WIND AND STORAGE SYSTEM BASED DISPERSED GENERATION CONTRIBUTION TO POWER GRID ANCILLARY SERVICES AND NETWORK RELIABILITY

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Introduction

The dispersed generation increases into the distribution system. Until now, this generation has generally been considered as "negative loads" because it does not participate directly to the ancillary services (voltage and frequency control, islanding…) [1]. But this approach will not be acceptable in the future when the level of penetration of dispersed generation will be over 20% [1] which will be the case in numerous countries by 2010-2020. Indeed, the network stability would be endangered which would increase the risk of black-out. It is then necessary to evaluate the ability of the dispersed generation to participate directly to the ancillary services [2]-[4], which are now priced on the open market [5]. Moreover, the dispersed generation would have to be able to continue to generate in case of network failures like a voltage sag or an islanding. The dispersed generation would then have to be able to work without auxiliary source, ensures the generation-consumption balance, set the adequate frequency, the amplitude of the voltage wave, enhance the network safety and reliability.

To reach these objectives with wind generation, we consider a Variable Speed Wind Turbine (VSWT) coupled to a Permanent Magnet Synchronous Generator (PMSG) combined to an energy storage system [6]. Due to important fluctuations of the wind generator power, conventional electrochemical batteries are not adapted [7]. We consider then a Flywheel Energy Storage System (FESS) [5]-[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 interconnection of two of them with a network including passive loads and a power grid. Generating systems are working as voltage sources with the help of a frequency droop. 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 [8]-[10]. Finally, it is shown that the proposed generating system is able to continue to generate power during an unbalanced 600ms voltage sag of 20%. It may be noticed that electrical quantities in the network connection of the generating system are controlled with the help of resonant controllers [6].

Studied Generating System

a) Generating System structure

Figure 1 shows the generating system under study [6]. 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 figure 1. The inductance L_2 in figure 1 may represent a transformer one.

b) Generating System Proposed control

b.1) General principles

In figure 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 connected by 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
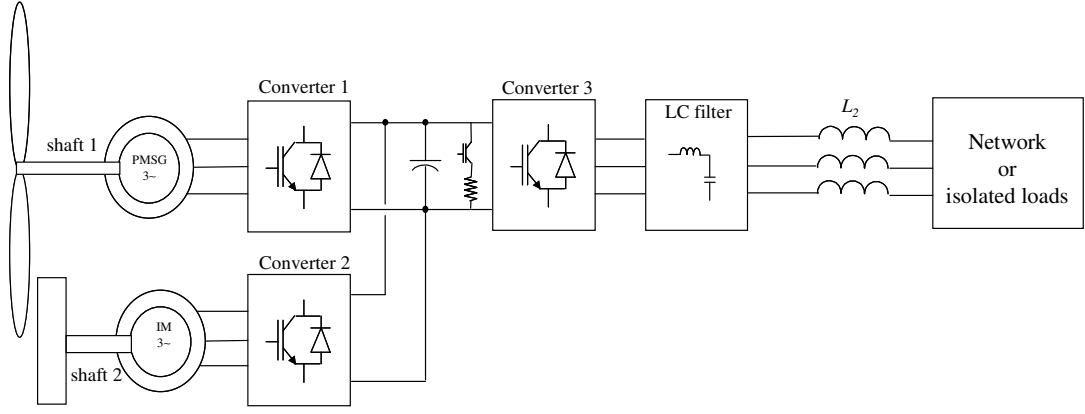
Figure 1 : *Scheme of a generating system.*

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 frequency droop in case of low flywheel speed (3500 rpm). Figure 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 [6], allowing the generating system to work as an ideal voltage source. Transfer function of these controllers is given in (1) :

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

In this equation, ω_0 is the network frequency, r_{ui0} to r_{ui3} and σ_{ui0}, σ_{ui1} are coefficients. s is the Laplace operator.

In figure 2, i_{g1} and i_{g2} are the generating system phase 1 and 2 currents.

b.2) Voltage and frequency control

The frequency of the voltage reference wave is determined with the help of a 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 figure 3.
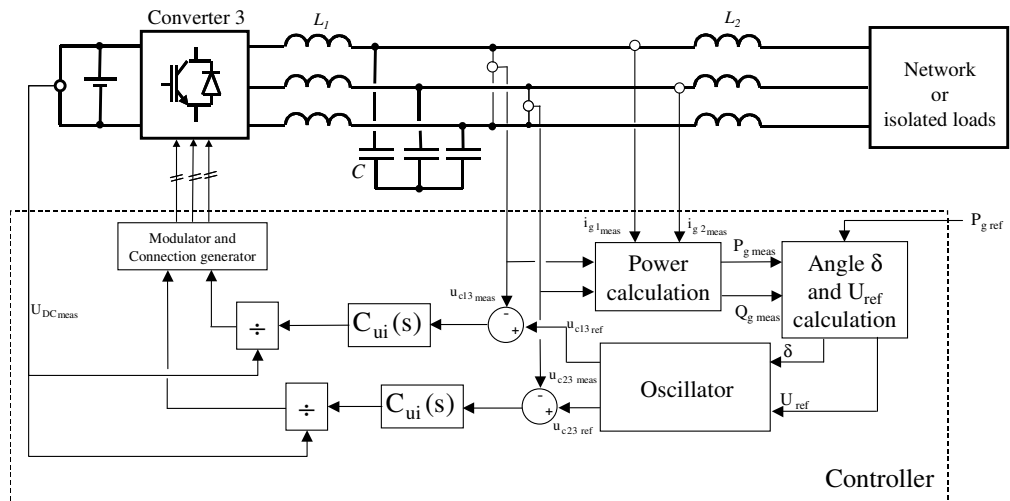

Figure 2 : *Control scheme of converter 3.*

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

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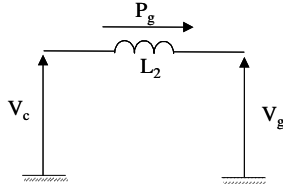

Figure 3 : *Active power generated onto the network.*

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

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

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

$$f = k\left(P_{g\,ref} - P_{g\,meas}\right) + f_0 \text{ where } k = \frac{\Delta f}{\Delta P_g} \qquad (5)$$
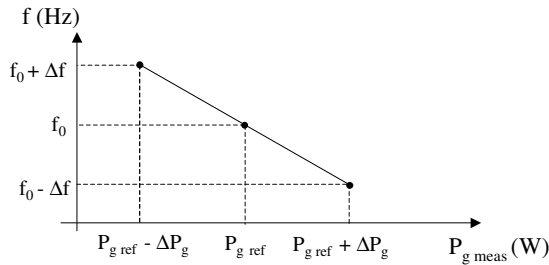
Figure 4 : *Frequency droop.*

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

$$\frac{d\delta}{dt} = \Delta\omega = 2\pi\left(f - f_0\right) = 2\pi k\left(P_{g\,ref} - P_{g\,meas}\right) \qquad (6)$$

Figure 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 figure 5, a second order active power transfer function can be deduced :

$$\frac{P_{g\,meas}}{P_{g\,ref}} = \frac{1}{1 + \frac{1}{2\pi kA}s + \frac{\tau}{2\pi kA}s^2} \qquad (7)$$
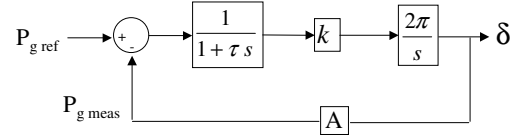

Figure 5 : *Generating system delivered active power closed loop control.*

(7) allows us to determine coefficient k.

b.3) Active power set point determination

We previously introduced the reference value of the active power feeding the network, P_{gref}. This value has to depend 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 3500rpm, we consider that the energy stored is sufficient to allow the generating system to deliver its rated power P_n. In this case, 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 figure 6.
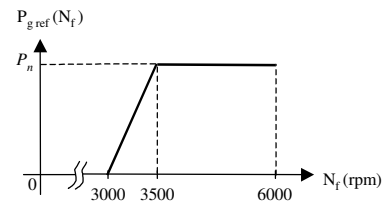

Figure 6 : *$P_{g\,ref}$ determination.*

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_{wg} and the FESS power P_f. P_{wg} reference value P_{wgref} relies as well on the FESS rotating speed. Between 3000 rpm and 5500 rpm, P_{wgref} is fixed to P_n. Above 5500 rpm, it is considered that the FESS is fully charged and therefore P_{wgref} 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 figure 7. P_{fref}, the FESS reference active power, is then deduced according to figure 8 by taking into account P_{wgref}, P_{gref} 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, figure 8, which depicts the active power references generation global principles, represents the precursory of a generating system supervisor.
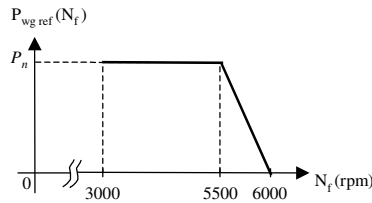

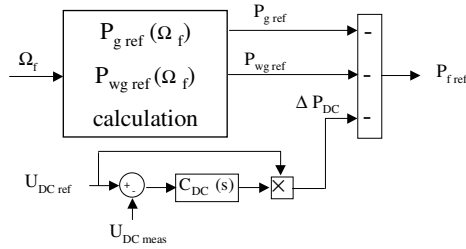**Figure 7 :** *$P_{wg\ ref}$ determination.*

Figure 8 : *Active power references generation global principles.*

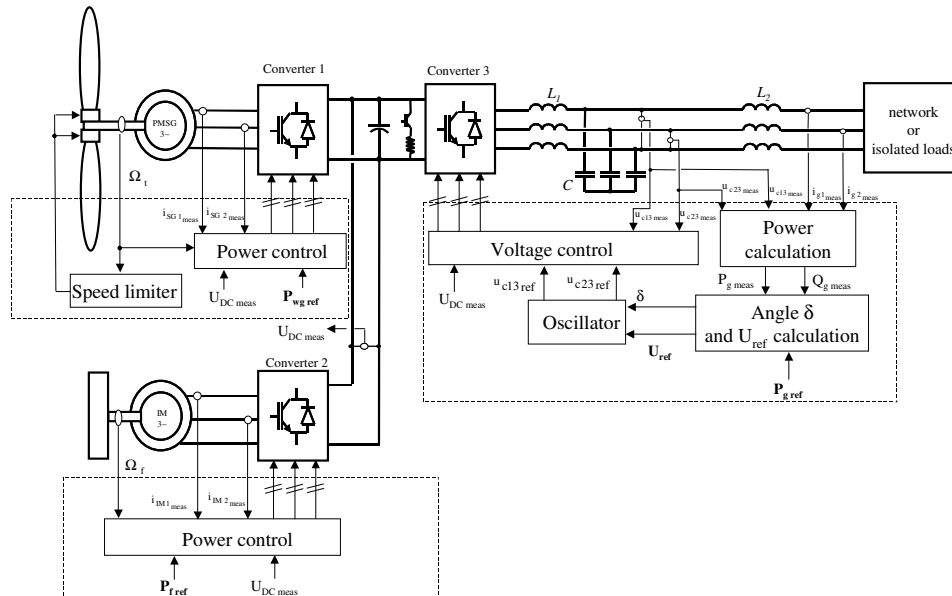Figure 9 depicts the whole system control which includes the LC filter capacitor voltage loop and active power ones described above. In this figure, i_{SG} and i_{IM} refer respectively to PMSG and induction machine currents. Ω_t represents the wind turbine rotating speed.

Generating system behaviour following grid failures

In this part of the paper, we simulate the network represented in figure 10 in which we consider two identical generating systems (GS1, GS2), like the one presented in the previous section. These wind turbine based generators are submitted to two different wind speeds, v_{w1}, v_{w2}, whose values were measured in the north of France. These wind speed evolutions are shown in figure 11. They have an average value of respectively 10 and 12 m.s^{-1}. Both generating systems are linked to the same bus bar named BB1 at which two fixed loads are connected as shown in figure 10. Two other bus bars are present : BB2 is connected to a power grid and, at BB 3, two other fixed loads are connected. The whole network has been simulated with Matlab Simulink™ software with the help of 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. Indeed in the future, wind power sources will have to participate to the ancillary services which comprise the ability to adjust their response to grid failures. Therefore we have chosen to simulate a grid disconnection, i.e. a generating system islanding, and a single-phase voltage sag of 600 ms duration time. In the first case, generating systems must supply the power demand of each load with rated voltage and frequency. The second event allows to point out the effect of generating systems on the voltage plan. Voltage sags, if duration time is too high, usually cause some protections to trip leading to a risk of cascaded trippings and consequently of grid instability. It will then be interesting if wind power systems can reduce this risk and therefore increase the grid reliability. For simulations, P_n is fixed to 600kW.
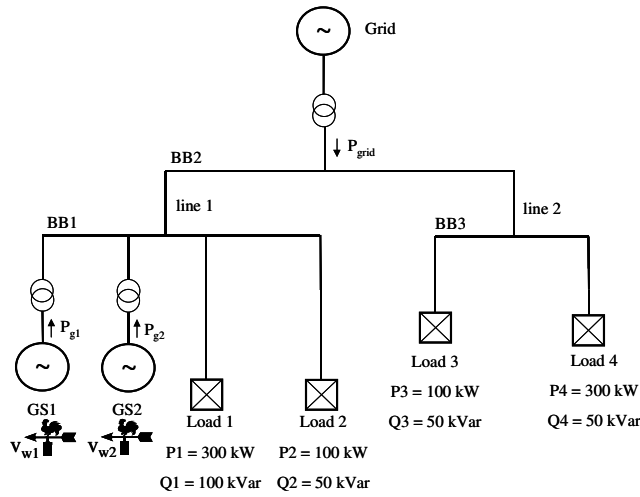

Figure 9 : *Generating system control scheme.*

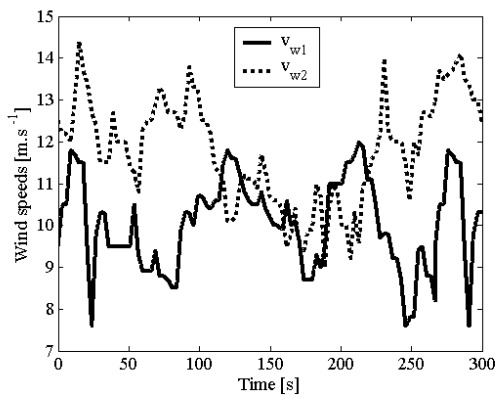*Figure 10 : Simulated network configuration.*

Figure 11 : Wind speed evolutions.

a) Islanding

Islanding occurs at time 150 s. At this moment, the active power P_{grid} supplied by the generating systems to the grid becomes null as shown in figure 12. Before disconnection of the grid, one can see in this figure that generating system wind speeds and storage levels are sufficient to let not only feed loads but also produce power, which is considered as negative one, onto the grid. Nevertheless, during this period, figure 13 shows that the flywheel rotating speed of both generating systems tends to decrease because of the FESS discharges. It is to be noticed that GS 2, which is submitted to the highest wind speed, supplies P_n frequently. At time close to 75 s, GS 1 FESS rotating speed reaches the threshold of 3500 rpm. According to the supervisory strategy, P_{g1ref} is reduced. Therefore P_{g1}, and consecutively P_{grid}, falls down, whereas P_{g2} increases slightly, until N_{f1} reaches 3500 rpm letting GS1 FESS to recharge. As shown in figure 14, this sudden power flow modifying causes, according to (6), the generating system reference frequencies to vary.

When islanding occurs, generating systems must feed the loads autonomously i.e. supply the needed active and reactive powers with a 20 kV, 50Hz voltage. Figure 15 shows bus bar voltages. At each bus bar, voltage is always equal to 20 kV with

small deviations not exceedeing 1,4 % of rated value. As wind speeds are relatively high, active power is available and sufficient to feed loads and to store energy in the flywheel. Once N_{f2} has reaches the high threshold of 5500 rpm, P_{wg2ref} is reduced leading to a P_{wg2} decrease as seen in figure 16. These results show that generating systems have a good behaviour in this case because of the FESS use.

b) Single phase grid voltage sag

In this section, a 600 ms single phase grid voltage sag has been simulated. At time 150 s, the grid line-to-line voltage falls down rapidly to reach a value close to 86,5% of 20 kV. The voltage sag time duration has been fixed to 600ms as this value is critical for network managers.
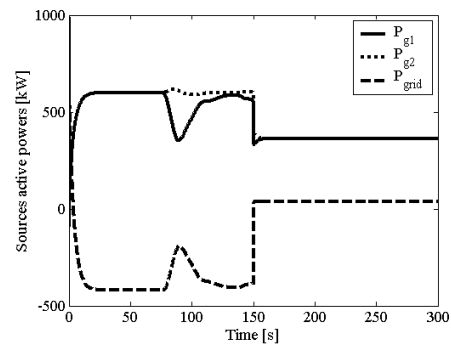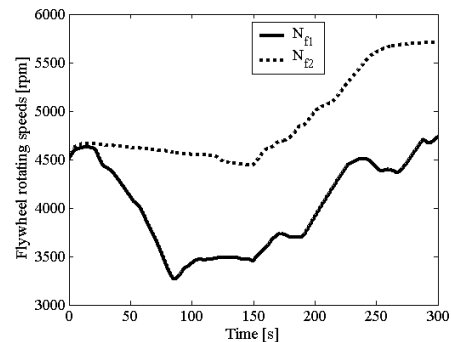

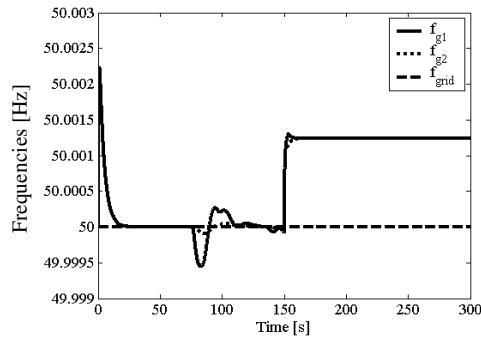*Figure 12 : GS and grid active powers.*

Figure 13 : Flywheel rotating speeds.
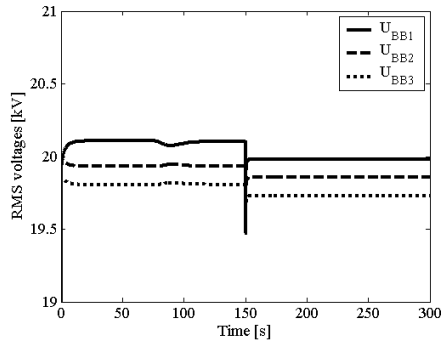
Figure 14 : *Generating system reference frequencies.*

Figure 15 : *Bus bar voltages.*

Figure 16 : *Wind generator active powers.*

Figure 17 : *Bus bar voltages during a voltage sag without generating systems.*
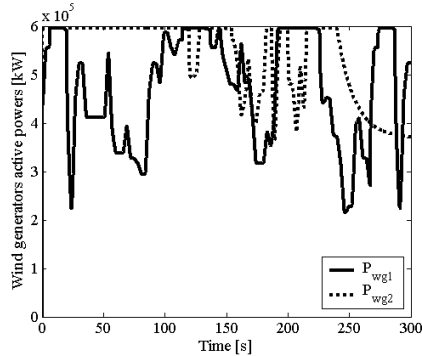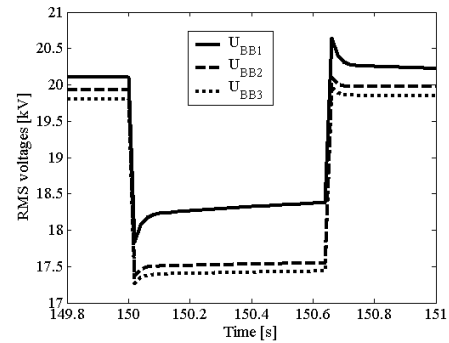

Figure 18 : *Bus bar voltages during a voltage sag with generating systems.*

Figure 17 and figure 18 show bus bar voltages respectively without and with generating systems connected. These generating systems allow to perceptibly reduce the impact of the voltage sag on BB1 bus bar. They could play a significant role in the voltage control and the improvement of the network reliability by avoiding the disconnection and therefore allowing loads to be fed, in the condition that the rating of the network interface power converter is designed according to this fault possibility.

Conclusion

In this paper, a generating system, based on a wind generator linked to a flywheel energy storage system, and its main control principles, have been presented. This generating system has been settled into a network including loads and a power grid. The aim of this article was to test our source under critical events like an islanding or a voltage sag to bring to the fore the influence of the FESS use and the supervisory strategy. Simulation results are quite good and encourage us to continue in this way by means of,
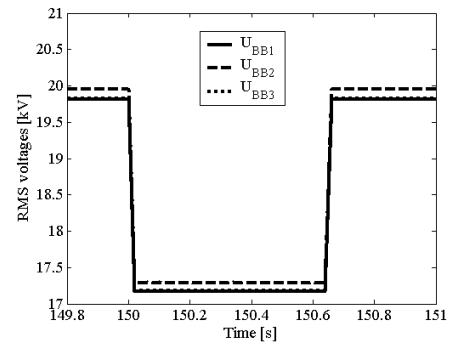
among other topics, developping an improved supervisor. A 3 kW test bench is currently being developed in our laboratory to validate the proposed generating system.

References

[1] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, *Embedded generation*, The Institution of Electrical Engineers (IEE), London, 2000.

[2] W. Leonhard, "Feeding the grid from regenerative sources, the way to a sustainable energy supply?", *EPE Journal*, vol. 13, n°3, August 2002, pp. 38-42.

[3] M. Crappe, "*Commande et régulation des réseaux électriques*", Hermès Science, Paris, 2003.

[4] J.-L. Fraisse, "Le raccordement de la production décentralisée en HTA et BT", *Revue REE*, n°7, July 2002.

[5] "Energy storage. A key technology for decentralized power, power quality and clean transport", European Communities, 2001, ISBN 92-894-1561-4.

[6] L. Leclercq, A. Ansel, B. Robyns, "Autonomous high power variable speed wind generator system", *EPE 2003*, Toulouse, France, September 2003.

[7] R. Hebner, J. Beno, A. Walls, "Flywheel Batteries Come Around Again", *IEEE SPECTRUM*, April 2002, pp. 46-51.

[8] U. Borup, F. Blaabjerg, P. N. Enjeti, "Sharing of Nonlinear Load in Parallel-Connected Three-Phase Converters", *IEEE Transactions on Industry Applications*, Vol. 37, n° 6, November/December 2001, pp. 1817-1823.

[9] A. Tuladhar, H. Jin, T. Unger, K. Mauch, "Control of Parallel Inverters in Distributed AC Power Systems with Consideration of Line Impedance Effect", *IEEE Transactions on Industrial Applications*, Vol. 36, n° 1, January/February 2000, pp. 131-137.

[10] E. A. A. Coelho, P. C. Cortizo, P. F. D. Garcia, "Small-Signal Stability for Parallel-Connected Inverters in Stand-Alone AC Supply Systems", *IEEE Transactions on Industrial Applications*, Vol. 38, n° 2, March/April 2002, pp. 533-542.