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Supplementary Control for Wind Power Smoothing

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Abstract— Wind fluctuations result in even larger wind power fluctuations because the power of wind is proportional to the cube of the wind speed. This report analyzes wind power fluctuations to investigate inertial power smoothing, in particular for the frequency range of 0.08 – 0.5 Hz. Due to the growing penetration rate of wind power, the susceptibility of the power system to power fluctuations increases. Wind turbines operating at a higher rotational speed compared to optimal tip speed ratio’s have the ability to smooth power. However, the efficiency of a wind turbine with inertial power smoothing capabilities will be lower. Full inertial power smoothing for fluctuations of 0.01Hz and higher will decrease the overall wind turbines efficiency with less than 1.5%.

Keywords— Fourier transformation, kinetic energy, power balancing, power smoothing, rotor inertia, speed control, torque set-point, wind power fluctuations.

I. INTRODUCTION

The increase of penetration of renewable energy sources in the electricity market is an effect of the awareness of the depletion of fossil fuels, global warming, and the desire of energy independency. The share of Distributed Generation (DG) will become larger and wind power will play an important role in future’s power generation. However, wind power has some drawbacks. A: Wind power is not controllable like conventional fossil generators. B: The supply curve of wind power does not follow the load curve. C: Wind power is generally installed in areas with good wind resources, where power grids are not designed for large power flows. D: Wind fluctuations result in wind power fluctuations which affect the power system [1] and as a result, more ancillary services for balancing are required [2]. E: The use of variable speed wind turbines leads to a relative decrease of inertia of the power system, because variable speed wind turbines are not mechanically and electrically coupled [3]. F: Wind power has high initial costs and low operational costs, therefore wind turbines are mostly Maximum Power Production (MPP) controlled and do not provide spinning reserve. Grid support like providing ancillary services is currently in most countries not obligated for wind power [4]. Due to the above mentioned drawbacks, wind power’s penetration rate is still limited and the main electricity sources of Europe are fossil fuel based. The Dutch cleanest energy supplier even states: ”From the wind we cannot live” [26].

Supplementary wind turbine control systems are, however, able to solve several drawbacks stated above. Common used controls are Aerodynamic Power control, Generator Speed control, and Reactive Power control. However, these control systems some along with power losses [5]. Nevertheless, the sacrifice of energy capture in order to achieve a higher controllability of wind power becomes more common [6]. This research will use a model of a Variable Speed 2 MW, Doubly Fed Induction Generator (VS 2MW DFIG) to investigate wind power smoothing. Variable speed wind turbines are widely applied due to their larger energy yield, they offer extensive controllability of both active and reactive power, they can easily comply with the requirements of grid companies, and their power output fluctuates less [7]. The induction generator is often used because of its low initial costs, it’s simple and rugged construction, the relatively simple connection and disconnection from the grid, its reduced maintenance, and the higher reliability compared to synchronous generators [8].

This paper is organized as follows. In section II the effects of wind power on the system balance is described in terms of wind power fluctuations regarding the susceptibility of a power system. Section III continues with the general description of wind energy conversion into wind power by applying a VS 2MW DFIG. Section IV analyses wind fluctuations of an offshore wind site. Wind fluctuations are converted in wind power fluctuations and are analysed in the frequency domain. Section V describes (inertial) wind power smoothing, especially for the frequency range of 0.08 – 0.5 Hz.

II. WIND POWER’S EFFECT ON THE BALANCE SYSTEM

Generation and consumption of electricity must continuously be in almost equilibrium to maintain a constant power frequency. Due to the synchronous interconnection of the power system, the moment of inertia (network constant λ) is large and a sudden loss of power (±GW) will usually result in controllable frequency deviations. If a sudden loss of power evolves, the moment of inertia of the power system will protect the frequency to decrease infinitely fast. Primary-, secondary- and tertiary control (PC,SC,TC) will restore the imbalance of the power system and brings the frequency back to its nominal value [9]. To prevent large imbalances, Balance Responsible Parties (BRP) have to submit their E-programme a day ahead to the Transmission System Operator (TSO). The
E-programme consists of the scheduled trades of electricity per Programme Time Unit (PTU). However, still imbalances occur and PC, SC, and TC will maintain grid stability. PC, also known as speed control, automatically supports the frequency stability. The synchronous coupled generators automatically change their speed to supply or absorb a certain amount of (kinetic) energy. Full PC will be provided by all countries synchronously coupled to the power system. Within 30 sec., PC is activated and must be able to sustain for several minutes. The restoration of the normal situation will be provided locally by SC, also called regulating power, in which spinning reserve will supply or absorb power for a longer time. SC starts typically after 30 sec. and should be fully activated within 900 sec [10]. TC, also known as reserve power will relieve PC and SC such that new imbalances can be restored again. TC also maintains an economic optimum to provide adequate balancing power in the longer run, starting within a PTU’s [11].

A. Stresses regarding wind fluctuations

Wind power fluctuations pressure the power system’s operation and the requirements for ancillary services [3]. In isolated or local power systems, frequency deviations could lead to load shedding in the network and the quality of operation is related to the ability of wind power smoothing.

B. Susceptibility of the UCTE power system to power fluctuations

The susceptibility of the power system to power fluctuations of 0.0001-0.1Hz can be determined by four subsystems, stated in Fig. 1. TC will not be treated because TC operates in a very low frequency range. Fig. 1 depicts the block diagram of the frequency response of a power system as a function of imbalance between supplied power and load. The susceptibility of the UCTE power system has been depicted in Fig. 2., and its methodology can be found in [12]. The applied parameters of the UCTE power system can be found in [Appendix, Table A]. Fig. 3. depicts the frequency range in which the four subsystems operate. Their properties are:

- Inertia – A decrease of moment of inertia $I$ [$kg\cdot m^2$] of the power system due to more DG and wind power will increase the susceptibility of its frequency range and the peak of Fig. 2. will shift to a lower frequency.
- Self-regulating effect of load (SREL) – The SREL refers to the effect that a decrease of power system’s frequency automatically results in a slight decrease of the load. A lower SREL will result in a higher susceptibility of its frequency range, however the peak of Fig. 2. remains at the same frequency.
- Primary Control – Less PC power will result in a higher susceptibility of its frequency range. The peak of Fig. 2. will become larger and shifts to a lower frequency if PC becomes smaller.
- Secondary Control - Less SC power will result in a higher susceptibility of its frequency range. The peak of Fig. 2. will not change, neither in amplitude nor frequency.

In general, conventional wind power does not contribute to inertial response, PC and SC. Due to the penetration of wind power, the susceptibility of the power system will therefore be affected over the whole frequency range. In [13], [14] and [15] supply of inertial response of wind turbines is investigated and in [14] and [16] primary control is investigated. This paper will investigate wind power smoothing for power fluctuations of 0.08-0.5 Hz depicted in Fig. 2. with section B. These fluctuations are most hazardous for grid stability [17]. Without supplementary control, wind power can amplify these power fluctuations as will be seen in section IV.

III. WIND TURBINE – VS 2MW DFIG

A. From wind to wind power

Wind turbines are able to convert the aerodynamic torque of the wind into electric power via their rotor and generator. Using (1), the aerodynamic torque of the wind reflected on the blades and rotor can be calculated.
\[ T_{\text{aero}} = \frac{D C_p(\lambda, \theta) \pi R^3 V_w^2}{2} \]  

Here \( T_{\text{aero}} \) is the aerodynamic torque reflected on the wind turbine [kg·m²·s⁻²], \( \rho \) is the air density of the wind site [kg/m³], \( R \) 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 the wind turbine, also named the rotor power factor or the performance coefficient. The capacity factor is a function of the tip-speed ratio \( \lambda \) and the blade pitch angle \( \theta \) [deg]. The tip-speed ratio is defined as

\[ \lambda = \frac{\omega R}{V_w} \]  

in which \( \omega \) is the rotational speed of the rotor [rad/sec].

The \( C_p(\lambda, \theta) \) of the VS 2MW DFIG used in this research is given by (3) and can be found in [18].

\[ C_p(\lambda, \theta) = 0.22 \left( \frac{116}{\lambda} - 0.4\theta - 5 \right) e^{-\frac{12.5}{\lambda}} \]  

Here \( \lambda \) is defined as

\[ \lambda = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta + 1} \]  

The capacity factor determines how well the wind turbine performs. To maintain a safe, reliable, and controllable power generation, control systems like blade pitching control adjust the capacity factor.

**B. Generator’s torque control**

The electric power extracted from the generator can be controlled by the torque set-point of the generator. 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. As soon as the wind speed changes, the generator’s torque set-point will be adjusted to keep the wind turbine running in stable mode and to generate maximum energy yield. Equation (5) describes the acceleration and deceleration of the wind turbine as a function of the difference between aerodynamic torque and the generator’s torque set-point.

\[ I_{\text{wt}} \frac{d\omega}{dt} = T_{\text{aero}} - T_{\text{elec}} \]  

Here \( I_{\text{wt}} \) is the moment of inertia [kg·m²] of the wind turbine and \( T_{\text{elec}} \) is the electric torque generated by the generator [kg·m²·s⁻²]. In [2], the general equation of the moment of inertia of a wind turbine is described.

Due to a sudden wind gust, the aerodynamic torque increases however the electric 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. Torque set-point control is used to protect the components of the wind turbine for speed and torque overloading, to enable a stable operation of the wind turbine, to maintain optimal tip-speed ratio for a maximal energy yield, and it can be used for power smoothing and limiting the use of spinning reserve [10].

**IV. WIND SPEED FLUCTUATIONS**

Wind originates by the rotation of the earth and by temperature differences due to sun irradiation. Atmospheric molecules will flow from higher pressurised areas to lower pressurised areas. Due to surface friction and temperature deviations between layers, wind fluctuates. Local temperature deviations and surface roughness lead to local turbulence, wind fluctuations with a frequency of ~0.001Hz – 1Hz.

**A. Wind fluctuations in the frequency domain**

In general, wind fluctuations contain all frequencies. The amplitude and probability of those wind fluctuations depend on the wind site. Low frequency fluctuations are seasonal, day and night, and hourly based fluctuations. These small frequency wind fluctuations are totally incorporated and adapted by wind turbines to create maximum energy yield. However, at a certain frequency, wind turbines cannot any more completely follow wind fluctuations. High frequency wind fluctuations are even very hard to be adapted by the wind turbine, due to their moment of inertia and the rotor disk averaging effect. Equation (6) describes the used transfer function in this research for the VS 2MW DFIG to determine the adaption of wind fluctuations.

\[ H_{\text{wt}} = 1/(3s + 1) \]  

**B. Low frequency wind fluctuations**

This research has analysed a dataset of an offshore wind site containing wind speeds at a certain height. Fig. 4. depicts the probability of absolute power fluctuations of a VS 2MW DFIG as a function of a 10 min. wind speed average. The lighter colour represents lower probability of wind power fluctuations as a function of the average wind speed within 10min. The darker colour represents higher probability of wind power fluctuations. The negative power fluctuations at 5-6 m/s and the positive power fluctuations at 11-12 m/s are more concentrated and have a low amplitude, however still affect the power system and amplify the susceptibility of the power to power fluctuations in the higher frequency range. Instead of controlling conventional, high voltage power generators to maintain the stability of the power system, wind turbines itself could prevent those effects via power smoothing of frequencies of section B, Fig. 2.
V. POWER SMOOTHING

Wind power smoothing will induce power losses. But still, attention is paid to power smoothing for a better dispatch of wind power and to decrease the power amplitude of higher frequency fluctuations. Natural power smoothing due to the large moment of inertia of a wind turbine and the rotor disk averaging effect, smoothes power fluctuations above 0.25Hz for a VS 2MW DFIG. This section treats wind power smoothing for the frequency range of ~0.08Hz and higher. To attenuate power fluctuations of e.g. 0.1Hz with 10dB for the VS 2 MW DFIG, a controller with a transfer function of (7) can be used.

\[ H_{\text{contr}} = \frac{1}{(54s^2 + 10s + 1)} \] (7)

Depending on several parameters, different controllers are imaginable, each suitable for a different application.

A. Power smoothing for power fluctuations of 0.08-0.5 Hz

Fig. 5. depicts wind power fluctuations in the frequency domain for a VS 2MW DFIG also in combination with the controller. The total energy losses due to the applied controller do not exceed 0.01% of the total generated energy yield. Power smoothing for lower frequencies coincide with absolute larger losses because the power amplitude of those fluctuations is larger. Instead of wasting the power for power smoothing, energy could be captured in a power peak and released in a power drop. Different concepts are suitable and will be discussed in the next two paragraphs.

B. Power smoothing applications

There are several applications suitable for wind power smoothing. Energy storage can be used to smoothen wind power’s output. In [20] power smoothing is discussed for frequencies of 0.01-1Hz via superconducting magnetic energy storage, ultra capacitors and a flywheel. In [21] voltage-source converters (VSC’s) are used to smooth wind power fluctuations. For wind power fluctuations with frequencies of 0.001-0.01Hz and even lower, power smoothing can be supplied via batteries, pumped hydro, compressed air, and redox flows (hybrids of secondary batteries and fuel cells).

These storage facilities with a capacity of several MWh [22] put however additional investment-, operational- and maintenance- costs to the system. The natural moment of inertia of a wind turbine smoothes power fluctuations above a frequency of ~0.25Hz. In [23] and [24] supplementary control uses the moment of inertia for power smoothing without significant power losses. The pitch control in [25] can be applied in a wide frequency range, however, the smaller the frequency the larger the power losses.

C. Inertial power smoothing via torque set-point control

The inertial power of the turbine’s rotor can be used for power smoothing. Therefore the wind turbine will operate at a higher rotational speed compared to the optimal \( \lambda \), which consequently results in a lower \( \text{Cp} \). Fig. 6. depicts the efficiency of inertial power smoothing as a function of power frequency, in relation to a MPP controlled wind turbine (if power will be smoothed to generate a constant power output). Kinetic energy will be stored during a wind peak and be released during a wind drop. Power smoothing for frequencies lower than the vertical dotted lines is only possible if the turbine will decelerate below its optimal rotational speed, otherwise, no sufficient kinetic energy is available at the assumed constant wind speed and extra power losses are involved, not included in Fig. 6.
Inertial wind power smoothing to prevent an increase of the susceptibility of the power system due to more wind power in the frequency range of 0.01Hz and higher will coincide with wind power losses up to 1.5%.

VI. CONCLUSIONS

The penetration of wind power in the power system decreases the share of inertia of the power system and decreases the supply of ancillary services. Without significant additional costs, wind turbines could be equipped with a control system for inertial power smoothing of power fluctuations in the frequency range of 0.01Hz and higher. The power system cannot easily cope with those power fluctuations and more wind power without a method for wind power smoothing will increase the susceptibility of the power system to power fluctuations. The losses for inertial power smoothing of power fluctuations at 0.01Hz and higher will not be larger than 1.5% independent of the wind speed. However, the freedom of inertial power smoothing in the frequency domain is limited and depends on the wind speed. At higher wind speeds, the potential of inertial power storage is lower because of the speed limitation of the generator.

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