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Constant Grid Power control of Wind Turbines with DFIG and Long Duration Storage Unit

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Abstract – This paper deals with the design, analysis and simulation of a constant grid power wind energy conversion system based on electrical energy storage and indirectly controlled doubly fed induction generator (DFIG). This horizontal axis wind turbine system generates a constant active power through the grid under all wind conditions. The incorporation of a battery or other energy storage device in the DC link enables temporary electrical energy storage. The modelling of the mechanical part of the turbine is particularly detailed. Then, modelling and indirect control of the DFIG are presented. Independent control of active and reactive powers is achieved and the storage unit rating for this operation is performed. The control of this unit is also discussed. Simulation results validate the study for two experimental long duration wind speed profiles.

Index Terms—Constant power generation, doubly fed induction generator (DFIG), wind energy conversion system, electrical energy storage

I. INTRODUCTION

Wind energy is becoming one of the most important renewable energy sources in most European countries. Even if a Wind Energy Conversion System (WECS) is inherently less reliable than the traditional units based on conventional energy sources, it is taking a growing place in future utilities since it guarantees environmental benefits and is encouraged by public support and government incentives [1]. However, economic benefits of exploitation of a WECS are proportional to the generated active power [2].

Renewable energy has intermittency and non-controllability inherent characteristics. The optimization of wind energy production and consequently the economic benefits derived from its grid connection will be one of the most important issues in the very near future. A wind turbine generator (WTG) produces no power in the absence of sufficient wind and consequently makes no contribution to the power system. Considering a given site, there is a definable probability that there could be an insufficient wind. The authors of [1] propose one way of improving WTGs reliability performances by locating the WTGs at independent wind sites, the probability of having no wind simultaneously at two widely separated and independent wind sites being much less. Wind site independence has a significant positive impact on the WTG reliability contribution, and therefore, locating WTG units at multiple independent wind sites can improve the whole system reliability [1]. One other solution for guaranteeing a constant power generation ([3], [4], [5]) consists in associating, with the WTG, a flywheel storage

system which can only reduce power variations for small duration [6]. Other solutions for long duration energy storage such as compressed air, hydrogen generation or battery are also studied, without providing a constant grid power ([7], [8], [9]). More, to have a maximum efficiency of the WTG, the turbine should include a variable blade pitch setting controlled by the wind speed and propeller rotation speed for a maximum power generation at any time. This is generally named Maximum Power Point Tracking (MPPT) [10].

In this paper, we studied a WECS based on an horizontal axis wind turbine with MPPT control allowing the production of a constant grid power thanks to an electrical storage unit. The incorporation of a battery or other energy storage devices in the DC link enables temporary storage of energy and therefore, the ability to provide constant output active power, which is both deterministic and resistant to wind speed fluctuations. More, high power quality of generators is critical and for this reason, independent control of active and reactive powers is necessary [10]. To do this, a robust indirect control method of the DFIG is studied. The particularity of this study is to present a complete operating system including the wind turbine, the generator, the power control, the storage unit and the general power strategy of the whole system to provide constant grid power.

In next section, the model of the mechanical part of the turbine is developed with a particular attention. Then, in section III, modelling and control of the WTG are examined. Section IV deals with WECS control, including storage unit design, rating and control. Finally, simulation results are presented in the last section for two typical wind speed profiles. All simulations are performed with SABER Computer Aided Design tools.

We present in this paper the current state of our research where all results are performed with low power machine parameters. However, the proposed control models could be used for high power WECS.

II. MODELING OF THE MECHANICAL PART

The wind turbine involves many physical elements from different disciplines, aerodynamics to electricity passing by mechanical structures, as shown in figure 1. Consequently, the modelling of such system requires an in-depth study of each of these fields. In order to obtain the most realistic mechanical torque versus speed characteristics, we detailed in next section the model we developed for the propeller of the wind turbine.

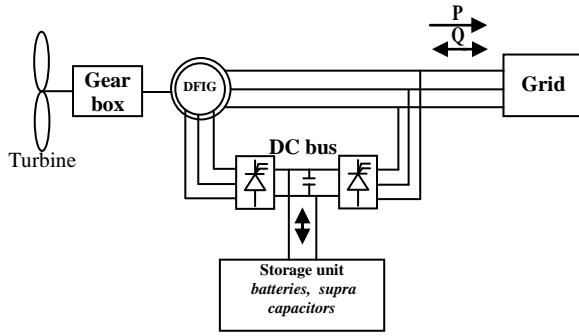


Fig. 1. Synopsis of the wind energy conversion system

A. The turbine

The air flow over a stationary airfoil provides a lift force, dP , and a drag force, dT . The lift force is perpendicular to the direction of the air flow and the drag force is in the direction of the air flow. If the airfoil moves in the direction of the lift force, the effective direction of the air flow has to be taken into account. We note β the pitch angle between the chord line of the blade and the rotation plane (figure 2).

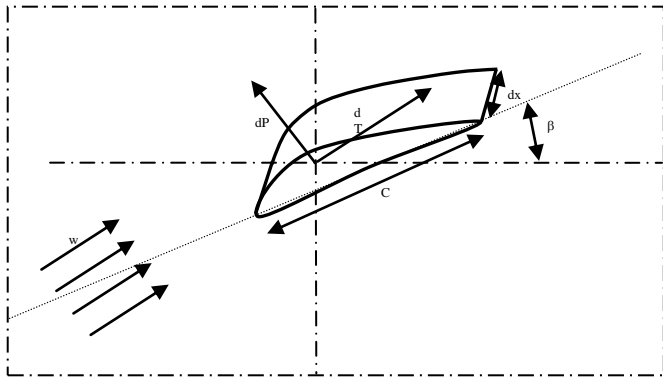


Fig. 2. Elementary effort on the airfoil

The elementary lift and drag forces can be expressed as:

$$dP = \frac{1}{2} C_z \cdot \rho \cdot w^2 \cdot C \cdot dx$$

$$dT = \frac{1}{2} C_x \cdot \rho \cdot w^2 \cdot C \cdot dx$$

where ρ is the density of the air, C_z the lift coefficient, C_x the drag coefficient, C the chord length of the airfoil section, w the relative wind speed, and dx the increment of the span length.

Lift and drag coefficients are given as function of the attack angle [11].

The model presented in this section allows calculating the mechanical torque generated by the wind on the propeller, by calculating the mean lift P and drag T efforts applied on each blade.

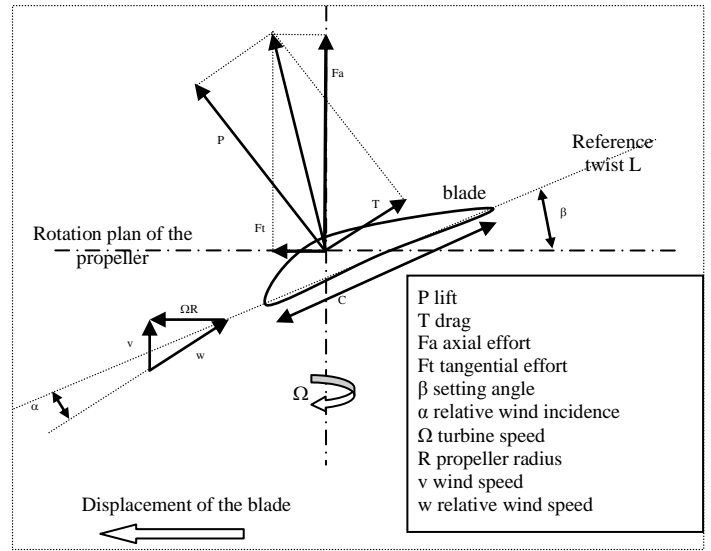


Fig. 3. Blade diagram

The blades of the wind turbine are twisted so that the angle of incidence α is the same at each point and the chord length of the airfoil section is smaller in the end of the blade than in the center of the propeller, because the relative wind speed varies on the blade according to the radius. In this case, any section of the blade is in the same aerodynamic conditions and supports the same effort. This allows calculating the mean effort in the medium of the blade and when considering this effort as uniform, we obtain an average torque for each blade.

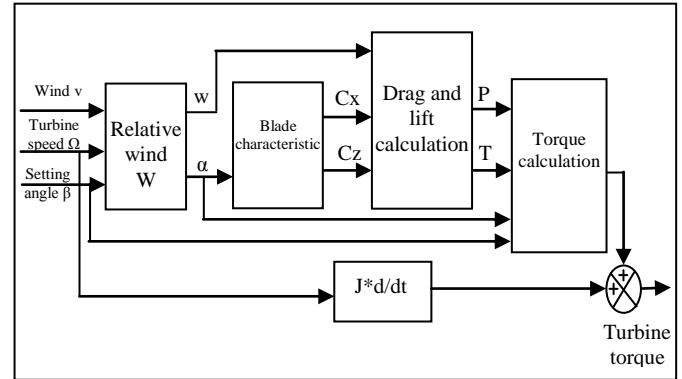


Fig. 4. Torque calculation diagram

The model calculates the torque available on the shaft by using the aerodynamic characteristics (C_x and C_z values depend on the relative wind incidence α) of the blades to determine the drag T and lift P of each blade. Then, the propeller torque C is calculated from the blade setting angle β and relative wind incidence α , as shown in figure 3. Finally the propeller inertia is taken into account.

The theoretical relations are the following:

$$w = \sqrt{v^2 + (\Omega \cdot r)^2}$$

$$\alpha = \arctan\left(\frac{v}{\Omega R}\right) - \beta$$

$$P = \frac{1}{2} C_z \cdot \rho \cdot w^2 \cdot A$$

$$T = \frac{1}{2} C_x \cdot \rho \cdot w^2 \cdot A$$

$$C = N \cdot L \cdot \frac{r}{2} (P \cdot \sin(\alpha + \beta) - T \cdot \cos(\alpha + \beta))$$

Where N is the number of blades and r the radius of the propeller.

The diagram figure 4 is used to compute the model of the mechanical part of the wind turbine.

The propeller fixes the torque while the speed depends on the generator load. Our objective is to obtain an optimised wind energy conversion by extracting total wind resources, for wind speed below a maximal limit. Variable pitch and speed propeller are used to adapt themselves with the various wind conditions and realizes MPPT. At any time, the blade setting angle is adjusted to put the propeller at its maximum efficiency to produce the maximum power from the wind. To do this, the model's input variables are the turbine speed Ω , the wind speed v and the blade setting angle β .

B. The gear box

The gear box is modelled by a gain applied to speed and torque. Losses are modelled by dry and fluid frictions torques to take into account the efficiency of the gear box. Then the gearbox inertial torque is considered.

$$C_{generator} = \frac{C_{propeller} - k_1 - k_2 * |\Omega_{propeller}| + J_m \frac{d\Omega_{propeller}}{dt}}{r}$$

$$\Omega_{generator} = r_g * \Omega_{propeller}$$

with : k_1 friction coefficient
 k_2 viscose friction coefficient
 J_m gear box inertia
 r_g gear box ratio

C. The wind

In order to model a realistic wind case we used experimental measurements of wind speed characteristics from a data base [12]. From this base, one can use different characteristics to model various sites and wind conditions. The two typical wind speed profiles we used in this paper are presented in figures 5 and 6. They respectively describe high wind speed conditions and low wind speed conditions over one day. Wind speed is measured every 10 minutes, which leads to 144 measurements over one day.

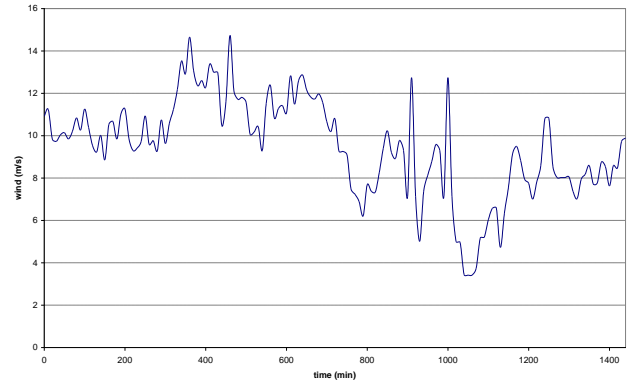


Fig. 5. Wind speed profile in high mean conditions

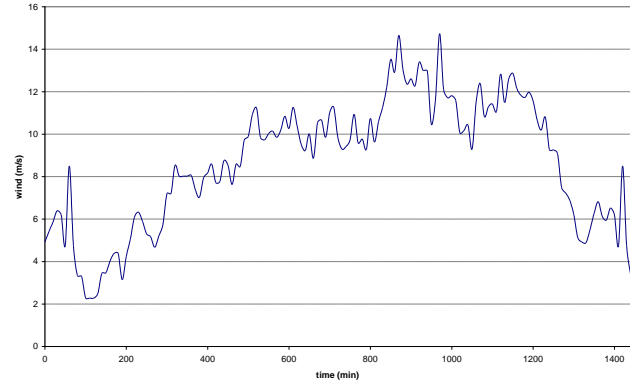


Fig. 6. Wind speed profile in low mean conditions

III. MODELING AND CONTROL OF THE INDUCTION GENERATOR

A. Wind turbine generator

Wind turbine can operate with either fixed or variable speed. For fixed-speed wind turbine, it is not possible to store wind turbulence in form of rotational energy. Consequently, the turbulence of the wind results in power variations, and therefore decreases power quality of the grid and economic benefits of the WECS. For a variable-speed wind turbine, the induction generator is controlled by power electronic equipment. Wind variations and associated power fluctuations can also be reduced despite of power quality impact due to the use of static converter. However, power quality could be improved by using the same induction generator as an active filter [13].

The electrical WECS studied in this paper uses a DFIG, one of the most used WTG in recently built wind farms [14]. For a DFIG, both stator and rotor terminals are available for power flow (see figure 1). The stator is directly connected to the grid. The active power transmitted to the grid is the sum of stator power and rotor power if we assume that the power inverters are loss less. DFIG presents the following characteristics and performances:

- rotor speed can vary about +/-30% around synchronous speed;
- power electronic cost is reduced, typically about 25% of total power system;
- active power is generated at constant frequency;

- active and reactive powers can be controlled independently.

A DC common bus for both bi-directional converters is connected to the storage unit (Figure 1).

B. Modelling of the DFIG

The DFIG is used to produce electrical power at constant frequency whatever wind and shaft speed conditions. We used the classical d-q modelisation of the induction generator in the Park reference frame [14], [15]. The equations for a DFIG and a classical squirrel cage generator are identical, excepted the rotor voltage which is not null for the DFIG.

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt} \varphi_{ds} - \theta_s' \varphi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d}{dt} \varphi_{qs} + \theta_s' \varphi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d}{dt} \varphi_{dr} - \theta_r' \varphi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d}{dt} \varphi_{qr} + \theta_r' \varphi_{dr} \end{cases} \quad \begin{cases} \varphi_{ds} = L_s I_{ds} + M I_{dr} \\ \varphi_{qs} = L_s I_{qs} + M I_{qr} \\ \varphi_{dr} = L_s I_{dr} + M I_{qr} \\ \varphi_{qr} = L_r I_{qr} + M I_{qs} \end{cases}$$

V_{ds} , V_{qs} , V_{dr} , V_{qr} are the stator and rotor voltages in the d-q reference frame.

I_{ds} , I_{qs} , I_{dr} , I_{qr} are the stator and rotor currents in the d-q reference frame.

θ_s is the stator field angle and θ_r the rotor field angle.

φ_{ds} , φ_{qs} , φ_{dr} and φ_{qr} are stator and rotor flux in the d-q reference frame.

The mechanical equation is:

$$\Gamma_{em} = \Gamma_r + f\Omega + j \frac{d\Omega}{dt}$$

Γ_{em} is the electromagnetic torque, Γ_r the resistance torque, f the viscose torque coefficient, Ω the mechanical rotation speed and j the global inertia.

The electromagnetic torque depends on the d-q flux and current :

$$\Gamma_{em} = p \frac{M}{L_s} (I_{qr} \varphi_{ds} - I_{dr} \varphi_{qs})$$

To achieve an independent control of active and reactive power, we established the equations between powers and rotor variables of the DFIG.

We choose to set the stator flux vector aligned with the d axe. Consequently:

$$\varphi_{ds} = \varphi_s \quad \text{and} \quad \varphi_{qs} = 0$$

The grid is assumed to be stable and consequently φ_{ds} is constant. By neglecting the stator resistance of the DFIG, we obtained :

$$\varphi_s = \frac{V_s}{\omega_s}$$

where V_s is the RMS value of the grid voltage. The active and reactive power of the DFIG can be expressed by :

$$P = V_s I_{qs}$$

$$Q = V_s I_{ds}$$

or from the rotor currents by:

$$P = -V_s \frac{M}{L_s} I_{qr}$$

$$Q = \frac{V_s^2}{\omega_s L_s} - \frac{V_s M}{L_s} I_{dr}$$

Rotor voltages can be expressed by:

$$V_{dr} = R_r I_{dr} - g \omega_s \left(L_r - \frac{M^2}{L_s} \right) I_{qr}$$

$$V_{qr} = R_r I_{qr} + g \omega_s \left(L_r - \frac{M^2}{L_s} \right) I_{dr} + g \frac{M V_s}{L_s}$$

The resulting bloc diagram of the DFIG is presented figure 7.

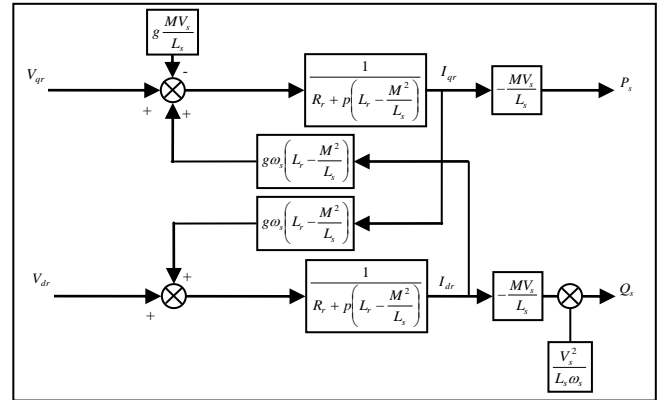


Fig. 7. Diagram of the DFIG

C. Indirect control of the DFIG

The stator of the DFIG is directly connected to the grid and the rotor is fed by two bi-directional converters connected between the rotor and the grid.

The indirect control method is based on regulating the active and reactive powers of the DFIG, by controlling the d-q rotor currents. The control diagram figure 8 is directly established from the equations of the DFIG model. However, to avoid any static error on power control, Proportional Integral (PI) correctors are introduced in the control loops. Then, the robustness of the generator control against the parameter variations is improved. More, no supplementary electrical sensor is necessary to achieve these loops because grid powers are already measured for the general control of the wind turbine.

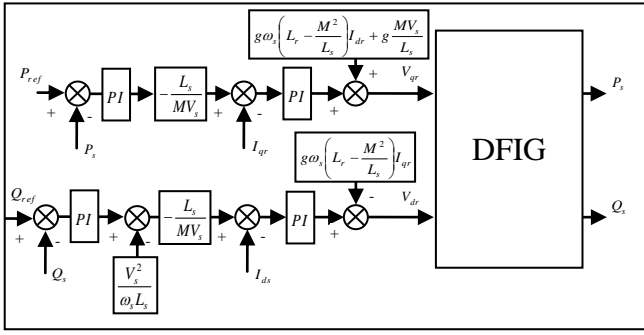


Fig. 8. Diagram of the indirect control

IV. WIND ENERGY CONVERSION CONTROL

First of all, the wind turbine must be controlled to deliver a constant active power to the grid.

A. Storage unit design, rating and control

A.1. Storage unit design

A long duration electrical storage unit is included in the WECS. Battery or supercapacitor could be used. Other storage systems, like flywheel, are not well suited because a large amount of energy is needed in our system.

The long duration storage unit connected to the DC bus allows producing a constant active grid power for all wind conditions. In high wind speed conditions, the DFIG provides energy to the grid and refills the storage unit. Furthermore, in insufficient wind conditions, the storage unit allows compensating the lack of energy. To do this, the DC bus voltage must be kept constant and the rectifier must be bi-directional to store or feed energy to the grid. A PWM rectifier which limits the harmonics injected into the grid is used. The inverter is also controlled by PWM for harmonic minimisation.

A.2. Storage unit rating

Storage unit rating is extremely site specific. Wind speed measurements over a given period, such as depicted in figures 5 and 6, indicate the stochastic availability of this resource. They also allow rating WECS active power reference and storage unit.

For a given wind speed v , we obtain directly the maximum wind power $P_{w,max}$. The maximum theoretical efficiency of the turbine is about 59% [10]. So, the power $P_{w,max}$ is computed by the following equation:

$$P_{w,max} = \frac{1}{2} * \rho * S * v^3 * 0.59$$

in which S stands for the turbine area and ρ for the air density.

This power $P_{w,max}$ must be limited by the nominal power of the generator. In our case, this maximal value corresponds to the power available on the turbine shaft because we studied a turbine with pitch control and MPPT. The pitch control effectively sets the efficiency of the turbine at the maximum.

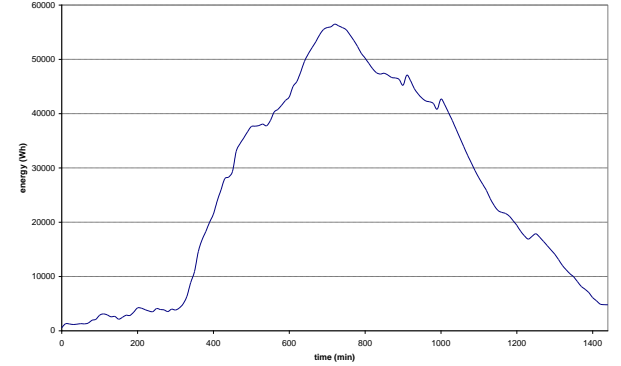
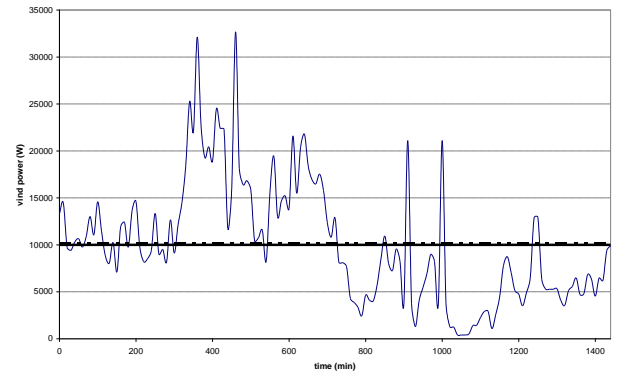


Fig. 9. From top to bottom: Wind power and storage unit energy for wind profile in figure 5

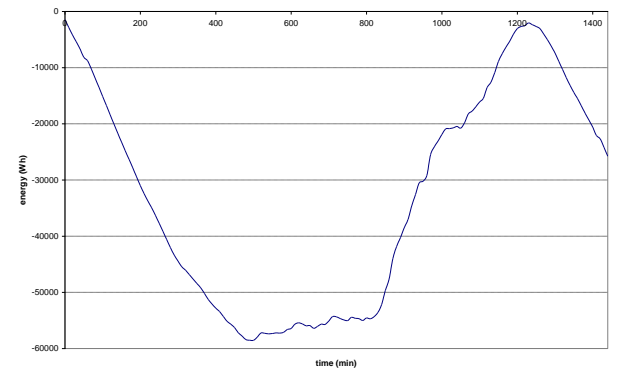
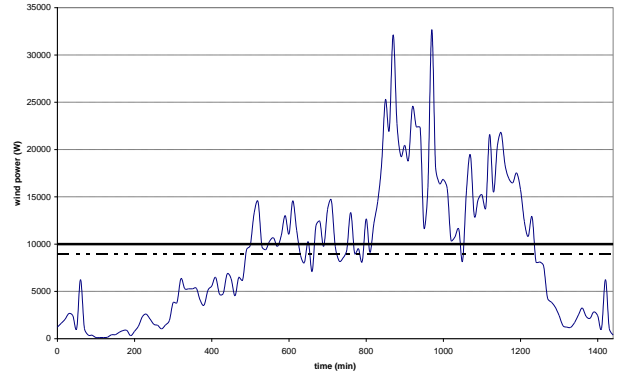


Fig. 10. From top to bottom: Wind power and storage unit energy for wind profile in figure 6

The WECS active power reference should be chosen according to the mean value of wind power over the considered period, i. e. 24 hours for our application.

Figures 9 and 10 present two cases, respectively based on wind profiles depicted in figures 5 and 6. In the first case, active power reference is chosen according to the mean value of wind power, i. e. 10 kW, then the storage unit energy is balanced. In the second case where the power reference is larger than the mean value of wind power, unbalanced energy storage is observed. Storage unit capacity should be chosen equal to the maximal variation of the storage unit energy.

Consequently, for a real wind turbine, only the wind speed is needed to compute the power reference of the generator and the storage unit rating. Only one wind sensor is also necessary.

A.3. Storage unit control

The nominal power of the storage unit is controlled during charge and discharge periods. The electrical energy available in the storage unit is calculated and limited as its dimension depends on the wind speed condition for a given site, according to the conclusion of the previous section.

Storage unit control is based on the computation of the instantaneous energy stocked or to be stocked in the unit. The instantaneous power stocked in the storage unit is calculated from Vdc voltage and storage unit current. By integrating this power, we obtain the instantaneous energy value W_{stock} . According to the studied WECS, we define minimal and maximal values of W_{stock} , respectively W_{min} and W_{max} . Here, W_{min} corresponds to the minimal energy value which must be remained stocked in the storage unit, to prevent any fatal storage discharge. More, W_{max} corresponds to the maximal energy value which can be stocked in the storage unit, to prevent any fatal excessive storage charge. By comparing W_{stock} , W_{max} and W_{min} values, we defined storage unit power and DFIG active power references, as depicted figure 11, where active power reference is set at 10 kW.

DFIG active power reference is equal to $P_{w,max}$, excepted when the storage is full. In this case, reference is set to the WECS active power reference. In charge or discharge conditions and for a given wind speed, the power reference is calculated and subtracted from the constant power injected to the grid to fix the power reference for the storage unit. This power can be positive or negative according to wind speed conditions, as depicted in figure 11.

B. Turbine control

The active power reference is calculated from the wind speed and limited to the nominal power of the DFIG. The reactive power reference can be set at any value, by considering the rating of the generator, during the operation of the wind turbine then, it is also possible to improve the power factor on the grid.

The generator speed depends on the produced power and the wind speed. When using a DFIG, the generator can

produce power in hyper or hypo synchronous conditions and the pitch control will keep the generator speed around the synchronous speed.

The pitch control achieves the maximum efficiency of the turbine. It is also possible to turn off the turbine when wind speed becomes too large to prevent any mechanical damage.

The PWM rectifier controls the DC bus voltage. The power can be positive or negative if the generator performs at hyper or hypo synchronous conditions and when the storage unit absorbs power from the wind turbine or provides power to the grid.

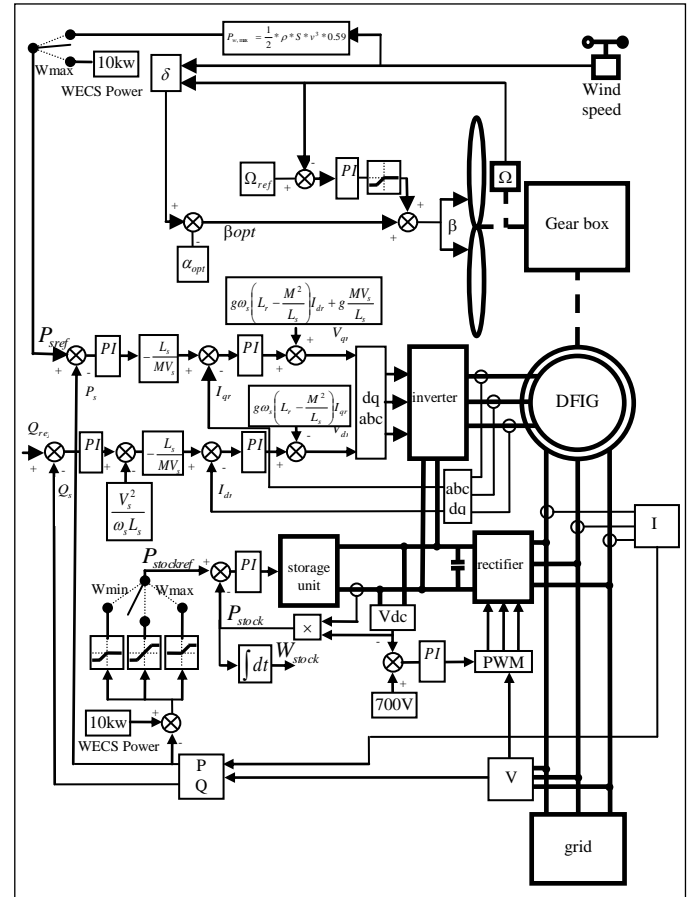


Fig. 11. Wind Energy Conversion System diagram

V. SIMULATION RESULTS

In this section, we present simulation results for a 20 kW DFIG associated with an electrical storage unit (figure 11). The wind turbine is controlled in order to inject a constant power of 10kW into the grid under all wind conditions. The reactive power reference is kept constant at 0Var.

A day long simulation is time consuming. To reduce simulation time, we considered wind profiles of figures 5 and 6 over 15 minutes instead of 24 hours, as depicted in figures 12 and 13. In this case, wind speed is considered as measured every 6.5 seconds instead of 10 minutes for figures 5 and 6.

This time reduction is justified by low WECS time response, shorter than 6.5 seconds. Consequently, the storage unit energy must be reduced by the time ratio, i. e. 96 in our case.

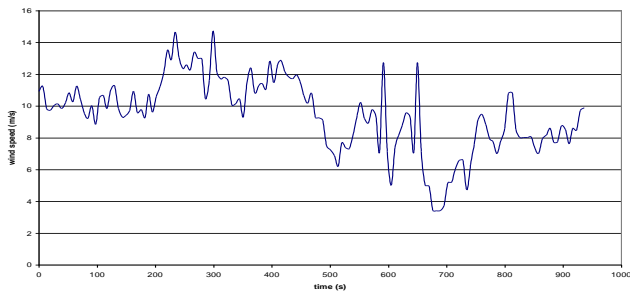


Fig. 12. Time reduced wind speed profile in high mean conditions

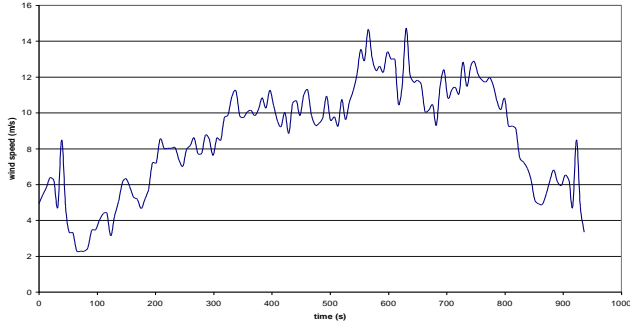


Fig. 13. Time reduced wind speed profile in low mean conditions

Simulation results are presented in figures 14 and 15. They are respectively performed with wind speed profiles presented in figures 12 and 13. To reduce simulation time, we used MAST language, associated with SABER tool to model all parts of the WECS (mechanical, electrical, DFIG, ...) depicted figure 11.

For results presented in figure 14, the active power of the DFIG follows correctly the power reference calculated from the wind speed. This power is limited by the generator nominal power (20 kW). Simulation results for active power of the DFIG demonstrate the impossibility of generating a constant active power equal to 10 kW under all wind speed conditions. However, a constant active power of 10kW can be injected into the grid by the WECS thanks to the storage unit. The reactive power is correctly regulated. Simulation results for power of the storage unit correspond to a negative power when charging the storage unit and a positive power when feeding the grid. This power allows compensating active power of the DFIG when wind conditions do not allow generating 10kW. Consequently, the power injected to the grid is kept constant for all wind conditions. This corresponds to the sum of the DFIG and storage unit powers. Consequently, this wind energy conversion system can be assimilated as a constant generator for active power under wind speed profile given in figure 12.

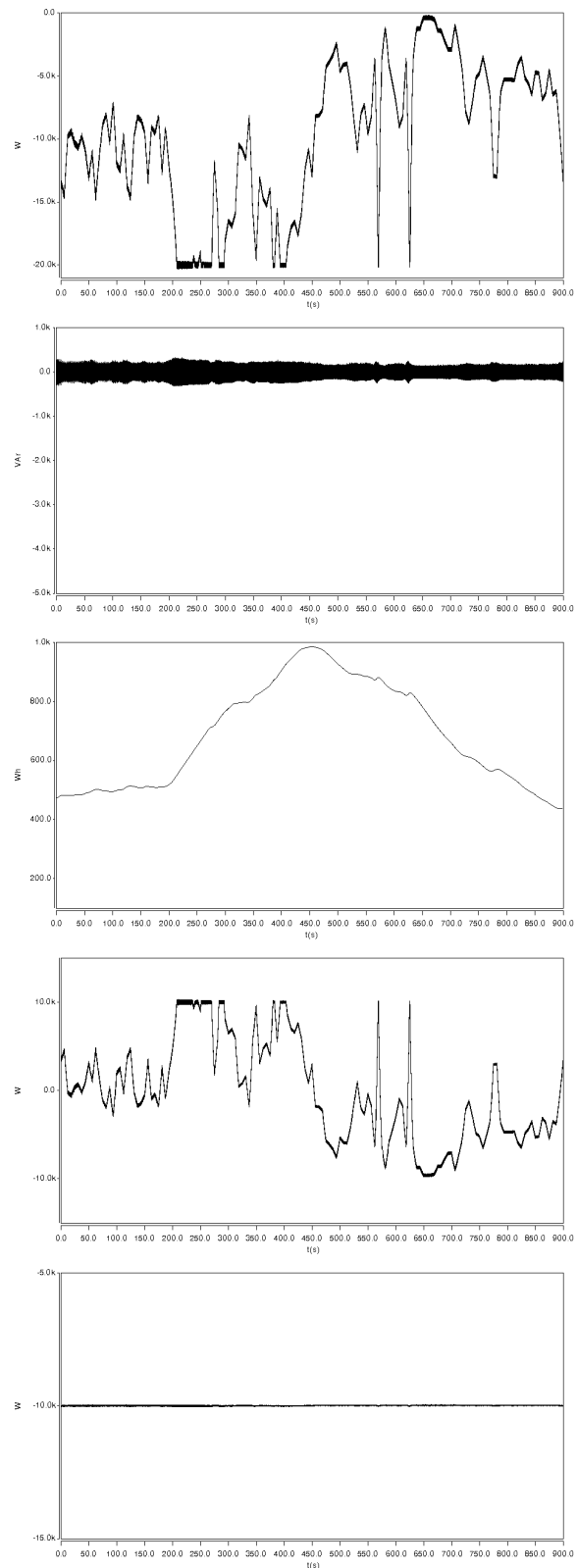


Fig. 14. From top to bottom : Active stator power of the DFIG (W), reactive stator power of the DFIG (VAr), storage unit energy (W.h), storage unit power (W), active power injected to the grid (W) for wind speed conditions figure 12.

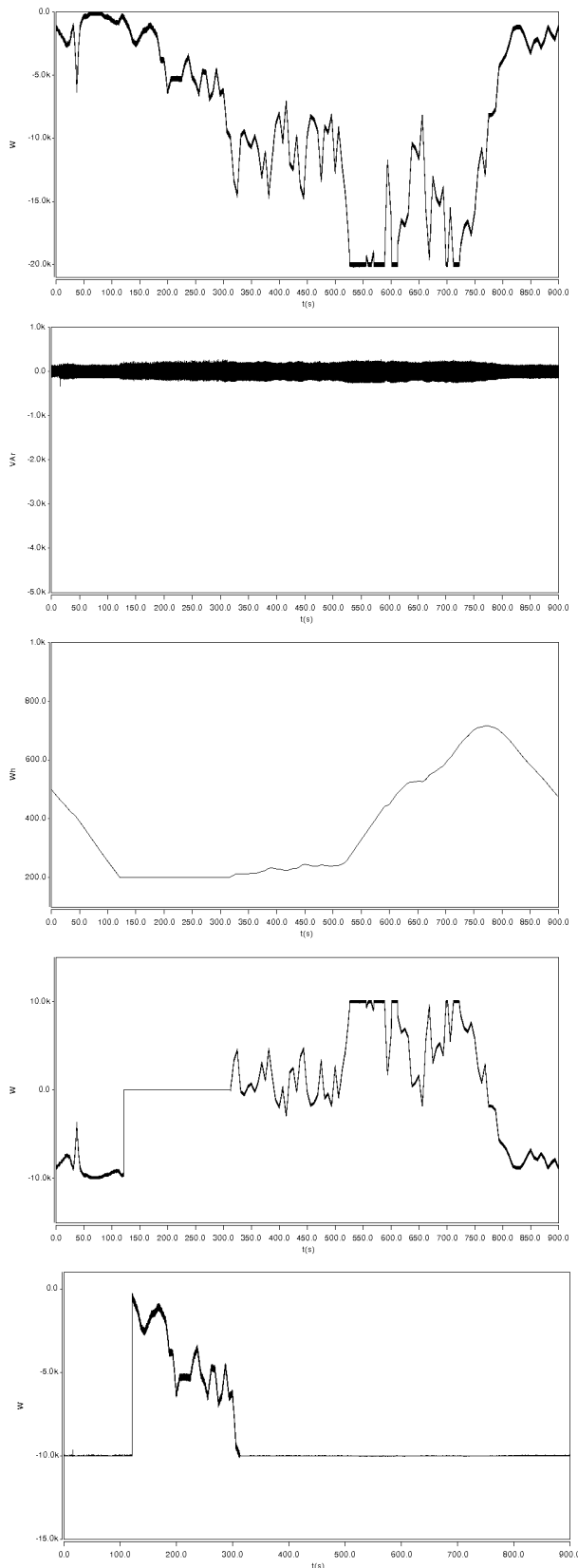


Fig. 15. From top to bottom : Active stator power of the DFIG (W), reactive stator power of the DFIG (VAr), storage unit energy (W.h), storage unit power (W), active power injected to the grid (W) for wind speed conditions figure 13.

Simulations results presented figure 15 illustrate the impossibility to inject into the grid a 10kW constant power under wind speed profile of figure 13. This results from the imposed power reference which does not correspond to the real mean value of the wind power. More, in low wind condition period between 150 s and 300 s, storage unit power is null because storage energy has reached its limit W_{min} .

VI. CONCLUSION

The DFIG is nowadays a popular choice for wind energy conversion systems. This popularity is mostly due to its ability for large variable speed drive. We presented and validated in this paper two major aspects to achieve high power quality: active and reactive power control and energy storage included in the DC link. We evaluated energy storage and associated WECS in terms of interest and limits. If the storage unit is well dimensioned, stored energy is well suited under long-term considerations and simulation results demonstrated good performances in term of power control. However, a cost study should be performed for any wind speed case to justify the use of energy storage unit.

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