Frequency Control in Power Systems with High Wind Power Penetration

Germán Claudio Tarnowski, Philip Carne Kjær, Jacob Østergaard, Poul E. Sørensen

Abstract—**The fluctuating nature of wind power introduces several challenges to reliable operation of power system. With high wind power penetration, conventional power plants are displaced and wind speed fluctuations introduce large power imbalances which lead to power system frequency control and operational problems. This paper analyses the impact of wind power in the frequency control of power systems for different amount of controllable variable speed wind turbines. Real measurements of short term wind power impact tests in a power system are shown and used to study the amount of total regulating power needed from conventional power plants. Dynamic simulations with validated model of the power system support the studies. The paper also presents control concepts for wind power plants necessary to achieve characteristic of frequency response and active power balancing similarly to conventional power plants, therefore allowing higher wind power penetration. As the power system dependency on wind power increases, wind power generation has to contribute with dynamic response and control actions similarly to conventional power plants.**

Index Terms— **Wind power plants, wind power integration, active power balance, frequency control, frequency response, variable speed wind turbines, power curtailment, inertia.**

I. Introduction

WIND power is an important source of electricity generation. Nevertheless, the fluctuating nature of wind power introduces several challenges to reliable operation of power systems. During the first two decades of wind turbines being connected to the public grid, a fairly strong grid was assumed and the turbines and controls were designed accordingly. With increased integration of wind power connected to the transmission network, modern wind power plants employ variable-speed wind turbines (VSWT) and are required and designed to fulfill increasingly demanding grid codes [1-7].

In power systems with high wind power penetration, conventional power plants are displaced and wind speed fluctuations can introduce large power imbalances which lead to power system frequency control and operational issues [12].

As the power system dependency on wind power increases, wind power generation will have to contribute with services normally delivered by thermal or hydro generation [2,6,8]. In some power systems, mainly with weak interconnections and/or high wind power penetration, frequency reserves can be more valuable to the system than maximizing the wind power generation yield [2,6,9]. In such power systems, wind power generation will have to provide fast regulating capability and a reliable, deterministic and repeatable frequency response to support the grid and decrease costs of reserve power allocation.

This paper shows the dynamic impact of wind power in the frequency control of a power system for different amount of fluctuating wind power. Real measurements from a power system operating with high wind power penetration are shown and used as a basis for the study. The measurements show different levels of short term grid frequency fluctuations for different levels of wind power penetration. The study determines the amount of total regulating power needed from the conventional power plants. The analysis is supported with dynamic simulations using a validated model of the respective power system, which is composed of thermal power plants and variable speed wind turbines. The paper also presents control concepts for modern wind power plants necessary to achieve characteristic of frequency response and active power balancing similarly to conventional power plants, therefore allowing higher wind power penetration.

The paper is organized as follows. Section II shows measurements of impact of fluctuating wind power in the power balance of a power system; Section III shows simulation results of the same power system when increasing the Regulation Capacity (RC) for allowing higher wind power penetration; Section IV presents modern WPP architecture and control philosophy to allow higher wind power penetration. Conclusions are in Section V.

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II. Measurements of Wind Power Penetration Impact on System Power Balance

Some power systems with significant amount of wind power are experiencing problems for balancing the power fluctuations caused by regional wind speed fluctuations [9,13]. To investigate more about the impacts that this type of fluctuations cause, specific operations of a real power system with large amount of wind power were carried out, where strong balancing issues are registered. Figure 1 shows a basic diagram of the power system where the tests were conducted. It consists of one conventional power plant with droop characteristic (Plant 1, steam turbine); one CHP power plant with a normally disabled droop characteristic (Plant 2, steam turbine), both plants are concentrated in a main busbar; two controllable wind power plants (WPP) located at two different busbars in the system which are app. 20 km distant. The WPP are composed of variable speed wind turbines-doubly fed generators based, and controlled centrally via SCADA. The WPP can be operated at optimal production as well as controlled by power limitation or curtailment. The consumption load is spread all over the system which covers an area of app. 700 km^2, with a maximum record of 55MW. The installed capacity of Plant 1 is about 0.9 pu of the system peak demand registered during the tests. The installed capacity of Plant 2 is about 1.05 pu of the system peak demand registered during the tests. The installed controllable wind power capacity is about 0.35 pu of the system peak demand registered during the tests. The wind plants are controllable by remote set points. The wind turbines can be disconnected individually by remote instruction.

The wind power impact operational results presented here were obtained in 5 steps which are identified as cases. Initially, the power system was operated by allowing the largest possible amount of wind turbines to inject their respective available power into the grid. Subsequently, the number of connected wind turbines was reduced in periods of about 30 minutes until the complete remotion of wind power from the power system. During the tests, the wind speed conditions were approximately unchanged, i.e. frequency and amplitude of fluctuations, turbulence, mean value, etc.

- Case 1: Figure 2. Power system operation with 0.65 pu of wind power capacity, with no restriction on wind power production. The wind power fluctuations introduce large imbalances which are reflected as large frequency deviations. The frequency fluctuations are just inside the acceptable range, therefore, the acceptable fluctuation level have been reached, and measured as 4% of actual demand.
- Case 2: Figure 3. Power system operation with 0.50 pu of wind power capacity, with no restriction on wind power production.
- Case 3: Figure 4. Power system operation with 0.35 pu of wind power capacity, with no restriction on wind power production.
- Case 4: Figure 5. Power system operation with 0.15 pu of wind power capacity, with no restriction on wind power production.
- Case 5: Not shown. Power system operation with no wind production.

Figure 6 shows the measured droop response of Plant 1 for each test case, except for Case 5. From this figure the Regulation Capacity (RC) of Plant 1 can be measured as app. 0.25 pu/Hz.

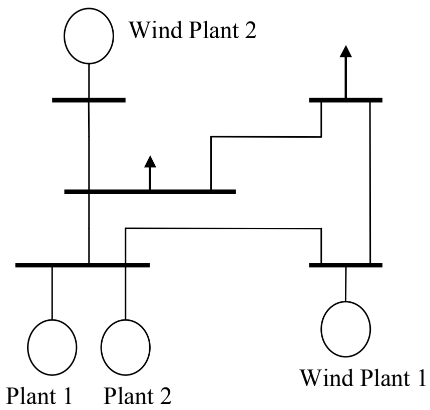

Fig. 1. Basic diagram of the real power system used for the wind power impact operational tests.

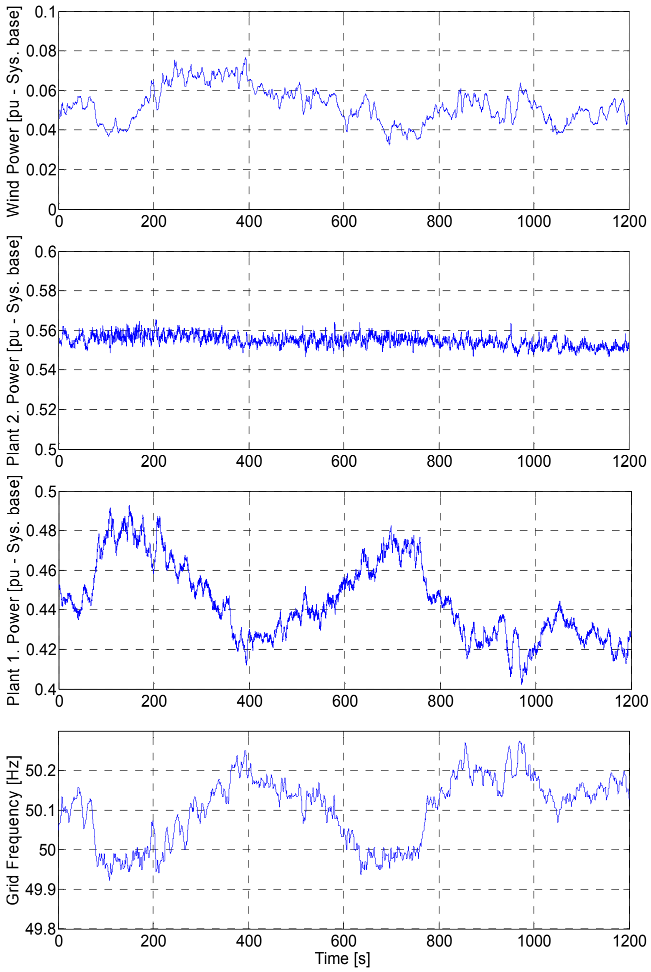

Fig. 2. Measurements. Wind power penetration case 1. Plant 1 with droop action. Plant 2 constant output. Wind power 0.65pu capacity.

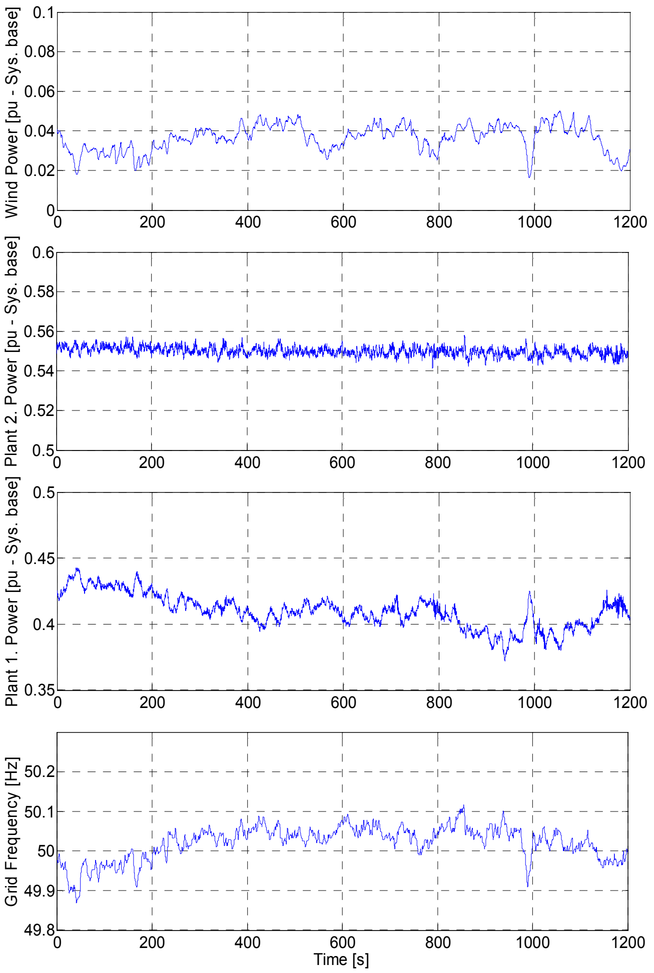

Fig. 3. Measurements. Wind power penetration case 2. Plant 1 with droop action. Plant 2 constant output. Wind power 0.50pu capacity.

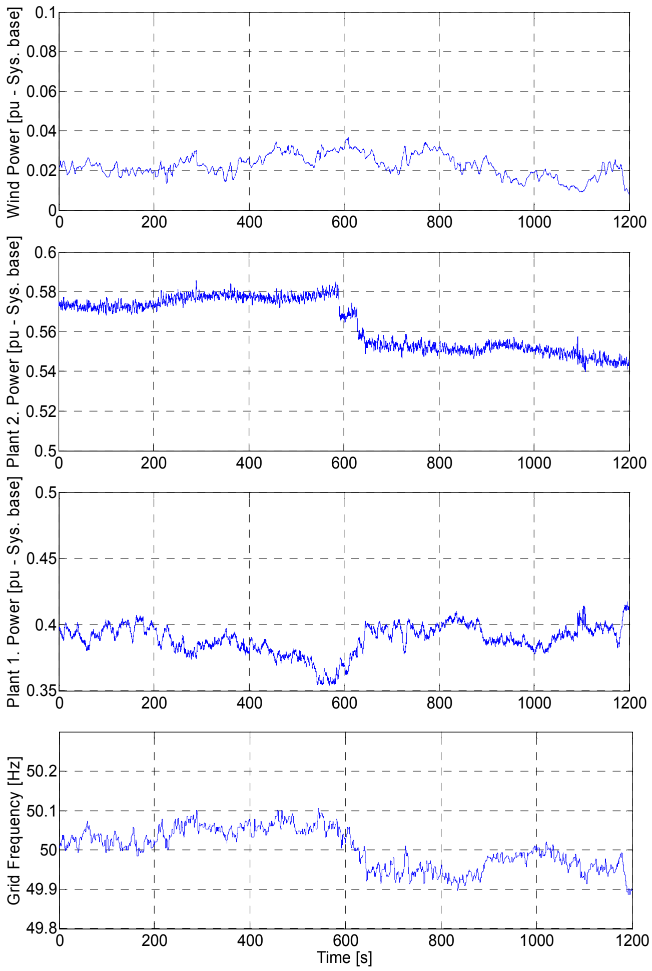

Fig. 4. Measurements. Wind power penetration case 3. Plant 1 with droop action. Plant 2 output step adjusted. Wind power 0.35pu capacity.

III. Increasing Wind Power Penetration by Increasing System Regulation Capacity

Accurate simulations were carried out to investigate the effect of increasing the system Regulation Capacity (RC) on system power balance. The simulation model is representing the test power system of fig. 1 with a high level of accuracy.

For comparison, the conditions of Case 1 where taken for simulations, i.e. wind speed conditions and connected generators as well as number of wind turbines. The droop response of Plant 2 (normally disabled) was simulated active, with a setting similar to Plant 1, i.e. same droop and response.

Figure 7 shows the simulation results. The new droop response of Plant 2 is in the same amount than Plant 1. The balance of wind power fluctuations is shared equally by Plant 1 and Plant 2 and the frequency fluctuations have been reduced in app. a half compared with fig. 1.

Figure 8 shows the droop response of Plant 1 and Plant 2 for the simulated scenario with no droop in Plant 2 (case 1) and for the simulated scenario with droop in Plant 2 (increased RC). Clearly, as the droop setting of Plant 2 is similar to Plant 1, the share of load is equal. As the wind power fluctuations are similar to case 1, the frequency fluctuations are reduced in 50%. Therefore, the new system RC has increased by 50%, i.e. 0.5 pu/Hz.

The following expression can be written:

$$\Delta P_{fluct} = \frac{\Delta F_{grid}}{RC_{system}} \tag{1}$$

Where ΔP_{fluct} (pu) is the amount of acceptable wind power fluctuation in the power system, ΔF_{grid} is the amount of allowed grid frequency fluctuation around the nominal value and *RC* (pu/Hz) is the system regulation capacity given by the amount of power plants providing droop response.

The same power system effect could be obtained if e.g. the RC of Plant 1 could be increased to 0.5 pu/Hz while Plant 2 continues to operate with no droop action. However, the control effort of Plant 1 for power system balance would increase, probably to unacceptable levels due to boiler thermal stress, time constant effects, machine limitations, etc. The increase in individual plant balancing activity may also make the thermal plant operate at a non optimal point, therefore increasing operational costs due to decrease in thermal efficiency.

Splitting the balancing activity among power plants in the system reduces the individual plant balancing effort; however the number of conventional plants on-line in the system is being reduced due to increase in wind power generation.

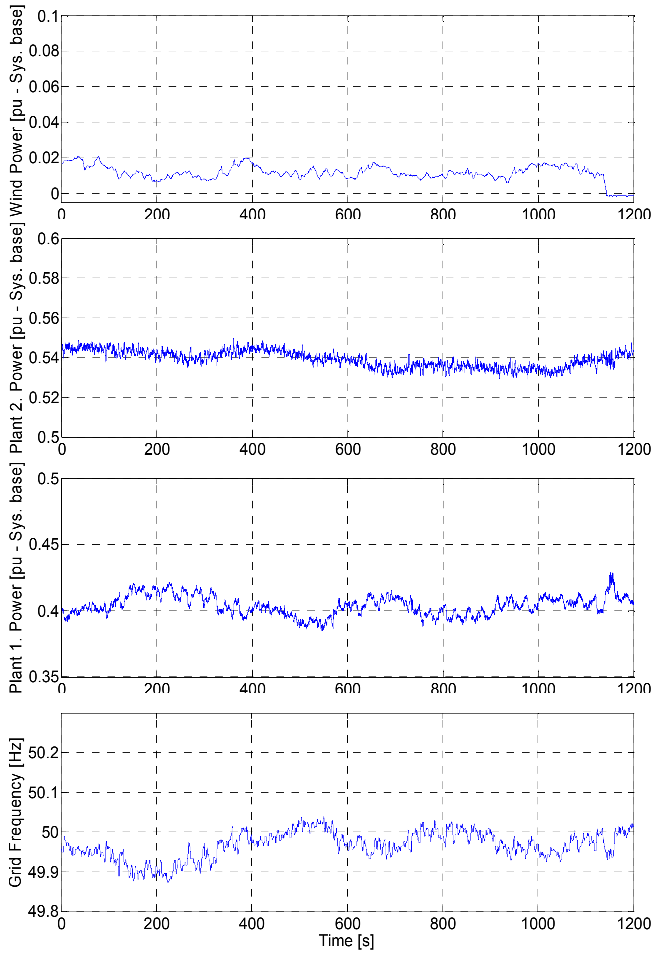

Fig. 5. Measurements. Wind power penetration case 4. Plant 1 with droop action. Plant 2 constant output. Wind power 0.15pu capacity before total turbines disconnection.

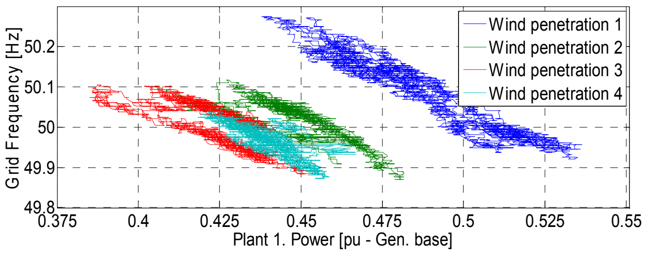

Fig. 6. Measurements. Grid frequency vs. Power output of Plant 1 for each test case.

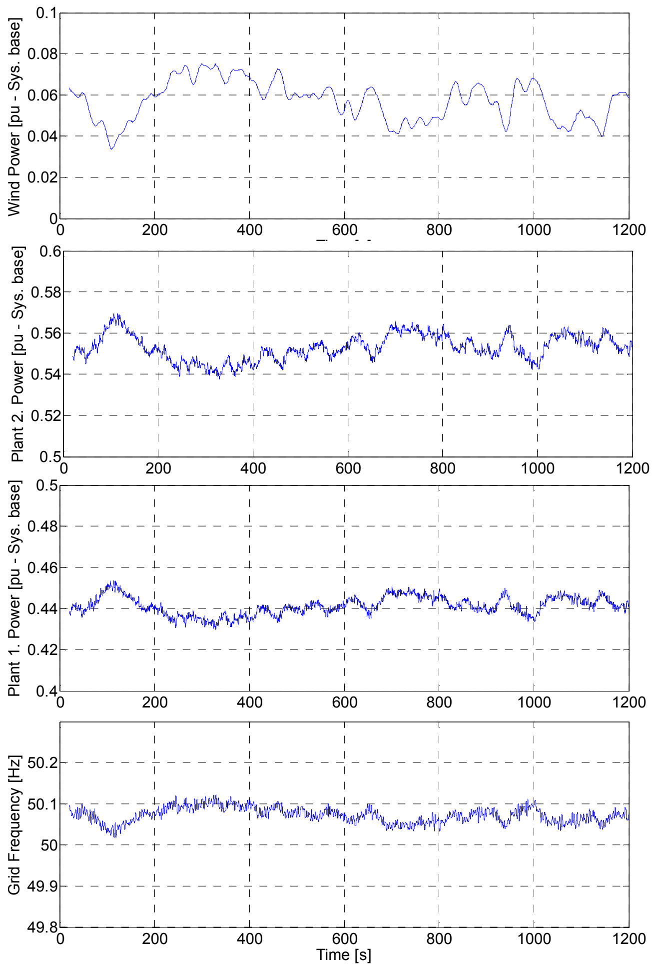

Fig. 7. Simulation. Wind power penetration case 1. Plant 1 and Plant 2 with droop action. Wind power 0.65pu capacity. Load demand is lower than in fig. 2. Compare powers and frequency fluctuations with fig. 2.

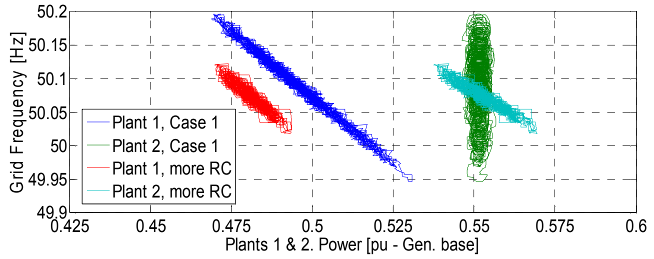

Fig. 8. Simulations. Grid frequency vs. Power output of Plants 1 & 2 for case 1 and for new case with 50% more regulation capacity (RC).

IV. Win Power Plant Control for Power Balance

A typical WPP configuration is exemplified in Figure 9. In this example the turbine power is collected in the MV cable network, and fed through radials to the plant substation. The substation hosts HV and MV switchgear, plant transformer, measurements, protection, master controller and communication, reactive power compensation equipment (SVC, STATCOM, etc). The Point of Measurement (PoM) for three-phase voltages and currents may coincide in most of the cases with the Point of Common Coupling (PCC) – but the PCC may also be upstream from the PoM. A centralized power plant controller (PPC) receives inputs from PoM and executes the WPP control loops, e.g. voltage, frequency, reactive and active power controls using the reference targets sent by, for instance, the Grid Operator and further dispatches the active and reactive power references to the VSWTs and other equipments.

A. *Wind Power Plant Regulation Services*

Most of the active power control forms in a WPP implicate an output power below the available production from the wind, which means a reduction in revenue. By contrast, for conventional power stations the lost revenue is compensated, to some extent, by a reduction in fuel cost. Therefore, system operators and energy regulators recognize that a reduction in wind power output should be used as a last resort [2,6]. Meanwhile, regulation and frequency response services are mostly needed for example during transmission congestion, system power balance, faults to transmission lines and loss of load or generation, among others [2,6,7]. Modern WPPs can provide with useful regulation services during such events.

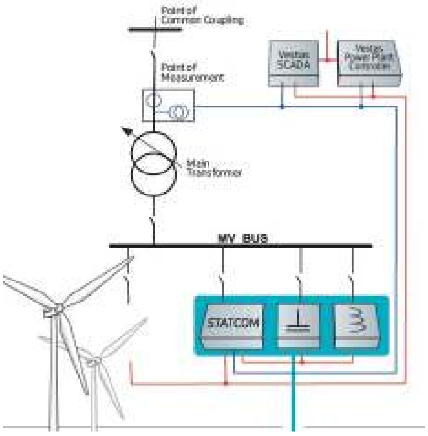

Fig. 9. Generic wind power plant layout showing the main components and signals.

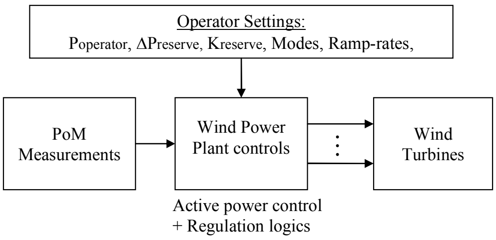

Fig. 10. Simplified block diagram of wind power plant active power control and spinning reserve functionality.

The simplest method for WPP regulation is an absolute limitation value $P_{Operator}$ for the total output power. A more complex version of this limitation is to establish a WPP spinning reserve which can be a fixed amount of power $\Delta P_{Reserve}$ below the available wind power independently of the actual wind speed, or it can be a per cent $K_{Reserve}$ of the actual available wind power.

Figure 10 shows a simplified block diagram with examples of main signals from plant operator for active power and spinning reserve regulation.

B. *Derating and Spinning reserve*

The WPP control allows the possibility of providing other regulation services, e.g. Secondary Reserve (automatic generation control –AGC), if enough spinning reserve from the WPP is demanded [2,6,7].

Some definitions of curtailment mean a restriction of maximum available wind power (derating), which in fact is an absolute production limitation $P_{Operator}$ established by the plant operator. But here we make a difference between derating and spinning reserve. Spinning reserve reduces the WPP production by a specified level below available wind power at any normal wind condition. Thus spinning reserve differs from derating only in partial production operation. Figure 11 illustrates the difference between spinning reserve and derated production – note the curves are idealized. In partial production a derated WPP (blue line) will not produce differently than a non-derated one, nevertheless it will limit the production to the derated power level. A WPP running as spinning reserve will produce less than possible at all wind speeds. A 10% WPP spinning reserve (red line) produces 90% of what is possible both in partial production and maximum production, thus there is always a 10% power reserve from available. Another option is to have a fixed amount of spinning reserve (green line) at all wind speeds.

The PPC spinning reserve controller is designed to decrease the WPP grid power production to attend a given operator request, to enable WPP under-frequency response or to enable WPP upwards regulation capacity.

Equations (1) to (3) describe as example three different modes of operation for WPP regulation. P_{ref}^{Mode-n} represents the PPC active power reference for the respective mode; $P_{Operator}$ is the absolute WPP production constraint set by the operator and which maximum value is the WPP rated power P_{Rated}; P_{Avail} is the total available power at the WPP (given by the actual wind speed distribution); $\Delta P_{Reserve}$ is a fixed amount of power set by the operator for spinning reserve operation (fixed reserve) independently of wind speed conditions; ΔP_{MAX} is a maximum fixed power reserve; $K_{Reserve}$ represents a per cent (or per unit) of spinning reserve from available power P_{Avail} set by the operator ($K_{Reserve}$ can be among 0.0 and 1.0):

1) *Mode 1: Normal or Derated WPP production*

$$P_{ref}^{Mode-1} = \begin{cases} P_{Operator}, & \forall\ P_{Operator} \le P_{Avail} \\ P_{Avail}, & \forall\ P_{Avail} \le P_{Operator} \end{cases} \tag{1}$$

$$P_{Operator} = [0.0, \ldots, P_{Rated}]$$

2) *Mode 2: Absolute spinning reserve. Fixed reserve*

$$P_{ref}^{Mode-2} = \begin{cases} 0, & \forall\ (P_{Avail} - \Delta P_{Reserve}) \le 0 \\ P_{Avail} - \Delta P_{Reserve}, & \forall\ P_{Avail} \le P_{Rated} \\ P_{Rated} - \Delta P_{Reserve}, & \forall\ P_{Avail} > P_{Rated} \end{cases} \tag{2}$$

$$\Delta P_{Reserve} = [0.0, \ldots, \Delta P_{MAX}]$$

3) *Mode 3: Relative spinning reserve. Wind dependant*

$$P_{ref}^{Mode-3} = \begin{cases} (1 - K_{Reserve}) \cdot P_{Avail}, & \forall\ P_{Avail} \le P_{Rated} \\ (1 - K_{Reserve}) \cdot P_{Rated}, & \forall\ P_{Avail} > P_{Rated} \end{cases} \tag{3}$$

$$K_{Reserve} = [0.0, \ldots, 1.0]$$

The spinning reserve and ramp-rate parameters can be remotely set by the plant operator e.g. as shown in Fig. 10.

C. *Frequency Response (Governor Characteristics)*

In networks with relatively high wind power penetration, there is an increased demand that also WPPs provide frequency response (Droop). Modern VSWTs are able to change the active power output very fast at any moment driven by a set point signal. A frequency control loop allows the WPP to contribute towards stabilizing the grid frequency.

The basic principle is that, when instructed, the WPP reduces its output power at a ratio to nominal power rating or available power, and then adjusts it in response to the system frequency. This is done in coordination with the spinning reserve functionality in order to obtain a power reserve. By increasing the power output when the frequency is low, or decreasing the power output when frequency is high, the WPP can contribute with governor characteristics.

Frequency response service is automatic response, which is carried out by the power governor of the WPP. The governor measures the frequency of the system and changes the output of the WPP based on configurable settings. The WPP active power reference is modified according to positive or negative deviations in grid frequency, predefined slope characteristics, dead-band, frequency references and limits.

The WPP frequency controller stationary requirements can be characterized as shown in Fig. 12. Setting parameters as droops (up/down), dead-band, frequency reference, limits and operational modes can be set by the plant operator. Figure 13 shows a simplified block diagram of the WPP frequency response functionality.

The PPC can have the following operation modes for frequency response:

- High and Low Frequency Mode (HLFM): Controller responses to upwards and downwards frequency deviations from reference frequency (power reserve needed).
- High Frequency Mode (HFM): Response only to frequency changes above the reference frequency (no power reserve needed).
- Frequency control Off: The grid frequency does not affect the WPP power set point.

Figure 14 shows an example of a measured WPP frequency response. For the test the WPP was derated to 0.4 pu. The frequency controller was configured with particular droop characteristics for over-frequency and under-frequency respectively (HLFM). In this case, the WPP delivers 100% of set point at frequencies below 49.3Hz. It delivers around 95% of set point value at frequencies from 49.95 to 50.05. At 50.8Hz the WPP delivers approximately 0.17 pu or 44% of set point value.

Figure 15 shows a measurement example of an individual turbine over-frequency response (HFM). The figure shows the wind turbine power response due to a grid over-frequency condition. The over-frequency was simulated using special signal injection. Notice that in this example the gradient of electrical output power is limited by the ramp-rate controller in 1.5 pu/min, which is configurable to a desired value.

With configurable frequency controller architecture, the slope characteristic for over-frequencies and under-frequencies, as well as dead-band and limits can be freely chosen and adapted to specific grid codes, local grid conditions and wind conditions.

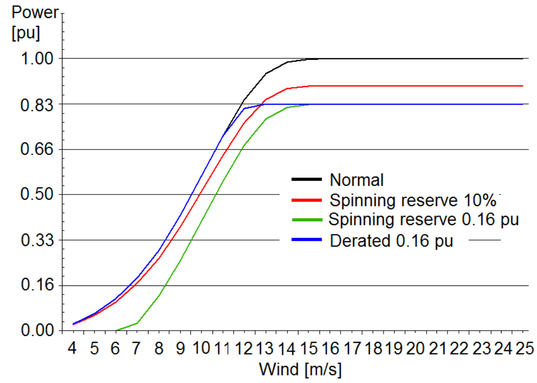

Fig. 11. Power curves showing the difference between derated and spinning reserve operation. Note this plot is ideal but still representative.

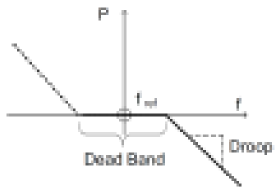

Fig. 12. Characteristics of frequency controller.

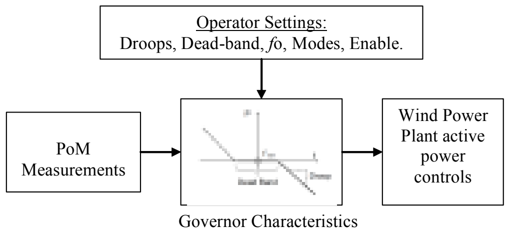

Fig. 13. Simplified block diagram of WPP governor functionality.

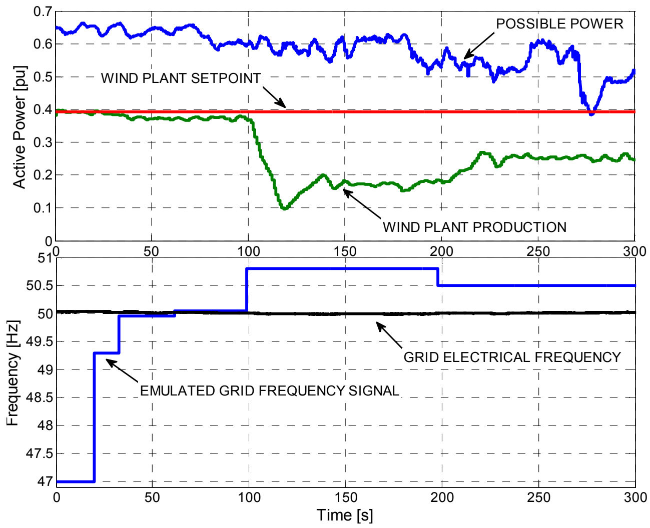

Fig. 14. Measurement example of wind power plant frequency response: For this test the WPP was derated to 0.4 pu.

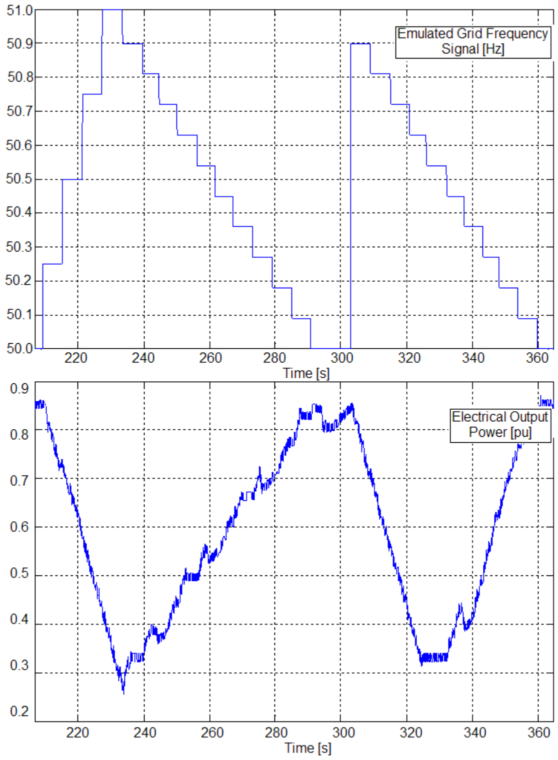

Fig. 15. Measurement example of wind turbine over-frequency response: Test carried out on an individual wind turbine. The figure shows the turbine power response due to a grid over-frequency condition. The over-frequency condition was emulated by frequency signal injection.

D. Inertia Response

During the first few seconds following a power imbalance in the grid the rate of change of the grid frequency is dependent on the total rotating inertia on the power system. Such a grid disturbance can be mainly caused by load disconnection, removal of large generator or large changes in the grid power flow.

The higher the total system rotating inertia, the slower will be the rate of change of frequency. Large thermal or hydro units have large rotating masses, which slow the rate of change of the system frequency. This characteristic is called the 'inertial effect'. Large inertial effect is desirable for grid frequency stability so that primary frequency control on conventional power plants has time to act supplying the deficit in power balance caused by the grid event, thus maintaining the system frequency stability and system power balance.

In modern variable-speed wind turbines, its rotational speed is normally decoupled from the grid frequency by the power electronic converter configuration. Therefore variations in grid frequency do –per default –not alter the turbine output power. With high wind power penetration there is a risk that the power system inertial effect decreases, thus aggravating the grid frequency stability. The decrease of inertia effect on the grid may be even worse in power systems with slow primary frequency response such as those with large amount of hydropower, or in small power systems with inherent low inertia such as islanded systems [9,10].

Power systems similar to the tested in this work, with high wind power penetration, have reached operational conditions where the inertial response potentially available from wind turbines is really needed. Nevertheless, the actual wind power penetration in the vast majority of power systems, in despite of growing fast, has not yet created inertial effect problems because of the presence of large number of thermal and hydro power plants and interconnections with other power systems. Grid codes are still to quantify requirements to turbine inertial response. Research activities are being conducted in this direction, e.g. [10,11], but the focus on functional and real needs for the power system as a whole must be kept. Modern wind turbines are indeed programmable power sources, and present flexibility for very fast control of generated active and reactive powers, inside design limits. It is therefore possible to inject into the grid an active power boost from the wind turbine in such a way that a desired inertial response can be emulated (in a wide range) following a grid disturbance. Figure 16 shows a simplified block diagram of inertia response functionality. Figure 17 shows simulation results of a wind plant providing inertia response in comparison with a conventional plant. At the first power swing the wind turbine is delivering a controlled power boosting to the grid while temporary supporting the system power balance and damping the system frequency change. After the first power swing the wind turbine can absorb a controlled power from the grid providing support to the grid for damping the system frequency change. As modern VSWTs are programmable fast-response power sources, different inertial contribution can be obtained inside design limits. It is especially important to take care of the stability of the wind turbine during the 'recovery period' following a positive active power variation from inertia response [11]. The inertia response capability depends on rotational speed variations, turbine mechanical inertia, and wind speed [10,11], thus the inertia response capability varies with the turbine operational conditions.

Future grid codes may well include wind power inertial response requirements, and such functionality is perfectly possible and reasonable to include in WPP solutions. Thermal & hydro synchronous generation offer higher inertial contributions than wind (per unit MW installed). However, this may be outweighed by the increased configurability presented by the wind power inertial response.

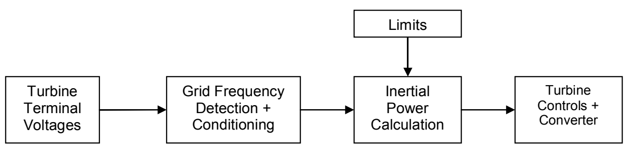

Fig. 16. Simplified block diagram of the inertial response functionality.

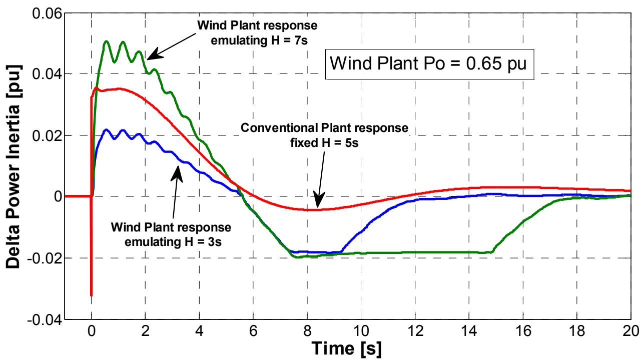

Fig. 17. Simplified simulation of wind plant inertia response functionality.

V. Conclusion

This work analyzed the impact of wind power fluctuations on the power balance and frequency control of a power system with high wind power penetration. Measurement results from real scale tests were presented, where different amount of fluctuating wind power were injected into a power system. The allowed limit for system power fluctuation was shown, which is given by the acceptable variation on grid frequency.

The total amount of wind power fluctuation in the power system can be increased if enough regulation capacity (pu/Hz) is allocated from power plants with droop response; nevertheless this action implies an increase in balancing activity.

The main challenges of wind power for grid integration are the wind speed variability and the location in remote/weak electrical systems. As wind power continues to penetrate in power systems, more advanced functionalities are required from wind power plants (as well as from remaining thermal/hydro plants and power exchange corridors) in order to accommodate large amounts of wind power.

The main features of a wind power plant controller were summarized and supported with performance examples. Modern wind power plants present high flexibility for configuration and settings to match grid code requirements. New features for wind power plants control for providing regulation and frequency response services were presented.

As wind power generation continues to increase, m ore power reserve, more system regulation capacity and higher inertia will be needed from the remaining conventional power plants if the power system frequency stability is intended to be kept by means of standard mechanisms. As the power system dependency on wind power increases, wind power generation has to contribute with dynamic response and control actions that are normally provided by conventional power plants.

VI. Acknowledgment

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