Experimental research and Control of PMSG Based Wind Turbine connected to Grid

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Abstract: *This paper presents an experimental study of a wind energy conversion system based on a permanent magnet synchronous generator (PMSG). The objective of this work is to make an operational test bench platform and propose a control strategy for all the system (generator side control and grid side control). The wind turbine has been replaced by an emulator based on a DC motor.*

The proposed strategy comprises the control of the generator for maximum power point tracking (MPPT) under varying wind conditions; the DC motor is controlled so as to have the same functioning as a wind turbine. The system is connected to a three-phase network by means of: an IGBT rectifier, a DC bus, an IGBT inverter and a transformer. A detailed study of the test bench elements and its control scheme is presented. The experimental results are obtained and captured from the controlDesk software in real time using two DSPACE cards; however they show the feasibility and robustness of the proposed control strategy.

Key words: *Wind energy conversion system (WECS), PMSG, PLL, Wind turbine emulator, maximum power point tracking (MPPT).*

1. Introduction

In recent years, wind energy has become one of the most popular and economical renewable energy because of the primary source of this energy production system (Wind), which is unpredictable. The main advantages of electricity generation from renewable sources are the absence of harmful emissions and the infinite availability of the prime mover that is converted into electricity [1, 2].

The amount of energy extracted from wind depends not only on the incident wind speed, but also on the control system applied on the wind energy conversion system (WECS).

Variable speed wind generation systems make it possible to extract the maximum energy from wind with widely varying speeds. The permanent magnet synchronous generators (PMSGs) are suitable for small variable-speed wind turbine generator systems. The wind generation system with a PMSG represents one important trend of development for wind power applications with numerous advantages like higher efficiency due to the absence of field copper loss, lower operating speed due to higher number of poles with smaller pole pitch, and the elimination of gearbox [3].

The aim of this paper is to present the test bench realized and to propose some control strategies. In the first section, we detail the test bench elements. The second part is devoted to modeling and controlling the wind turbine emulator and controlling the PMSG, a vector control is applied to the PMSG in order to enable the system to track maximum power point. In the third part, we control the grid side, starting by controlling the DC voltage to a fixed value and then the grid currents; a PLL block is used to adjust the frequency of the system at the frequency of the network. The power from the wind energy conversion system (WECS) is normally fed to an ac grid [3].

2. Wind energy conversion system (WECS):

Fig. 1 shows an overall system configuration of WECS connected to the grid. The system consists of a wind turbine coupled to a PMSG with a generator side converter linked through a DC-link to the grid side converter and transformer. The converters are used to control the PMSG and to connect the system to an utility grid. The generator-side converter is used to control the generator for maximum power point tracking (MPPT). The grid-side converter is used to keep the voltage of DC-link constant and to regulate the active power given to the grid [4].

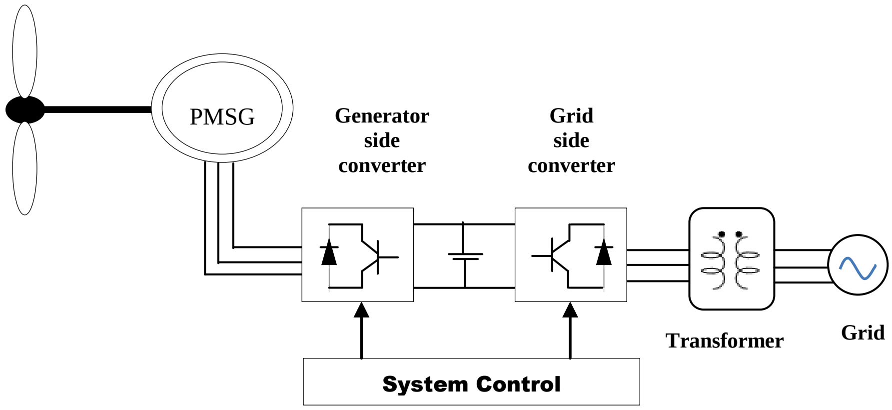

Fig.1 The structure of the wind turbine string conversion.

3. The test bench:

The test bench that is used comprises a wind turbine emulator based on a DC motor controlled by a chopper, a permanent magnet synchronous generator, two pulse Width Modulation (PWM) converters and a transformer. This system is connected to a three phase network of 127 V (50 Hz). The whole system is controlled by means of two DSPACE cards (DSPACE 1104 and DSPACE 1103), using controldesk software. The first card controls the generator side (wind turbine emulator and PMSG) and the second Controls the grid side.

The connections between the DSPACE cards and the power converters are carried out by two interface cards which adapt the control signals levels. The signals (currents, voltages, speed) are measured by means of sensors which are connected to the interface cards.

4. The control:

4.1. Generator side:

In this section, we present and detail the control of the generator side that contains the control of the DC motor and the PMSG by means of chopper and rectifier respectively as shown in the Fig. 3.

4.1.1. Wind turbine emulator:

The mechanical power output from the wind turbine can be expressed as [5]:

$$P_w = C_p(\lambda,\beta).\frac{\rho.A.V_w^3}{2} \qquad (1)$$

$$A = \pi.R^2 \qquad (2)$$

Where P_w is the extracted power from the wind, ρ is the air density [kg/m^3], A is the area swept by the rotor blades of the wind turbine, V_w is the wind speed, and C_p is the power coefficient which is a function of both blade pitch angle β and tip speed ratio λ as given by (3) in which, Ω is the angular speed of the turbine rotor, and R is the radius of the turbine blades [5,6].

$$\lambda = \frac{R.\Omega}{V_w} \qquad (3)$$

The power coefficient C_p can be expressed as [7]:

$$C_p(\lambda,\beta) = C_1.(C_2.\frac{1}{\lambda_i} - C_3.\beta - C_4)\exp^{(-C_5.\frac{1}{\lambda_i})} + C_6.\lambda \qquad (4)$$

Where: $$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1}) \qquad (5)$$

$C_1 = 0.5176$, $C_2 = 116$,$C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$.

As it can be observed from (4), the power coefficient depends on β and λ, representing the aerodynamic characteristics of the turbine. Fig.2 illustrates C_p versus λ for different values of the pitch angle β.

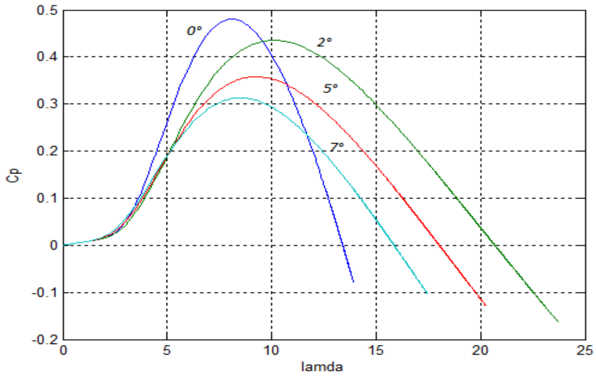

Fig.2 Power coefficient vs tip speed ratio.

The maximum value of C_p that is $C_{p\_max} = 0.48$, is achieved for β=0° and λ=8.1. This particular value of λ is defined as the optimal value λ_{opt} where the maximum power is captured from wind by the wind turbine. So it is necessary to keep the rotor speed at an optimum value of the tip speed ratio λ_{opt}. If the wind speed varies, the rotor speed should be adjusted to follow the change [7, 8].

The aerodynamic torque of the turbine can be expressed as:

$$T_{em} = \frac{P_w}{\Omega} = \frac{1}{2} C_p(\lambda, \beta).\frac{\rho.A.R.V_w^2}{\lambda} \quad (6)$$

The DC motor is controlled in current to have a similar functioning as the wind turbine, where the reference of the current I_{m_ref} is calculated from the aerodynamic torque T_m of the wind turbine model, in order to reproduce the turbine aerodynamic torque on the DC motor [2]:

$$I_{m\_ref} = \frac{T_{em}}{K_\Phi} \quad (7)$$

Where: K_Φ is the constant of the DC motor

I_m : DC motor armature current.

4.1.2 The PMSG:

The voltage equations of a permanent magnet synchronous generator in the *d-q* reference frame are given by [9, 10, 11]:

$$\begin{cases} v_{sd} = -R_s.i_{sd} - L_d.\dfrac{di_{sd}}{dt} + \omega_e.L_q i_q \\ v_{sq} = -R_s.i_{sq} - L_q \dfrac{di_{sq}}{dt} - \omega_e.L_d i_d + \omega_e.\Phi_f \end{cases} \quad (8)$$

where: R_s is the stator resistance , L_d , L_q are the inductances of the stator in *d-q* reference ,i_{sd} and i_{sq} are respectively, the *d* and *q* axis components of stator current; V_{sd} and V_{sq} are respectively the *d* and *q* axis components of stator voltage, Φ_f is the permanent magnetic flux and the electrical rotating speed ω_e is given by:

$$\omega_e = n_p.\Omega \quad (9)$$

Where: n_p is the number of pole pairs .

The expression of electromagnetic torque in the rotor can be written as [11]:

$$T_{em} = \frac{3}{2} n_p \Phi_f i_{sq} \quad (10)$$

The active and reactive power can be expressed as:

$$\begin{aligned} P &= \frac{3}{2}(V_{sd} i_{sd} + V_{sq} i_{sq}) \\ Q &= \frac{3}{2}(V_{sq} i_{sd} - V_{sd} i_{sq}) \end{aligned} \quad (11)$$

The mechanical equation of *PMSG* is given by:

$$J.\frac{d\Omega}{dt} = T_m - T_{em} - F\Omega \quad (12)$$

Where: T_m is the mechanical torque input from the wind turbine emulator, T_{em} is the electromagnetic torque of PMSG, *J* the moment of inertia, *F* the friction coefficient.

In a variable-speed wind turbine, maximum power is a cubic function of rotational speed. To maximize efficiency, losses for a given load must be minimized.

A stator *q-axis* current component is used to develop generator torque. A direct-axis current component can be set at zero to minimize current for a given torque, and therefore, minimize resistive losses [14].

To control the generator power, it is enough to control the PMSG electromagnetic torque T_{em} by regulating the stator q-axis current component.

The reference electromagnetic torque T_{em_ref} , can be developed in operating at maximum power [12], this aims at improving the aerodynamic output of the turbine in order to extract the maximum wind power. This power is extracted when the turbine operates at maximum power coefficient C_{p_max}.

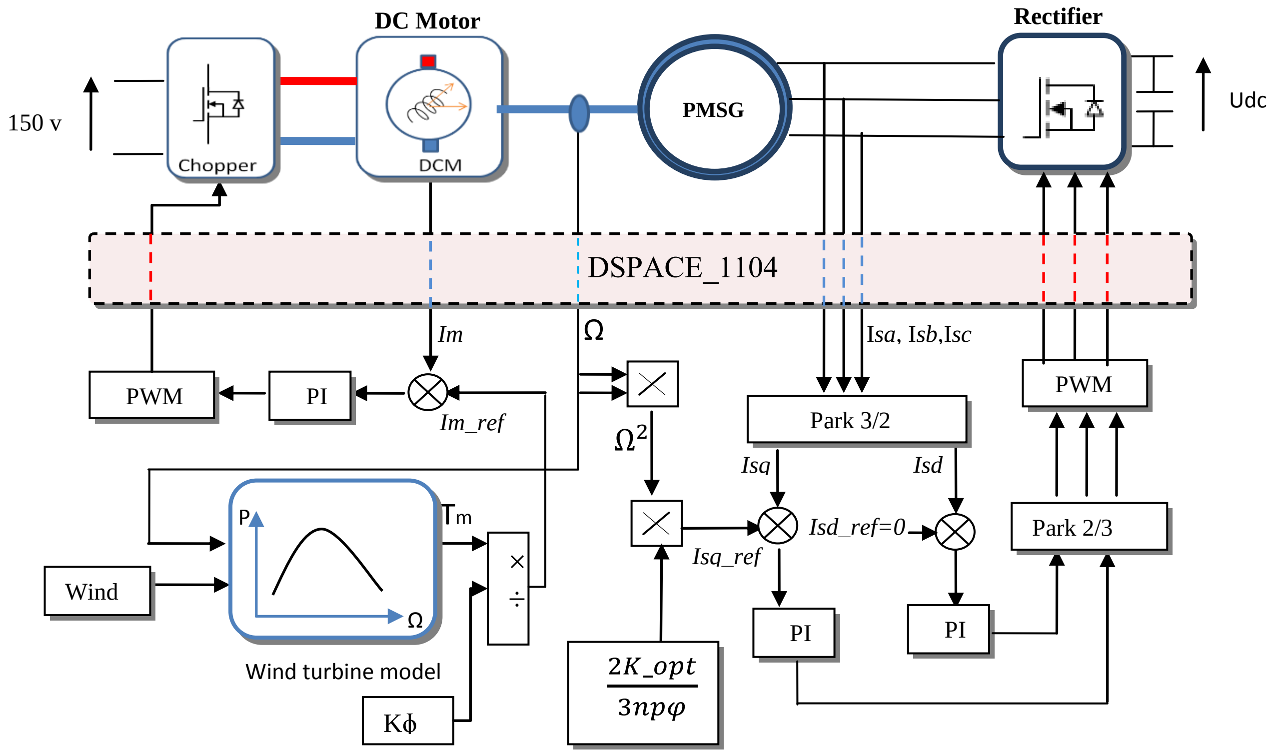

Fig.3 Generator side control.

The expression of the maximum power obtained using the strategy MPPT (Maximum Power Point Tracking) where the turbine works in optimum values λ_{opt} and C_{p_max} is given by:

$$p_{w\_max} = \frac{\rho\pi.R^5 C_{p-max}}{2\lambda_{opt}^3}\Omega^3 = K_{opt}.\Omega^3 \qquad (12)$$

$$T_{em\_ref} = \frac{P_{w\_max}}{\Omega} = K_{opt}.\Omega^2 \qquad (13)$$

The value of the current reference in the *q*-axis is determined from the electromagnetic reference torque (T_{em_ref}), from (10) and (13) we can write:

$$I_{sq\_ref} = \frac{2T_{em\_ref}}{3n_p\Phi} = \frac{2K_{opt}}{3n_p\Phi}\Omega^2 \qquad (14)$$

It is clear from equation (8) that we can control the current components by means of applied voltages, V_{sd}, V_{sq} , these quantities are necessary for the rectifier PWM control [13].

As seen in Fig.3 which shows the schematic diagram of the control loops of the permanent-magnet generator side converter, the required *d–q* components of the rectifier voltage vector are derived from two proportional plus integral (*PI*) current controllers: one of them controlling the *d-axis* component of the current and the other one, the *q-axis* component. The control requires the measurement of the stator currents, and rotor position. Pulse Width Modulation (PWM) is used to generate the switching signals for the rectifier.

4.2. Grid side controller:

The Fig. 4 shows the control of the grid side. The control system must allow the DC bus to remain constant, and to obtain sinusoidal currents from PMSG, an amplitude and frequency identical to those of the network in order to generate the PMSG active power to the grid. [11, 14].

The dynamic model of the network connection, in reference frame rotating synchronously with the network voltage, is given as follows [14, 15]:

$$\begin{cases} v_{Nd} = V_{id} - R\ .i_{Nd} - L\ .\dfrac{di_{Nd}}{dt} + \omega_N .L\ i_{Nq} \\ v_{Nq} = V_{iq} - R\ .i_{Nq} - L\ .\dfrac{di_{Nq}}{dt} - \omega_N .L\ i_{Nd} \end{cases} \quad (15)$$

Where: R and L are the electrical network inductance and resistance, respectively.
V_{Nd}, V_{Nq}: d–q components of grid voltages.
$V_{id}. V_{iq}$: d–q components of inverter voltages.
Active and reactive power of the grid is given by:

$$\begin{aligned} P_N &= \frac{3}{2} V_{Nd}\, i_{Nd} \\ Q_N &= \frac{3}{2} V_{Nd}\, i_{Nq} \end{aligned} \quad (16)$$

The provided energy by the generator is applied to an inverter which makes it possible to control the continuous voltage and the active and reactive powers exchanged with the grid.
Active and reactive power control can be achieved by controlling direct and quadrature current components, respectively as shown in (16).

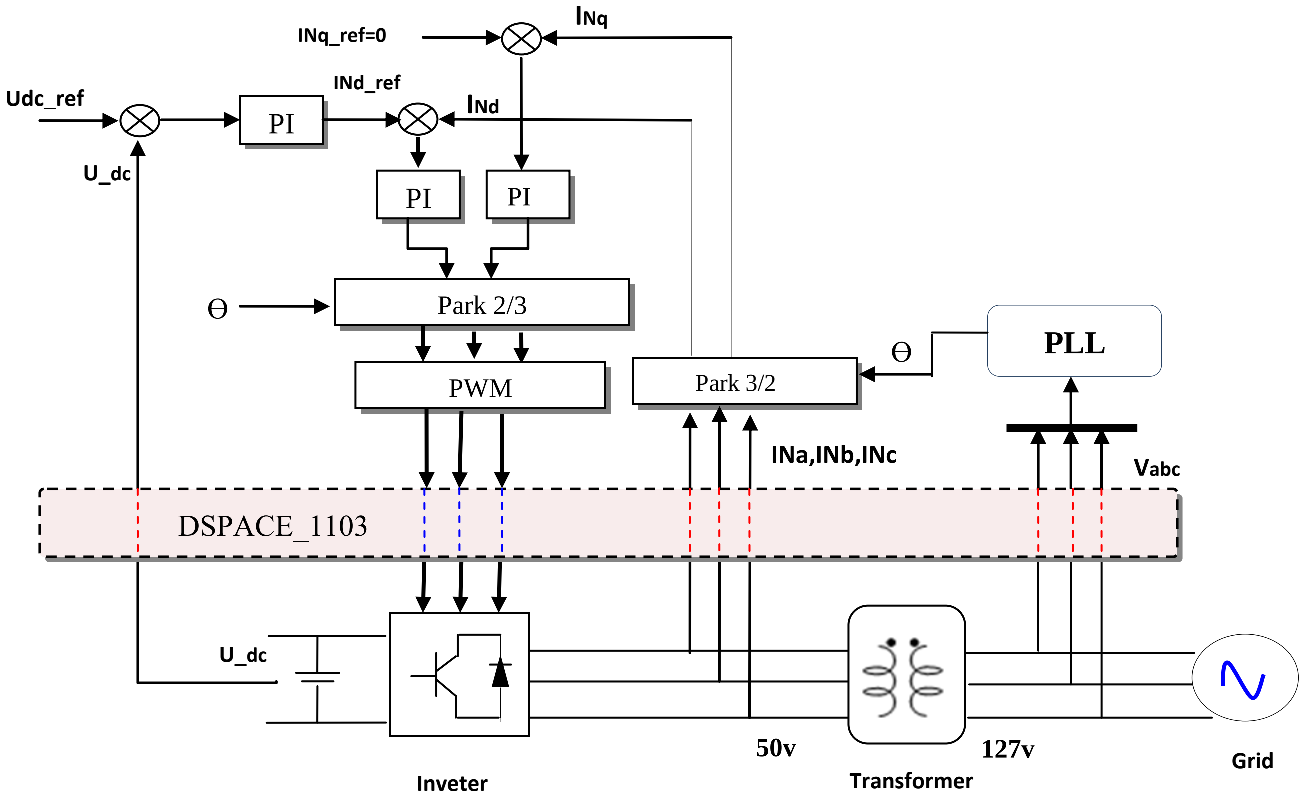

Fig.4 Grid side control.

As shown in Fig.4, the control of the grid side contains two control loops structure voltage outer loop and current inner loop. They are used to control the active and reactive power, respectively [16].
DC-Link voltage control is necessary to provide a stable DC-voltage to the connected grid-inverter. An outer dc voltage control loop is used to set the *d-axis* current reference for active power; this assures that all the power coming from the rectifier is instantaneously transferred to the grid by the inverter.

The Dc-link controller regulates the capacitor voltage by driving it to the reference value U_{dc_ref} , and outputs the current I_{Nd_ref} .
The second channel controls the reactive power by setting the q-axis current reference I_{Nq_ref} to zero to have a null reactive power.
The current controllers provide voltage references which are used to generate PWM signals for the inverter.

4.2.1. PLL:

The phase-locked loop is designed to control the frequency of the *d-q* axis voltage through minimizing the difference of the output voltage phase angle and the given voltage phase angle until the output voltage phase angle tracks the given voltage phase angle [17,18].

The angle of the transformation is detected from the three phase grid voltages (V_a, V_b, V_c) using phase locked-loop (PLL) as shown in Fig. 4.

5. Experimental results:

In this section we present and discuss the experimental results of the test bench.

To run all the system we must activate the commands step by step, starting by the command of the DC motor and after that the command of the generator (PMSG) then the command of the grid side.

The results are captured from controlDesk interface in real time after having run all the systems over many periods of 15 s.

The DSPACE 1104 card commands the generator side of the system, firstly the wind turbine emulator by imposing the command to the chopper. The generator is controlled to have an optimal functioning and extract the maximum power; the generator side converter (rectifier) is controlled by a PWM signal in order to transform the alternative voltage to a direct voltage.

The DSPACE 1103 card controls the grid side of the system by keeping the DC voltage at a constant value and controlling the grid currents; however, this control generates a PWM signals that control the inverter.

Fig. 5 shows the applied wind profile that varies between 11 m/s and 13 m/s. This variation changes the value of the aerodynamic torque given by the wind turbine model. The torque change varies the current reference of the DC motor armature(I_{m_ref}); thus, the rotor speed, so the rotor speed varies following the changes in the wind speed profile as shown in Fig. 7.

The regulation of the DC motor armature current is represented in Fig. 6, where it is noticed that the measured current follows the current reference, this regulation is used to command the chopper that controls the voltage applied to the DC motor.

The Fig. 8 present the control of the direct and quadrature components of the stator currents, a negative sign is added to the quadrature current reference value (I_{sq_ref}) in order to have a negative value because the currents in the generator (PMSG) are reversed (negatives).

The form of the currents generated by the PMSG is presented in Fig. 9, where it is noticed that the current amplitude varies following the changes in the wind speed; a zoom of the generator currents is presented in Fig. 10.

Fig. 11 presents the direct current form at the output of the rectifier.

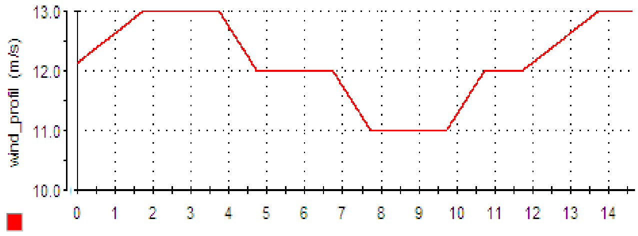

Fig.5 wind profile

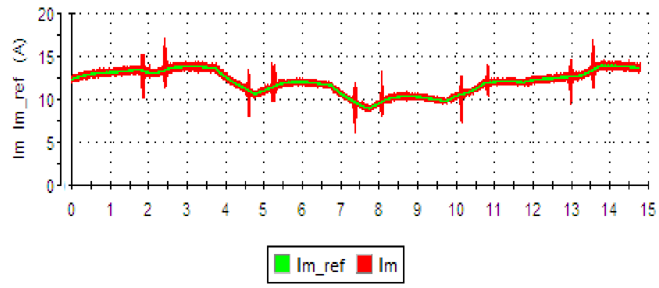

Fig.6 DC motor current.

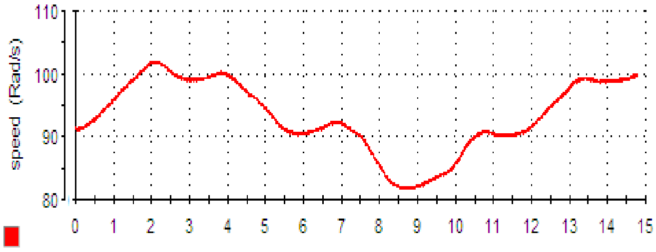

Fig.7 Rotor speed.

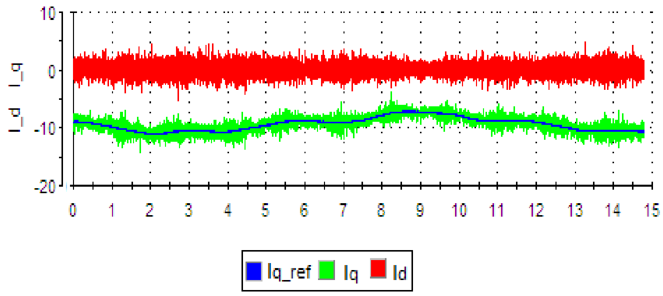

Fig.8 *d-q* stator current.

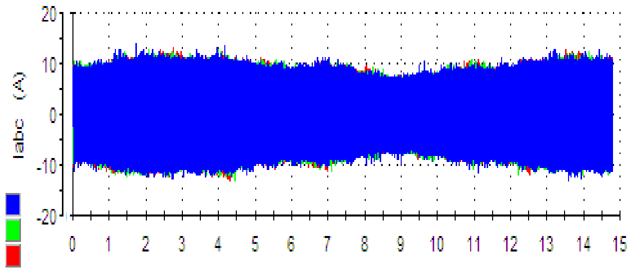

Fig.9 Generator currents.

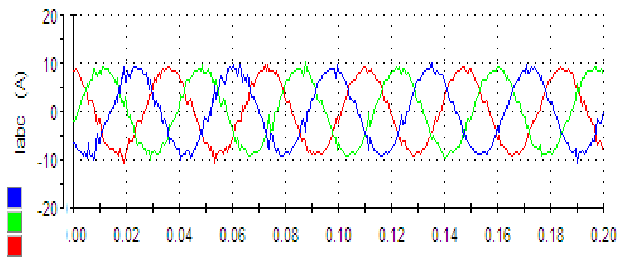

Fig.10 zoom in generator currents.

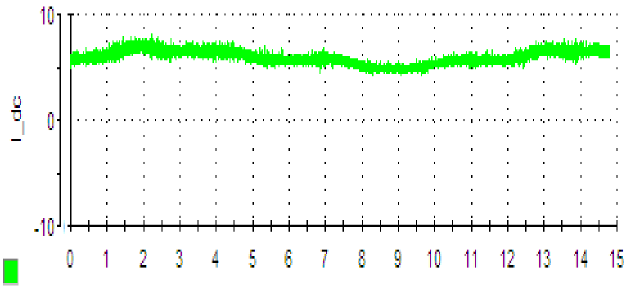

Fig.11 Output rectifier current.

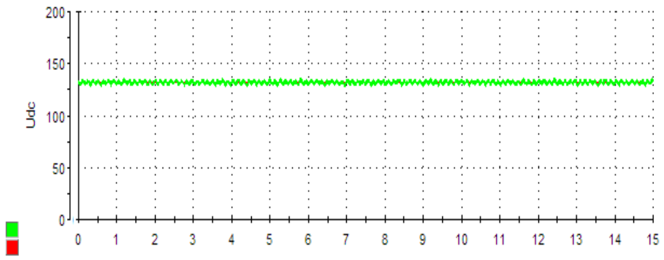

Fig.12 Dc Link voltage.

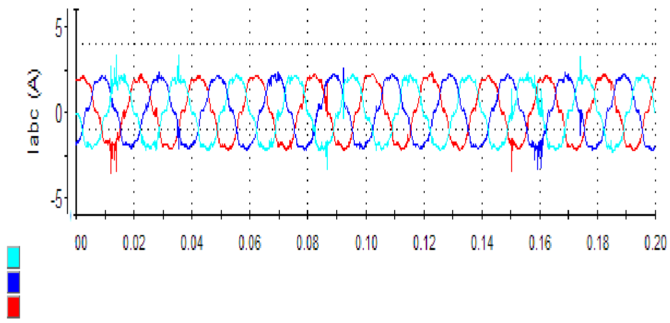

Fig.13 Grid currents.

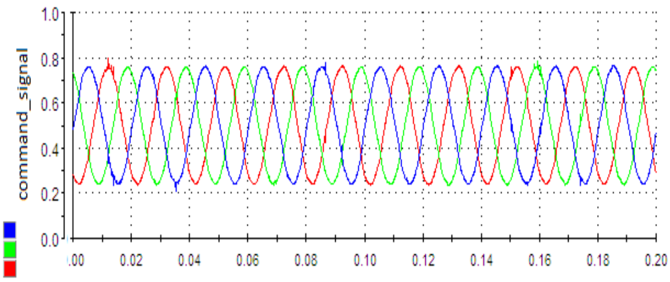

Fig.14 Command signal of PWM.

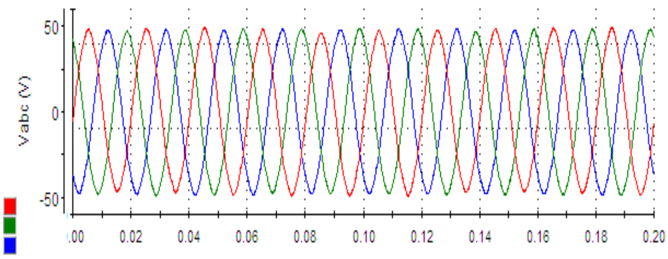

Fig.15 Line-to-line voltages.

The variation of the wind speed generates a variable DC voltage. The grid side controller ensures the regulation of the DC bus voltage that must be maintained constant at a constant reference value. Fig. 12 shows the regulation of the DC bus voltage which is perfectly kept constant at 130V and thus proves the effectiveness of the established regulators.
Fig. 13 shows the sinusoidal waveform of output currents I_{Na}, I_{Nb}, I_{Nc} that are transmitted to the grid, where it is clear that they have a sinusoidal form with a constant frequency equal to 50 Hz.
The Fig. 14 presents the command signal which will be compared with a triangular signal of (0,1) amplitude to generate the duty cycles of the inverter PWM control signals.
Fig. 15 shows the line-to-line voltages. These voltages are transformed by means of a transformer in order to have 127v that are connected to the grid.

6. Conclusion:

This article proposes and details an experimental study of a test bench that replaces a system of wind turbine conversion.
The system has been successfully run and controlled via two DSPACEs cards: one controlling the generator side (wind turbine emulator, PMSG) and the other the grid side.

A complete control strategy is proposed for all the system. The PMSG has been controlled to have an optimal functioning and extract the maximum of energy; the DC voltage was set to a constant value applied to the input of the inverter. The system is successfully integrated to the grid.

The objective of this study is reached, the experimental results validate the fact that the system works well.

Appendix A

PMSG:

Nominal power : P = 2.54 kW

Nominal speed: 3000 tr/min

Stator resistance : R = 0.45 Ohm

Inductance: $L_d = L_q = 7.75\text{mH}$

Permanent magnetic flux = 0.52

Number of pole pairs: p = 3

DC motor:

Resistance: Ra = 0.3 Ohm

$K\phi$=0.73

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