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Experimental study of a stand-alone variable speed wind turbine feeding a DC load

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Abstract. *This study was interested in the control of a variable speed wind turbine (VSWT) supplying a DC load and associated to a dummy load. The control strategies of the wind energy conversion system (WECS) were implemented on a DSP card and tested using an experimental test bench. The objective of this work was to regulate the DC bus voltage to a fixed reference by ensuring a balance between the production and the consumption through an appropriate control of the dummy load. Some experimental results were presented to validate the effectiveness of the wind turbine emulator (WTE) and the control strategies applied to the WECS.*

Keywords. *Wind energy, DSP system, Test bench, DC load, Dummy load.*

1. Introduction

In recent years, the energy consumption increased considerably due to the demographic trends and also the massive industrialization of many countries. The prediction of the energy requirements for the coming years confirm, even amplify, this tendency [1], [2]. Currently, the deposit of the traditional energy resources, from fossil origins especially, can be exploited only for a few decades, which lets predict a shortage energy situation on a world level in an imminent way. In addition, waste of the nuclear thermal power stations poses other problems in terms of radioactive waste pollution, nearest dismantling of the old power stations and industrial risk [3].

To satisfy the energy requirements for the current population, it is necessary to find solutions adapted to this problem. As a matter of fact, the new tendency of several countries is to exploit, as much as possible, the renewable energy resources [4], [5]. The wind energy is one of the most promising between these renewable energies with a very high world rate growth [6], [7]. Generally, the wind turbines are installed in a wind park connected to the electrical network. However, among the fields where the

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aerogenerators can be integrated is that which consists in producing electricity for the isolated sites. When the conventional methods of electricity production for distant or isolated sites become too expensive or difficult to implement, renewable technologies present a very encouraging alternative, from technical and economic point of view.

In addition, the stand-alone wind turbines which produce electricity for small communities become more frequent. Because of the wind fluctuation, hybrid wind systems with a diesel or photovoltaic support with the help of an energy storage system are increasingly widespread in the isolated sites [8], [9], [10]. With regard to the small wind turbines, the tendency today is to develop effective and robust control devices, using electronics power conversion structures to work at variable speeds and to exploit a large wind range while respecting the produced power quality. In this general context, our study is interested in the investigation of a stand-alone wind energy conversion system feeding a DC load. The objective of this work is to control an experimental test bench of a VSWT based on a DC motor driving a permanent magnet synchronous generator (PMSG), which is associated to a dummy load. This test bench will enable us to test in real time, the behaviour of a VSWT supplying a DC load. In the first part, the physical and material descriptions of this bench are established. The WTE, the PMSG, the dummy load and the power converters are studied. Then, in the second part, the modelling and the control strategies applied to the WECS are detailed. In this part, a torque control is applied to the DC motor to emulate the wind turbine. Then, a vector control of the PMSG allows the extraction of the maximum power and its transfer towards a DC bus through a rectifier [11], [12], [13]. The voltage control of the DC bus is carried out thanks to the dummy load through a proportional integral (*PI*) regulator. Some experimental results carried out on this test bench are then presented.

2. Description of the studied system

The investigated test bench depicted in Fig.1 is used to test in real time the behaviour of a VSWT, associated to a dummy load and connected to a variable DC load. This test bench comprises a WTE, a PMSG which converts the mechanical wind turbine energy into electric power and three Pulse Width Modulation (PWM) converters, a rectifier and two choppers, built around IGBT modules. In order to ensure a balance between the production and the consumption, a dummy load is added.

The test bench is controlled via a dSPACE1104 card equipped with a TMS320F240 DSP (20MHz) and a microprocessor PowerPC 603e (250MHz). The connections between the dSPACE cards and the power converters are carried out using two interfaces which adapt the control signals levels from 5V to 15V and vice versa. The currents and voltages measurements are ensured by two acquisition cards based on current sensors (LA25NP) and voltage sensors (LV25P). Fig.2 shows the achieved test bench with its different elements.

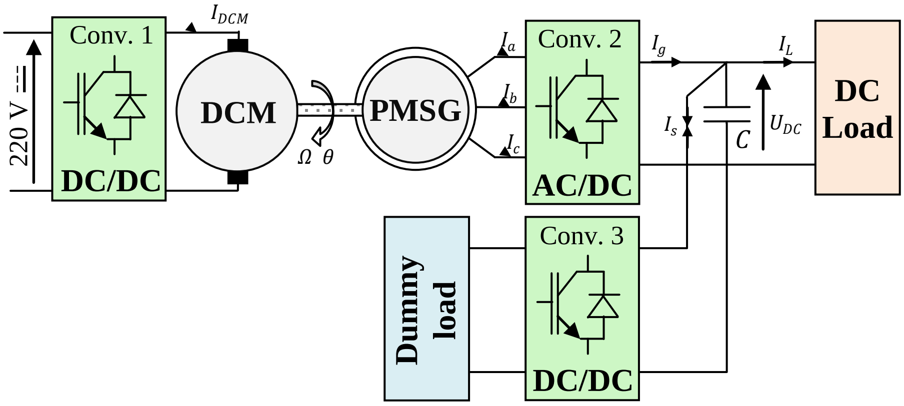

Fig. 1. Test bench configuration

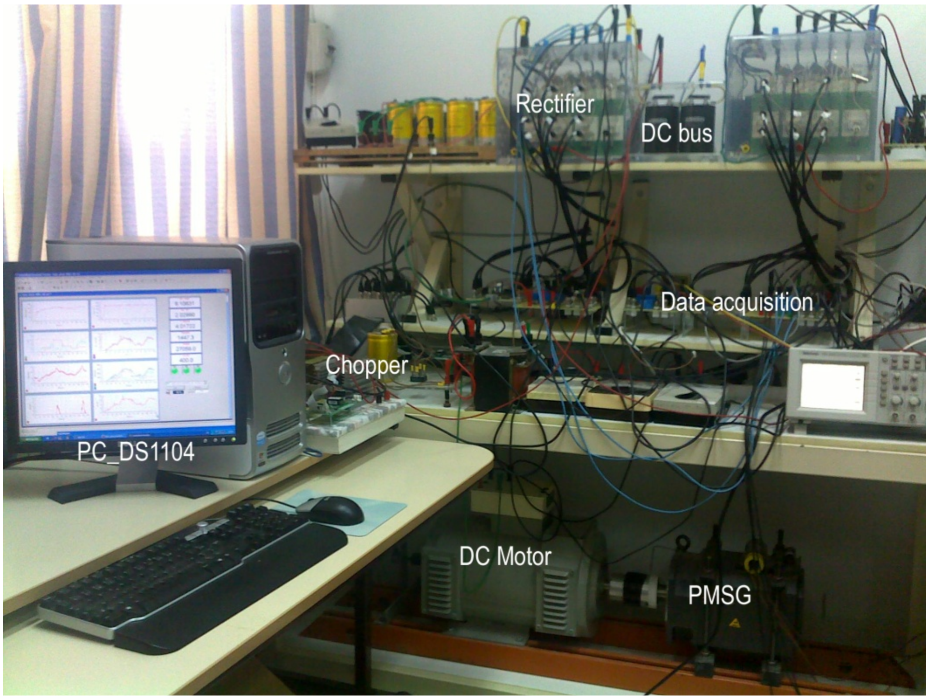

Fig. 2. Experimental test bench

2.1. Wind Turbine Emulator (WTE)

This emulator is based on a DC motor which has a rated power of 3 kW and a nominal speed of 1500 rpm. This motor is controlled in order to reproduce the mechanical behaviour of a VSWT through a chopper and a driver card ARCAL2106.

The control of this unit is ensured by a DS1104 card. An acquisition card allows the measurement of the rotor current and voltage, whereas the rotational speed is measured by an RI32 incremental coder implemented on the DC motor shaft. All these values are necessary for the DC motor control.

2.2. Permanent Magnet Synchronous Generator (PMSG)

The PMSG has a rated power of 3 kW and a nominal speed of 1500 rpm. It is rigidly coupled to the DC motor emulating the wind turbine. Produced energy is transmitted towards a DC bus which is made up of associated capacitors. This transit of power is carried out via a PWM converter controlled by DS1104 card. The incremental coder installed on the DC motor shaft allows the determination of the angular position θ between rotor and stator. The acquisition cards allow the measurement of currents I_1, I_2 and I_3. These three currents are necessary for the PMSG vector control.

2.3. Dummy load

In the case where the wind turbine generates more electricity than the DC load consumption, the dummy load absorb excess electricity in order to guarantees the adjustment of the DC bus voltage. This regulation ensures the balance between the current generated by the wind turbine and that requested by the load. A voltage regulator is used to determine how much electricity is diverted to the dummy load in order to adapt the currents flow and to regulate the voltage to the reference value of 400V.

3. Control of the test bench

3.1. Wind generator

Fig.3 shows the control structure of the wind generator which includes two parts: the WTE control which allows generating the PWM control signal of the DC motor armature chopper and the PMSG control which allows generating three PWM control signals of the rectifier.

WTE control. The mathematical relation of the mechanical power extracted from the wind depends proportionally on the cube of the wind speed, as [14], [15]:

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

The power coefficient expresses the rotor aerodynamics as a non-linear function of both the tip speed ratio (TSR) λ and the pitch angle β. The TSR is defined as follows:

$$\lambda = \frac{R\Omega}{V_w}\,. \qquad (2)$$

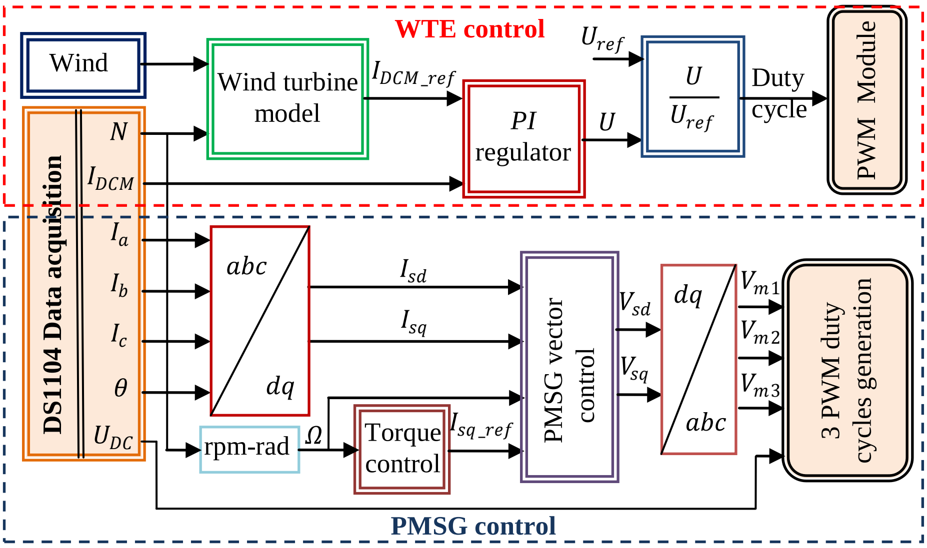

Fig. 3. Wind generator control

The torque coefficient is linked to the power coefficient by:

$$C_t(\lambda,\beta) = \frac{C_p(\lambda,\beta)}{\lambda}. \tag{3}$$

Similarly, the aerodynamic torque on the turbine axis is given by:

$$T_{em} = \frac{P_w}{\Omega} = \frac{1}{2}\,\rho\pi R^3 V_w{}^2\, C_t\,. \tag{4}$$

The DC Motor armature reference current I_{a_ref} is determined according to the reference electromagnetic torque T_{em}:

$$I_{a\_ref} = \frac{T_{em}}{K_\Phi}. \tag{5}$$

From this current, we regulate the DC motor armature current using a *PI* regulator in order to reproduce the turbine aerodynamic torque on the motor shaft.

PMSG control. The model generally used of the PMSG is the Park model. The theory of the space vector gives the dynamic equations of the stator voltages as follows [16]:

$$V_{sd} = R_s I_{sd} + L_s\,\frac{dI_{sd}}{dt} - p\,\Omega\,L_s\,I_{sq}\,. \tag{6}$$

$$V_{sq} = R_s I_{sq} + L_s\,\frac{dI_{sq}}{dt} + p\,\Omega\,L_s\,I_{sd} + p\,\Omega\,\phi_m\,. \tag{7}$$

Among the strategies of vector control applied to a synchronous machine, we find the one which consists in imposing a null reference direct current I_{sd}. The electromagnetic torque depends only on the q axis component current. The flux being constant, the torque and the current I_{sq} are thus proportional.

$$T_{em\_SG} = p\ \phi_m I_{sq}\ . \qquad (8)$$

For a real time application, the direct and quadratic currents can be pre-calculated and memorized in a table, where its input is the reference electromagnetic torque.
The reference torque controlling the synchronous machine is elaborated from equations (2) and (3), considering the operation at the Maximum Power Point Tracking MPPT:

$$T_{em\_SG_{ref}} = k_{opt}\ \Omega^2\ . \qquad (9)$$

with:

$$k_{opt} = \frac{\rho\pi {R_t}^5 C_{p_{max}}}{2{\lambda_{opt}}^3}\ . \qquad (10)$$

λ_{opt} corresponds to the optimal TSR giving the maximum power coefficient value $C_{p_{max}}$

The value of the PMSG reference current in the q-axis is determined from the electromagnetic reference torque $T_{em\_SG_{ref}}$ as follow:

$$I_{sq\_ref} = \frac{T_{em\_SG_{ref}}}{p\Phi_m}\ . \qquad (11)$$

From this current and the d-axis reference current, we use two *PI* regulators to regulate the PMSG currents and then we establish the stator voltages V_{sd} and V_{sq}. These terms are necessary to the rectifier PWM control.

3.2. DC bus regulation

The DC bus regulation is carried out via the dummy load control, which has the essential role in the energy management because the power production is made for an isolated site. In this case, the DC load consumption should be always less than the production and the over production is diverted to the dummy load. Indeed, if the DC load demand is higher than production, an energy storage system should be added in order to provide energy for the peak periods.

Fig.4 shows the control principle of the dummy load and thereafter the DC bus voltage control by the determination of the diverted reference current I_{s_ref} , with :

$$I_{s\_ref} = I_g - I_L - I_c\ . \qquad (12)$$

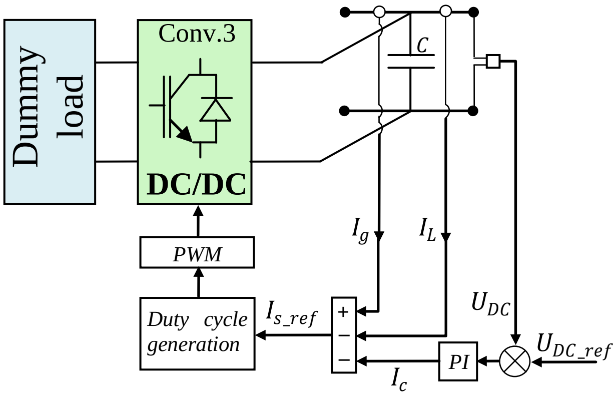

Fig. 4. DC bus voltage control

4. Experimental results

The experiment consists in running the test bench during 120 s. The first 10 s ensures that the DC motor is starting. This latter must reach a certain speed to be able to follow the wind profile during the remaining time, which corresponds to the emulation time.
In the following paragraphs, we will present the experimental results obtained with the « Controldesk » software in relation with dSPACE card.
As depicted in Fig.5, we have applied to the WTE a variable wind profile between 6 and 13 m/s which lasts 120 s. Fig.6 shows the measured speed of the DC motor which is correlated with the wind profile after a starting phase of 10 s. If the wind speed exceeds the nominal speed, the pitch control system varies the pitch angle β, presented in Fig.7, to limit the mechanical speed of the WT to its nominal value. The applied voltage to the DC motor through the chopper is obtained by the regulation of the armature current illustrated in Fig.8.

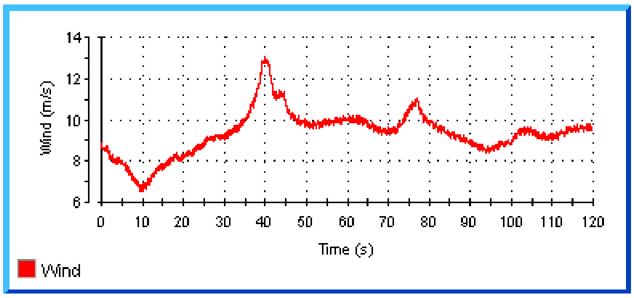

Fig. 5. Wind speed

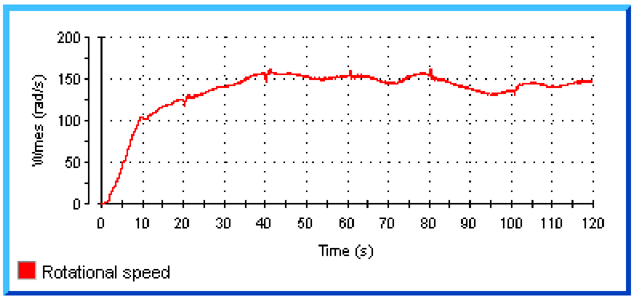

Fig. 6. DC Motor speed

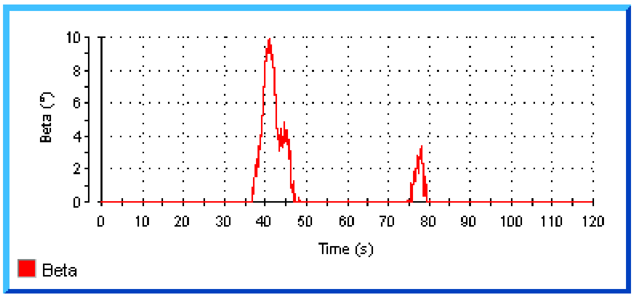

Fig. 7. Pitch angle

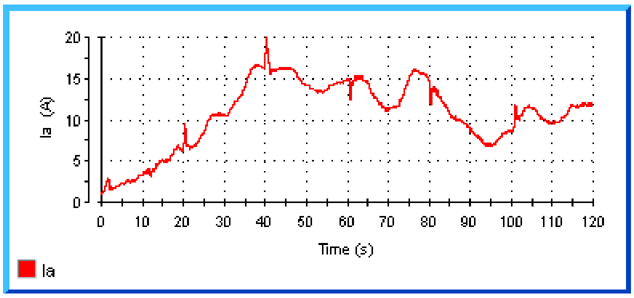

Fig. 8. DC Motor armature current

The PMSG being mechanically coupled with the DC Motor, it provides three sinusoidal currents with a variable frequency and amplitude according to the wind speed variation as shown in Fig.9.a and the zoom in Fig.9.b. The transformation of these currents into the Park frame gives the I_{sd} and I_{sq} currents illustrated in Fig.10. From these currents and the reference currents I_{sd_ref} and I_{sq_ref}, the PMSG vector control gives the voltage V_{sd} and V_{sq} represented in Fig.11. By changing these voltages into the natural frame we obtain the regulation voltages V_{m_reg} as shown in Fig.12.a and the zoom in Fig.12.b.

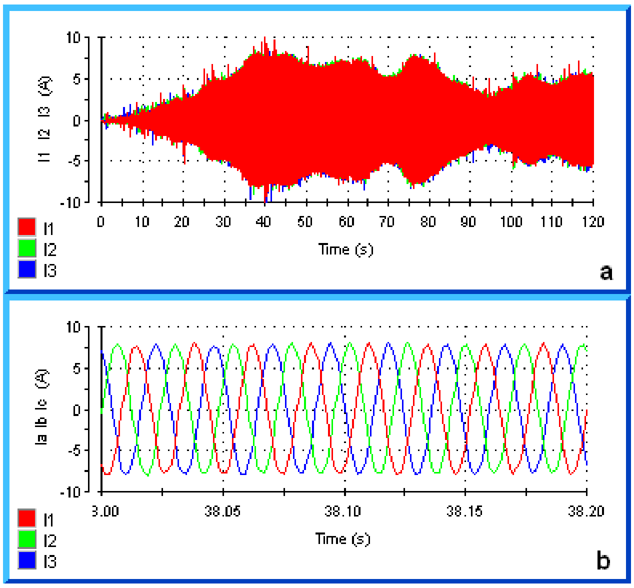

Fig. 9. PMSG currents

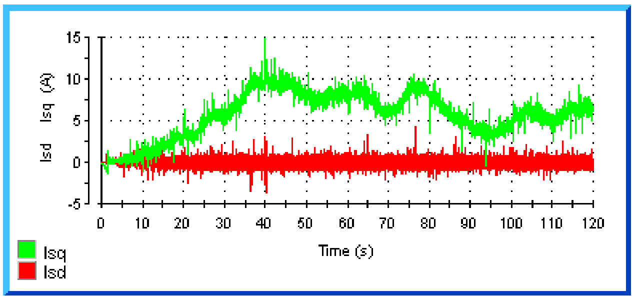

Fig. 10. PMSG currents in the Park frame

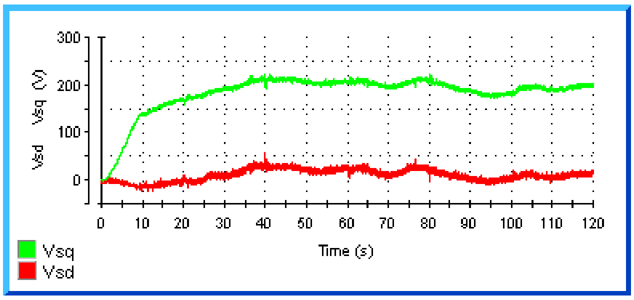

Fig. 11. PMSG voltages in the Park frame

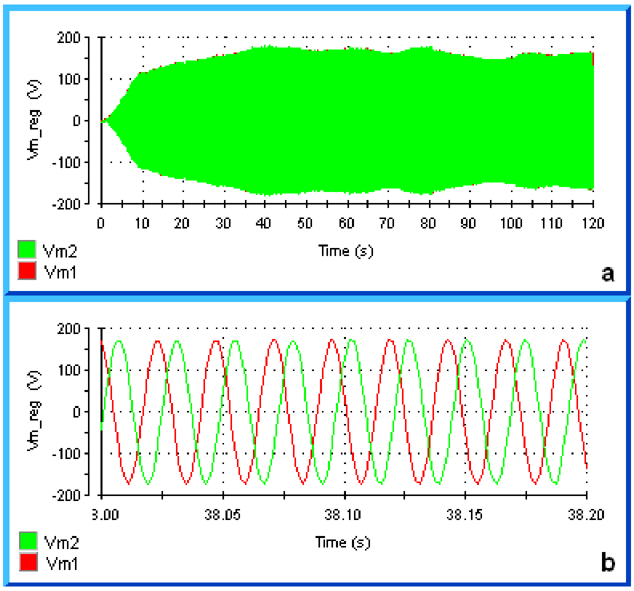

Fig. 12. Regulation voltages

The MPPT is ensured by the rectifier controlled by PWM signals. The duty cycles presented in Fig.13.a and Fig.13.b are established from the regulation voltages. Fig.14 shows the DC load current and the dummy load current. The sum of these two currents is confused with the current generated by the WTE as Fig.15 shows.

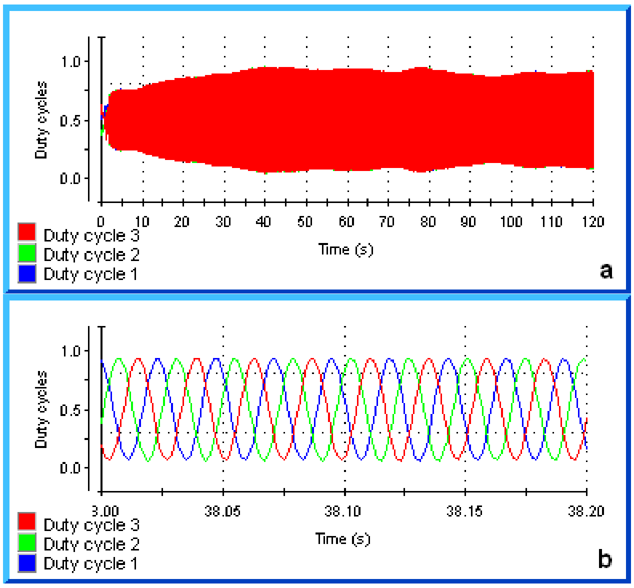

Fig. 13. PWM signals duty cycles

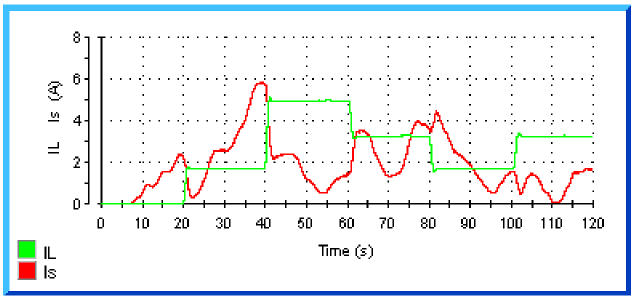

Fig. 14. Load and storage currents

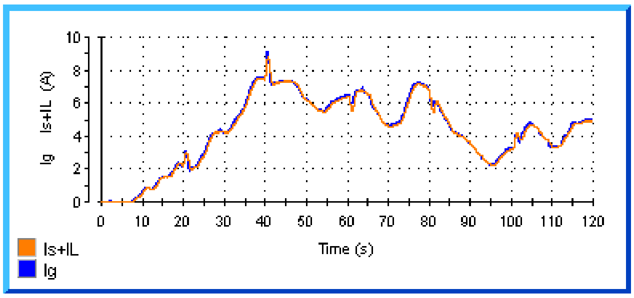

Fig. 15. Currents superposition

The balance between the produced energy and the sum of the consumed one with that diverted to the dummy load enable us to obtain a constant DC bus voltage at the reference value fixed at 400V as represented in Fig.16, which proves the efficiency of the control strategy applied to the dummy load. Fig.17 illustrates the powers assessment of in the DC bus.

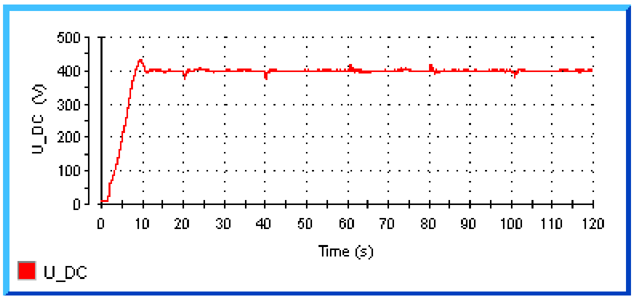

Fig. 16. DC bus voltage

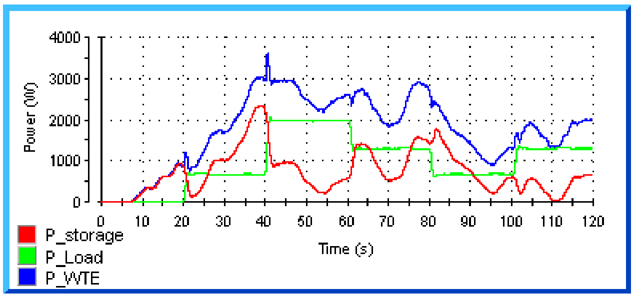

Fig. 17. Power assessment

5. Conclusion

In this paper, an experimental test bench emulating a VSWT and supplying a DC load has been developed. The test bench comprises a DC motor, a PMSG, a rectifier and a dummy load controlled through a chopper. The real time control of the test bench is ensured by a dS1104 card. It has been shown that an emulator representing the main dynamics of a VSWT can be constituted by a simulation model and a DC motor reproducing the electromagnetic torque of this model. In addition, the control of the DC bus voltage depends on the control of the dummy load current. The experimental results validate the WTE and the control strategies applied to the WECS.

Nomenclature

I_a	DC motor armature current (A)
Ω	rotational speed (rad s^{-1})
θ	angular position (rad)
I_1, I_2, I_3	PMSG currents (A)
U_{DC}	DC bus voltage (V)
I_g	WTE current (A)
I_i	DC load current (A)
I_s	Dummy load current (A)
C	DC bus capacitance (μF)
P_w	power extracted from the wind (W)
ρ	air density (1.22 Kg m^{-3})
R	blade radius (m)
V_w	wind speed (m s^{-1})
C_p	power coefficient
K_Φ	emf coefficient of the DC motor
R_s	stator winding resistance (Ω)
L_s	stator winding inductance (H)
Φ_m	permanent magnetic flux (Wb)
V_{sd}, V_{sq}	d-q components of the stator voltages (V)
I_{sd}, I_{sq}	d-q components of the stator currents (A)
p	number of pole pairs

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