Frequency behavior of grid with high penetration rate of wind generation

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***Abstract*—The increasing penetration rate of wind generation in power system is likely to change frequency behavior of grid. This is due to the specific response of these technologies to frequency changes.**

In order to better assess these changes, this paper focuses on the primary frequency control requirements. It now appears that an active contribution of wind power will be required to cope with high level of wind penetration.

This paper also addresses the low contribution of wind generation to power system inertia. With high wind penetration, larger frequency changes are to be expected within the first few seconds following a grid contingency. To manage this, specific control loops should be implemented.

***Index Terms*—Wind power, primary frequency control, dynamic response**

I. Introduction

Large scale integration of wind generation raises many issues related to grid behavior, especially in small-size systems like islands.

Among other issues like low voltage ride-through, the question of wind energy impact on grid frequency has to be addressed. Many TSO are thus defining new requirements for a contribution of wind generation to frequency control.

This paper focuses on the impact of frequency behavior of grids with large share of wind power. The frequency behavior of wind turbines is first described. Then, the impact of wind generation on frequency control performed by all generating units is detailed. To conclude, simulations are performed to assess the changes in the overall power system dynamic.

II. Wind turbine response to frequency changes

In order to operate grid with high wind penetration, it is required to assess the dynamic response of wind generation with enough precision. This paper therefore details wind generation behavior in case of frequency deviation.

A. Simplified test case

The main existing generator types are considered:

- Squirrel cage induction generator (IG)
- Doubly-fed induction generator (DFIG)
- Synchronous generator connected through power converter (SG)

Wind turbines mechanical modeling:

Wind generation may be considered as constant in the time frame of primary frequency control. Therefore no sophisticated aggregated model of mechanical power calculation is considered here. Wind generation is represented by a single machine model at rated power.

The determination of the mechanical power that can be extracted from wind is given by the following classical formula:

$$P_{mech} = \frac{1}{2}\rho C_p A v^3$$

With:

ρ	air density
A	area swept by the turbine
v	wind speed
C_p	power coefficient of the wind turbine

The power coefficient is a function of λ (the tip speed ratio) and β (pitch angle). Even though its exact determination may be rather complex, it can usually be represented by a simplified equation as done by [1] and [2] for instance. The power coefficient calculation is required to define both active power and rotor speed reference with consideration to the actual rotor speed of wind turbine.

The turbine rotor is modeled using a two-mass shaft model including both turbine and generator inertia. Thus, shaft stiffness and damping ratio are considered in dynamic studies.

Wind turbines electrical modeling:

As explained by [1], power electronic does not require a detailed modeling due its fast response with respect to the time constants of power system. The converters action is therefore represented by small time constants in the 10 ms range. For both doubly-fed and full converter synchronous turbines, the grid-side converter is a controlled current source. The rotor-side converter of DFIG is represented as an ideal controlled voltage source.

The full converter synchronous generator is represented by a current injection on the network. The reference currents are issued from the generator model including speed and voltage regulation (cf. Fig. 1). The inputs of the model are the voltage at connection point and the active power and rotor speed reference issued from mechanical model of turbine.

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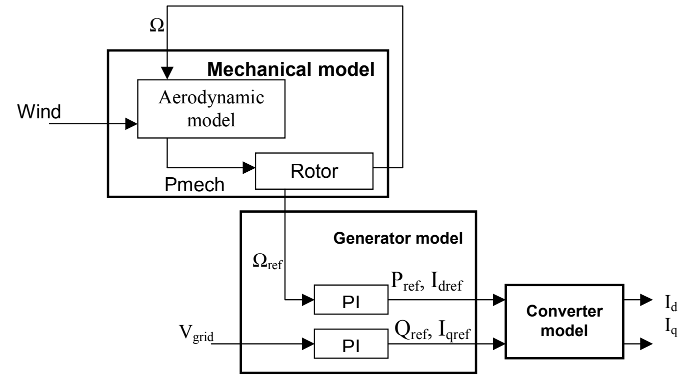

Fig. 1: Overall structure of synchronous generator model

The DFIG was modeled with a single-cage representation. As reported by [4], this model is less suitable than higher order models to study faults behavior of DFIG due to a lower accuracy of transient and subtransient events simulation. As a consequence [4] and [5] used high order models of DFIG. However, as stated in [1], single cage models result in a sufficient accuracy for stability studies. Detailed equations describing the single-cage DFIG model may be found in [1] and [4].

Test grid:

Simulations are performed to assess wind generation behavior on the basis of a simplified grid. A 3 MW wind turbine is connected through a HV line and a transformer to a single node representing the whole network (1000 MW load and high rated power synchronous generator representing conventional generating units).

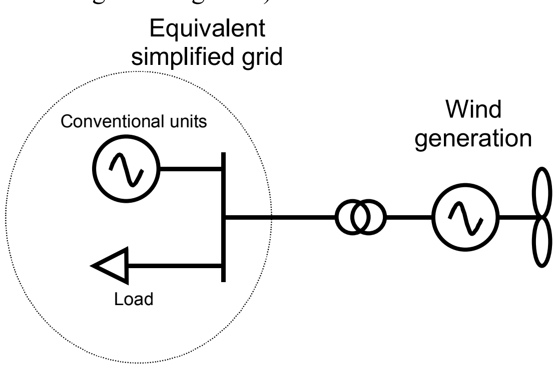

Fig. 2. Simplified network for wind turbine technologies comparison

Frequency deviations are produced by load variations. Primary frequency control is performed by synchronous generator. The resulting frequency deviation is 49.2 Hz in transient and 49.6 Hz in steady-state.

Simulations are performed on the grid reported on Fig. 2 with commercial software Eurostag.

B. *Wind generation behavior depending on the generator type*

After sudden frequency change, more or less significant active and reactive power variations should be observed if wind generation contributes to global system inertia. But due to grid side converters fast response, active power is usually kept constant during disturbance for both currently used DFIG and SG. As a consequence, their contribution to the global power system inertia may be considered as negligible.

On the contrary, due to its direct connection to the grid, IG is more sensitive to frequency changes. This technology therefore supplies a slight contribution to system inertia.

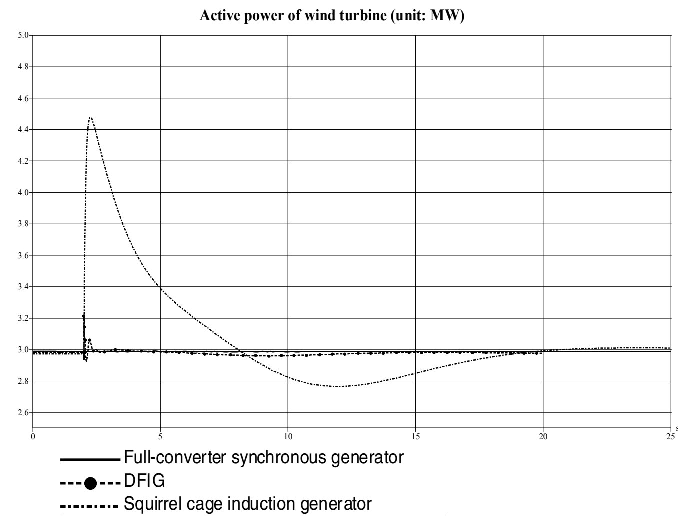

Fig. 3. Active power variations during grid disturbance

As a consequence, at high penetration rates, the issue of wind generation impact on the dynamic behavior of the whole system is raised with technologies which are currently connected to the grid and based on a pure MPPT.

In order to take into account this missing contribution to global system inertia, an appropriate inertial control loop may be considered. Some examples may be found in references like [1], [2] and [3]. The aim of such a control loop is the emulation of the behavior of a conventional generating unit.

As explained by [2], such a control loop may thus be implemented in the considered model according to the scheme reported on Fig. 4. P_{MPPT} is the active power reference issued from the MPPT control of the wind turbine, f_{grid} the frequency to be measured at the connection point of wind turbine, and P_{ref_inert} is the modified active power reference to be applied to the power converter.

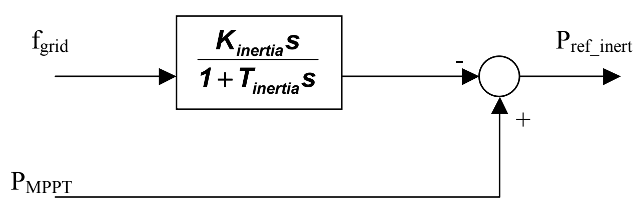

Fig. 4: Control loop scheme for active power with inertial behavior emulation

This kind of regulation is not strictly equivalent to a conventional synchronous generator behavior. As explained in [5], this would require the generation of a signal equivalent to the rotor angle of a synchronous generator (to be issued from effective rotor speed of wind turbine). Nevertheless, it was noticed by the authors that a control scheme similar to the one considered here (based on grid frequency variations) is resulting in a satisfactory response of wind generation.

Such a control loop was implemented on the full-converter synchronous generator model with the following values: $K_{inertia} = 15$ and $T_{inertia} = 0.01$. A generation loss is applied to the grid, whereas wind generation operates at 2 MW. The resulting power feed-in variations are reported on Fig. 5, with comparison to the response of a conventional generator (same rated power and inertia constant H=6s).

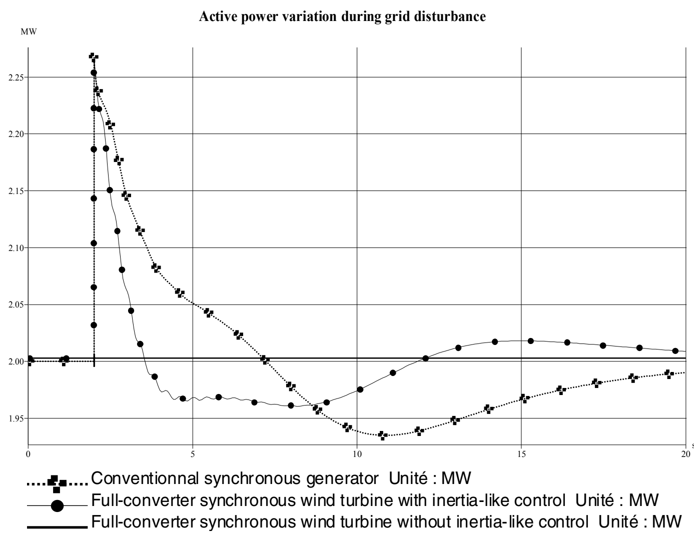

Fig. 5: Behavior of wind generation with inertial control in case of generation loss (case of full converter synchronous generator)

Thanks to an appropriate control loop it is therefore possible to mimic the inertia of conventional generating unit, which results in a similar active power increase immediately after the contingency. However, power feed-in drops quickly thereafter. This is due to the observed turbine rotor deceleration which provokes a decrease of the maximum power that can be extracted when rotor speed is restored after the fault. This phenomenon may not be avoided insofar as wind generation is operated at its maximum available power feed-in.

III. Frequency control with high wind penetration rate

Until recently, wind generation was not expected to contribute to frequency control. This was not supposed to be an issue insofar as the installed capacity was low. Nevertheless, at higher penetration rate, wind generation is likely to reduce the efficiency of primary frequency control.

A. Impact on reserve allocation

It is usually admitted that wind generation has no impact on the primary frequency control reserve margin. The wind generation fluctuation within the considered time frame are indeed far below the maximum generation loss to be managed by primary frequency control. For instance, it is explained in [6] that the disturbance reserve is not impacted by wind generation. Due to the smoothening of generation and the good fault-ride-through capabilities of actual wind turbines, wind generation does indeed not induce any risk of significant disturbance.

However, at high wind power feed-in, wind generation may replace conventional generating units with contribution to primary frequency control. As a consequence, the reserve allocated to each remaining regulating unit should be increased, even if the global reserve margin in the system remains unchanged.

B. Test case

To illustrate the impact of wind generation on primary frequency control, simulations of a small-size transmission test case were performed.

The considered test case is a 90 kV transmission grid with 80 MW load.

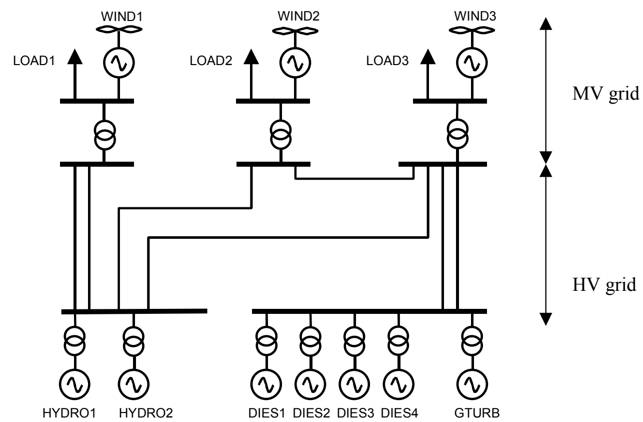

Fig. 6: Test case for transient behavior of grid with large share of wind

Generation is made of two 25 MW hydraulic power plants, four 8 MW diesel steam units and one 20 MW open cycle gas turbine (OCGT). The wind farms are connected on 20 kV grid, and their maximum rated power is 10 MW each. The total load is 80 MW (network loss is about 1 %). The penetration rate of wind is 25 % of load.

C. Dispatching of generation

To assess the wind-related changes in frequency control, both no-wind case and 20 MW wind generation are simulated. Dispatching of generation is considered as described in Tab. 1.

Tab. 1: Units commitment for considered test case

		No wind	Case 1	Case 2
Diesel.	DIES1	6 MW	0 MW	6 MW
	DIES2	8 MW	8 MW	8 MW
	DIES3	0 MW	0 MW	6 MW
	DIES4	7.8 MW	7.7 MW	7.7 MW
Hydro.	HYDRO1	21 MW	16 MW	20 MW
	HYDRO2	21 MW	16 MW	0 MW
OCGT	GTURB	17 MW	13 MW	15 MW
Wind	WIND1	0 MW	10 MW	10 MW
	WIND2	0 MW	5 MW	5 MW
	Wind3	0 MW	5 MW	5 MW
Reserve:		13.2 MW	25.3 MW	15.1 MW

Results of simulations are reported on Fig. 7. The considered event is the loss of DIES2 generating unit. In case

1, it was decided to keep biggest generating units online. The steady-state frequency deviation is not changed compared to no-wind case.

However, these units are running closer to their technical minimum, and a limit may have to be set to wind penetration rate when too many generating units operate close to their minimum feed-in.

In case 2, even if the amount of primary reserve is not reduced (with respect to the no-wind case), steady-state frequency deviation may be higher in case of a sudden generation loss. Due to the redispatch of generation, the network power frequency characteristic is indeed decreased.

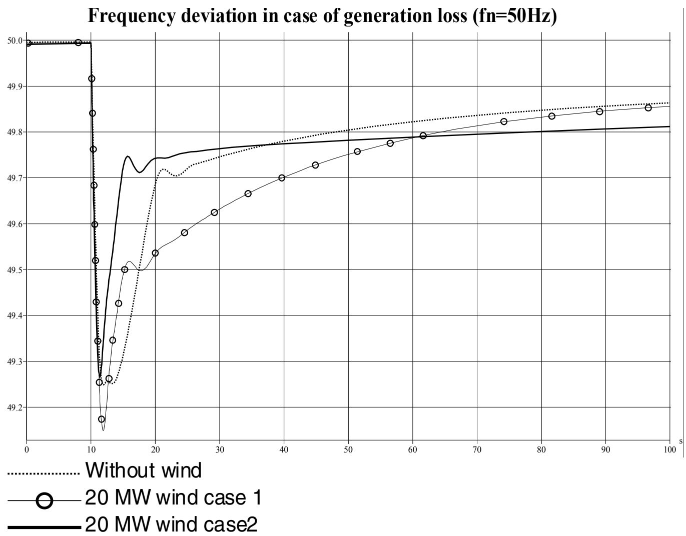

Fig. 7: Frequency response depending on wind generation and generation dispatching (penetration rate of wind up to 25 %)

In order to reduce frequency deviation, a contribution of wind generation to primary frequency control is therefore required. On one side, it would make active power reserve available. On the other side, thanks to its contribution to frequency control, wind generation could increase the network power frequency characteristic.

If no contribution of wind generation to primary frequency control is admitted, a limitation of the share of wind in the power system might be required, especially in small-size systems which are likely to experience large share of fluctuating generation in a near future.

However, it is now well established that an active contribution of wind generation may be obtained from variable speed wind turbines. Examples of such frequency control features are described by [2], [7] (for the permanent magnet synchronous generator case) and by [8] (for DFIG). In all cases, wind turbines control include a droop characteristic. As a consequence, such requirements are already included in some grid codes of power systems with high penetration rates of wind (cf. Irish grid code in [9]).

The contribution of wind generation nevertheless raises some technical issues. As reported by [7], getting a constant reserve supply by a wind farm requires an adapted control strategy. Below a given wind speed, the availability of reserve is not guaranteed at partial load. This may be a limitation for small systems with a poor smoothening of wind generation. In this case, available amount of reserve should be monitored on real-time depending on the observed changes in wind speed.

IV. Impact of Wind Generation on the Overall System Dynamic

As described in the upper section, wind contribution to primary frequency control is expected to reduce steady-state frequency deviation in case of contingency. However, the transient behavior of grid at high penetration level should be defined.

A. Base case: no inertial control loop

Two cases are considered: no wind generation and 37.5 % penetration rate. Wind generation does not contribute to primary frequency control. However, the generating units replaced by wind are not contributing to frequency control also. The reserve thus remains constant, as well as the power frequency characteristic.

The loss of a 8 MW thermal power plant is simulated. Results are reported on Fig. 8.

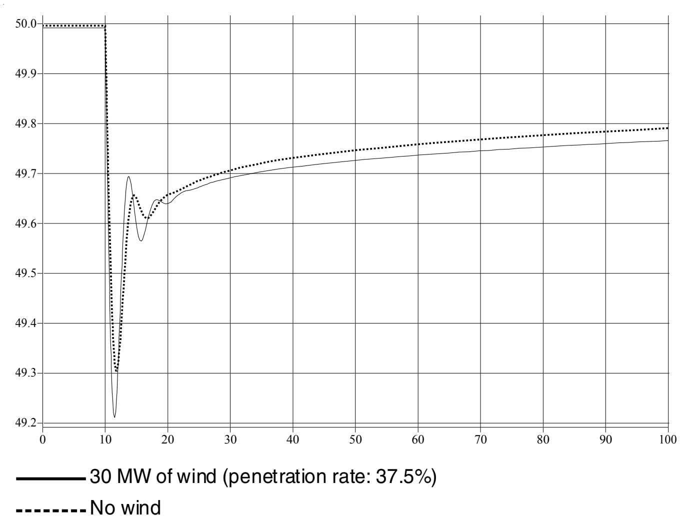

Fig. 8: Frequency deviation the loss of DIES3 (unit: Hz)

Due to the dispatching of wind generation in this case, the steady-state frequency is not impacted by the share of wind generation (same reserve and power frequency characteristic unchanged). But during the first few seconds after the generation loss, the resulting drop in frequency is deeper and sharper in case of high wind feed-in.

This evolution is due to the decrease in the whole system inertia provoked by the displacement of conventional generating units.

As a consequence, dynamic behavior of wind generation may be a limiting factor when coping with large share of renewable. Even though the primary frequency control is performed either by wind or conventional units, frequency is likely to drop to a lower transient value within the first few seconds. This may result for instance in more load-shedding at high wind penetration.

Another consequence from this modified power system dynamic could be a greater sensitivity of frequency to slight variations in system loads. An example is given on Fig. 9.

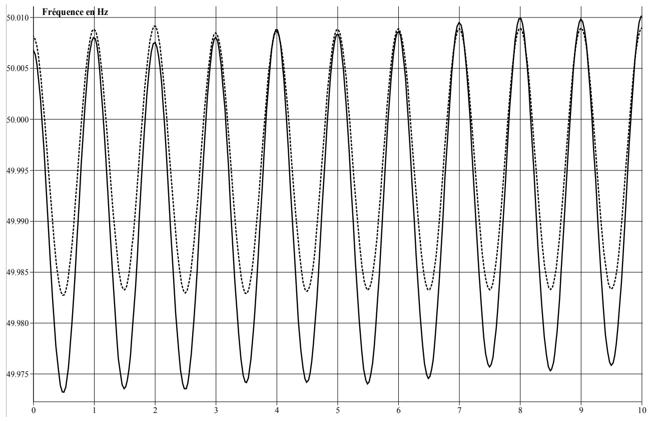

Fig. 9: Frequency response to fast load variations (dotted line: no-wind case)

Small and fast load variations (within the time frame of 1s) were applied. The resulting frequency variations are in the range of 20 mHz for the base case. The insertion of a large amount of wind generation result in an increase by 40% of the observed frequency variations.

Large scale integration of wind generation may therefore increase short-term frequency variations provoked by load changes. Furthermore, the short-term variability of wind itself is also likely to amplify this frequency deviations, especially in the case of small island systems whose wind resources are sometimes poorly smoothed.

It was explained by [10] that wind variability in an island grid may therefore have an impact on the frequency control provided by generating units. The consequence may be the need for a wider dead-band of frequency control or a change in the dispatch of reserve taking into account the technical performance of power plants.

B. Impact of an improved control loop

A solution to this problem would be the implementation of the additional control loop described in section II. The resulting frequency response is reported on Fig. 10 (with the same dispatch of generation).

As expected, the frequency response of simulated power system is improved by the short-term contribution of wind generation to power system. In a first approach, the response of the high-wind system may even be considered as better than the no-wind case. The initial rate of change of frequency is indeed reduced whereas the minimum frequency is the same.

However, it takes more time to reach steady-state again. As explained above, this is due to the deceleration of wind turbines resulting from the release of kinetic energy required by turbine power output increase. As a consequence, wind generation contribution to frequency support results in a significant decrease in power feed-in to bring wind turbine back to its initial rotor speed.

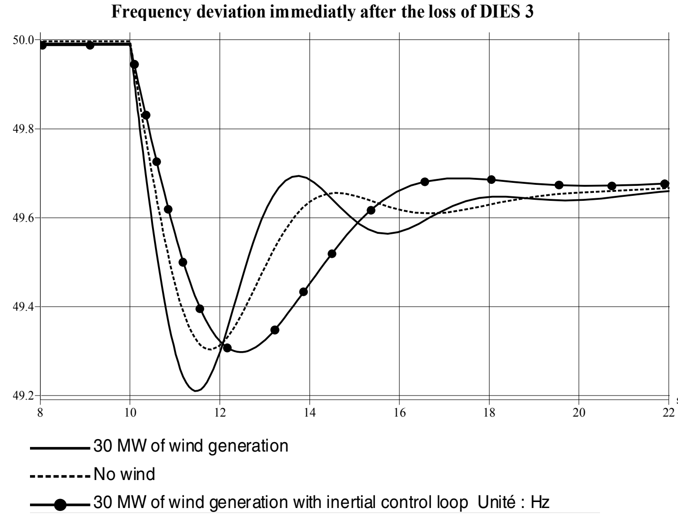

Fig. 10: Frequency deviation depending on the implement control loop

As reported in Fig. 11, this active power drop is much more significant than the one of a conventional generator. Even with the considered additional control loop, wind generation behavior is therefore not able to be strictly equivalent to a conventional generator in this case.

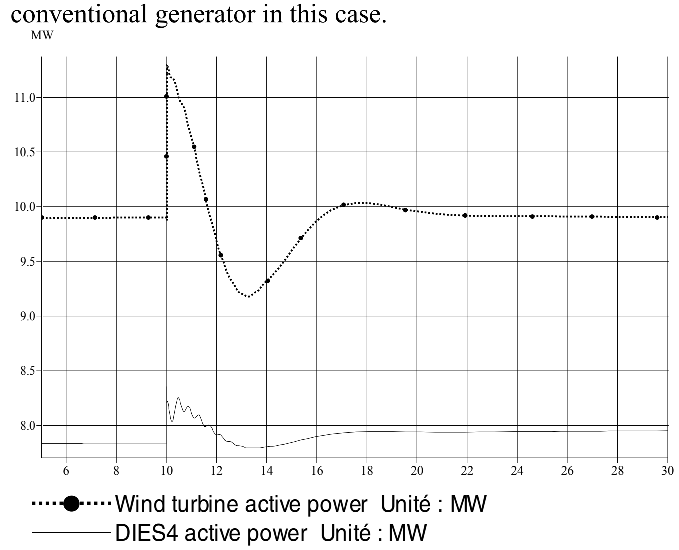

Fig. 11: Compared active power output of wind and conventional generator

C. The issue of voltage control

Even though the network power frequency characteristic remains constant in the base case represented in Fig. 8, a small difference in the steady-state value of frequency may be observed. This is partly due to differences in resulting voltages after generation loss.

Due to the location of wind generation (closer to the load in the considered test grid), the voltage applied to load is kept higher after disturbance. As a consequence, at a given frequency, the load consumption is kept higher due to the voltage behavior of loads.

Such an effect was already described in [11]. It was established by the authors that voltage controlled wind generation resulted in deeper frequency drop compared with constant Q wind injection. The proposed solution consists in integrating frequency criteria in wind generators voltage control in order not to remove natural load support in case of frequency deviations.

However, it was stated in [12] that contribution of wind generation to voltage control is also required by grid stability concerns in case of voltage drop. Voltage controlled turbines have indeed a better dynamic behavior in case of voltage drop since voltage drop following a generator trip could result in rotor speed instability for some turbines (especially constant-speed).

V. Conclusion

Frequency behavior of wind will be a key issue in integrating a large share of wind, especially in small-size power systems. Active contribution to primary frequency control will therefore be required in a near future, insofar as wind generation may replace conventional units. Actually, such requirements are presently beginning to be included in some grid codes.

Nevertheless, in addition to wind contribution to frequency control, the impact of a lower system inertia on transient frequency deviations should also be addressed. At high wind penetration, it might be necessary to maintain a minimum inertia in power system. To do so, solutions like inertial control loops of wind turbines may for instance be considered. Even though this solution is not strictly equivalent to the conventional generators dynamic behavior, it may however result in a significant improvement of global power system frequency response with high wind generation.

References

[1] R.G. de Almeida, J.A. Peças Lopes and J.A.L. Barreiros, "Improving power system dynamic behavior through doubly fed induction machines controlled by static converters using fuzzy control", *IEEE Trans. On Power Systems*, vol. 19, no.4, pp. 1942-1950, nov. 2004

[2] J.F. Conroy and R. Watson, "Frequency response capability of full converter wind turbine generators in comparison to conventional generation", *IEEE Trans. On Power Systems*, vol. 23, no.2, pp. 649-656, may. 2008

[3] J.B. Ekanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency", *IEEE Trans. On Energy Conversion*, vol. 19, no.4, pp. 800-802, dec. 2004

[4] J.B. Ekanayake, L. Holdswoth, X. Wu and N. Jenkins, "Dynamic modeling of doubly fed induction generator wind turbines", *IEEE Trans. On Power Systems*, vol. 18, no.2, pp. 803-809, may 2003

[5] F.M. Hughes, O. Anaya-Lara, N. Jenkins and G. Strbac, "Control of DFIG-based wind generation for power network support", *IEEE Trans. On Power Systems*, vol. 20, no.4, pp. 1958-1966, nov. 2005

[6] H. Holtinen and R. Hirvonen, "Power system requirements for wind power", in *"Wind power in power systems"*, T. Ackermann editor, chapter 8, pp.143-167, 2005

[7] M. El Mokadem, V. Courtecuisse, C. Saudemont, B. Robyns and J. Deuse, "Experimental study of variable speed wind generator contribution to primary frequency control", *Renewable Energy*, vol. 34, no.3, pp. 833-844, mar. 2009

[8] R.-G. de Almeida and J.-A. Peças Lopes, "Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation", *IEEE Trans. On Power Systems*, vol. 22, no.3, pp. 944-950, aug. 2007

[9] "WFPS1 – Wind farm power station grid code provisions", available: http://www.cer.ie/

[10] L. Dangelmaier and D. Brooks, "HELCO Wind AGC Impact Analyses", presented at the UWIG 2008 Spring Meeting, Fort-Worth, TX, apr. 2008

[11] I. Erlich, K. Rensch and F. Shewarega, "Impact of large wind power generation on frequency stability", *IEEE PES 2006 general meeting*, Montréal, CA, June 18-22, 2006

[12] J.G. Slootweg and W.L. Kling, "Impact of wind power on power system dynamics", in *"Wind power in power systems"*, T. Ackermann editor, chapter 28, pp.629-651, 2005

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