Variable speed turbine based wind farm including storage system connected to a power grid or islanded

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Abstract. In this paper, the possibility of a generating system, which associates a variable speed wind turbine and a flywheel energy storage system, to participate to the ancillary services is investigated. The connection to a power grid of a farm including three of them is considered. A solution is proposed to allow wind generators to work as voltage sources with the help of a frequency droop. It is shown that the power generated by these systems can be controlled by fixing the power set point when they are connected to the grid, and that, in case of islanding, they can share the global load of the isolated network.

Keywords

Dispersed generation, wind farm, energy storage, power converter, ancillary services, islanding.

1. Introduction

The electricity market liberalization and the development of the decentralized production induce many new scientific and technical problems. The major problem experienced with decentralized energy sources, and particularly renewable energy ones, is that they do not usually contribute to the power network management [1]. Their rate of penetration is then limited (to 30 % of the consumption for instance according to some experience feedback [1] [2]) in order to be able to guarantee the network stability under acceptable conditions. Among these sources, wind energy is expected to grow quickly in Europe during the coming years. Increasing its rate of penetration will be thus possible if this type of source takes part in the ancillary services [2] – [4], and can work in islanding mode.

To reach these objectives with wind generators, we consider a Variable Speed Wind Turbine (VSWT) coupled to a Permanent Magnet Synchronous Generator (PMSG) combined to an energy storage system [5]. Due to important fluctuations of the wind generator power, conventional electrochemical batteries are not adapted [4]. We consider then a Flywheel Energy Storage System (FESS) [6] [7]. Owing to the use of power electronics, the generator and the storage system are electrically coupled via a DC link.

To evaluate the possibility of the proposed generating system (GS) to participate to the ancillary services, we consider in this paper the connection of a wind farm including three generating systems with a network including passive loads and a power grid. Generating systems are working as voltage sources with the help of a frequency droop [8]. It is shown in this paper, with the help of simulations, that the power generated by each generating system can be controlled by fixing the power set point when they are connected to the grid. It is also shown in case of islanding, that they can share the global load of the isolated network like Uninterruptible Power Supply (UPS) parallel connection [9] – [11]. This paper focus particularly on the system behaviour working in islanding mode when load varies.

2. Studied Generating System

A. Generating System structure

Fig. 1. shows the generating system under study [5]. The pitch controlled wind turbine is directly coupled to a PMSG of 42 pole pairs. The flywheel is coupled to an induction machine of one pole pair. The rated power of the induction machine is 600 kW. The inertia of the flywheel is determined in order to generate the induction machine rated power during two minutes with a speed range of 3000 – 6000 rpm. Working over the rated speed and then, in the field weakening region, allows to generate or store the rated power of the induction machine. To ensure a good voltage quality and to allow the feeding of isolated loads, a LC filter is included between converter 3 and the network as shown in Fig. 1. The inductance L_2 in Fig. 1 may represent a transformer one.

B. Generating System proposed control

1) General principles

In Fig. 1, Converter 1 allows to extract the maximum power from the wind. If necessary, the power generation can be controlled in order to be lower than the maximum, leading to a speed limitation by pitching the blades. In this particular case study, the maximum power value of the generating system is fixed to 600 kW. The DC link voltage U_{DC} can be controlled by one of the three power converters. In classical VSWT this voltage is usually regulated by converter 3. Owing to the storage system
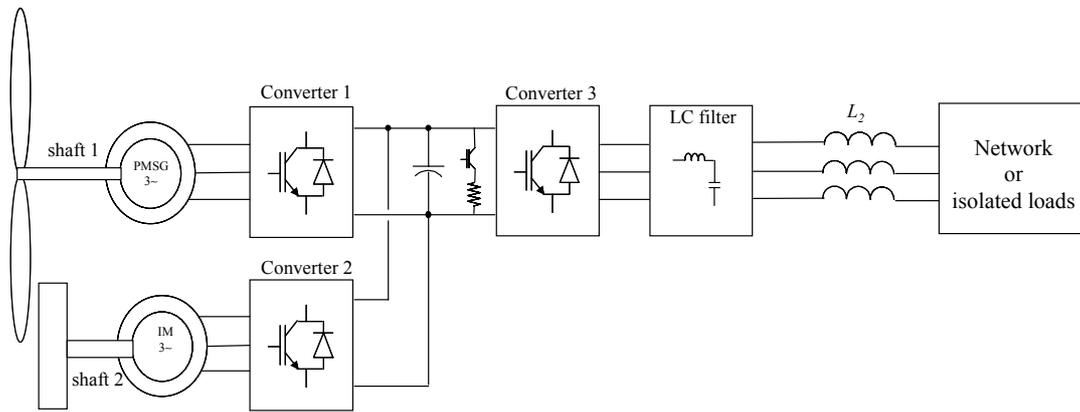
Fig. 1. Scheme of a generating system.

connected to converter 2, converter 3 can then focus on the network voltages and frequency control. Converter 2 then controls U_{DC} by storing or producing power to ensure the generation/consumption balance.

As the FESS cannot store or generate indefinitely, it is proposed to decrease the power generation of the VSWT in case of high flywheel speed (5500 rpm) and to change the level of the active power supplied by converter 3 in case of low flywheel speed (3500 rpm). Fig. 2 (subscripts "meas" and "ref" refer respectively to measured and reference values) shows the control scheme of converter 3 which therefore directly controls the phase – to – phase capacitor voltages u_c of the LC filter with the help of resonant controllers [5], allowing the generating system to work as an ideal voltage source. Transfer function of these controllers is the following :

$$C_{ui}(s) = \frac{r_{ui0} + r_{ui1}s + r_{ui2}s^2 + r_{ui3}s^3}{(\omega_0^2 + s^2)(\sigma_{ui0} + \sigma_{ui1}s)} \qquad (1)$$

In this equation, ω_0 is the pulsation associated with the network frequency f_0, r_{ui0} to r_{ui3} and σ_{ui0}, σ_{ui1} are coefficients. s is the Laplace operator. In Fig. 2, i_{g1} and i_{g2} are the generating system phase 1 and 2 currents.

2) Voltage and frequency control

The frequency of the voltage reference wave is determined with the help of frequency droop allowing a load sharing when generating systems are interconnected. The phase – to – phase capacitor voltage reference waves are determined as follows :

$$u_{c13ref} = U_{ref}\sqrt{2}\sin\left(2\pi f_0 t - \frac{\pi}{6} + \delta\right) \qquad (2.a)$$

$$u_{c23ref} = U_{ref}\sqrt{2}\sin\left(2\pi f_0 t - \frac{\pi}{2} + \delta\right) \qquad (2.b)$$

f_0 is the rated frequency. U_{ref} is the rms reference voltage. δ is the phase difference between the LC filter capacitor voltages and the network ones. In case of islanding, U_{ref} is determined in order to compensate for L_2 voltage drop which depends on the reactive power Q_g. The angle δ allows to control the active power P_g generated by the generating system onto the network as shown by (3) deduced from Fig. 3.
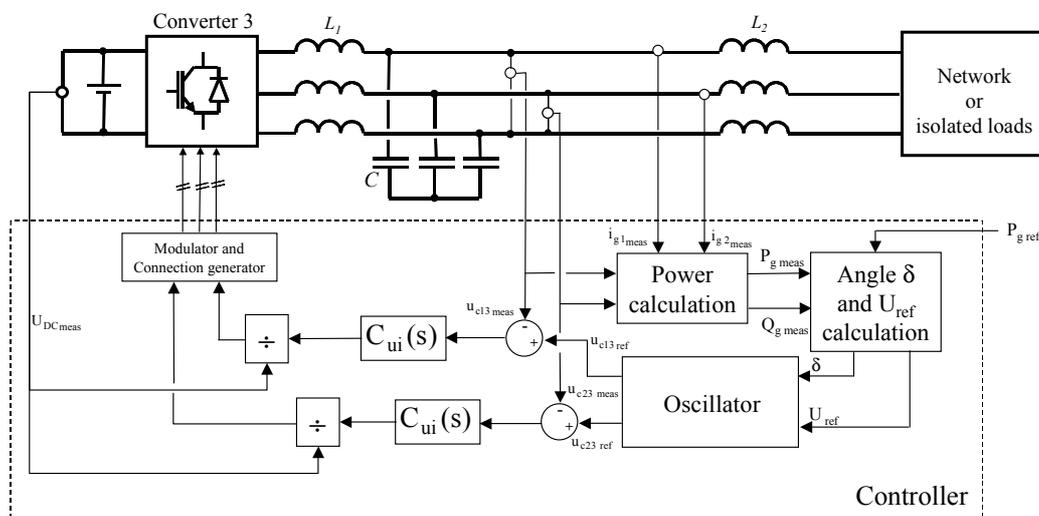

Fig. 2. Control scheme of converter 3.

$$P_g = \frac{3V_cV_g}{L_2\omega_0}\sin\delta \qquad (3)$$

V_c and V_g are respectively capacitor and grid phase – to – ground rms voltages. ω_0 is the pulsation associated with f_0.
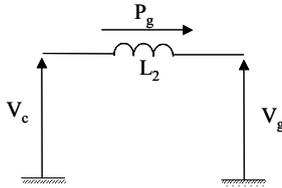

Fig. 3. Active power generated onto the network.

For small values of δ, we can approximate the previous equation by :

$$P_g \approx A\delta \quad \text{where} \quad A \approx \frac{3V_c^{\,2}}{L_2\omega_0} \qquad (4)$$

δ is determined with the help of a frequency droop as shown in Fig. 4. The equation of this droop is :

$$f = k(P_{gref} - P_{gmeas}) + f_0 \quad \text{where} \quad k = \frac{\Delta f}{\Delta P_g} \qquad (5)$$
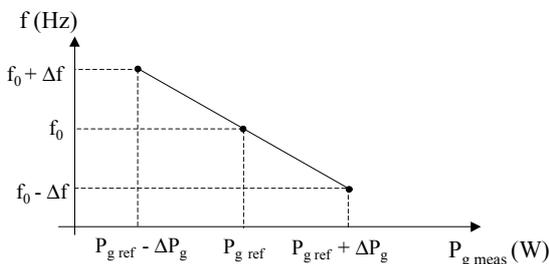
Fig. 4. Frequency droop.

The angle δ is related to (5) by the following relationship:

$$\frac{d\delta}{dt} = \Delta\omega = 2\pi(f - f_0) = 2\pi k(P_{gref} - P_{gmeas}) \quad (6)$$

Fig. 5 shows the δ angle determination deduced from (4) and (5) by neglecting the voltage control time response. An unity gain low pass filter, whose time constant is named τ, is included to reduce the amplitude of an eventual fluctuating power due to unbalanced loads (moreover, a filter is necessary in case of single phase scheme). The low pass filter is placed after the comparator to avoid a zero in the closed loop control.
From Fig. 5, a second order active power transfer function can be deduced :

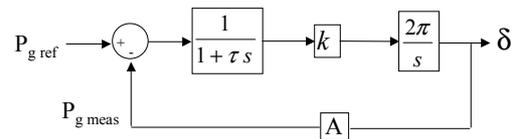$$\frac{P_{gmeas}}{P_{gref}} = \frac{1}{1 + \dfrac{1}{2\pi kA}s + \dfrac{\tau}{2\pi kA}s^2} \qquad (7)$$

Fig. 5. Generating system delivered active power closed loop control.

(7) allows us to determine coefficient k (droop effect) and τ (damping effect).

3) Active power set point determination
We previously introduced the reference value of the active power feeding the network, P_{gref}. This value depends on the energetic state of the flywheel energy storage system i.e. its rotating speed. In fact, when the FESS speed N_f (Ω_f in rad.s^{-1}) is over 3500 rpm, we consider that the energy stored is sufficient to allow the generating system to deliver its rated power P_n. But, if the wind is too slow, i.e. the wind power is too small, then the flywheel will discharge and its speed will decrease. Below 3500 rpm, we consider that the FESS energy state is relatively low. This leads to a lower P_{gref} value. If speed reaches 3000 rpm, the FESS is no more charged and P_{gref} becomes null allowing, if possible, the flywheel speed to grow. This procedure is summarized in Fig. 6.
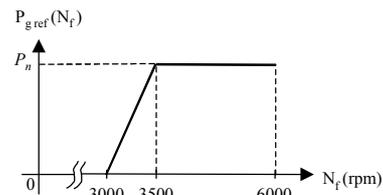

Fig. 6. P_{gref} determination.

It may be noticed that the control of P_g is only possible in case of power grid feeding. If the generating system is connected to isolated loads, delivered power is fixed by them.
Besides, we have to manage active powers supplied by both components of the generating system i.e the wind generator power $P_{wgrefmax}$ relies as well on the FESS rotating speed. Between 3000 rpm and 5500 rpm, $P_{wgrefmax}$ is fixed to P_n. Above 5500 rpm, it is considered that the FESS is fully charged and therefore $P_{wgrefmax}$ tends to decrease. As the speed reaches 6000 rpm, wind power generation is stopped in order to discharge the FESS. These considerations are summarized in Fig. 7. P_{fref}, the FESS reference active power, is then deduced according to Fig. 8 by taking into account $P_{wg\,meas}$, $P_{g\,meas}$ and an active power ΔP_{DC} allowing to control the DC link voltage.

The strategy, presented previously, may be improved in the future as it would be preferable to generate the maximum power onto the network even if the storage system is fully charged. However this very simple strategy is interesting when feeding isolated loads in case of islanding. In this context, Fig. 8 which depicts the power reference of the storage system determination, represents the precursory of a generating system supervisor.
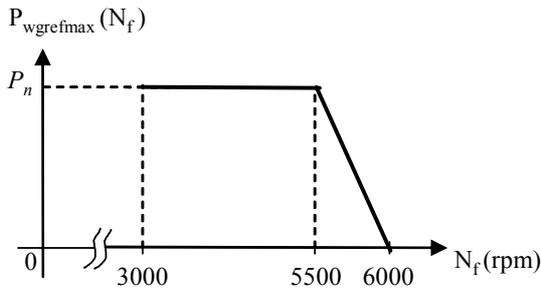
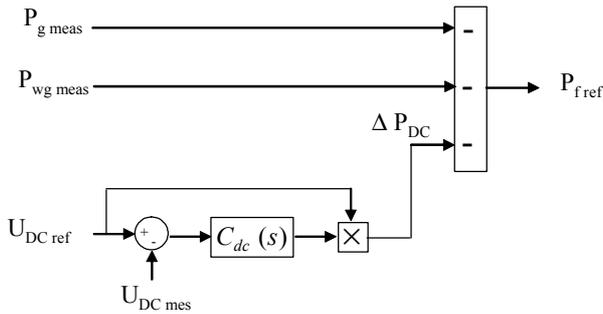Fig. 7. $P_{wgrefmax}$ determination.

Fig. 8. Power reference of the storage system determination.

Fig. 9 depicts the whole system control which includes the LC filter capacitor voltage loop and active power ones described above. In this figure, i_{SG} and i_M refer respectively to PMSG and induction machine currents. Ω_t represents the wind turbine rotation speed.
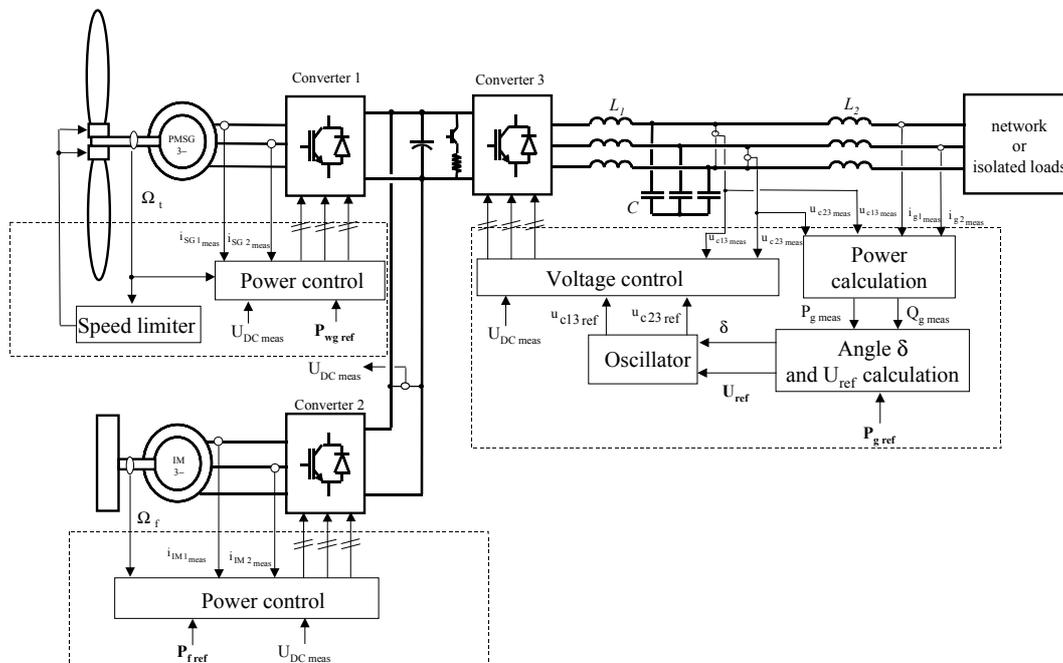
3. Wind Farm simulation

A. Network connection

We simulate the network represented in Fig. 10 in which we consider three identical generating systems (GS1, GS2, GS3), like the one presented in the previous section. These wind turbine based generators are submitted to three different wind speeds, v_{w1}, v_{w2}, v_{w3} whose values were measured in the north of France. These wind speed evolutions are shown in Fig. 12. They have an average value of respectively 6 m.s^{-1}, 10 m.s^{-1} and 12 m.s^{-1}. The three generating systems are linked to the same bus bar named BB1, considering connection line impedances Z1, Z2 and Z3, and at which three loads are connected. Two other bus bar are present : BB2 is connected to a power grid and, at BB3, three other fixed loads are connected. The six balanced loads, load 1 to load 6, of inductive nature, have same active and reactive powers : with P = 200 kW and Q = 50 kVAR. The whole network has been simulated with Matlab – Simulink ^{TM} software with the help of the Sim Power System toolbox. The aim of simulations is to introduce severe events on the network in order to point out the behaviour of wind generators associated with flywheel energy storage systems. Therefore we have chosen to simulate a grid disconnection at time 150 s with a total load which varies between [400 kW; 100 kVAR] and [1200 kW; 300 kVAR] as shown in Fig. 11, i.e an islanding mode where generating systems must supply the power demand of each load with rated voltage and frequency. The rated active power of each generating system is 600 kW.

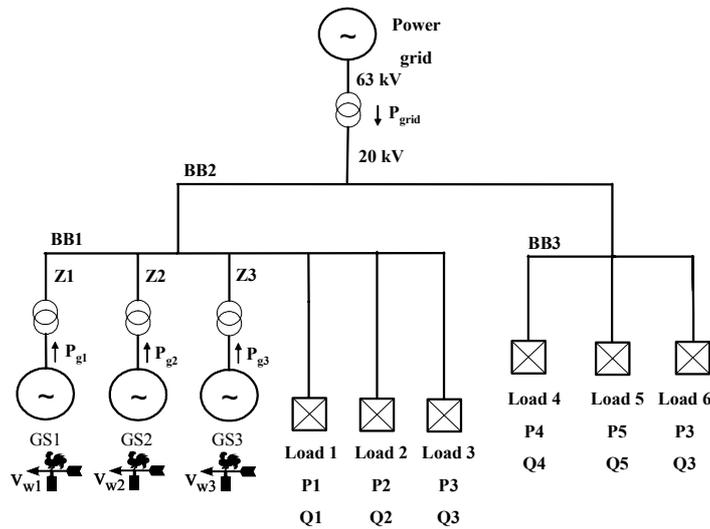Fig. 9. Generating System control scheme.

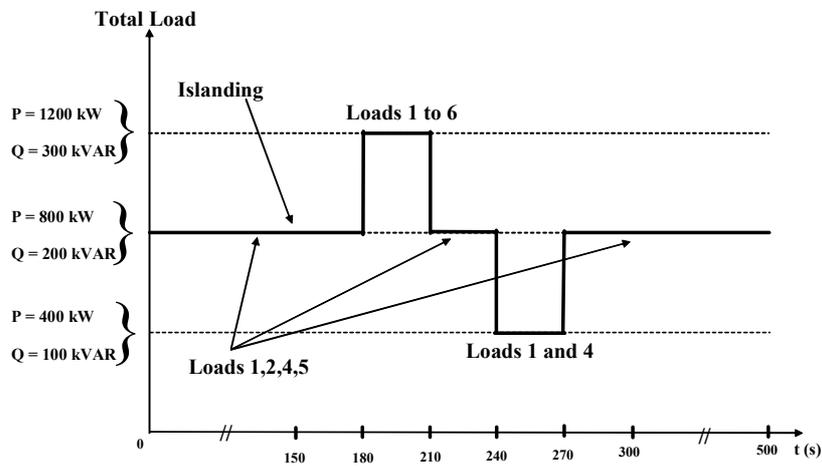Fig. 10. Simulated network configuration.
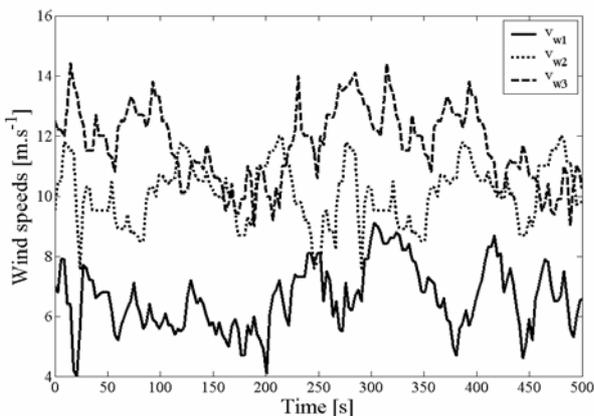

Fig. 11. Load curve.

Fig. 12. Wind speed evolutions.

B. Simulation

1) Constant wind speed

A first simulation has been made by considering constant wind speed (respectively the average value of the wind speed shown in Fig. 12). The simulation allows to show the behaviour of the system in case of an islanding followed by significative load variations.

Simulation results are presented in Fig. 13 to Fig. 18. Fig.13 shows the three wind generator active powers P_{wg1}, P_{wg2} and P_{wg3}, i. e. measured at the exit of converter 1 of each generating system. Fig. 14 shows the active powers P_{g1}, P_{g2} and P_{g3} generated by the three generating systems (at the beginning of the simulation $P_{g1} = P_{g2} = P_{g3}$) and P_{grid}, the active power supplied by the grid. Fig.15 shows the corresponding reactive powers. Fig.16 shows the FESS flywheel rotating speeds. Fig. 17 represents the three bus bar rms voltages U_{BB1}, U_{BB2} and U_{BB3}. Fig. 18 represents the generating system reference frequencies f_{g1}, f_{g2}, f_{g3} and f_{grid}, the grid frequency.

a) Grid connected

From t = 0 s to t = 150 s, the power grid, the generating systems and a part of the loads are connected. The generating systems supply the total load active power as shown in Fig. 14. The bus bar voltages U_{BB1}, U_{BB2} and U_{BB3} are close to 20 kV as shown in Fig.17. The generating system reference frequencies vary, according to the active power variations that they inject, around

50Hz (Fig. 18). As shown in Fig. 13, when the wind speed is high enough, the wind generators supply the rated power, else they supply the maximum power which may be extracted from the wind. Fig. 16 shows that the flywheel rotating speed of GS1 and GS2 tend to decrease because the FESS discharges. This is due to the fact that V_{w1} and V_{w2} have small values and that we try to generate the rated power into the grid. To avoid the limitation of the FESS, the power set point is changed, according to the supervisory strategy, when the flywheel rotating speed becomes lower than 3500 rpm. Therefore, when the flywheel rotating speed N_{f1} of GS1 and N_{f2} of GS2 become inferior to that threshold (at a time close to 30 s for N_{f1} and to 100 s for N_{f2}), the power generation P_{g1}, P_{g2} and P_{grid} decrease as shown in Fig. 14.

b) Grid disconnected : Islanding Mode
A t = 150 s the grid is disconnected. Only the generating systems supply the loads. Between t = 180 s and t = 270s, the load varies. The bus bar voltages U_{BB1}, U_{BB2} and U_{BB3} remain close to 20 kV as shown in Fig. 17. The generating system reference frequencies remain close to 50 Hz (Fig. 18). The generating systems generate the active and reactive powers consumed by the loads and react correctly to sudden load variations.
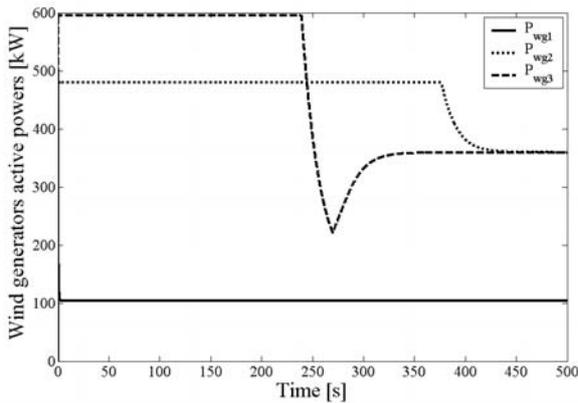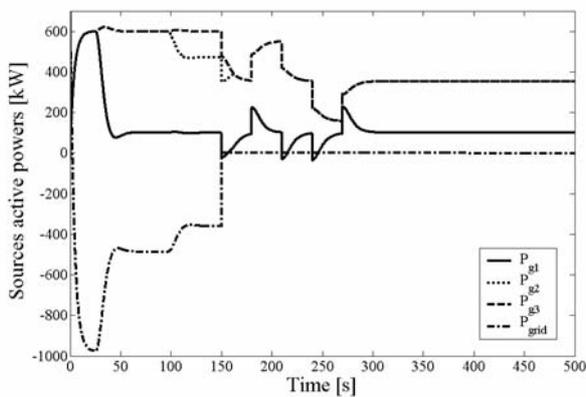

Fig. 13. Wind generator active powers.

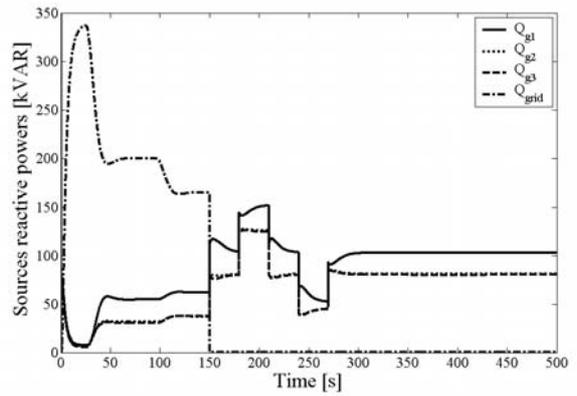Fig. 14. GS and grid active powers.

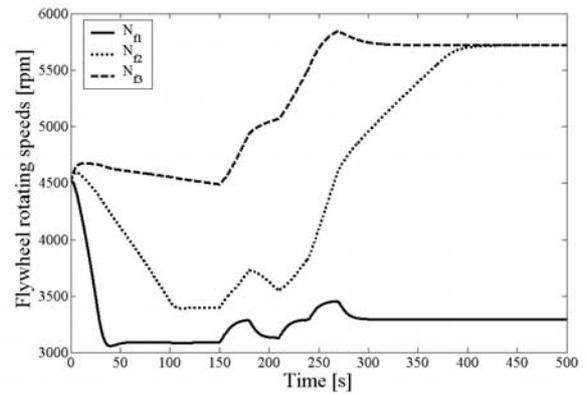Fig. 15. GS and grid reactive powers.
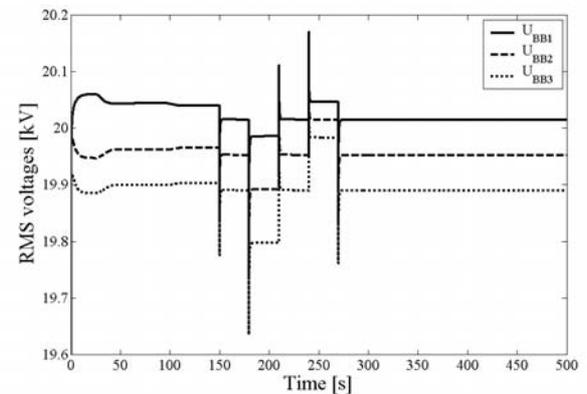

Fig. 16. Flywheel rotating speeds.
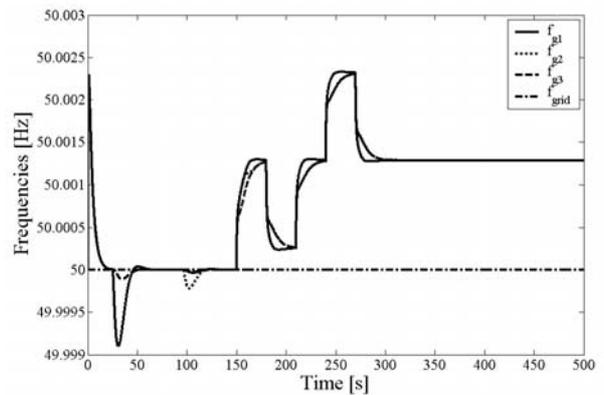

Fig. 17. Bus bar voltages.

Fig. 18. Generating system reference and grid frequencies.

2) Variable wind speed

In simulation results presented in Figs. 19 to 24, the same scenario (islanding and load variations) has been considered like in previous simulation (Figs. 13 to 18) but the variable wind speed shown in Fig. 12 are considered. The same comments as in previous simulation can be made in spite of an increase of the fluctuation of the different powers. The comparison of Figs. 19 and 20 points out that the storage system contributes well to power smoothing.
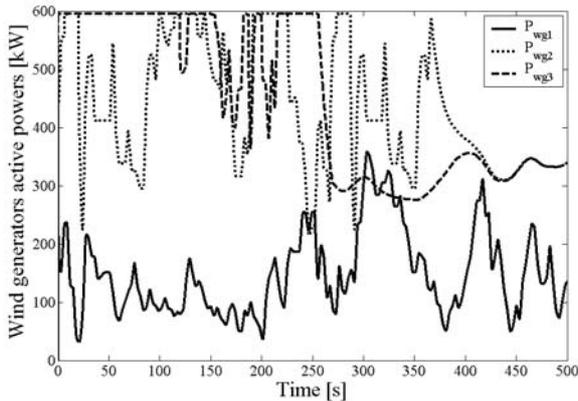

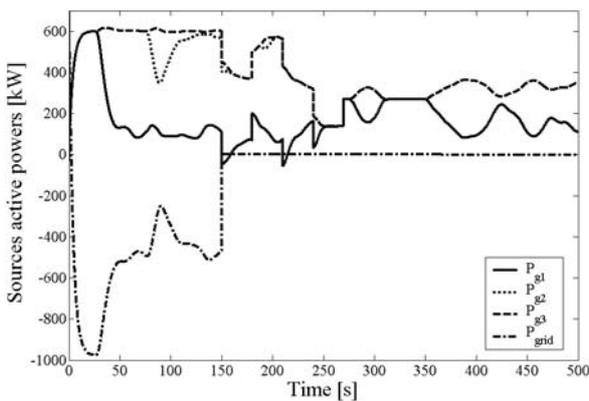Fig. 19. Wind generator active power.

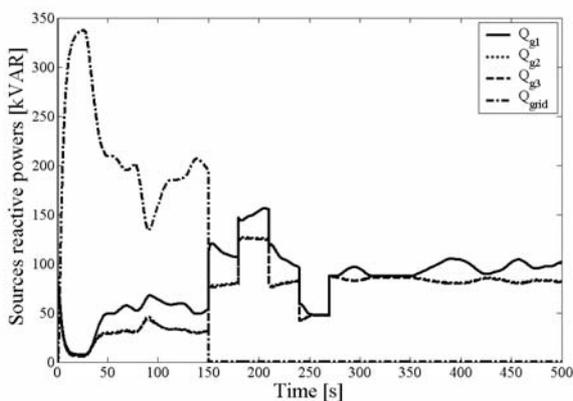Fig. 20. GS and grid active powers.
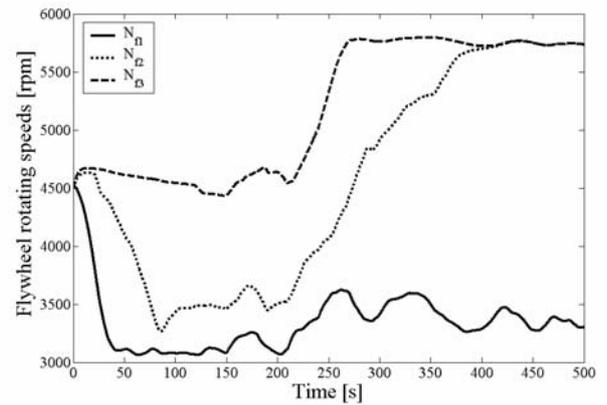

Fig. 21. GS and grid reactive powers.

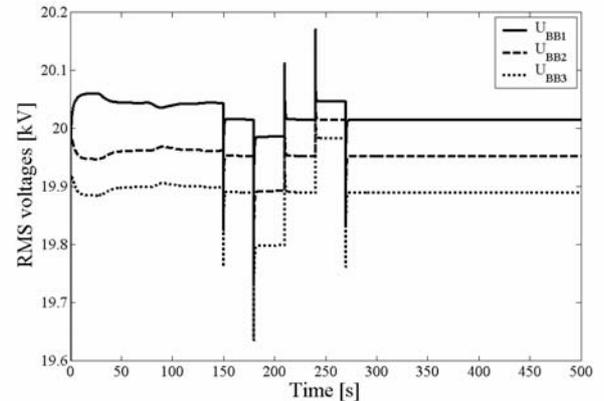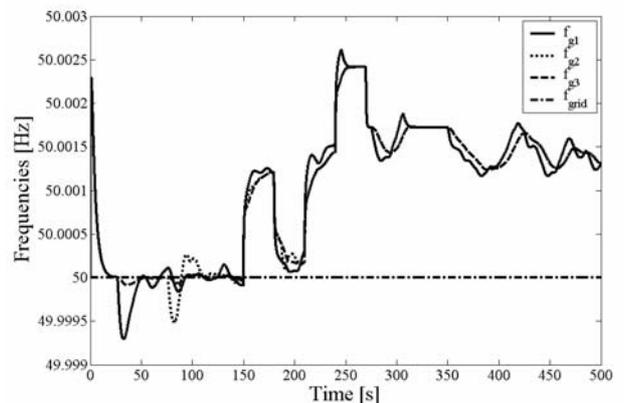Fig. 22. Flywheel rotating speeds.

Fig. 23. Bus bar voltages.

Fig. 24. Generating system reference and grid frequencies.

4. Conclusion

In this paper, a wind farm, which associates three generating systems, each composed of a variable speed wind turbine and a flywheel energy storage system, connected to a power grid has been presented. It has been shown that the power generated by the wind farm can be controlled by fixing the generating system power set points when it is connected to the grid and that it can supply the loads in islanding mode. In this last operation mode, the bus bar voltages and the frequency are close, respectively, to 20 kV and 50 Hz in spite of load variations. The wind farm limitation is, of course, the wind speed level but it can play a significant role during

disturbances on the power grid (power generation losses, islanding mode…). Simulation results, with this generating system, are encouraging. A 3 kW test bench is currently being developed in our laboratory to validate the proposed generating system [12].

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