Mitigation of wind power fluctuations in smart grids

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Mitigation of Wind Power Fluctuations in Smart Grids

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Abstract—Future’s penetration of more distributed generation will have an effect on the power system’s stability and controllability. In general, wind power as a distributed generator does not have inertial response and does not supply control power. A third characteristic of wind power is that it is not conventionally controlled and its main resource is fluctuating. This paper describes a methodology to calculate wind power fluctuations in the frequency domain to compare it with load fluctuations for higher frequency power fluctuations. In relation, the approach of wind power smoothing is mentioned to mitigate the grid impact of power fluctuations. To smooth power, the concept of inertial wind power smoothing is briefly discussed for the low wind speed range of wind turbines, between the cut-in and rated wind speed. A smart grid could be equipped with a control system to control the power output of wind turbines and wind farms to mitigate the grid impact of wind power fluctuations on the frequency stability of a power system.

Index Terms—Fourier transform, inertial energy, pitch control, power fluctuations, rotor kinetic energy, smart grid, susceptibility of power system, speed control, torque set-point control, wind power smoothing.

I. NOMENCLATURE

λ	Tip speed ratio
P_{aero}	Aerodynamic Power of the wind, in W
ρ	Air density, in $kg \cdot m^{-3}$
C_p	Capacity factor of wind turbine
R	Radius of wind turbine’s swept area, in m
V_w	Wind speed, in m/s
θ	Blade pitch angle, in deg
ω	Rotational speed, in rad/sec
ω_H	Higher rotational speed, in rad/sec
ω_L	Lower rotational speed, in rad/sec
T_{aero}	Aerodynamic torque, in $kg \cdot m^2 \cdot s^{-2}$
T_{elec}	Electric torque of generator, in $kg \cdot m^2 \cdot s^{-2}$
T_{mech}	Mechanic torque of rotor, in $kg \cdot m^2 \cdot s^{-2}$
I_{WT}	Inertia of wind turbine, in $kg \cdot m^2$
H_{WT}	Time constant of a wind turbine
H_{WF}	Time constant of a wind farm
H_{WTIWPS}	Time constant of a wind turbine with IWPS

II. INTRODUCTION

THE awareness of depletion of fossil fuels, the desire of energy independency, and global warming have increased the interest in renewable energy sources. Because the conversion process into electricity has in general a lower energy density, its capacity per unit does not equal nuclear, coal- and gas-fired power plants, and when implemented as Distributed Generation (DG) it is often connected to the

medium- and low- voltage grid (MV/LV) in smaller unit sizes. As a result, the topology of the power system is changing. The total electric energy consumption is still growing due to the development of the global gross domestic product. Besides, the introduction of the heat pump and the electric car will in future also contribute to a higher electric demand. The combination of more unconventional controlled power generation connected to the MV and LV grid, and a higher electric demand have increased the interest in and the desire of a smart grid. A smart grid is defined as: “Electricity networks that can intelligently integrate the behavior and actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies” [1].

Instead of controlling wind power by the wind farm operator, wind power could be controlled by the smart grid to converge wind power with the e.g. electric car storage facilities. This research will outline the methodology to mitigate the impact of wind power by controlling wind turbines within a smart grid. Wind power does not automatically follow a load curve and conventional power has to balance the power system’s nominal frequency. This research describes a general methodology to calculate wind power fluctuations and proposes a possible role for the smart grid to mitigate the impact of wind power to frequency fluctuations within a power system.

This paper is organized as follows:

Section III describes the cause and effect of frequency deviations. Section IV describes future changes in power supply and analyzes load fluctuations. Section V treats the susceptibility of the power system to power fluctuations. Section VI discusses wind power in general. More details on wind power fluctuations are discussed in section VII. A general methodology to calculate wind power fluctuations is shown. Section VIII discusses concepts of inertial wind power smoothing and its limitations. Section IX concludes the research by stating that a smart grid with wind power control could mitigate the impact of wind power fluctuations on the power system’s frequency.

III. POWER SYSTEM’S FREQUENCY FLUCTUATIONS

Supply of power is continuously adjusted to follow the load in order to maintain a (nearly) constant nominal power frequency. Even though load can be forecasted, deviations between forecast and actual load occur. However, power supply also deviates because of sudden loss or surplus of power due to failures, errors, or fluctuating generators. The gap between supply and demand, noted as “ ΔP ”, leads to a

change of the frequency. The amplitude of this change depends on the gap between supply and load and on the susceptibility of a power system (time needed to alleviate the gap). The concept of frequency fluctuations with respect to load and supply deviations is depicted in Figure 1.

Wind power fluctuates and therefore both smoothens and amplifies the gap between load and supply, depending on the frequency, amplitude and phase angle of those fluctuations. But, wind power does not only lead to a larger ΔP , it also increases the susceptibility of the power system because without extra control, it does not supply inertial response and spinning reserve. This will be discussed more in detail in Section V.

IV. SUPPLY AND LOAD

This section treats different types of generation in a power system and analyzes load fluctuations of the Dutch power system in the frequency domain by using a Fast Fourier Transform (FFT) analysis. The Dutch power system is part of the synchronously coupled Western European power system (formerly named UCTE interconnection).

A. Supply

Currently, supply of power in the Western European power system is mainly based on fossil fuel generators such as coal, gas and nuclear power. These fossil fuel generators are usually connected to the transmission grid. Sustainable generation such as hydro power and biomass is in some cases also connected to the transmission grid and have conventional control capabilities. However, some other sustainable generation like solar and wind power, part of the DG, is connected to the MV and LV grid (distribution grid) and its resources are often fluctuating. E.g., wind and solar are predictable to some extent, however, higher frequency fluctuations (within 15min) are not forecasted and put extra pressure on the short-term stability of the power system. Figure 2 depicts the characteristics of a general central power production compared to the upcoming decentralized power production.

B. Load

In general, load can be forecasted relatively accurate and its behavior is well predictable. As an example, the Dutch load profile for a certain period has been depicted in Figure 3. Its behavior follows a daily pattern, which is relatively similar for every working day. In the weekend, the peaks are lower and shifted in time, and the total amount of consumed power is less.

To investigate load fluctuations in the frequency domain, an FFT is applied and shown for the Dutch load in Figure 4. The load fluctuations in the frequency domain have been depicted per unit where 1 unit equals the maximum load occurred in the whole time series. The time series has a length of a week and the sampling time is 4sec.

Figure 1: Concept of frequency fluctuations with respect to power deviations caused by the gap between load and supply. Primary, secondary and tertiary control are incorporated in the susceptibility of the grid.

Figure 2: Characteristics of centralized power generation versus decentralized power generation [2].

Figure 3: Dutch load for week 50 in 2008.

Figure 4: Dutch load (FFT).

The FFT shows on which frequency level, load fluctuations occur and what their amplitudes are. It must be considered, that a FFT cannot give information, which frequency fluctuations propagate at the same time. Depending on the phase angle of both fluctuations, they damp out or amplify each other.

V. SUSCEPTIBILITY OF THE POWER SYSTEM INCLUDING WIND POWER

The interconnected power system is able to maintain the nominal frequency within certain ranges, because of its moment of inertia and the control systems of all synchronous coupled networks. Primary-, secondary-, and tertiary- control have the ability to absorb or supply a certain amount of energy to force the frequency of a power system back to its desired frequency level. The susceptibility of a power system in relation to wind power is discussed in [3], [4], and [5]. The susceptibility of the Dutch power system is depicted in [6].

More wind power will not only lead to larger and more often deviations between supply and load, also the susceptibility of the power system to power fluctuations will increase. E.g., currently, widely installed wind turbines are variable speed asynchronous generators. These wind turbines are not mechanically and electrically synchronously coupled, which implies that this type of wind power does not supply inertial response. Secondly, wind power is currently more expensive than fossil fuel based power generation. In combination with the high initial costs and low operational costs, wind turbines are in general Maximum Power Production (MPP) controlled. Therefore, wind power does not supply or absorb extra power and there is no participation in primary, secondary and tertiary control. To demonstrate a possible impact of wind power, the inertial response and the droop of primary and secondary control of the (formerly named) UCTE power system have been changed arbitrary and the result is depicted in Figure 5. The initial power system parameters are stated in Appendix B. And the arbitrarily chosen power system parameters are stated in Appendix C.

This research will focus on higher frequency wind power smoothing to mitigate the impact of wind power on the power system's frequency. A higher susceptibility and larger power fluctuations will result in even larger frequency deviations as was concluded from Figure 1.

VI. WIND POWER

A. From wind to wind power

Wind turbines are able to (partly) capture the power of the wind reflected on the blades and rotor. This aerodynamic torque is exposed on the rotor.

Figure 5: Susceptibility of the UCTE power system, including a possible change due to more wind.

The generator is able to extract the mechanic power and convert it to electric power. Equation (i) gives the aerodynamic power of the wind reflected on the blades and rotor.

$$P_{aero} = \frac{\rho}{2} C_p(\lambda, \theta) \pi R^2 V_w^3 \quad (i)$$

Here P_{aero} is the aerodynamic power reflected on the wind turbine [$\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$], ρ is the air density of a wind site [kg/m^3], R is the radius of swept area covered by rotor and blades [m], V_w is the wind speed [m/s], and $C_p(\lambda, \theta)$ is the capacity factor of a wind turbine. The capacity factor is a function of the tip-speed ratio (λ) and the blade pitch angle θ [deg].

The tip speed ratio is the ratio between the speed of the wind turbine's tip and the actual wind speed as stated in (ii).

$$\lambda = \frac{\omega_r R}{V_w} \quad (ii)$$

In which ω_r is the rotational speed of the rotor [rad/sec].

B. Power control of wind turbines

The amount of electric power generated by a wind turbine can be controlled with the blades and with the generator. If a wind turbine is equipped with pitch control, the position of the blades can be adjusted to change the aerodynamic power. The generator is also able to control the power by using torque set-point control. At constant wind speed, the wind turbine will rotate constantly if the torque set-point of the generator is as high as the aerodynamic torque reflected on the wind turbine. However, due to a sudden wind gust, the aerodynamic torque increases and the torque set-point of the generator is not immediately adjusted. As a result, the wind turbine starts to accelerate. Without changing the generator's torque set-point, the rotor will continue its acceleration. Adjustment of the generator's torque-set point to a higher set point controls the speed of the wind turbine and a higher energy yield can be obtained. Equation (iii) describes the relation between speed and torque.

$$\frac{d\omega}{dt} = \frac{T_{aero} - T_{elec}}{I_{WT}} \quad (iii)$$

Here $d\omega/dt$ is the acceleration or deceleration of a wind turbine [rad/sec²], I_{WT} is the moment of inertia [$\text{kg} \cdot \text{m}^2$] of a wind turbine and T_{elec} is the electric torque generated by the generator [$\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$].

In [7], the general equation to determine the moment of inertia of a wind turbine is described. The general control of a wind turbine is discussed more detailed in [8] and [9].

VII. WIND POWER FLUCTUATIONS

In the previous sections it is mentioned that power fluctuations occur. In combination with the susceptibility of the power system, the effect of power fluctuations on frequency fluctuations is determined.

Currently, single wind turbines can reach sizes up to 7MW [10] and new installed offshore wind farms in general reach above 100MW [11]. Therefore wind turbines are more and more treated as normal power plants [12]. To determine wind power fluctuations, three data sets are essential.

A: Wind speed time series data set.

B: Power – Wind speed curve.

C: Transfer function of the wind turbine and farm.

The next approach is only valid if the wind turbines are equal in size, concept and control. In relation, the distinction is made between a single wind turbine and a complete wind farm. Due to the fact that within a wind farm not every single wind turbine faces the exact same wind speed, higher frequency power smoothing occurs, $10^{-5} \text{ Hz} \rightarrow 10^{-4} \text{ Hz} \rightarrow \infty$.

A. Wind speed time series data set

To determine power fluctuations of one single wind turbine, one wind speed time series data set is sufficient. However for a large wind farm or several wind farms, more wind speed time series data sets must be determined and the methodology for that is described in [13].

B. (Aggregated) Power curve of a wind turbine

The power curve of a particular wind turbine is mostly free accessible. In [14] the properties of a variable speed 2 MW doubly fed induction generator (VS 2MW DFIG) is given and it has been used in the simulations depicted in this paper. However, due to the aggregation of wind turbines, the power curve of one single turbine is not sufficient. A multi-turbine power curve must be determined. In [13] the methodology is described to determine a multi-turbine power curve. This aggregated power curve takes charge for the cut-in and cut-off smoothing behavior of wind turbine aggregation as can be seen in Figure 6. The aggregated Power-Wind speed curve is valid for every single wind turbine within the area as is described in [13].

C. Transfer function

Wind turbines are not able to adapt high frequency wind speed fluctuations. The moment of inertia and the rotor disc averaging effect will attenuate high frequency wind fluctuations.

Figure 6: Multi-turbine power curve of a wind turbine compared to the aggregation of multiple wind turbines with different wind site conditions (σ depends on the wind site [13]).

In [5] the moment of inertia of a wind turbine is described and stated in (iv).

$$H_{WT} = \left(2 \frac{d\omega}{dt} \right)^{-1} (T_{mech} - T_{elec}) \quad (iv)$$

Where H_{WT} is the inertial constant of the wind turbine [s], T_{mech} is the mechanic torque [p.u.] and T_{elec} is the electric torque [p.u.].

Secondly, the rotor disc averaging effect of a large wind turbine will smoothen higher frequency wind fluctuations. This rotor disc averaging effect is treated in [15]. At last, if a wind farm instead of a wind turbine is regarded, the smoothing effect of several wind turbines facing not exactly the same (turbulent) wind speed at the same time must be considered. This smoothing effect is called the wind farm coherence. In Figure 7, the concept of a transfer function of a wind farm is depicted. The wind farm coherence is a parameter which is determined by the wind site and the layout of the wind farm. On the contrary, the rotor disc averaging effect and the moment of inertia are wind turbine parameters. Depending on wind farm and wind turbine characteristics, the three effects all operate in a different frequency range and can have different slopes.

In the next paragraph of this section, some simulations are depicted using a wind turbine as treated in [14]. The time constant to cope with the moment of inertia and the rotor disc averaging has been arbitrary chosen and is stated in (v). An arbitrary chosen time constant for a wind farm is stated in (vi).

$$H_{WT} = \frac{1}{2.7s + 1} \quad (v)$$

$$H_{WF} = \frac{(34s + 1)}{(1500s + 1) + (2.7s + 1)} \quad (vi)$$

D. FT analysis of wind power

A wind speed time series data set of 4 Hz belonging to an offshore location in the North Sea near Egmond aan Zee (the Netherlands) has been used to apply an FFT analysis. Wind power fluctuations of a single wind turbine and of a wind farm existing of several wind turbines have been depicted in Figure 8. The arbitrary chosen transfer functions of (v) and (vi) are applied. A multi-turbine power curve as depicted in Figure 6 with a $\sigma=1.2$ has been used for the wind farm, related to the dataset of the offshore wind site in the North Sea. For this simulation case, it can be concluded, that the aggregation of wind turbines smoothen wind power fluctuations above a frequency of $2 \cdot 10^{-4}$ p.u./Hz.

Figure 7: Bode diagram of a wind farm including the wind farm coherence of the wind farm and the rotor disc averaging effect and moment of inertia of the single wind turbines.

Figure 8: FFT of a wind turbine WT and a wind farm WF. Especially in the high frequency range, a WF smoothens wind fluctuations.

VIII. METHODOLOGY OF WIND POWER SMOOTHING

Several concepts, technologies and appliances are capable of applying wind power smoothing and are briefly summarized in [1]. This research makes the distinction between inertial wind power smoothing (IWPS) and blade pitch control to smooth power in the lower wind speed range of a wind turbine. The lower wind speed range is the range between the cut-in and rated wind speed of a wind turbine. The higher wind speed range is between the rated wind speed until the cut-off wind speed of a wind turbine. The concept of IWPS for the lower wind speed range is that the wind turbine will absorb and release kinetic energy to its rotor, described in [16] and [17]. For the higher wind speed range, a wind turbine already uses pitch control to protect the generator for speed overloading. The power is already nearly constant. However, pitch control can also be used to smoothen wind fluctuations in the lower wind speed range, described in [18]. Both concepts are mentioned in [3] and [9]. In [19] it is concluded that IWPS for the lower wind speed range has more advantages above pitch control. Due to the speed limits of the generator, IWPS is not suitable to be applied in the higher wind speed range.

A. Inertial Wind Power Smoothing

IWPS characterizes itself by storing and releasing kinetic energy, respectively in and from the rotor.

The concept of IWPS is to accelerate the wind turbine beyond its optimal λ to store kinetic energy, if a wind gust

shows up. If a wind drop shows up, after absorbing kinetic energy, kinetic energy is released which will be converted into electric energy. Extra power can be supplied to the grid due to the extra deceleration of the wind turbine. The smart grid could be equipped with control systems allowing the smart grid to store or release extra kinetic energy, respectively in and from wind turbines and wind farms connected to the control system. However, IWPS has limits, described in [1], and the amount of stored energy depends on the wind turbine's rotating mass and the current wind speed. At higher wind speeds, the wind turbine is already operating against its speed limit, where extra kinetic energy cannot be stored. Figure 9 depicts the torque-speed curve of a VS 2 MW DFIG and depicts the limitations of IWPS with respect to the wind speed with the black dotted lines.

Figure 10 depicts the speed range of the VS 2 MW DFIG for IWPS. Instead of following an optimal λ as discussed in [1] and [8], the wind turbine will rotate with a higher λ if a wind gust occurs. This is depicted in Figure 10 with arrow I. After the wind gust, to be assumed a wind drop, the wind turbine can decelerate to a lower λ , depicted with arrow II. If demanded, the amount of released energy can be increased by a larger deceleration of the wind turbine, indicated with arrow II'. The amount of energy stored and released can be calculated with equation (vii).

$$E_{\text{stored}} = \frac{1}{2} I_{\text{WT}} (\omega_H - \omega_L)^2 \quad (\text{vii})$$

In which E_{stored} [J] is the kinetic energy stored in the rotor, ω_H the higher rotor speed in [rad/sec] and ω_L the lower rotor speed in [rad/sec].

However, after deceleration of a wind turbine by releasing kinetic energy of its rotor, the wind turbine needs to accelerate again to produce the power it could generate if an optimal λ would be followed, during this restore time the power production is not maximal. Power losses due to IWPS depend on ω_H and ω_L , on the current wind speed, and on the frequency of power fluctuations.

Figure 9: Torque-speed curve of a VS 2 MW DFIG with its speed limits and its generator capacity limit. The higher the wind speed, the higher the torque-speed curve.

Figure 10: Speed range of rotor to apply IWPS.

B. Pitch control

Pitch control is the concept in which the blades of a wind turbine can be pitched to increase or decrease the aerodynamic power reflected on the wind turbine. In general, pitch control is used to protect the components of the wind turbine against speed overloading near and above rated wind speed. However, pitch control can be applied to adjust the aerodynamic torque below rated wind speeds as is discussed in [20].

C. Simulation and limits of inertial wind power smoothing

Figure 11 depicts the result of IWPS if a wind turbine with IWPS would be developed with a transfer function stated in (viii). Wind fluctuations with a frequency of $1 \cdot 10^{-2}$ Hz and higher will be attenuated.

$$H_{WTIWPS} = \frac{1}{3933s^3 + 935.7s^2 + 59.9s + 1} \quad (\text{viii})$$

IWPS is a wind power smoothing concept without the necessity of supplementary appliances. If a suitable IWPS control system can be developed and controlled by the smart grid, power smoothing can be applied at wind speeds between the cut-in and rated wind speed of the installed wind turbines. Above rated wind speed, the power output is already controlled due to the speed limits of the generator.

Depending on the wind site, different wind speeds occur and wind fluctuations have different amplitudes. An FFT determines the amplitude of power fluctuations and a Weibull distribution [21] determines the probability of possible IWPS and pitch control for power smoothing. In relation, if IWPS is applied with an obligation not to exceed a certain percentage of power losses, the actual wind speed will influence the level and frequency range of wind power smoothing.

If the deceleration of a wind turbine is significant, a larger amount of aerodynamic power is needed after power smoothing to accelerate the wind turbine back to its optimal λ . This will be at the expense of the electric power output of the wind turbine. In practice, this can also be hazardous for grid stability, especially if more wind turbines have been IWPS controlled [22].

It is assumed that after the wind fluctuation, the wind has again the same speed as before the wind fluctuation, however in practice this can deviate. This fact has not been taken into account.

IX. SMART GRID'S POWER CONTROL

A. Smart grid's wind power control

To mitigate the impact of wind power on the frequency of the power system, a smart grid could be equipped with a control system to control the active power output of a wind turbine or wind farm. The smart grid should meter the frequency of the grid to take action if necessary. The control which has to be developed should be fed with information about several aspects. The control system should be informed about the state of operation of the wind turbines and wind farms connected to the control system. The control system should also frequently investigate the effect of an unforeseen event if wind farms and wind turbine are in IWPS mode. The power system will then be protected against uncontrolled power disturbances. A general lay out of a smart grid, controlling wind turbines and wind farms to mitigate the impact of wind power fluctuations is depicted in Figure 12.

B. Inertial Response and Spinning Reserve by Wind Power

This research investigates wind power smoothing to be controlled by a smart grid. However, the smart grid could play a more advanced role in controlling wind power. Inertial response and spinning reserve of wind power could both be controlled by a smart grid. In [7], research is done on inertial response of wind turbines, and in [9] and [23] research is done on frequency support like primary control by wind power. In [24] and [25] both inertial response and spinning reserve are discussed. In [26] a control approach for system frequency regulation by wind turbines is discussed and [27] describes a possible control approach to mitigate the impact of wind power.

Figure 11: FFT of a Wind Turbine (WT) and a Wind Turbine with IWPS, neglecting power losses due to IWPS.

Figure 12: Smart grid's wind power control to mitigate power fluctuations of the grid caused by wind power.

X. CONCLUSIONS

The growing penetration of wind power increases the pressure on grid frequency stability. In general, wind power does not provide inertial response or any other types of ancillary services. In relation, wind power fluctuations aggravate the effect of wind power. Wind power fluctuations can smoothen load fluctuations, however if in antiphase, both fluctuations amplify power systems frequency deviations. The approach to determine wind power fluctuations has been mentioned using FFT analysis. FFT is a tool to determine the amplitude of power fluctuations for different frequencies. Figure 13 shows a result of an FFT analysis where the ratio between power frequency amplitudes of load, wind farm, wind turbine and wind turbine with IWPS is depicted. However, an FFT does not give information about the probability of power fluctuations, the combination between several frequency fluctuations at the same time and their phase angle.

A smart grid could be equipped with a control system to mitigate the grid impact of wind power in terms of frequency stability. IWPS can be controlled by the smart grid for the lower wind speed range (cut-in to rated wind speed of a wind turbine). The smart grid will be able to control the power output of wind turbines and wind farms if necessary. IWPS applications do not need additional appliances however power losses occur, depending on the actual wind speed, the amplitude of wind fluctuations, the level of wind power smoothing and the frequency of the smoothed power fluctuations. The smart grid will control the level and probability of wind power smoothing to mitigate wind power's impact and the smart grid limits power losses.

Figure 13: An FFT of load, a wind turbine, a wind turbine with IWPS, and a wind farm.

XI. APPENDIX

A. Wind Turbines properties

Rotor diameter	75 m
Rotor speed	9-18 rpm
Nominal Power	2 MW
Cut-in wind speed	3.5 m/s
Nominal/rated wind speed	12 m/s
Gear box ratio	1:100
Rotor's moment of inertia	$6.3 \cdot 10^6 \text{ kg.m}^2$
Mass of rotor and blades	40.000 kg

B. Power system properties

Network constant (λ_{net})	$I_{\text{net}} = 2.5 \cdot 10^8 \text{ kg.m}^2$
Droop of primary control	$s = 0.08$
Secondary control	$K_i = 0.005$
	$K_p = 0.01$
Self-regulating effect of load	$1\% / \text{Hz}$
Nominal frequency	$f_0 = 50 \text{ Hz}$
Nominal Power	$P_0 = 300 \cdot 10^9 \text{ W}$
Nominal Load	$L_0 = P_0$
Delay	$1/(10 \cdot s + 1)$
Droop equation	$s = (\Delta f / f_0) / (\Delta P / P_0)$

C. Arbitrarily chosen power system properties to simulate more wind

Network constant (λ_{net})	$I_{\text{net}} = 1.7 \cdot 10^8 \text{ kg.m}^2$
Droop of primary control	$s = 0.11$
Secondary control	$K_i = 0.003$
	$K_p = 0.005$

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XIII. REFERENCES

- [1] www.smartgrids.eu, July 2010.
- [2] J. Driesen, R. Belmans, "Distributed Generation: Challenges and Possible Solutions", Power Engineering Society general Meeting, 2006, Montreal, Canada, 2006.
- [3] C. Luo and B.-T. Ooi, "Strategies to Smooth Wind Power Fluctuations of Wind Turbine Generator", IEEE Transactions on Energy Conversion, Vol. 21-3, pp.708-716, Sept. 2006.
- [4] P. Kundur, N.J. Balu, and M.G. Lauby, "Power System Stability and Control", Chapter 12, McGraw-Hill, Inc., ISBN: 9780849392917, 1994.
- [5] C. Luo, H.G. Far, H. Banakar, "Estimation of Wind Penetration as Limited by Frequency Deviation", IEEE Transactions On Energy Conversion, Vol.22, NO.3, September 2007.
- [6] J.E.S. de Haan, J. Frunt, A. Kechroud, W.L. Kling, "Supplementary Control for Wind Power Smoothing", accepted for UPEC2010 conference, Cardiff/Wales, August 2010.
- [7] J. Morren, J. Pierik, and S.W.H. de Haan, "Inertial response of variable speed wind turbines", Elec. Power Systems research 76, 2006.
- [8] T. Thiringer, and A. Petersson, "Control of a Variable-Speed Pitch-Regulated Wind Turbine", Sweden, 2005.
- [9] G. Ramtharan, J.B. Ekanayake and, N. Jenkins, "Support for Spinning Reserve from DFIG based wind turbines", ICIIS, Sri Lanka, 2007.
- [10] www.enercon.de, July 2010.
- [11] M. Jungner, A. Faaij, W.C. Turkenburg, "Global experience curves for wind farms", Energy Policy Vol. 33, Issue 2 pp.133-150., January 2005.
- [12] W.L. Kling and J.G. Slootweg, "Wind Turbines as Power Plants", Proceedings of the IEEE/Cigre workshop on wind power and the impacts on power systems, Oslo, Norway, 2002.
- [13] P. Norgaard, H. Holtinen, "A Multi-Turbine Power Curve Approach", Nordic Wind Power Conference, 1-2 March, 2004.
- [14] J.G. Slootweg, H. Polinder, and W.L. Kling, "Initialization of Wind Turbine Models in Power system Dynamics Simulations", IEEE Porto Power Tech Conference, Portugal, 2001.
- [15] P. Sorensen, A.D. Hansen, P. Andre, and C. Rosas, "Wind models for simulation of power fluctuations from wind farms", Wind Engineering and Industrial Aerodynamics, 2002.
- [16] L. Ran, J.R. Bumby, and P.J. Tavner, "Use of Turbine Inertia for Power Smoothing of Wind Turbines with a DFIG", 11th International Conference on Harmonics and Quality of Power, 2004.
- [17] T. Senjyu, Y. Ochi, Y. Kikunaga, M. Tokudome, E.B. Muhando, and A. Yona, "Output Power Levelling of Wind generation System using Inertia of Wind Turbine", ICSET, 2008.
- [18] T. Senjyu, R. Sakamoto, N. Urasaki, T. Funabashi, H. Fujita, and H. Sekine, "Output Power Leveling of Wind Turbine generator for All Operating Regions by Pitch Angle Control", IEEE Transactions on Energy Conversion, Vol. 21, No.2, June 2006.

- [19] P. Moutis, E. Loukarakis, S. Papathanasiou, and N.D. Hatziaargyriou, "Primary Load-Frequency Control from Pitch-Controlled Wind Turbines", *PowerTech*, 2009 IEEE Bucharest, June 28th- July 2nd, pp.1-7, Bucharest, Romania, 2009.
- [20] T. Senjyu, R. Sakamoto, N. Urasaki, T. Funabashi, H. Fujita, and H. Sekine, "Output Power Leveling of Wind Turbine generator for All Operating Regions by Pitch Angle Control", *IEEE Transactions on Energy Conversion*, Vol. 21, No.2, June 2006.
- [21] J.F. Manwell, J.G. McGowan, and A.L. Rogers, "Wind Energy Explained", Theory, Design and Application, John Wiley & Sons, LTD, University of Massachusetts, Amherst, USA, 2008.
- [22] J. Frunt, A. Kechrou, W.L. Kling, J. Myrzik, "Participation of distributed generation in balance Management", *PowerTech 2009 IEEE Bucharest*, pp.1-6, Romania, June/July 2009.
- [23] A. Teninge, C. Jecu, D. Roye, S. Bacha, J. Duval, R. Belhomme, "Contribution to frequency control through wind turbine inertial energy storage", *Renewable Power Generation, IET*, Vol.3, pp.358-370, Sept., 2009.
- [24] B.G. Rawn, M. Gibsecu, and W.L. Kling, "A Static Analysis Method to Determine the Availability of Kinetic Energy from Wind Turbines", accepted for PES General Meeting, July 2010.
- [25] G. Ramatharan, J.B. Ekanayake, and N. Jenkins, "Frequency support from doubly fed induction generator wind turbines", *IET Renew. Power Gener.* 2007,1,pp.3-9, 2007.
- [26] R.G. de Almeida, and J.A. Pecos Lopes, "Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation", *IEEE Transactions on Power Systems*, Vol.22 NO.3, August 2007.
- [27] B.G. Rawn, P. W. Lehn, and M. Maggiore, "Control Methodology to Mitigate the Grid Impact of Wind Turbines", *IEEE Transactions on Energy Conversion*, Vol.22, NO.2, June 2007.

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