Fuzzy logic based supervisor of a wind farm including storage system and able to work in islanding mode

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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 power network management 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. This paper focuses on the storage level management with the help of fuzzy logic.**

I. INTRODUCTION

According to the GWEC (Global Wind Energy Council), the European wind park could reach a working installed capacity of 230 GW in 2020 [1], that is to say more than five times the installed capacity working into 2005 which was about 40 GW [2]. The wind energy impact must thus be to consider ensuring the safety operation of the networks and specially the transmission network on an European scale. According to the UCTE (Union for the Coordination of the Transmission of Electricity), the wind power concentration in the north of Germany produces already significant discontinuous power flows on the close Central Europe and Benelux countries, grid systems.

The major problems experienced with the wind energy are:
- a random production and not easily foreseeable;
- a fluctuating production;
- not or little contribution to the power network management [3].

Their penetration rate is then limited to 20 or 30 % of the consumption (according to some experience feedback [3] [4]) in order to be able to guarantee the network stability under acceptable conditions. Increasing its penetration rate will be thus possible if this type of source takes part in the ancillary services [4]-[6], 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 [7]. Due to important

wind generator power fluctuations, conventional electrochemical batteries are not adapted [8]. We consider then a Flywheel Energy Storage System (FESS) [8] [9]. Owing to the use of power electronics, the generator and the storage system are electrically coupled via a DC bus link.

To evaluate the possibility of the proposed Generating System (GS) to participate to the power network management, 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 [10]. 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 [11]-[13]. This paper focuses particularly on the system behaviour working in islanding mode when load varies and on the fuzzy logic supervisor which control the FESS storage level.

II. STUDIED GENERATING SYSTEM

A. Generating System structure

Fig.1 shows the generating system under study. 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 induction machine rated power is 600 kW. The flywheel inertia 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 induction machine rated power. 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.
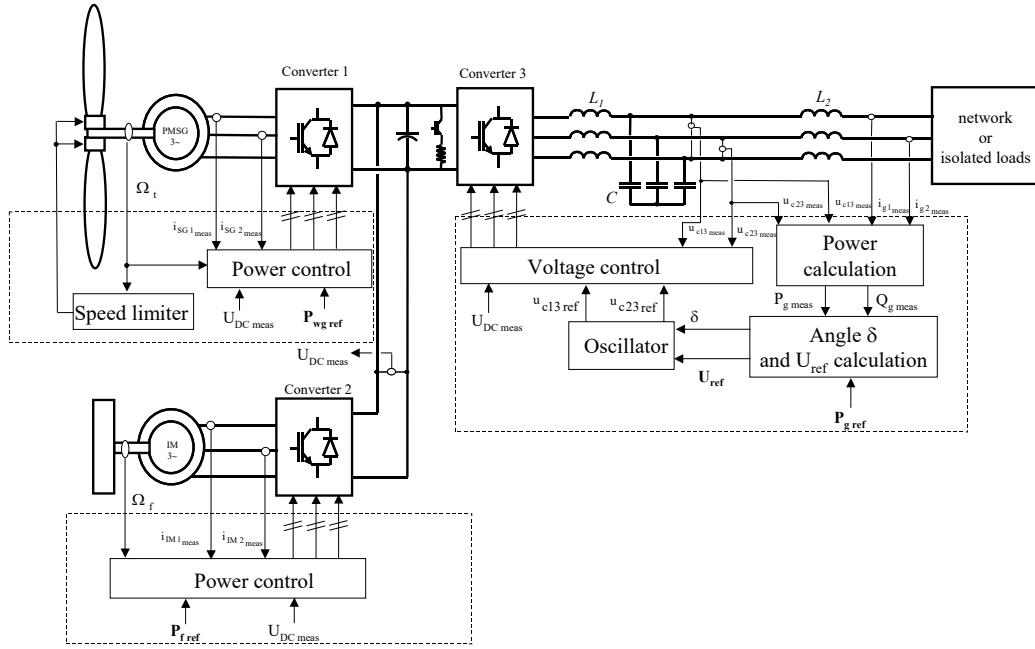
Fig. 1. Generating System control scheme.

B. Generating System general principles

In Fig. 1 (subscripts "meas" and "ref" refer respectively to measured and reference values), 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 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.

III. GENERATING SYSTEM PROPOSED CONTROL
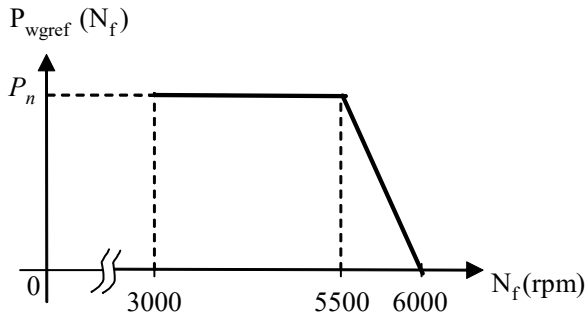
A. Wind Generator supervisor

Fig. 2. P_{wgref} determination.

As the FESS cannot store or generate indefinitely, it is proposed to decrease the power generation of the VSWT (P_{wg}) in case of high flywheel speed (5500 rpm) (Fig. 2). The wind generator control is carried out in the following way: if the wind is sufficient then $P_{wg} = P_{wgref}$ (the wind generator power reference) else P_{wg} is equal to the maximum power which can be extracted from the wind. The limitation power generated by the wind turbine is necessary when the generating system works in islanding mode.

B. Network interface supervisor

1) Voltage and frequency control

Fig. 1 shows the control scheme of converter 3 which therefore directly controls the phase – to – phase capacitor voltages Uc_{13} and Uc_{23} of the LC filter with the help of resonant controllers, allowing the generating system to work as an ideal voltage source [7]. 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 [7]. s is the Laplace operator. In Fig. 1, i_{g1} and i_{g2} are the generating system phase 1 and 2 currents.

The voltage wave reference frequency 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 Fig. 1. V_c and V_g are respectively capacitor and grid phase – to – ground rms voltages at the left and the right of L_2 shown in Fig. 1. ω_0 is the pulsation associated with f_0. For small values of δ, we can approximate the P_g expression:

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

δ is determined with the help of a frequency droop as shown in Fig. 3. The equation of this droop is:

$$f = k(P_{gref} - P_{gmeas}) + f_0 \quad \text{where} \quad k = \frac{\Delta f}{\Delta P_g}, \qquad (4)$$
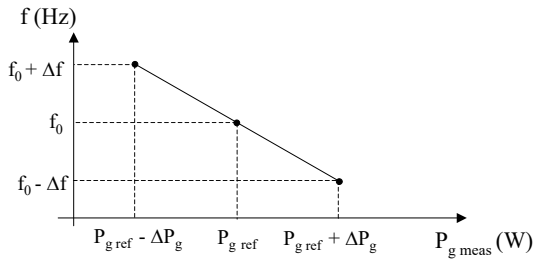

Fig. 3. Frequency droop.

The angle δ is related to (4) by the following relationship:

$$\frac{d\delta}{dt} = \Delta\omega = 2\pi(f - f_0) = 2\pi k(P_{gref} - P_{gmeas}), \qquad (5)$$

Fig. 4 shows the δ angle determination deduced from (3) 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.
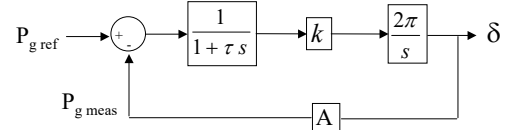

Fig. 4. Generating system delivered active power closed loop control.

From Fig. 4, a second order active power transfer function can be deduced:

$$\frac{P_{gmeas}}{P_{gref}} = \frac{1}{1 + \frac{1}{2\pi k A}s + \frac{\tau}{2\pi k A}s^2}, \qquad (6)$$

Equation (6) allows us to determine coefficient k (droop effect) and τ (damping effect).

2) Active power set point determination

We previously introduced the reference value of the active power feeding the network, P_{gref}. A filtered value P_{wgf} of the wind generator measured active power P_{wg} is considered in order to determine P_{gref}. As the speed of the flywheel was set in the range 3000 – 6000 rpm, it is necessary to take into account this speed to the determination of P_{gref} in order to avoid saturation of the FESS. P_{gref} depends thus on the energetic state of the flywheel energy storage system i.e. its rotating speed and the filtered value of the power generated by the wind generator, P_{wgf}. A Fuzzy Logic based supervisor is then developed to determine P_{gref} (Fig. 5).
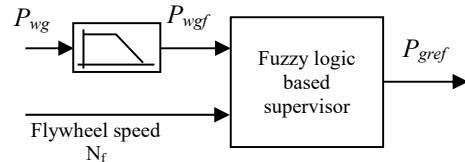

Fig. 5. Fuzzy logic-based supervisor.

Fuzzyfication. The membership functions of the normalized input variables are shown in Figure 6. Three fuzzy sets are considered: Small (S), Medium (M) and Big (B).

Inference. The fuzzy rules are determined from Table I. Seven fuzzy sets are considered for the output variable: Very Small (VS), Small (S), Small Medium (SM), Medium (M), Big Medium (BG), Big (B) and Very Big (VB).

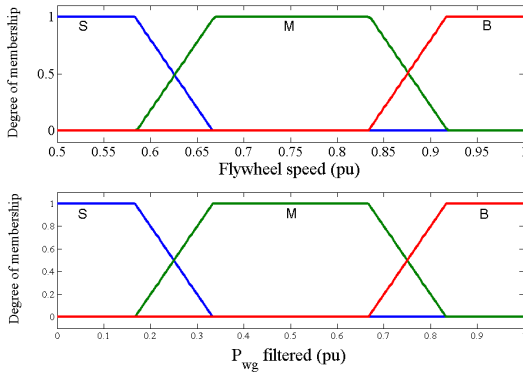**Defuzzyfication**. The membership functions of the normalized output variable are shown in Figure 7.

Fig. 6. Degree of membership of the input variables.

TABLE I
INFERENCE TABLE

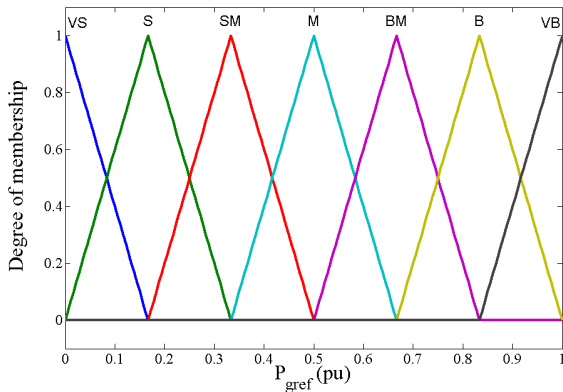| Flywheel Speed (N_f)	P_{wgf} / P_{gref}	Small	Medium	Big
Small		VS	SM	BM
Medium		S	M	B
Big		SM	BM	VB

Fig. 7. Degree of membership of the output variable.

It may be noticed that the precise 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 but the power distribution between the generating systems depends on the frequency droop (Fig. 3) and P_{gref}.

C. Energy storage system supervisor

The FESS reference active power, P_{fref}, is deduced according to Fig. 8 by taking into account P_{wgmeas}, P_{gmeas} and an active power ΔP_{DC} allowing to control the DC link voltage.
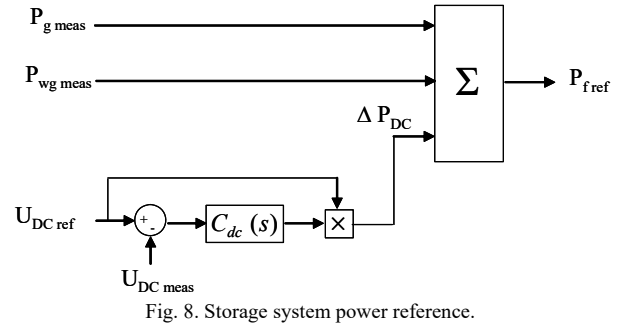

Fig. 8. Storage system power reference.

III. WIND FARM SIMULATION

A. Network connection

We simulate the network represented in Fig. 9 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. 10. 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™ 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.
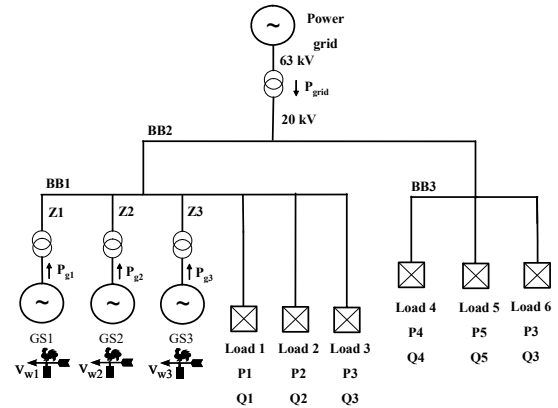

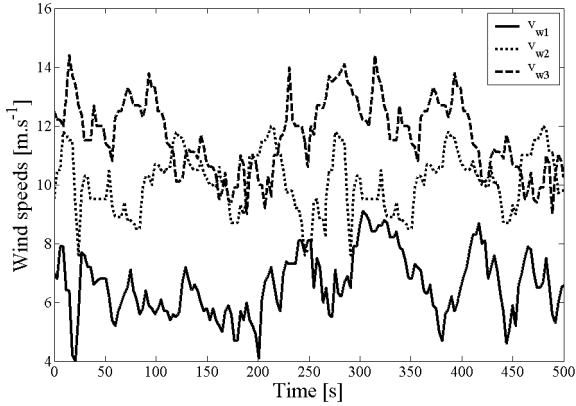Fig. 9. Simulated network configuration.
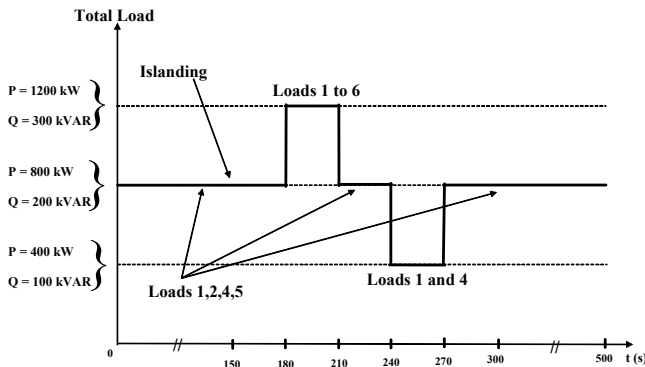
Fig. 10. Wind speed evolutions.

Fig. 11. Load curve.

B. Simulation

Simulation has been made by considering two different supervisors for the P_{gref} determination: the fuzzy logic supervisor proposed in this paper and a simplified supervisor proposed in [10] which takes into account only one input: the flywheel speed. Simulation results are presented in Fig. 12 to Fig. 15. For both supervisors:

- Fig. 12 and Fig. 14 represent the active powers P_{g1}, P_{g2} and P_{g3} generated by the three generating systems and P_{grid}, the active power supplied by the grid,

- Fig. 13 and Fig. 15 show the FESS flywheel rotating speeds.

1) Grid connected

a) Fuzzy logic supervisor

From t = 0 s to t = 150 s, the power grid, the generating systems and a part of loads are connected. The generating systems supply the total load active power as shown in Fig. 12. Fig. 13 shows that the flywheel rotating speed of GS2 and GS3 tend to increase because the FESS charges while the one of GS1 decrease because the FESS discharges due to low wind speed.

b) Simplified supervisor

From t = 0 s to t = 150 s, the power grid, the generating systems and a part of loads are connected. The generating systems supply the total load active power as shown in Fig. 14. The power injected by the generating systems is more important than previously. Fig. 15 shows that the flywheel rotating speed of GS1, GS2 and GS3 tend to decrease because the FESS discharges. This is due to the fact that the power injected to the power network is too big and thus, the storage level is mismanaged.

2) Grid disconnected

A t = 150 s the grid is disconnected. Only the generating systems supply the loads. Between t = 180 s and t = 270 s, the load varies. With the fuzzy logic supervisor, all the FESS are at high level while with the simplified supervisor, the FESS of GS3 is at very low level. In islanding mode, it is preferable to maintain the FESS at high level to have an energy reserve during a peak demand power. While comparing Fig. 12 and Fig. 14, it is noticed that supervisor type used to P_{gref} determination has a significant influence on the power generated by the generating systems in islanding mode.
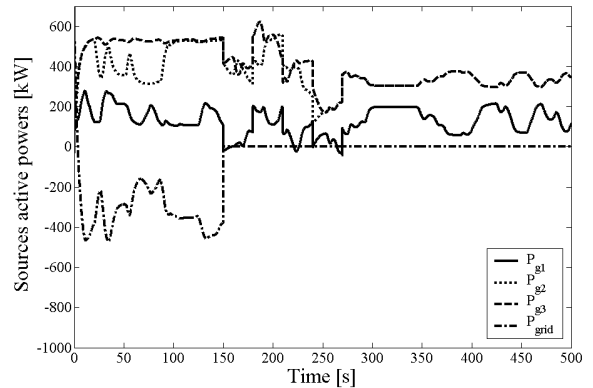

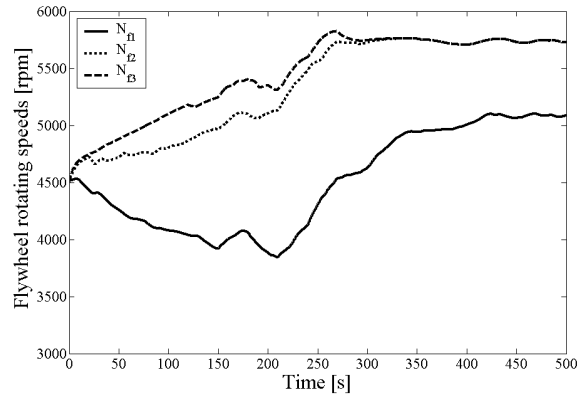Fig. 12. GS and grid active powers – Fuzzy logic supervisor.

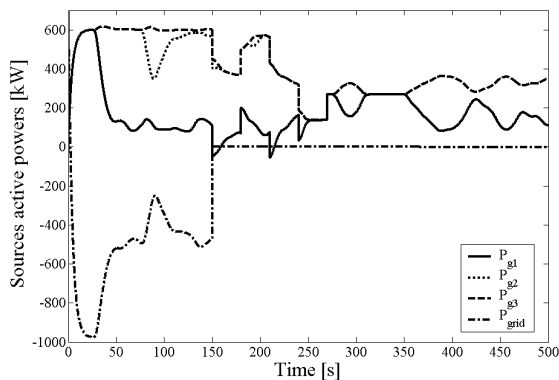Fig. 13. Flywheel rotating speeds – Fuzzy logic supervisor.

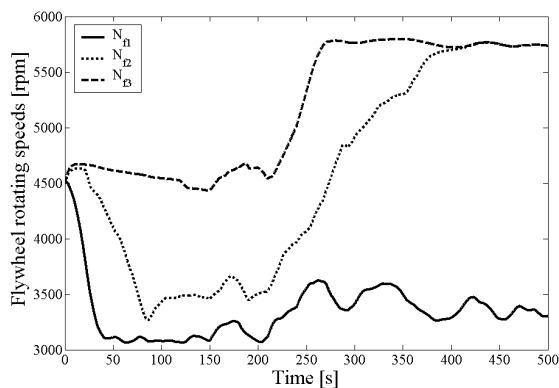Fig. 14. GS and grid active powers – Simplified supervisor.

Fig. 15. Flywheel rotating speeds – Simplified supervisor.

In the simulated fuzzy logic supervisor, the filter time constant (Fig. 5) is chosen small but for to obtain a more important power smoothing effect it can be chosen bigger, for instance 30 s [14].

IV. 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. The fuzzy logic supervisor allows to have, in islanding mode, a high storage level even if the wind is weak. In this last operation mode, it has been shown in [10] that the bus bar voltages and the frequency are close, respectively, to 20 kV and 50 Hz. 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 [15].

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