Regulation and Frequency Response Service Capability of Modern Wind Power Plants

Germán Claudio Tarnowski, Philip Carne Kjær, Søren Dalsgaard, Anders Nyborg
Technology R&D, Vestas Wind Systems A/S, Denmark

Abstract— **Wind speed variability generates the main challenges for grid integration of wind power. World-wide, requirements governing generator connection to the transmission grid evolve as the modern energy industry continues to develop. With increased wind power penetration, wind power plants are required to provide grid support and control actions similar to conventional power plants. Dedicated control systems for wind power plants employing variable-speed wind turbines can provide advanced control features for the transmission network operator. The paper summarizes the control characteristics of a modern wind power plant. It identifies the capability of modern wind power plants to offer fast regulation and frequency response services. Advanced functionalities for regulation and response to grid disturbances are also addressed.**

Index Terms— **Wind power integration, wind power plants, ancillary services, frequency control, voltage control, inertia response.**

I. INTRODUCTION

WIND power is an important source of electricity generation. During the first two decades of wind turbines being connected to the public grid, the basic rule for wind turbines was to disconnect from the grid in presence of disturbances. The turbines were designed accordingly and a fairly strong grid was assumed. 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].

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.

We expect emerging Grid Codes to include VSWT-based active and reactive compensation and regulation techniques, for support of participation in ancillary service markets, together with performance features including governor droop characteristics and inertial response.

The most common VSWT types are based on the doubly-fed induction generator (DFIG) and in recent years the synchronous generator full converter (SGFC). When installed into wind power plants (WPP), appropriate advanced turbine & plant control systems must be developed to provide those decisive ancillary services normally provided by synchronous generators powered from conventional sources.

Different control actions can be implemented in modern WPPs, such as:

- Absolute power constraint (derating)
- Power ramp rate control
- Power spinning reserve
- Frequency response (governor characteristics)
- Inertia response
- Reactive power and power factor control
- Voltage control
- Fault ride-through

This paper does not explain the background to why network operation would specify particular WPP control & service features relating to electrical performance. Rather, focus is on explaining features that can be offered by modern WPPs and therefore used in tomorrow's transmission system planning & operation, and in grid codes to come. Important characteristics of the WPP controller are summarized and supported with performance examples.

The paper is organized as follows. Section II introduces to the general WPP architecture and control philosophy; Section III presents regulation services that can be provided by modern WPPs; Section IV briefly presents the capabilities for reactive power and voltage control; Section V exemplifies the capability of modern VSWTs for fault ride-through. Conclusions are in Section VI.

II. WIND POWER PLANT ARCHITECTURE

A typical WPP configuration is exemplified in Figure 1. In this example the turbine power is collected in the MV cable network, normally rated 11kV to 35kV, and fed through

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Germán C. Tarnowski is with the Centre for Electric Technology, Technical University of Denmark and with Vestas Wind System A/S, (e-mail: gctar@vestas.com).

Philip C. Kjær, Søren Dalsgaard and Anders Nyborg are with Vestas Wind Systems A/S, Denmark (e-mails: pck@vestas.com, sdals@vestas.com, anny@vestas.com).

radials to the plant substation. The substation hosts HV and MV switchgear, plant transformer, measurements, protection, master controller and communication. In addition, the substation MV bus can connect to reactive power compensation equipment, such as mechanically switched capacitors or reactors (MSC, MSR) or static VAr compensators (SVC, STATCOM). Figure 1 shows the circuit to the point of common coupling (PCC) and exemplifies some relevant possible communication/control links.

The Point of Measurement (PoM) for three-phase voltages and currents may coincide in most of the cases with the PCC – but the PCC could 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 dispatch the active and reactive power references to VSWTs and any reactive power compensation equipment, so the PPC is acting as master controller of the WPP.

SCADA can be separate from power plant controller to realize reliable & deterministic plant performance. SCADA may still monitor all plant equipment.

Permutations with multiple plants or plant controllers can be extended from the basic configuration in Figure 1.

A. Power Plant Control Philosophy

The PPC controls the plant output power as defined by its actual settings. The PPC is able to provide a fast, dedicated and reliable control platform for fast and precise control of the reactive power and/or voltage and active power/frequency at the PCC. The core plant control algorithms can be located in the PPC and may consist of various loops in coordination:

- Active power limits and regulation
- Frequency response (governor characteristics).
- Reactive power control or power factor control.
- Voltage control.
- Low voltage ride through coordination.

The plant or grid operator remotely sets the desired control modes and specifies the appropriated control references.

III. 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.

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

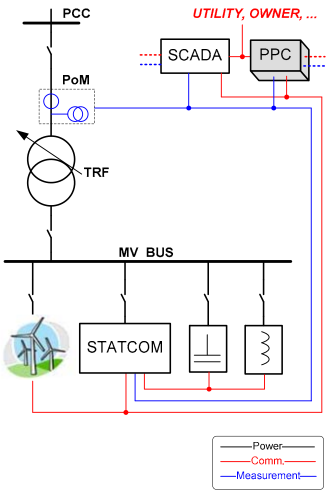

Fig. 1. Generic wind power plant layout showing the main components and signals.

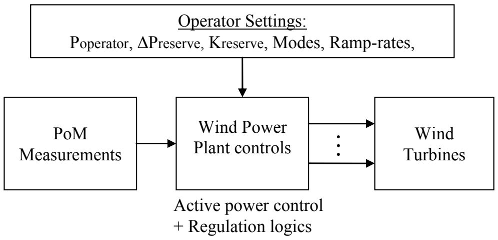

Fig. 2. Simplified block diagram of wind power plant active power control and spinning reserve functionality.

A. Ramp Rate Control

In parallel with production regulation, a modern WPP can be instructed to control the ramp rate (power gradient constraint). In other words, to limit the rate at which the output power can increase (e.g. due to increasing wind speed or turbines returning to operation after some outage). The ramp rate is defined over period of the order of minutes. This limits the network operator's demands on other forms of generation to adjust output rapidly.

It is more difficult for wind generation to control automatically the negative ramp rate if the wind drops suddenly. However, with good wind forecasting tools, it is possible to predict a reduction in wind speed in advance. The output of the wind generation can then be gradually reduced in advance of the wind speed reduction, thereby keeping the negative ramp rate at an acceptable level.

Figure 3 shows a measurement example of WPP ramp-down control. Tests were carried out with particular settings where a maximum ramp down of 0.18 pu/min is not exceeded (violet line). Figure 4 shows a measurement example of WPP ramp-up control. Tests were carried out with particular settings where a maximum ramp up of 0.18 pu/min is not exceeded (violet line). The ramp-rate parameters can be remotely set by the plant operator e.g. as shown in Fig. 2.

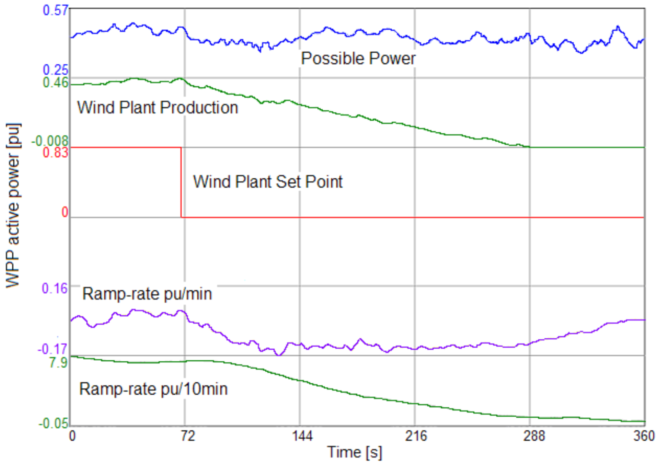

Fig. 3. Measurement example of wind power plant ramp-down control: Test with a particular setting where a maximum ramp down of 0.18 pu/min is not exceeded (violet).

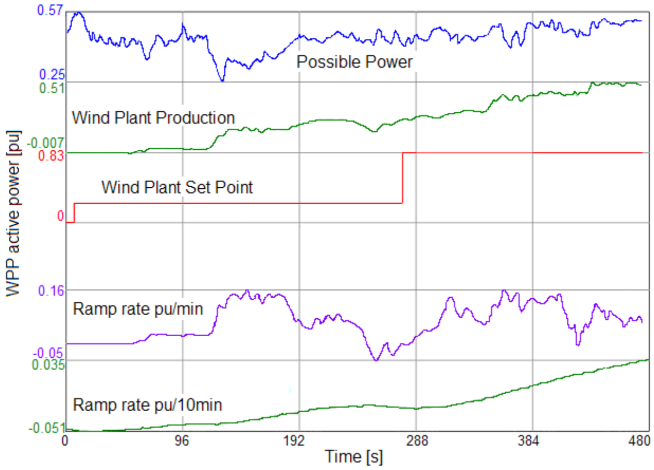

Fig. 4. Measurement example of wind power plant ramp-up control: Test with particular settings where a maximum ramp up of 0.18 pu/min is not exceeded (violet).

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 5 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*

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

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

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

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

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

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

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

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

Figure 6 shows a measurement example of WPP derated operation (Mode 1). With the WPP operating at available power (P_{Avail} ~0.68pu and $P_{Operator}$ ~0.85pu), the $P_{Operator}$ reference was reduced first to 0.39 pu and then to 0.33 pu. For all set points the WPP settles the power output at the corresponding active power constraint with high accuracy. The WPP start decreasing the power output within few seconds after receiving signal from control room. In this example the change in active power production is limited by the ramp-rate control in 0.18 pu/min as shown in Fig. 3. The spinning reserve and ramp-rate parameters can be remotely set by the plant operator e.g. as shown in Fig. 2.

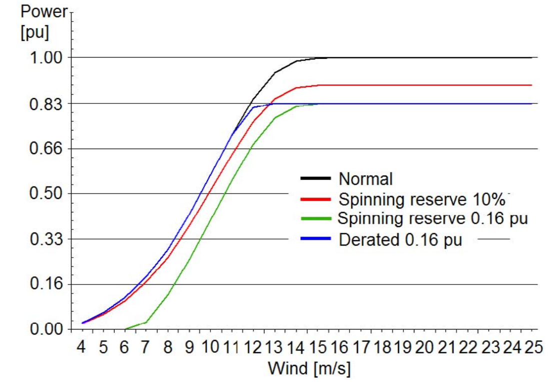

Fig. 5. Power curves showing the difference between derated and spinning reserve operation. Note this plot is ideal but still representative.

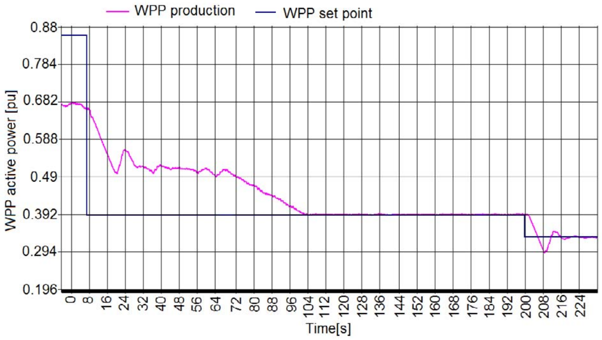

Fig. 6. Measurement example of wind power plant derating

C. *Frequency Response (Governor Characteristics)*

In networks with relatively high wind power penetration, there is an increased demand that also WPPs provide frequency response. 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. 7. Setting parameters as droops (up/down), dead-band, frequency reference, limits and operational modes can be set by the plant operator. Figure 8 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 9 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 10 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.

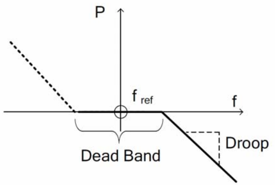

Fig. 7. Characteristics of frequency controller.

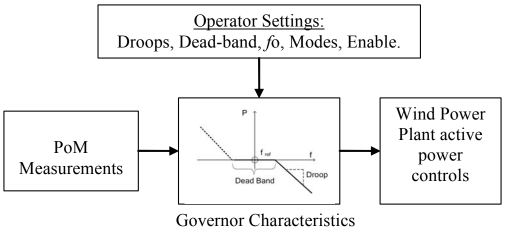

Fig. 8. Simplified block diagram of WPP governor functionality.

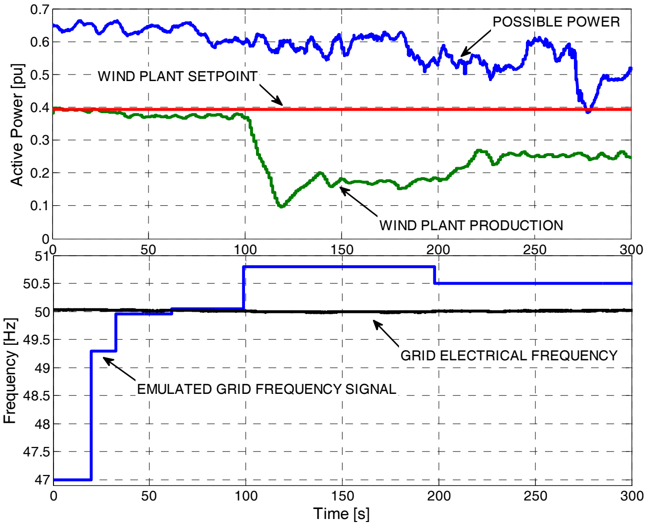

Fig. 9. Measurement example of wind power plant frequency response: For this test the WPP was derated to 0.4 pu.

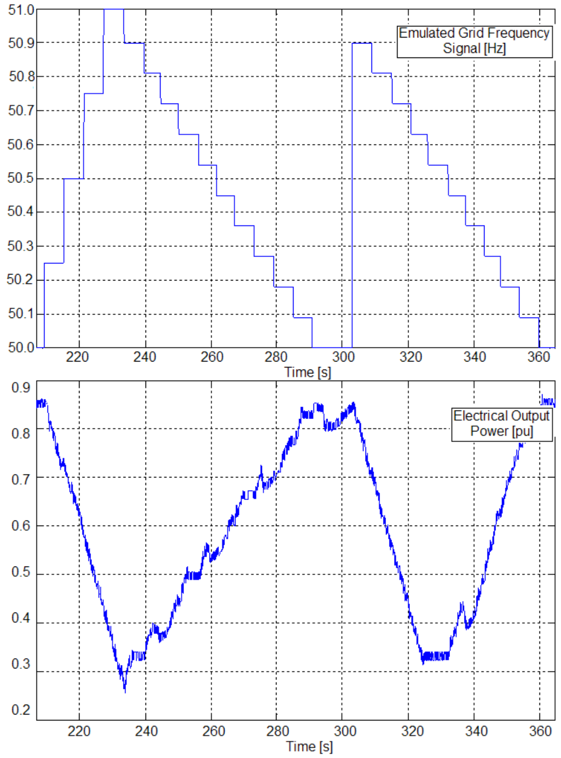

Fig. 10. Measurement example of wind turbine over-frequency response: Test carried out on an individual wind turbine. The figure shows the turbine power response due to a grid over-frequency condition. The over-frequency condition was emulated by frequency signal injection.

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].

We estimate that few, if any, power systems today with recognizable amounts of wind power installed have reached operational conditions where the inertial response potentially available from wind turbines is really needed. The actual wind power penetration in the vast majority of power systems, in despite of growing fast, has not 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.

Nevertheless, 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 11 shows a simplified block diagram of inertia response functionality. Figure 12 shows simulation results of a wind turbine providing inertia response. 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. Due to the short period of the event, the VSWT inertial response is practically energy neutral. 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.

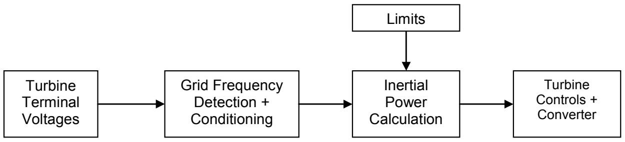

Fig. 11. Simplified block diagram of the inertial response functionality.

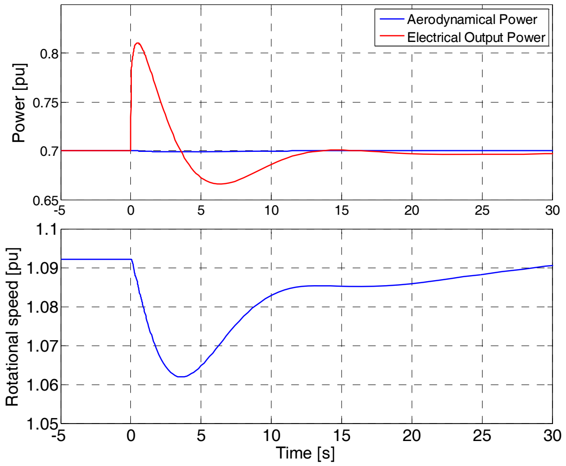

Fig. 12. Wind turbine inertia response functionality. Simulation results.

IV. WIND POWER PLANT REACTIVE POWER

Wind power plant reactive power control and voltage control can employ reactive power sourced from wind turbines taking advantage of their inherent VAr capabilities as well as from any substation-based reactive power compensator. The latter can be added if the turbines reactive power capability is insufficient to meet specific demands. Turbines and compensators can be dispatched alike from the PPC.

A. Reactive Power Control

The system needs are detected at the PCC and corrective actions with reactive power control are carried out with a fast, dedicated and reliable control platform in order to meet the requirements at the PCC. The needed reactive power from wind turbines is determined and, if required, from the external compensation equipment, taking into accounts the references and settings from plant operator. The WPP reactive power controller dynamic response is tuned according to the grid code requirements and local grid conditions.

Figure 14 shows an example of WPP Reactive Power Capability using only turbines. The test was carried out with the WPP producing 60% of active power output. The WPP was exporting VAr while maintaining the voltage at the Point of Common Coupling inside a narrow range (HV side) under variable active power output conditions.

B. Voltage Control

Voltage control is achieved through WPP reactive power capability. The WPP voltage control stationary requirements can be characterized as shown in Fig. 13. Besides a slope controller algorithm, a different voltage controller algorithm could be implemented for specific cases. The voltage controller dynamic response is tuned according to the grid code requirements and the local grid conditions.

Figure 15 shows a measurement example of WPP voltage control, where the test has been performed by changing the WPP voltage set-point (HV side) form 1.00 pu to 1.055 pu. This made the voltage controller see an under-voltage and change the reactive power reference from importing VAr's to exporting VAr's. As can be seen on the figure the plant voltage has reached beyond 90% towards its new target value in less than 1 second. This test includes plant substation capacitor bank switching, yet the response is very smooth thanks to well coordinated control of all reactive sources.

Figure 16 is a similar example of the plant voltage controller response to a negative step in voltage set-point.

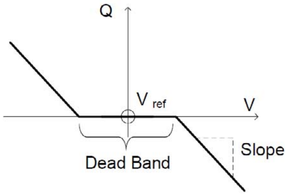

Fig. 13. Characteristic of the PPC – Voltage controller.

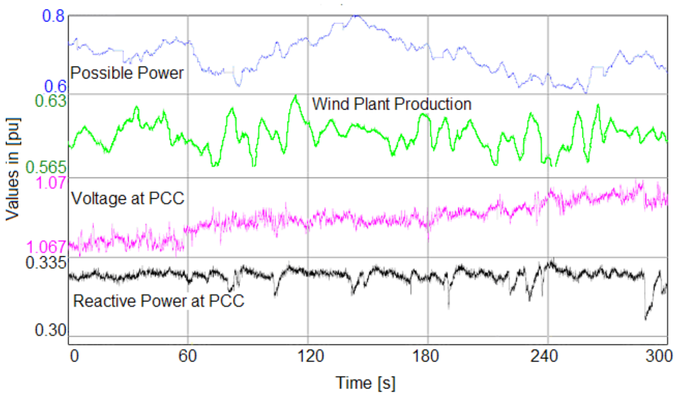

Fig. 14. Measurement example of wind power plant reactive power capability and voltage control: Test carried out with the WPP producing 60% of active power output.

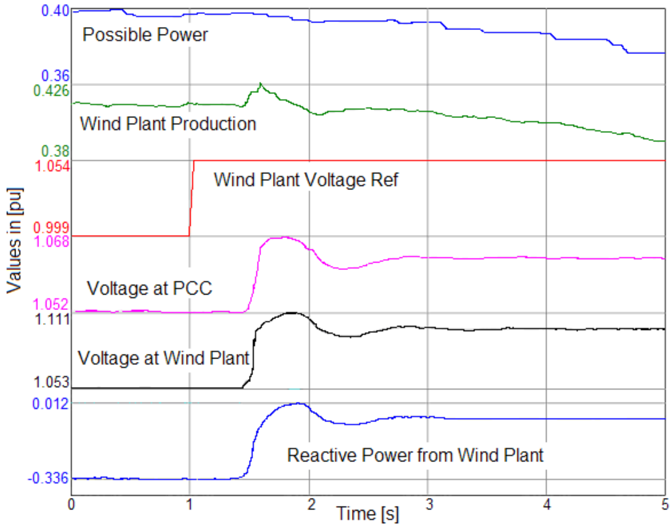

Fig. 15. Measurement example of wind power plant voltage control: This test was performed by changing the WPP voltage set point form 1.00 pu to 1.054 pu.

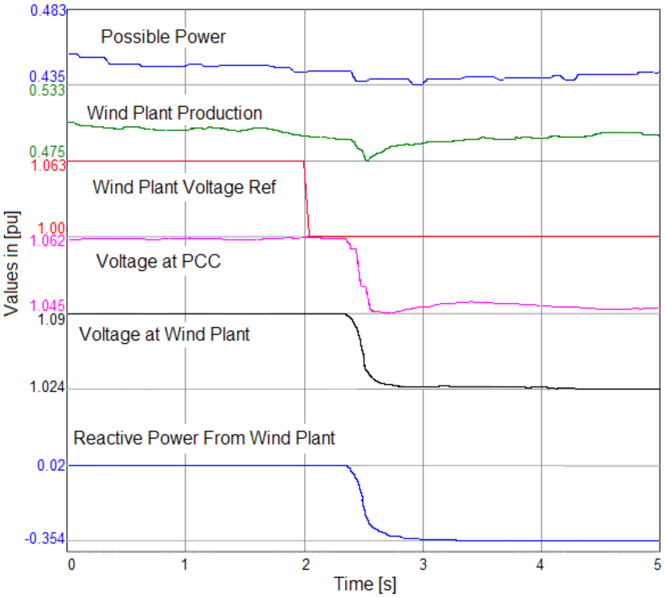

Fig. 16. Measurement example of wind power plant voltage control: Test performed by changing the WPP high voltage side reference from 1.063 pu to 1.00 pu.

V. FAULT RIDE-THROUGH CAPABILITY

Fault ride-through (FRT) standards require WPPs to remain in service during normally cleared system faults, characterized as a voltage-time profile present at the PCC [3-5,7].

Modern WPPs meet the fault ride-through requirements, regardless of whether doubly-fed generators or full-conversion turbines are used. In particular low-voltage ride-through (LVRT) functionality is scrutinised in today's wind plant installations. Tests are conducted at single-turbine level – for example by independent certifying entities employing dedicated equipment imposing short-circuits between turbine and collector grid. The turbine active and reactive current contributions are recorded for a range of fault emulations. Computational simulations are conducted at plant level, using simulation models of the accuracy required by the study in question.

An example of recorded turbine LVRT capability is shown in Figure 17. A 415 ms, 3-phase fault with voltage dip below 23% of rated voltage was applied to the turbine MV terminals. Figure 17 shows the RMS voltages for each phase of the faulted bus. Figure 18 shows the active, reactive and apparent powers from the wind turbine delivered at the MV bus, as result of the voltage dip. The wind turbine is never disconnected from the grid. During the fault the wind turbine controls the active and reactive powers according to pre-programmed profiles. After the fault the controlled active and reactive powers return to their pre-fault values. Figure 19 shows the wind turbine reactive current output during the voltage dip. The wind turbine is contributing with full reactive current (more than 1 p.u.) according to pre-defined profile. Figure 20 shows the wind turbine generator rotational speed during the voltage dip. The generator speed remains stable and well damped.

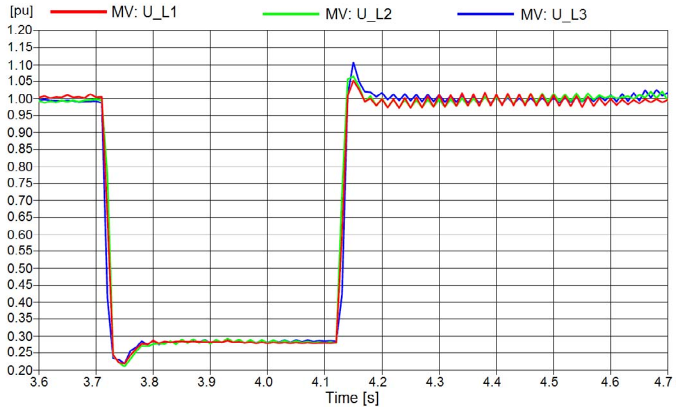

Fig. 17. Example of recorded test of Low Voltage Ride Through from WINDTEST report WT5284/06. It shows the recorded RMS voltage on each phase at the wind turbine terminal bus. Fault duration ~415ms and voltage dip below 23% of rated voltage.

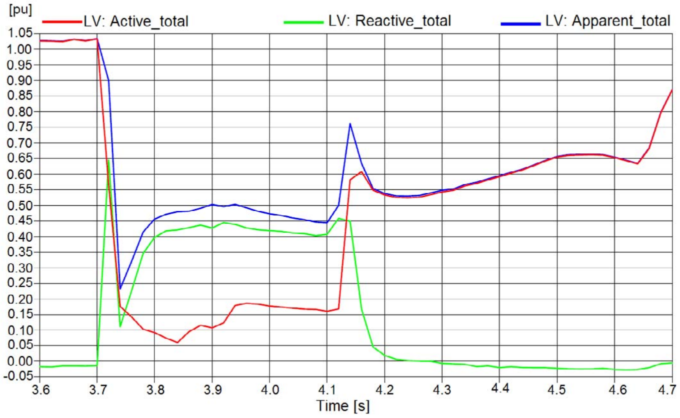

Fig. 18. Recorded active, reactive and apparent powers from the wind turbine as result of the voltage dip shown in Fig. 17. The wind turbine is never disconnected from the grid. During the fault the wind turbine controls the active and reactive powers, according to the pre-defined profiles. After the fault the controlled active and reactive powers are back to the pre-fault values.

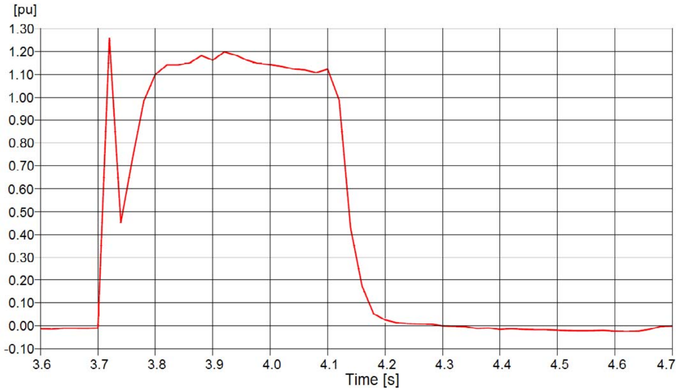

Fig. 19. Recorded wind turbine reactive current output during the voltage dip shown in Fig. 17. The wind turbine is contributing with full reactive current (more than 1 p.u. in this case) according to the pre-defined profile. After the fault the controlled active and reactive currents are back to the pre fault values.

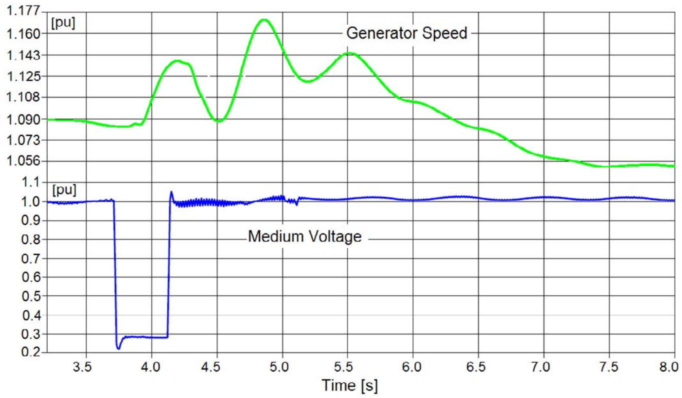

Fig. 20. Recorded wind turbine generator rotational speed during the voltage dip shown in Fig. 17. The generator speed remains stable and well damped.

VI. CONCLUSION

This work presented the functionalities and capability of modern WPPs for providing ancillary services to the grid. The main features of the wind power plant controller were summarized and supported with performance examples. New features for WPP control for providing regulation and frequency response services were presented. Modern wind power plants present high flexibility for configuration and settings to match grid code requirements.

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 system, more advanced functionalities are required from wind power plant in order to provide services and responses similarly to conventional power plants.

Modern wind power plants are able to provide services from active power production that helps the grid operator in different aspects of grid operation and stability, such as power balance and frequency control. Measurement examples of ramp-rate control, absolute constraint, spinning reserve and governor frequency response illustrate that modern wind power plants can provide suitable performance and capability for power regulation and frequency response services. Furthermore, future grid codes may well include wind power inertial response requirements, and such functionality is perfectly possible and reasonable to include in wind power plant solutions. Nevertheless grid codes are still to quantify requirements to turbine inertial response.

Modern wind power plants are able to provide ancillary services from reactive power production such as voltage or power factor control. Measurement examples of voltage control and reactive power production illustrate that modern wind power plants can provide suitable fast reactive power and voltage control capability.

Modern wind power plants meet the fault ride-through requirements from different grid codes, regardless of whether doubly-fed generators or full-conversion turbines are used. This characteristic greatly complements the capability of modern wind power plants for providing ancillary services.

Ancillary services are necessary to be provided from modern wind power generation in order to allow the integration and grid stability. With modern wind power plant controls, functionalities and settings flexibility, power systems can improve reliability and efficiency while increasing the penetration level of wind power.

Ancillary services from modern wind power plants give new possibilities to make extra profits for the owners of flexible power plants.

VII. ACKNOWLEDGMENT

The authors gratefully acknowledge the valuable contribution of Vestas Technology R&D colleagues.

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