Output power control of two coupled wind generators

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ABSTRACT:
In this paper we are interested to the power control of two wind generators coupled to the network through power converters. Every energy chain conversion is composed of a wind turbine, a gearbox, a Double Fed Induction Generator (DFIG), two PWM converters and a DC bus. The power exchange and the DC voltage are controlled by the use of proportional integral correctors.

For our study, initially we have modeled all the components of the one system energy conversion, and then we have simulated its behavior using Matlab/Simulink. In another part of this paper we present the analysis of the interaction and the powerflow between the two aerogenerators following a disturbance due to wind speed on every turbine. Also we have considered a connection fault to the DC bus. In each case the assessment of power brought into play is checked. Simulation tests are established.

1. INTRODUCTION

Wind energy is becoming one of the most important renewable sources. So many studies [1–4][6] are oriented toward this type of energy production in the aim to make it more efficient. Variable speed wind turbines are widely used in this field owing to their ability to maximize wind power extraction [1–5]. The one analyzed in this paper is based on a doubly fed induction generator (DFIG). This machine presents different advantages [4] such as: operating in a large game of speed, generation of a constant frequency active power and the possibility of the generated active and reactive power to be controlled independently.

Maximum power point tracking (MPPT) strategies play an important role in wind power conversion systems (WECS) because they maximize the power extracted from the wind, and therefore optimize the conversion efficiency. Two strategies are used in literature [1–6], with or without speed control. In this paper, we used the strategy with speed control; it permits to carry the speed wind turbine into the desired value which corresponds to the maximum power point. Using an appropriate control algorithm could improve the wind power efficiency.

To increase the power generated by wind power conversion chain and previously studied to optimize the number of static converters. In the present work, we are interested to a control of the power output for a conversion system composed of two turbines, based on double-fed induction generators. Their stators are directly connected to the network and the rotors are coupled to the network through static converters Figure. 1.

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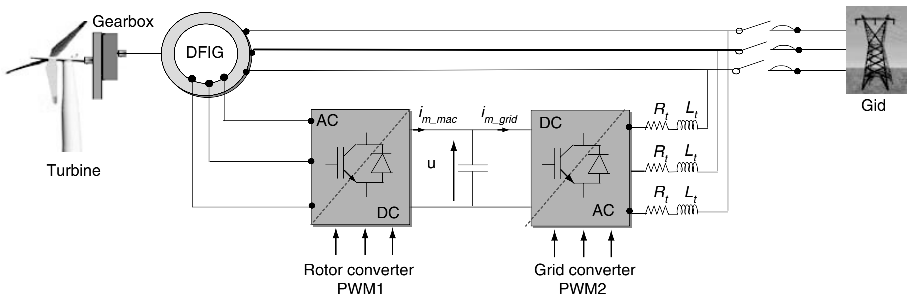

Figure 1 Scheme of rotor DFIG coupled to the network via static converters.

The use of variable speed wind turbines, allows maximizing the power recovered by exploiting the maximum power point tracking (MPPT) on each wind speed. First, we will simulate the conversion chain of one turbine model. Next, we studied the case of two wind turbines coupled by a single network-side converter. We will simulate the behavior of two wind turbines following a disturbance on one of the two turbines. The balance of power involved is checked. To make this work, we have organized our paper as follows:

The wind turbine model is presented in section 2. In section 3, we give the modeling of double-fed induction generator (DFIG) and the decoupled control of active and reactive powers (P and Q). Simulation results are presented in section 4.

In section 5 we present a model of converters in Park's frame. The model of the DC bus is given in section 6. In section 7, we present a filter model. Section 8 is devoted to two turbines connected to the network. Simulation results are presented in sections 9, 10 and 11.

2. WIND TURBINE MODELING

The aerodynamic power developed by a wind turbine is given by the following expression [2][4][5][6]:

$$P_{aer} = \frac{1}{2}, C_p(\lambda.\beta).\rho\pi.R^2.v^3 \tag{1}$$

ρ: air density, v: wind speed, C_p: power coefficient, β: blade pitch angle, λ: tip-speed ratio, it given by (12).

$$\lambda = \frac{R\Omega_{turb}}{v} \tag{2}$$

R: radius of rotor, Ω_{tutb}: the turbine rotor speed.

The power coefficient C_p defines the aerodynamic efficiency of the wind turbine rotor. It is represented by various approximation expressions. In this paper, C_p is expressed by (3), [1] :

$$\begin{cases} Cp(\lambda,\beta) = 0.5176 \bullet \left(\frac{116}{\lambda_i} - 0.4.\beta - 5\right).e^{\frac{-21}{\lambda_i}} + 0.0068.\lambda \\ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{\beta^3 + 1} \end{cases} \tag{3}$$

The system consists of an aero turbine, which converts wind energy into mechanical energy, a gearbox, which serves to increase the speed and decrease the torque and a generator to convert mechanical energy into electrical energy.

The mechanical Eqn of the shaft, including both the turbine and the generator masses, is given by:

$$J.\frac{d\Omega}{dt} = T_g - T_{em} - f.\Omega \tag{4}$$

J and fare the total moment of inertia and the viscous friction coefficient appearing at the generator side, T_g is the gearbox torque, T_{em} is the generator torque, and Ω is the mechanical generator speed.

We have:
$$\begin{cases} T_g = \frac{T_{aer}}{G} \\ \Omega_{turb} = \frac{\Omega}{G} \\ T_{aer} = \frac{P_{aer}}{\Omega_{turb}} \end{cases} \tag{5}$$

G is the gear ratio, and T_{aer} is the aerodynamic torque.

3. GENERATOR MODELING AND COMMAND

The generator dynamic model written in a synchronously rotating frame d-q [2, 3, 6] is given by the equation system below.

$$\begin{cases} V_{ds} = R_s i_{ds} + \frac{d}{dt}\phi_{ds} - \omega_s \phi_{qs} \\ V_{qs} = R_s i_{qs} + \frac{d}{dt}\phi_{qs} + \omega_s \phi_{ds} \end{cases} \tag{6}$$

$$\begin{cases} V_{dr} = R_r i_{dr} + \frac{d}{dt}\phi_{dr} - \left(\omega_s - \omega\right)\phi_{qr} \\ V_{qr} = R_r i_{qr} + \frac{d}{dt}\phi_{qr} - \left(\omega_s - \omega\right)\phi_{dr} \end{cases} \tag{7}$$

$$\begin{cases} \phi_{ds} = L_s i_{ds} + M i_{dr} \\ \phi_{ds} = L_s i_{qs} + M i_{qr} \end{cases} \begin{cases} \phi_{dr} = L_r i_{dr} + M i_{ds} \\ \phi_{qr} = L_r i_{qr} + M i_{qs} \end{cases} \tag{8}$$

$$T_{em} = p\frac{M}{L_s}(\phi_{qs} i_{dr} - \phi_{ds} i_{qr}) \tag{9}$$

$$\begin{cases} P_s = V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q_s = V_{qs} i_{ds} - V_{ds} i_{qs} \end{cases} \tag{10}$$

To be able to easily control the wind turbine power generation, we will realize an independent control of generator stator active and reactive power.

The control system adopts the oriented flux strategy, defined in the synchronous d-qframe fixed to the stator flux Eqn. 11.

$$\begin{cases} \phi_{ds} = \phi_s \\ \phi_{qs} = 0 \end{cases} \tag{11}$$

In addition, the electric network can be considered as an infinite energy source so that the stator voltage vector is a constant. And the pressure drop in stator resistance is negligible comparing with the stator voltage value.

With the above assumption, the mathematical model of DFIG in the synchronous reference frame (dq frame) linked to the stator flux is as follows:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s = \omega_s.\phi_{ds} \end{cases} \tag{12}$$

$$\begin{cases} V_{rd} = R_r.I_{rd} + \sigma.L_r.\dfrac{dI_{rd}}{dt} - s.\omega_s.\sigma.L_r.I_{rq} \\ V_{rq} = R_r.I_{rq} + \sigma.L_r.\dfrac{dI_{rq}}{dt} + s.\omega_s.\sigma.L_r.I_{rd} + s.\dfrac{M}{L_s},V_s \end{cases} \tag{13}$$

$$T_{em} = -p.\frac{M}{L_s}.\phi_{sd}.I_{rq} \tag{14}$$

$$\begin{cases} P_s = -V_S.\dfrac{M}{L_S}.I_{rq} \\ Q_s = -V_s.\dfrac{M}{L_s}L_{rd} + \dfrac{V_s^2}{\omega_s.L_s} \end{cases} \tag{15}$$

According to Eqn. 15, we can see that the stator active and reactive power P_s and Q_s could be controlled by the rotor current *d*, *q* components I_{rq} and I_{rd} respectively.

The DFIG control structure contains two cascaded control loops (inner and outer) for each axis *d* and *q*. One controls the current (the inner) and the other (the outer) the power. See Figure. 2.

4. SIMULATION OF THE INDEPENDENT POWER CONTROL

Figures 3, and 4 shown that the active and reactive powers references are correctly followed by the generator without static errors. Any change of reference of the two powers has little influence on the other one. Therefore, the control of the two powers is entirely independent.

For further work we consider that the reference magnitude desired P_{sref}, corresponds to the maximum power point given by the generator speed regulator. And the reference reactive power Q_{sref} is imposed equal to zero, in order to operate at unitary power factor.

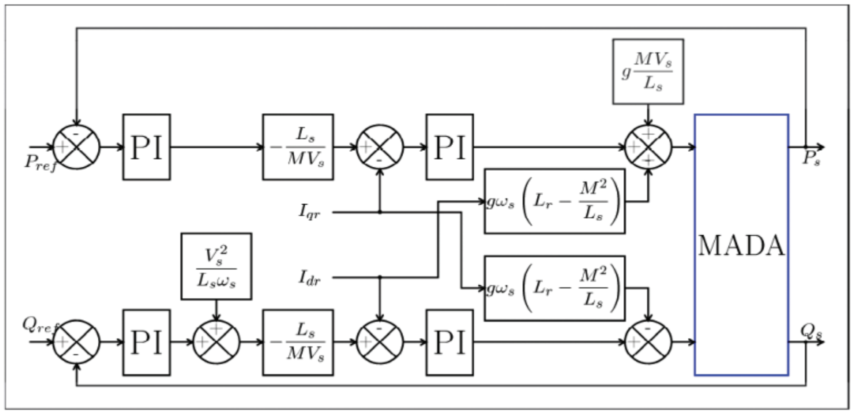

Figure 2 Closed loop indirect control scheme.

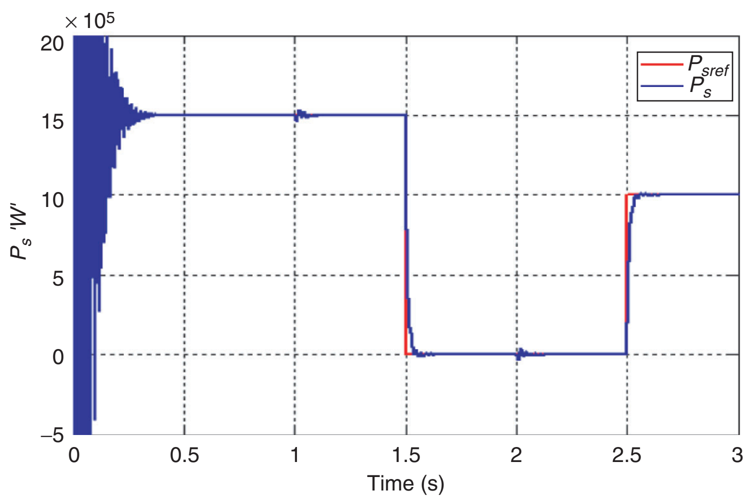

Figure 3 Active power response.

5. EQUIVALENT MODEL OF THE POWER CONVERTERS

An equivalent model of the converters in the Park frame is developed by considering that the voltages and currents are three-phase equilibrium systems. Thus, in the Park's frame, the modulated voltages by the converters PWM1 and PWM2 (alternative side) depend on the DC bus voltage [7]. They are expressed by:

$$v_{md} = r_d \frac{u}{2} \tag{16}$$

$$v_{mq} = r_q \frac{u}{2} \tag{17}$$

rd and *rq* are the direct and quadrature components of the control voltages of the static converter.

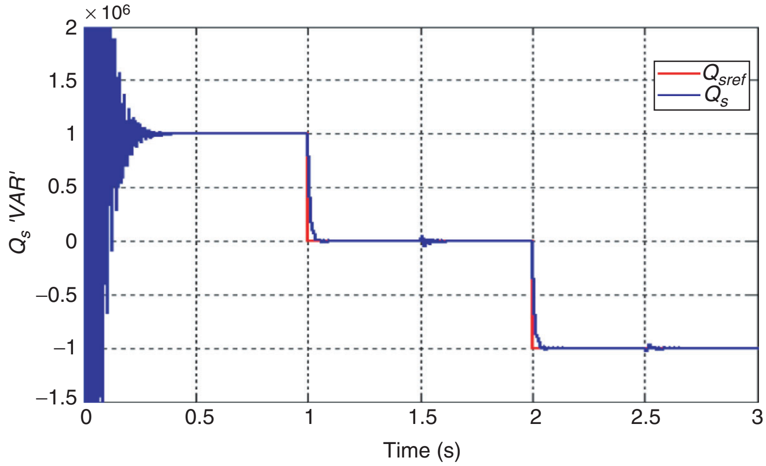

Figure 4 Reactive power response.

6. MODELING OF THE DC BUS

The variation of the DC bus voltage is proportional to the capacitive current as shown in the following differential Eqn:

$$\frac{du}{dt} = \frac{1}{C} i_c \tag{18}$$

The current ic which charges the capacitor C is then obtained by the following expression:

$$i_e = i_{m\_mac} - i_{m\_grid} \tag{19}$$

7. MODELING FILTER IN THE FRAME OF PARK

The mathematical filter model after applying the transformation of PARK, is given by the following matrix system:

$$\begin{bmatrix} v_{md} \\ v_{mq} \end{bmatrix} = \begin{bmatrix} R_t & -L_t\omega_s \\ L_t\omega_s & R_t \end{bmatrix} \begin{bmatrix} i_{td} \\ i_{tq} \end{bmatrix} + L_t \frac{d}{dt} \begin{bmatrix} i_{td} \\ i_{tq} \end{bmatrix} + \begin{bmatrix} v_{pd} \\ v_{pq} \end{bmatrix} \tag{20}$$

With:
R_t and L_t are the filter parameters
v_{pd} and v_{pq} are the Park's voltage components in the end of the filter
i_{td} and i_{tq} are the direct and quadrature current components sent to the network.

8. CONNECTING THE TWO VARIABLE SPEED WIND TURBINES TO A COMMON DC BUS

We considered a conversion chain consists of two variable speed wind turbines connected to the network as shown in Figure. 5.

The stator circuit generators are directly connected to the network. The rotor circuits are connected to a common DC bus via PWM1 converters. The DC bus is in turn connected to the network by PWM2.

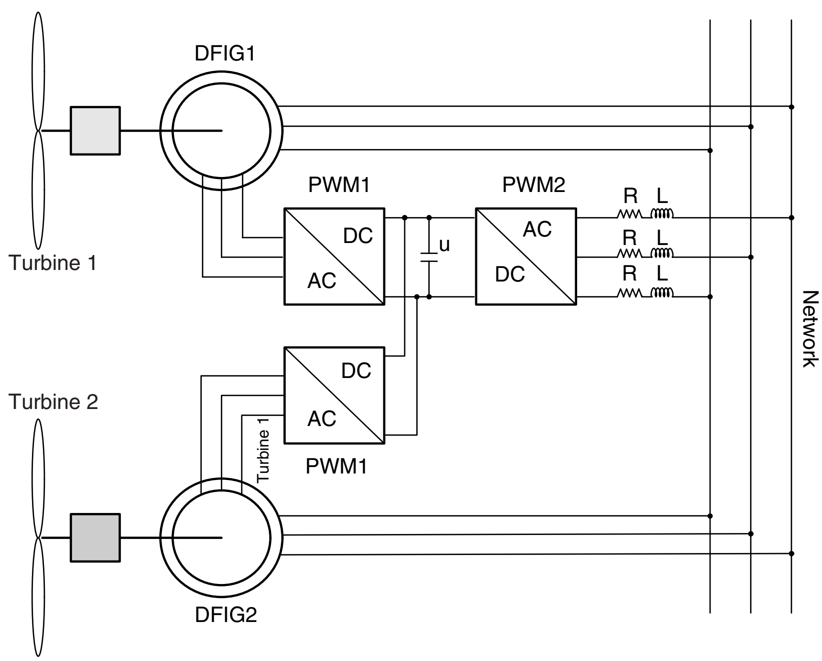

Figure 5 Scheme of the two DFIG coupled to the network.

The network-side converter PWM2 and the value of the DC bus voltage must be sized to pass the total power generated by two turbines working at ± 30% of synchronous speed. Then the two PWM1 converters are designed for 30% of the nominal power that corresponds to 450 KW. By cons, the PWM2 converter is sized for 60% of the nominal power that's equal to 900 KW.

9. SIMULATION OF THE CONVERSION CHAIN OF ONE WIND TURBINE

In this section we present simulation results of one chain conversion energy. Variable speed wind turbine based on a double-fed asynchronous machine of 1.5 MW. Wind speed varies between around 10.8 m/s (See Figure. 6). Figure. 7, shows that the generator speed is made variable so as to obtain maximum active power.

Figure. 8 shows that the rotor and stator active power delivered to the grid, fluctuate the rhythm of the wind speed. The total active power to the grid is the sum of stator and rotor active powers (super-synchronous operation). Wind chain conversion operates considered to

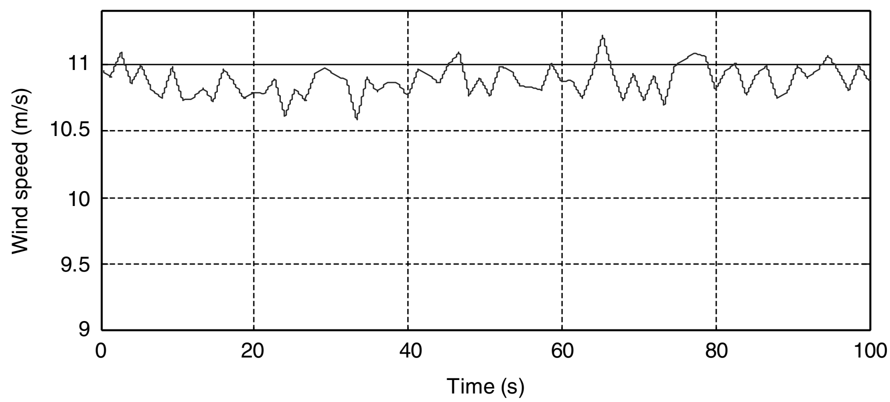

Figure 6 Wind speed.

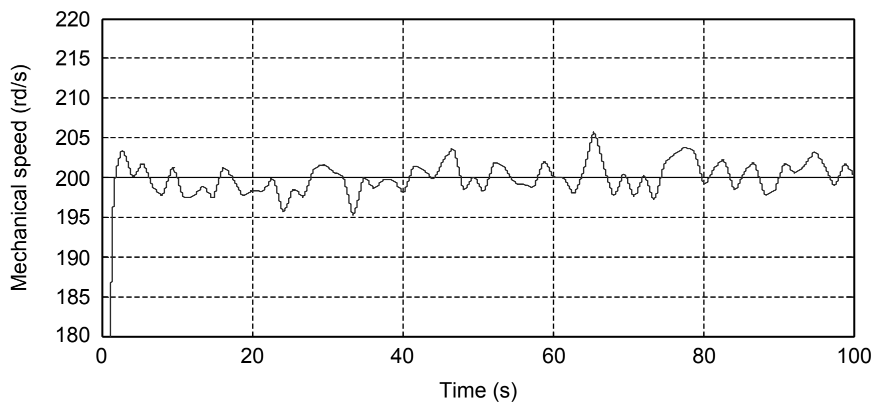

Figure 7 Mechanical speed of the DFID.

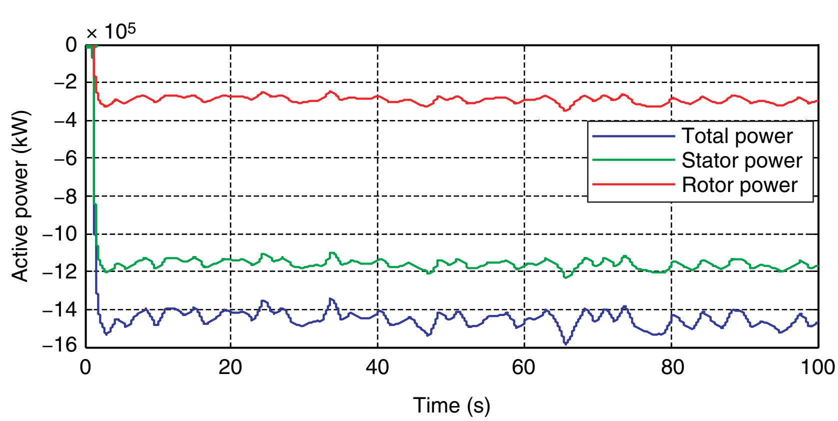

Figure 8 Active power sent to the network.

unity power factor as long as the total reactive power exchanged with the network is maintained zero regardless of the wind speed (Figure. 9).

Despite the fluctuation of the rotor active power sent to the network, the DC bus voltage is kept constant with insignificant fluctuations around its desired value (Figures. 10 and 11).

10. SIMULATION OF THE CONVERSION CHAIN OF TWO WIND TURBINES FROM DISTURBANCES

In this section we will test the effectiveness of the control system of the DC bus. For this, each of the two turbines is attacked by a level of wind speed (Figure. 12 and Figure. 13), which is considered as disturbances.

Simulation results show that the mechanical speeds (Figure. 14) and active power (Figure. 15) increase and the applied disturbance on one turbine don't influence the behavior of the second turbine. The total power is always the sum of the rotor and stator powers of the two generators.

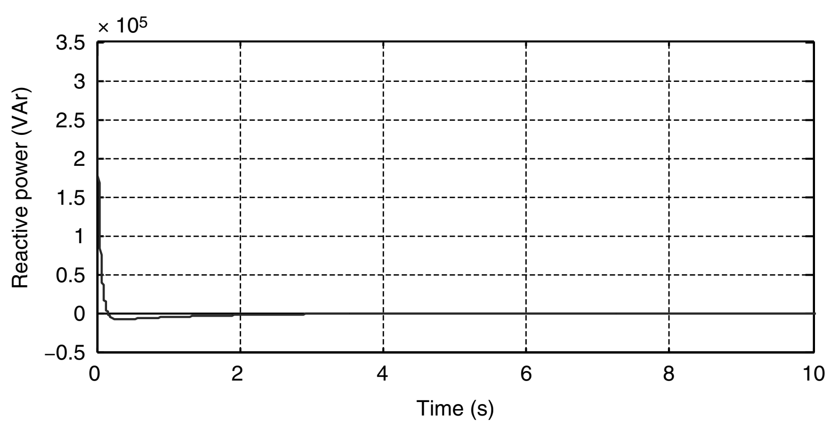

Figure 9 Reactive power.

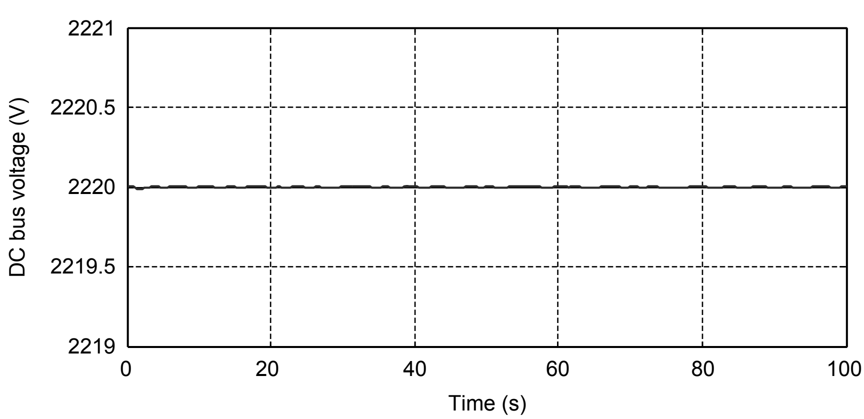

Figure 10 DC voltage bus.

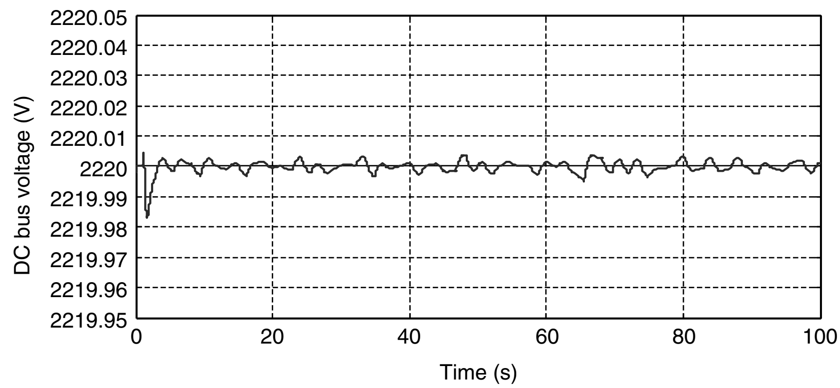

Figure 11 Zoom DC voltage.

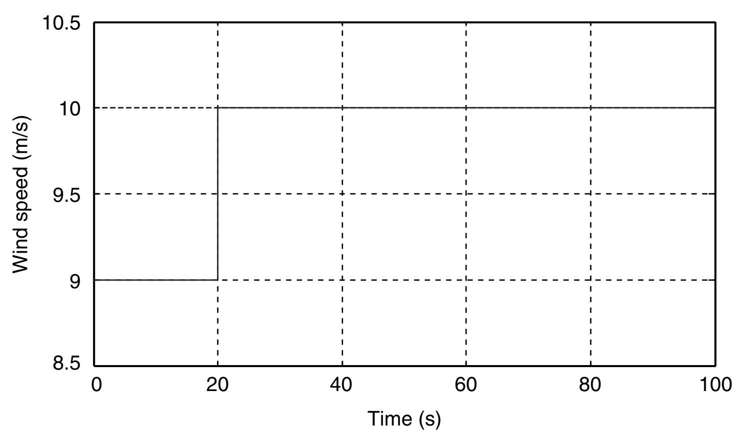

Figure 12 Wind profile of theturbine1.

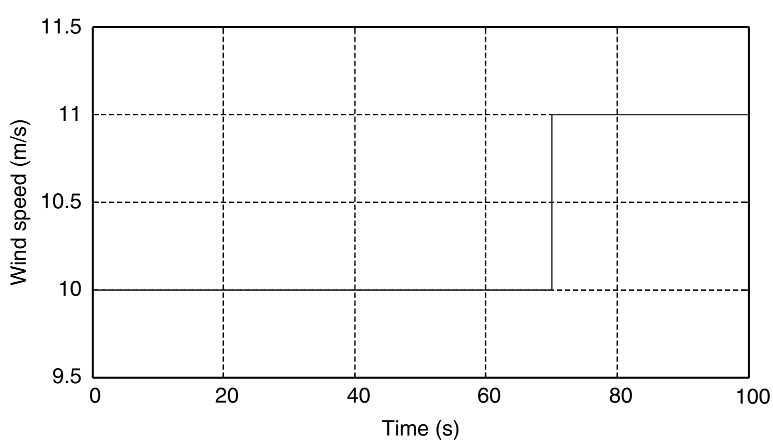

Figure 13 Wind profile of theturbine2.

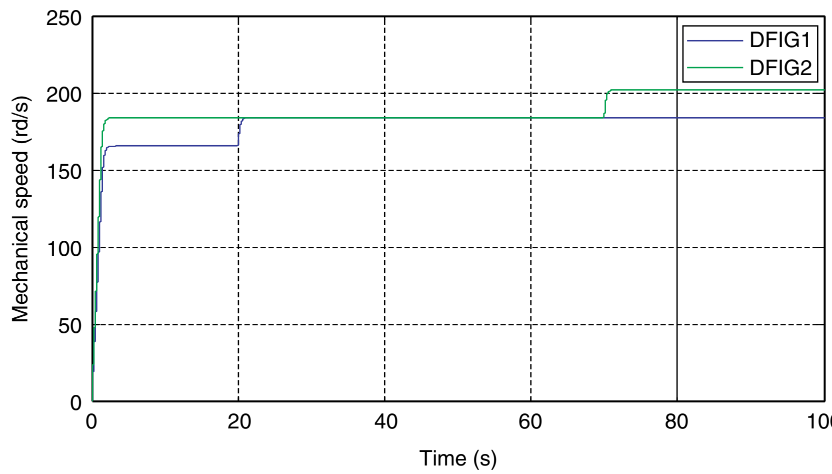

Figure 14 Mechanical speeds.

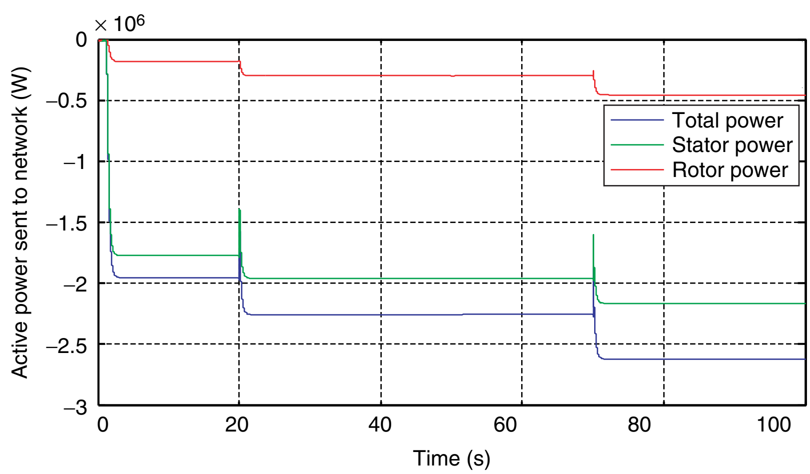

Figure 15 Active power sent to the network.

The control system regulates the voltage the DC bus voltage, despite the presence of disturbances. During a disturbance, the DC bus voltage is slightly disturbed, but it quickly adjusted to its desired value Figure. 16. Therefore, we can say that the two turbines are practically decoupled (reactive power is kept to zero Figure. 17), as long as the DC bus voltage is kept constant by the control system in place.

11. SIMULATION OF THE CONVERSION CHAIN OF TWO WIND TURBINES DUE TO A FAULT CONNECTION

We will simulate the case of a fault connection at t = 50 s of the DC bus to the PWM1 inverter of the second turbine. Figures.18, 19 and 20 show the impact of this defect respectively on active, reactive powers (exchanged with the network) and the DC bus voltage.

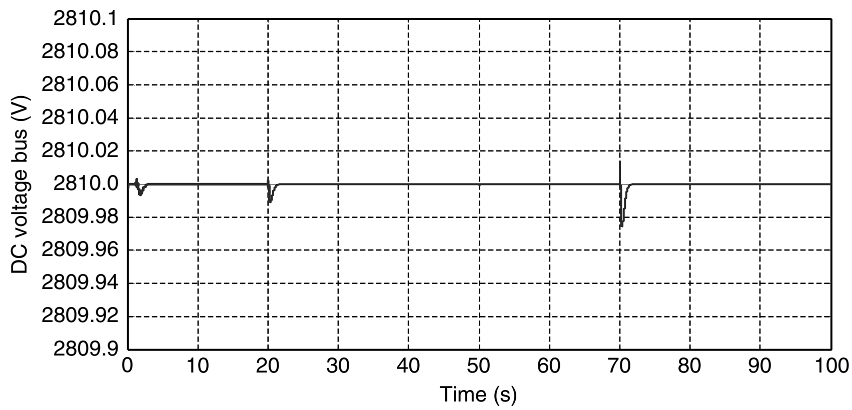

Figure 16 DC voltage bus.

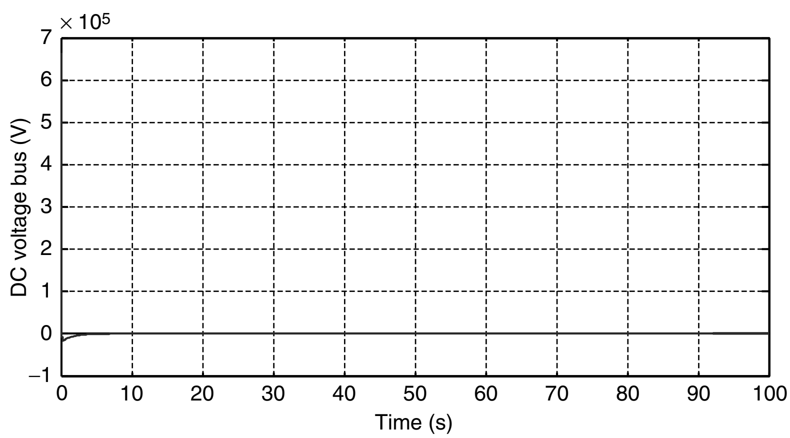

Figure 17 Reactive power.

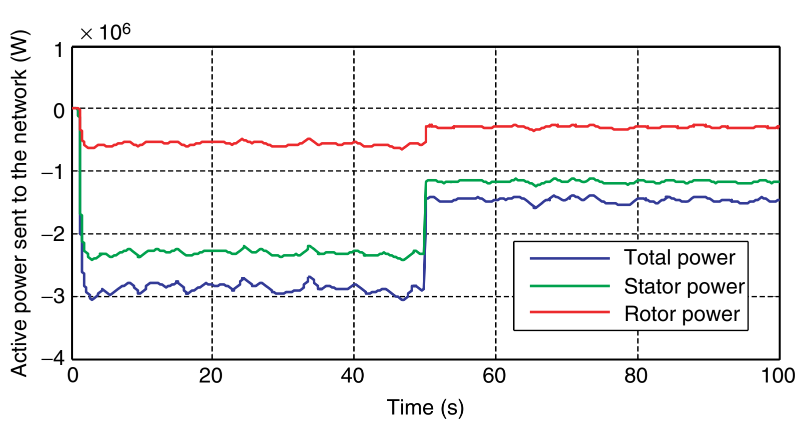

Figure 18 Active power sent to the network.

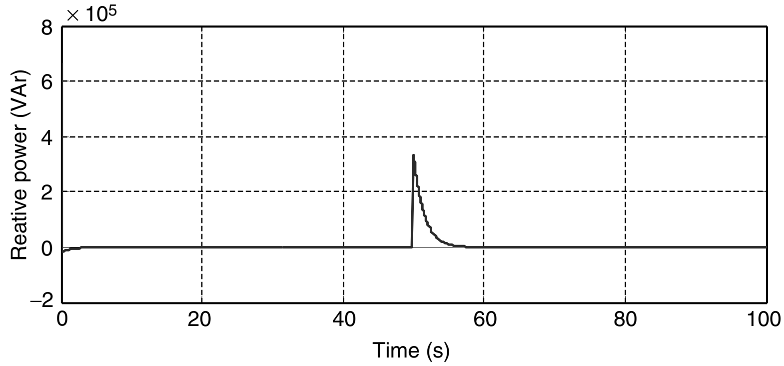

Figure 19 Reactive power.

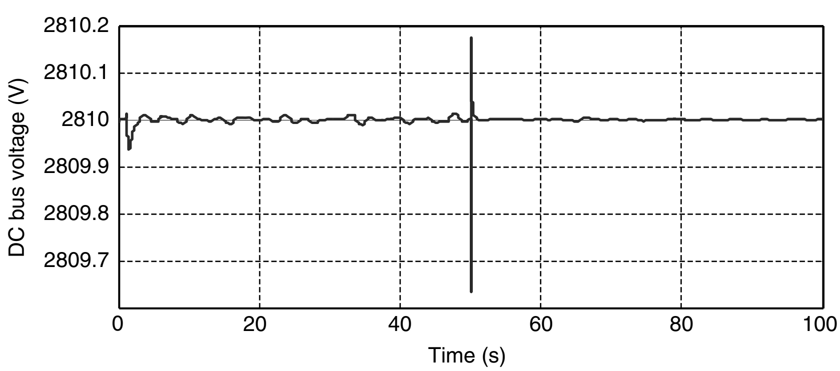

Figure 20 DC voltage bus.

Table 1 Wind turbine and dfig parameters.

	Parameter value	**Signification**
	Pn = 1,5	Rated power (MW)
Wind	N = 3	Number of blades
turbine	R = 35.25	A blade length (m)
	G = 80	Gearbox Gain
	J = 50	Turbine inertia (kg.m2)
	fvis = 0.0071	Viscous friction coefficient
	V = 690	Voltage (V)
	f = 50	Frequency (Hz)
	Pn = 1,5	Rated power (MW)
	p = 2	Pair polesnumber
DFIGD	Rs = 0.012	Stator resistance (Ω)
	Rr = 0.021	Rotor resistance (Ω)
	Ls = 0.0137	Stator Inductance (H)
	Lr = 0.0136	Rotor Inductance (H)
	M = 0.0135	Mutual Inductance (H)

According to the simulation results, we find that the total active power to the grid is reduced by half, after the time when the failure connection has occurred (Figure. 18). This means that the wind generator does not provide active energy to the grid while the rotor circuit of the DFIG2 is opened after t = 50 s.

In Figure. 19 we see that the reactive power increases presenting a peak then it joined her zero reference thanks to a control system. That ensures operation at unit power factor even in the presence of a connection fault of PWM1 or PWM2 converters.

Figure. 20 shows that the DC bus voltage is affected only at the moment of connection fault and it is regulated to the desired value. This confirms once again the effectiveness of the control system of the DC bus voltage.

12. CONCLUSION

In The first part of our paper was devoted to the establishment of a model of a chain of wind conversion based on a Double Fed Induction Generator driven by the rotor circuit and PWM converters connected to the network via a DC bus. From this model we have developed a control structure of the chain of global conversion to extract maximum power from wind energy.

A Double Fed Induction Generator is controlled by the stator field oriented strategy. Vector control permitted to obtain a separate control of the active and reactive powers. Correctors parameters were calculated for DC bus voltage regulation and powers exchange.

To increase a power generation, we have considered a configuration with two wind turbines connected to the network.

Simulation results show that it is possible to perform such configuration, but with a good sizing of the DC bus.

Finally, an effectiveness of the control system of the DC bus has been made. The effectiveness of the control system implementation is confirmed by the simulation results. The two turbines are decoupled so long as the DC bus voltage is well regulated even in the presence of disturbances at the two turbines.

REFERENCES

[1] Oscar Barambones, Patxi Alkorta and Manuel De La Sen + EUI de Vitoria, “ Wind Turbine Output Power Maximization Based on Sliding Mode Control Strategy,” *IEE 2010*, pp. 364–369.

[2] B. Beltran, M.E.H. Benbouzidand T. Ahmed-Ali, “High-Order Sliding Mode Control of a DFIG-Based Wind Turbine for Power Maximization and Grid Fault Tolerance,” *2009 IEEE*, pp. 183–189.

[3] Xuemei Zheng, Lin Li, DianguoXu and Jim Platts, “Sliding Mode MPPT Control of Variable Speed Wind Power System,” *2009 IEEE*.

[4] G.Tapia and A.Tapia, “Wind Generation Optimization Algorithm for a Doubly Fed Induction Generator,” *IEE Proc.-Gener.Transm. Distrib.*, March 2005, vol. 152(No.2), pp. 253–263,.

[5] S. El Aimani, *“ Modélisation de Différentes Technologies d’Eoliennes Intégrées dans un Réseau de Moyenne Tension*, ” Thèse de Doctorat, Ecole centrale de Lille Université des Sciences et Technologies, 2004.

[6] Tinglong Pan, ZhichengJi, Zhenhua Jiang, “Maximum Power Point Tracking of Wind Energy Conversion Systems Based on Sliding Mode Extremum Seeking Control,” *IEEE Energy* 2030, Atlanta, GA USA, 17–18 November, 2008.

[7] B. Robyns, Y. Pankow, L. Leclercq, B. Francois, “ Equivalent Continuous Dynamic Model of Renewable Energy Systems ”, 7th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems : *Electrimacs* 2002, CD, Montreal, Canada,18–21 Aout 2002.