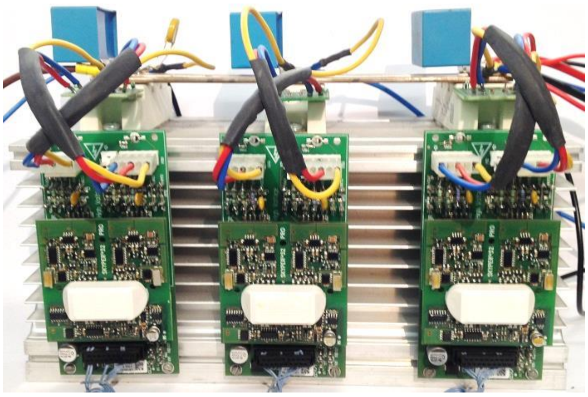

Fig. 7. Developed three-phase power inverter.

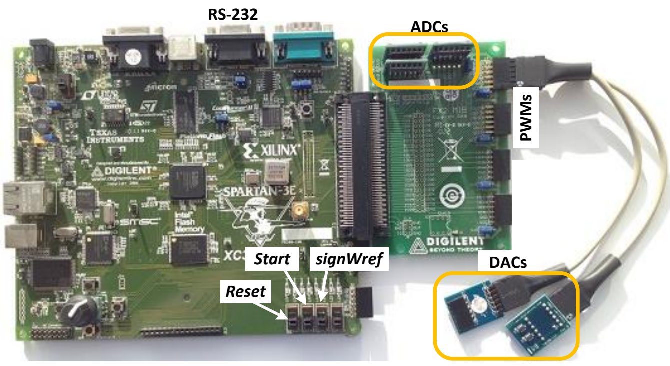

Fig. 8. Spartan-3E FPGA Starter Kit Board.

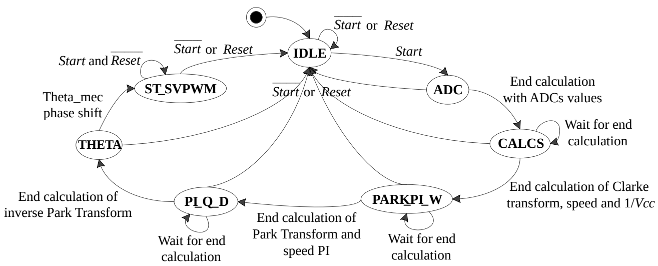

Fig. 9. The FOC state machine.

execution are shown in Fig. 10. The transaction between two different states takes one clock cycle.

The signal conditioning between the voltage and current sensors from the inverter, accelerator position, rotor position, and the FPGA is done by the board presented in Fig. 11 (a). The inverter command signals are adjusted by the board shown in Fig. 11 (b).

VI. Experimental Results

The experimental results were obtained with the support of the test bench shown in Fig. 12. With this test bench is possible to change the mechanical load between 0 and 47 Nm [13].

A. Experimental No-Load Test

In Fig. 13 are shown the motor speed and its reference with no-load condition. It is visible that the motor speed follows the reference. It is also visible that the system has a fast response to reference variations.

In Fig. 14 are shown the motor voltages (v_{ab}, v_{bc} and v_{ca}) and currents (i_a, i_b and i_c) at an angular speed of 44 rad/s. The voltages were acquired with an oscilloscope and a low-pass filter set with a 500 Hz cutoff frequency. The currents were measured using *FLUKE i400s* current probes set with a scale of 10 mV/A.

B. Experimental Load Test

In Fig. 15 are shown the motor speed and its reference with different mechanical loads. Five different time instants are depicted. At instant T_1, the mechanical load was changed from 0 to 10 Nm and the motor speed reference was set to 31 rad/s, resulting in a speed overshoot of about 4.5 rad/s, during 0.5 s. At instant T_2, the mechanical load is increased by 15 Nm. As

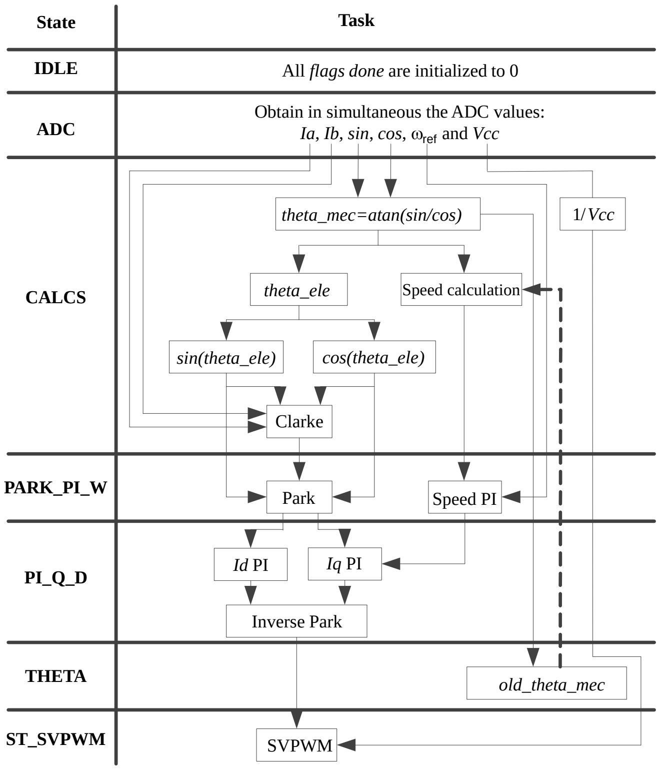

Fig. 10. The FOC state machine.

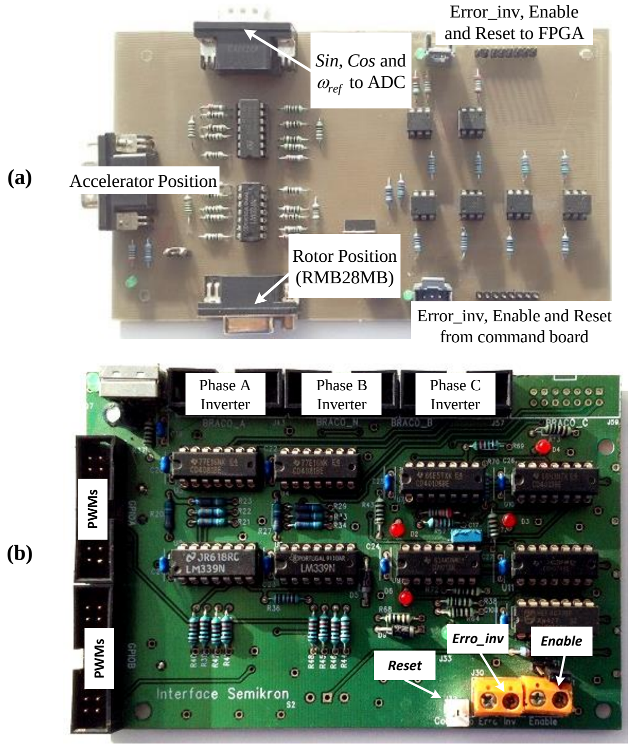

Fig. 11. Developed FPGA signal conditioning boards: (a) Input signals; (b) Inverter command signals.

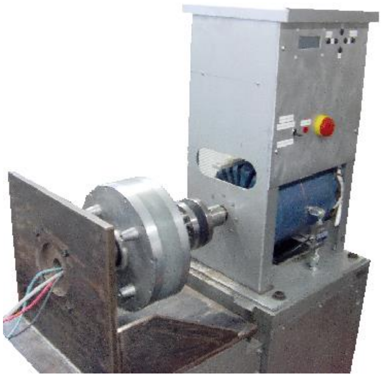

Fig. 12. Assemblage between the motor-in-wheel and the test bench.

consequence the speed slightly decreases, to increase again to the reference values 1 s later. At instant T_3, the mechanical load is decreased by 15 Nm, returning to the initial value. Consequently, the speed slightly increases, about 1 s later decreases to the reference value. At instant T_4, the speed reference starts decreasing to zero. Finally, at instant T_5, it was given a reference for the motor to stop.

In Fig. 16 are shown the motor voltages (v_{ab}, v_{bc} and v_{ca}) and currents (i_a, i_b and i_c) at 33 rad/s with nominal mechanical load. Like in the no-load test, the voltages and currents were also obtained with an oscilloscope and current probes.

VII. Conclusions

In this paper was presented a three-phase power inverter developed to drive an Axial Flux Motor-in-Wheel. It was also presented the simulation and experimental results obtained with a control system using Field Oriented Control (FOC) and Space

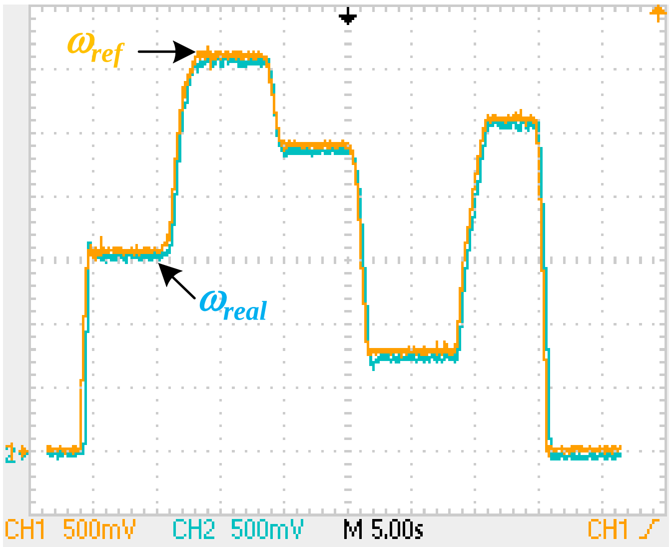

Fig. 13. No-load motor speed (ω_{real} - 8 rad/s/div) and its reference (ω_{ref} - 8 rad/s/div).

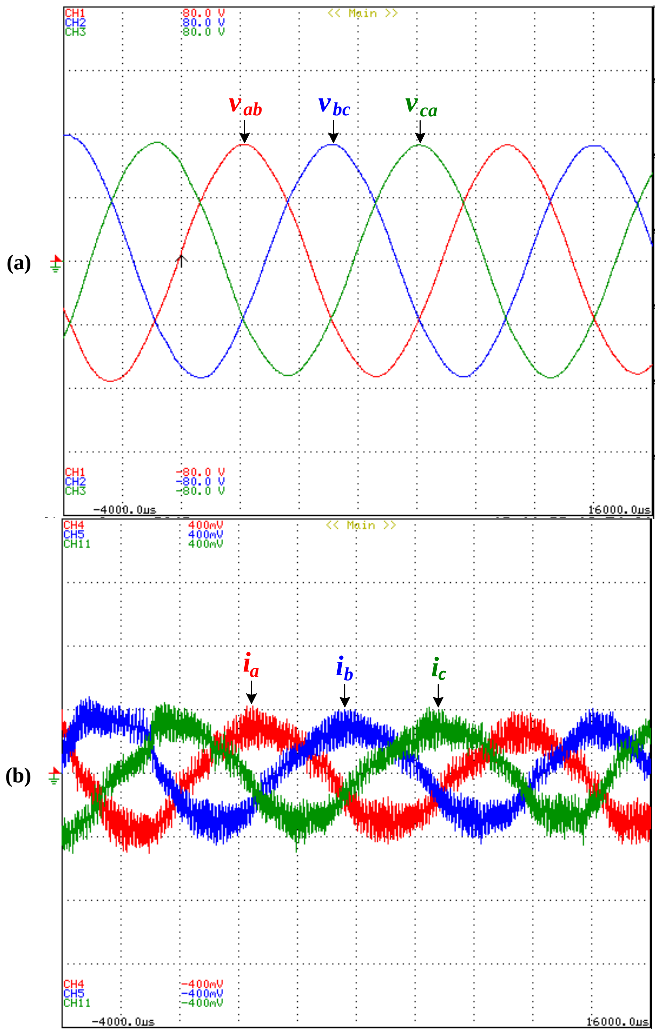

Fig. 14. Motor voltages and currents at speed of 44 rad/s without mechanical load: (a) vab, vbc and vca (20 V/div); (b) ia, ib and ic (10 A/div).

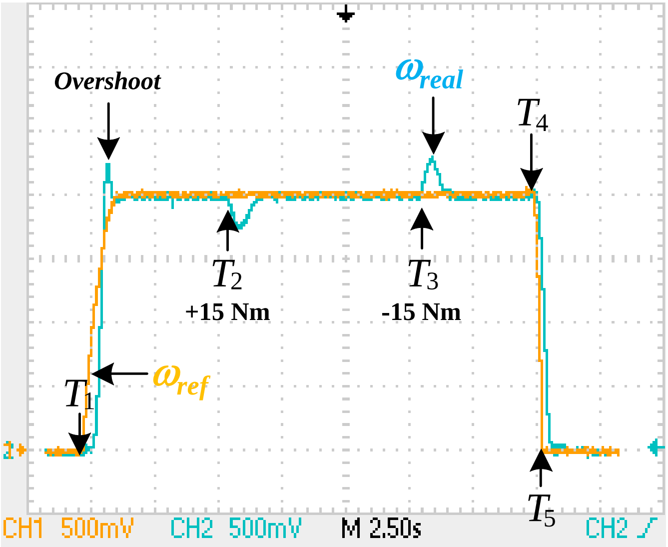

Fig. 15. Motor speed (ω_{real} - 8 rad/s/div) and its reference (ω_{ref} - 8 rad/s/div) for different mechanical loads.

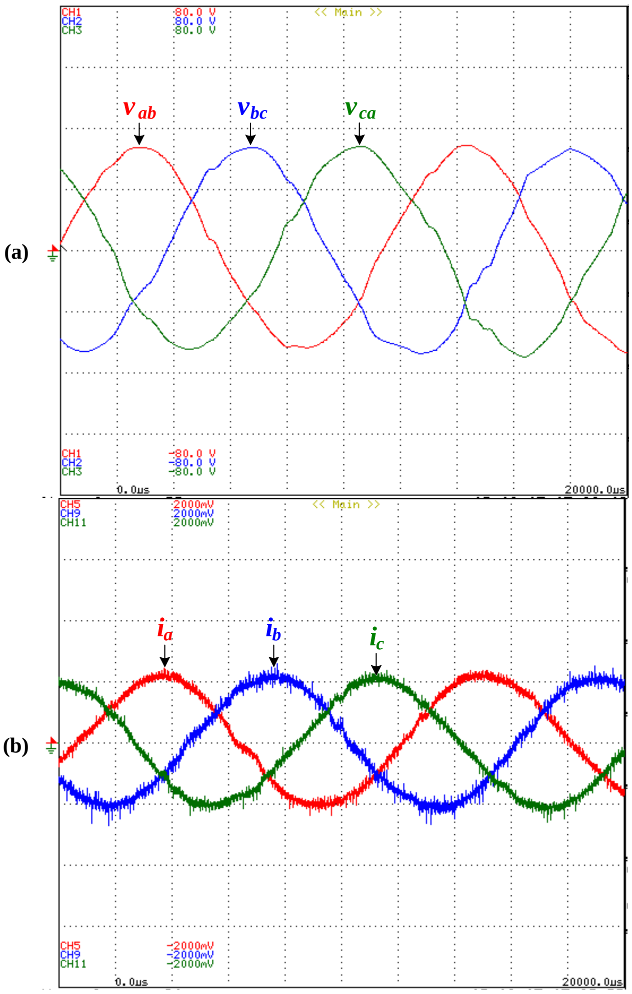

Fig. 16. Motor voltages and currents at 33 rad/s with nominal mechanical load: (a) v_{ab}, v_{bc} and v_{ca} (20 V/div); (b) i_a, i_b and i_c (50 A/div).

Vector Modulation (SVM). The experimental results showed that the FOC presents a good performance and fast response to speed reference variations in both no-load and load conditions.

The control platform used to implement the control system was a *Spartan-3E FPGA Starter Kit Board* from *Xilinx*. The code was programmed using Verilog language, in order to be achieved a faster system response. Currently the FPGA is already programmed in order to reduce the number of resources used. Even though, as future work it is intended to optimize the parallelization of the tasks, so that the resources consumption can be even more reduced.

ACKNOWLEDGMENT

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