

A Review of the State of the Art in Control of Variable-Speed Wind Turbines

Ömer Göksu, Remus Teodorescu, Pedro Rodriguez and Lars Helle

Abstract--The wind turbines constituting large wind power plants are challenged to satisfy the revised grid codes, which require them to withstand grid faults, support grid during faults, and provide ancillary services such as frequency control, and voltage control. In order to meet the grid code requirements, control strategies for variable-speed wind turbines are developed and reported by academy and wind industry, where these strategies are reviewed and discussed in this paper. The strategies for active and reactive power control at the wind turbine level, fault ride-through capability with contribution to grid voltage regulation by reactive current injection, and local voltage control at the wind turbine level are introduced. The support of wind turbines to grid frequency regulation is discussed for main three functions; primary frequency control, inertia emulation, and power oscillation damping. Also, coordinated control solutions between wind turbine controller and wind power plant controller are investigated.

Index Terms—fault ride-through, frequency control, grid code requirements, inertia emulation, power oscillation damping, variable-speed wind turbines, voltage control.

I. INTRODUCTION

As the price of the fossil fuels is increasing and their availability is decreasing; and above all as the environmental problems and climate change are being considered seriously, renewable energy, especially the wind energy is becoming more and more important. As installed capacity of the wind power plants (WPP) in a power system increases, share of the conventional power plants decreases. Conventional power plants, which are based on synchronous generators (SG) directly connected to the grid, have capabilities to provide reliable power system operation and participate in the balancing act. This replacement has influence on the security of the supply since the WPPs do not replace the functions of the conventional power plants. In order to provide reliable power system with high wind energy penetration, WPPs are requested to operate similar to the conventional power plants and to contribute to the power

system operation as stated in the recent grid codes [1] of the countries with high wind energy penetration. Hence, designs of the wind turbines (WT) are being improved by WT manufacturers; especially, control strategies are developed for variable speed WTs, which are the most suitable and promising type to satisfy the grid code requirements.

Research for the control strategies is reported as specific control functions as fault ride-through [2]-[9], voltage control [10]-[11], frequency control [12]-[25]. In this paper a general overview of these control strategies is made. The grid code requirements and wind turbine technologies are briefly introduced before the control strategies, and a discussion is made on feasibility of the strategies at the end.

II. GRID CODES AND WIND TURBINE TECHNOLOGIES

In general, active and reactive power control capabilities, fault ride-through requirements, and ancillary functions such as voltage and frequency control are defined in every grid code; however requirements differ and continuously revised by the progressing requirements of countries, and reviewed in the literature [1]. Grid code requirements are driving the WT manufacturers to modify and improve their designs, in order to satisfy the requirements. Main requirements of the grid codes and brief information about WT types are given below.

A. Active Power Control

For steady-state operations, WT active power output must be controllable according to the requests of the transmission system operator (TSO), which are given through WPP controller. In other words, it must be possible to decrease or increase the active power output from a working point to target value set by the TSO. For instance, in German grid code, the reduction of the power output to the specified value must take place with at least 10% of the network connection capacity per minute. In Denmark, TSO has described the power control requirements in various regulation functions, where the delta control function is shown in Fig.1.

B. Reactive Power Control

WPPs must regulate their reactive power output in response to the grid connection point voltage deviations and setpoint reactive power values commanded by the TSO. The reactive power requirement is related to the grid connection point characteristics as a voltage changing capability, which depends on the short-circuit power of the connection point and the power penetration level. There are three different

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possibilities for reactive power set points at the grid connection point set by the TSO; reactive power, power factor, and voltage set point.

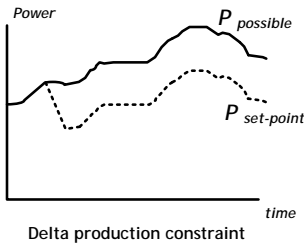


Fig. 1. Delta control requirement in Danish grid code.

C. Fault Ride-Through (FRT) Capability

During grid disturbances, voltage dips can typically lead to WPP disconnections that will cause instability and yield into blackouts. To avoid these problems, the grid codes require continuous operation even if the voltage dip reaches very low levels; and support the voltage recovery by injecting reactive current and active power restoration after the fault clearance with a limited ramp value.

D. Frequency Control

According to the grid codes, WPPs are required to support frequency stability of the power system. WPPs must follow the TSO active power orders by adjusting their active power reserves according to the bilateral agreements signed among the TSO and WPP operators. Hence, WTs must be capable of responding to frequency deviations by adjusting their active power outputs accordingly.

E. Future Functions

There are also functions defined in grid codes as prospective requirements for the near future. For instance, in Spanish grid code inertia emulation and Power Oscillation Damping (POD) functions are given, which mimic the characteristic inertial response and Power System Stabilizer (PSS) capability of synchronous generators to support frequency stability of the power system.

F. Wind Turbine Types

WTs are classified into four main types according to their rotor mechanisms and power structures as; fixed speed (stall or active stall) WT, variable rotor resistance (limited variable speed) WT with controllable external resistance, doubly fed induction generator (DFIG) WT, and full scale wind turbine (FSWT) [30]. The latter two are the variable speed WTs. Fixed speed and variable rotor resistance WTs were widely used for the last decade of twentieth century and had the highest number of installations, due to their simple and cost-effective solution, where the generators are directly connected to the grid. However they are not preferred nowadays, since direct coupling of generators with grid results in high interference, even it has been improved by soft-starters or other solutions, and since their efficiency is not sufficient enough.

DFIG WT has wounded rotor induction generator with slip ring, and the rotor is connected to the grid through two

back-to-back converters via slip ring, where stator is directly coupled to grid. Power is controlled by using the pitch system and also by control of the back-to-back converters. This type is most widely used today since; they provide high efficiency with their variable speed operation, interference with grid is reduced since the rotor is decoupled from the grid, and they are more cost-effective, as their back-to-back converter has partial (30%) rating of WT rated power, compared to the full scale type. However, there is more superiority with full scale type, which will be explained below, regarding the recent requirements of grid codes.

FSWTs are the state-of-the-art type WTs, where generator is completely decoupled from the grid with two back-to-back converters and whole power is transferred through controlled converters. One converter is used on the generator side and the other side is on the grid side. FSWTs can employ both induction (asynchronous) and synchronous type generators, where synchronous generators can be separately excited (conventional) or permanent magnet type.

Since generator and grid side converters are independently controlled, FSWTs provide high flexibility for both wide range of rotor speed operation and easy grid integration. Small changes or faults in the grid, which influence other types of WTs in a higher degree, have almost no effect on the operation of the FSWTs. Therefore, challenging requirements of grid codes create a trend towards FSWTs, whose structure is given in Fig. 2.

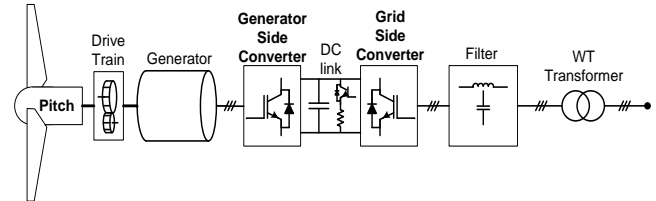


Fig. 2. Full scale wind turbine structure.

III. CONTROL STRATEGIES

In this section, control strategies are overviewed for variable speed WTs, especially for FSWTs. Strategies are analyzed as separate control functions defined in grid codes; additionally coordinated control, which is the hierarchical control structure between WPP and WTs, is introduced separately.

A. Active and Reactive Power Control

The active and reactive power references are commanded to the WT by the WPP controller. Available active power of the WT is calculated in the WT and sent to the WPP controller. WPP controller can command the WT to produce maximum available power value or less than available power value (as a setpoint or a percentage value or certain amount less than available). Reactive power reference is also sent by the WPP controller to the WT as a set value or as power factor. Reactive power capacity of the WT is dependent on the rating of the WT and its contemporaneous active power production. The active power reference is given to the generator side, and grid side converter is responsible for injection of reactive power to grid and DC link voltage regulation.

B. Fault Ride-Through

As stated in the grid codes, WTs are requested to withstand faults in grid, especially low voltage faults and support the grid voltage with reactive current injection during fault. During low voltage faults, power injected by the grid side converter is limited due to limited converter current ratings and power income from the blades cannot be decreased by pitch system as fast as voltage of the grid drops. Hence either acceleration of the WT or power imbalance between two back-to-back converters occurs. An imbalance between converters, results in increase of DC link voltage. In order to solve the imbalance problem, grid side converter is overloaded with high currents for a short time and/or chopper resistance is utilized. Moreover, reactive current support during fault has to be provided.

In [2], [3], it is shown that use of chopper resistance during low voltage faults and reactive current injection via voltage control improves fault ride-through capability of the FSWT. It is stated that voltage control capability of an offshore WPP comprised of FSWTs, can help an offshore WPP, in the vicinity of it, comprised of active stall WTs to ride through a low voltage fault. Also in [4], it is stated that, power imbalance can be solved by decreasing power income from the generator by employing a cross-coupling between two converters.

In [5] and [6], the power imbalance during the low voltage fault, as shown in Fig. 3, is shown to be solved by using chopper resistance. For the worst case, it is assumed that the WT was operating with full power initially and grid side converter cannot be overloaded. Also it is stated that, due to the low response of pitch system (max 10-20° per second), decrease of generator power is not effective for short time faults (as 100 ms) and chopper is the suitable solution. Additionally, sizing for the DC link capacitance required to solve the power imbalance problem is done and solution with using larger capacitance is shown to be impractical.

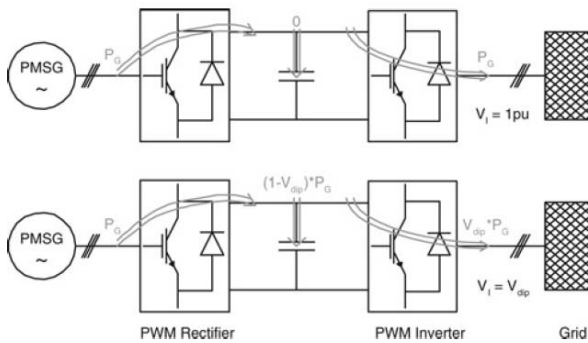


Fig. 3. Power imbalances during low voltage fault [5].

In [7], fault ride-through capability of a 3.6 MW Siemens FSWT is analyzed both by experiments and simulations. Two different low voltage faults are created as 0% retained voltage with 250 ms fault duration, and 50% retained voltage with 710 ms fault duration. Results show that, FSWT can ride through low voltage faults successfully. In [8], fault ride-through behaviors of DFIG WT and a SG are compared, where DFIG WTs are equipped with reactive

current injection proportional to the voltage drop, as required in grid codes. It is commented that; during deep voltage sags, the SG feeds in more reactive current than the DFIG-based WPPs and thus gives a stronger support to the grid voltage. However, for smaller voltage dips resulting from distant faults, the DFIG can feed-in higher reactive currents. Despite their rating and thermal limits, variable speed WTs with power electronic converters, have advantages such that fast control of the converters allows fast adjustment of the reactive and active currents within the current limits of the system during faults, while in the SG, the transient reactive current is determined by the generator parameters.

In [9], WPPs with DFIG and direct drive SGs (FSWT) are investigated both with a single machine infinite bus and four-machine system simulations. A three-phase ground is created and it is commented that, with its full converter the FSWT can provide more reactive power and ride-through better than DFIG WTs during faults.

Grid voltage support by reactive current injection during fault and post fault is further improved by voltage control methods, which are explained in the following section.

C. Voltage Control

WPPs are requested to support the grid with reactive power injection in order to provide voltage stability. Voltage control can be implemented mainly as two different ways: Injection of reactive current/power based on voltage drop amount (droop control) (Fig. 4) or injection of reactive current/power based on closed loop voltage control (PI control) (Fig. 5).

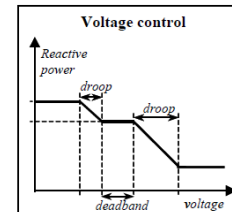


Fig. 4. Droop type voltage control [26].

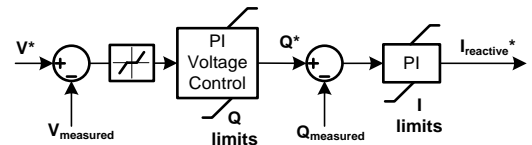


Fig. 5. Closed loop voltage control [2].

When voltage support is provided as droop control (Fig. 4), certain amount of reactive current/power proportional to the voltage drop is injected to the grid; even the converter is in a situation to provide more reactive current/power. However, when closed loop voltage control methods (Fig. 5) are employed, reactive power reference for the grid side converter is generated effectively, so that the converter can contribute with its maximum reactive power capability to voltage re-establishment.

Results of [10] shows that closed loop voltage control of the FSWT provides enhanced voltage stability when an inductive load is connected to the output bus of the FSWT.

In [11], a novel approach, shown in Fig. 6, where WTs are operated by reactive power commands and voltage control loop is implemented as an inner loop of reactive power loop at the WT level. In [11], time constants for reactive power loop are stated to be higher than of voltage loop. Hence, voltage loop is placed inside the reactive power loop, where the reactive power value is commanded from the WPP controller. It is stated that, voltage stability is improved by defining voltage limits and it is claimed that, proposed method mitigates voltage flickers at the output of the WT and prevents voltage deviations (caused by external events), while sustaining the requested reactive power both at the WT and WPP levels.

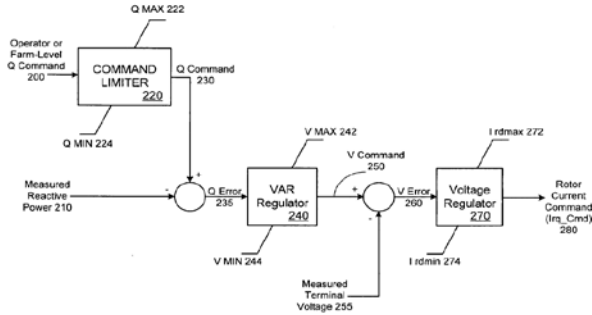


Fig. 6. Reactive power control based on voltage control [11].

D. Frequency Control

Frequency stability of power system is related with the balance of generation and load. When a change occurs in load or a generating unit disconnects, frequency deviates from the nominal value, and conventional power plants support the frequency stability of the system with the use of following capabilities of synchronous generators;

- Primary frequency control (governor) of SGs
- Inertial response of SGs
- Power System Stabilizer (PSS) units of SGs

Following the transient response of the SGs, if the power system settles to a new operating point but the frequency is retained in a value other than the nominal value, then the Automatic Generation Controller (AGC) of the TSO sets new active power references in long term, which is called secondary frequency control.

WTs, which constitute large WPPs, can be donated by frequency control functions as primary frequency control, emulation of inertial response, and power oscillation damping (POD). These functions differ regarding the characteristics of frequency change that they respond, however changing active power output is common for implementation of all three functions. These functions can be realized by WTs via changing their active power outputs, based on the measured grid frequency, as shown in Fig. 7 and explained below;

Primary Frequency Control (Droop):

Primary frequency control is realized as a droop function by governor of the SG, which changes mechanical power input proportional to deviations in grid frequency. For WTs, primary frequency control can be realized in similar way, by changing the active power output of the WT, proportional to the deviation of the grid frequency.

Inertia Emulation:

Synchronous generators (SG) of conventional power plants have high inertias, which can store huge amount of kinetic energy while rotating with synchronous frequency. During a frequency change in grid, which corresponds to speed change for a SG, that inertia provides extensive amount of energy to stabilize the frequency to nominal value; i.e. inertia is the opposing response of SGs to frequency (speed) changes. Control algorithms for converters of variable speed WTs are designed to mimic the inertial response of SGs, which is called as inertia emulation. Inertia emulation is realized by WTs, via changing the active power output of the WTs based on the derivative of the measured grid frequency.

Power Oscillation Damping (POD):

POD is damping of active power oscillations in power system, which are observed in grid frequency. Traditionally, power system oscillations are damped by PSS units of SGs by injection of active power counteracting the oscillations. PSS action can be realized by WTs, via changing the active power output of the WT based on the oscillations in the grid frequency. First, oscillations are detected by filtering and then counteracting response is given by the WT.

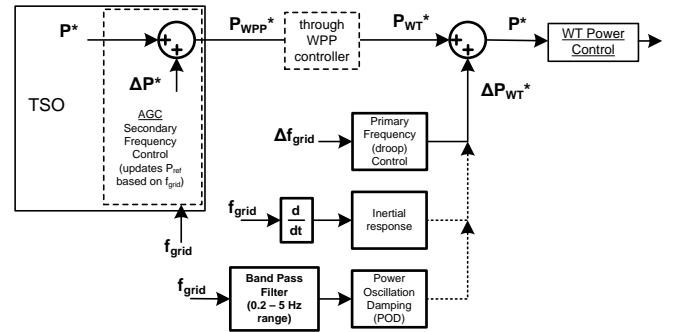


Fig. 7. Frequency control functions by WTs.

Briefly, for frequency control, active power output of the WT is changed based on the measured frequency of the grid. Challenging issue for frequency control has been to increase active power output of the WT in case of a frequency drop. Mainly the following methods have been developed in the literature to provide necessary active power from the WT:

1. Keeping a reserved power by operating the WT as derated (delta control)
2. Decelerating the WT to obtain extra power from the stored kinetic energy of the rotating inertia of the WT
3. Using excessive power if the WT is at rated power and wind speed is higher than rated.
4. Using energy storage (battery) system inside the WT

For the first method, where there is power reserve (derated operation), implementation of frequency control function is only changing active power reference.

In the second method, kinetic energy stored in the rotating WT rotor is extracted by decelerating the rotor. However, amount and duration of the extra power absorbed from the kinetic energy of the WT rotor is limited by its initial speed and recovery to initial speed after deceleration has to be controlled. This method is the most popular one in

the literature. Even it seems similar to the inertial response of the SGs; it is different for WT case; When the WT is decelerated, it can no longer provide same amount of power as before, since power input from the blades changes with tip speed ratio. Also, stored kinetic energy of the WT is dependent on the rotor speed, hence wind speed.

Third method can be used when there is excess wind power (above rated wind speed). Using this excess wind power by overloading the converter and generator (for limited duration) is considered to be another way to increase active power output for frequency response, which can bring thermal and mechanical stress problems.

The last way to provide extra power is to employ an energy storage (battery) system in the WT. Then, necessary active power for frequency support can be easily provided from the storage system.

In [12], active power outputs of the DFIG WTs are increased as a droop function. Results are given in Fig. 8, where response to a load increase is shown for different wind power penetration levels.

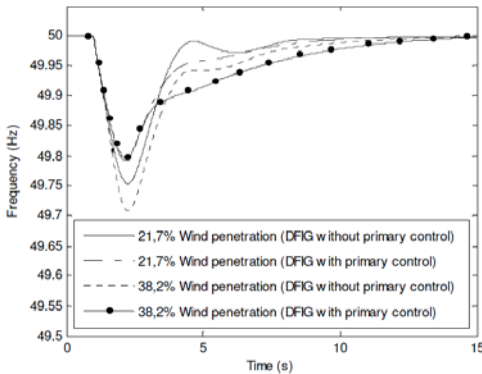


Fig. 8. Response with and without frequency support by WTs for different wind power levels [12].

In [13] the additional power is obtained from the kinetic energy that is stored in the rotating mass of the turbine (the second method above). Two different control strategies, inertia emulation and droop controller (primary frequency control) are implemented and compared. Active power output is changed based on the measured grid frequency by changing torque reference of the speed control loop. It is shown that, both control methods improve the frequency stability of the grid substantially (Fig. 9). However, increase in active power output is significantly lower for the droop control than for the inertia control. Thus, rate of change of power is less for droop control method, which lowers mechanical stress and torque pulsations in the drive train. Hence, droop controller seems to be preferable above the inertia controller.

In [14] only primary frequency control function is employed and activated when frequency drops to 49.9 Hz. When extra power is supplied during frequency support; speed of the WT decreases below its optimal value and power output of the WT decreases due to its aerodynamic characteristics. So, a drop in frequency is observed when WTs cease frequency support and start to recover to their initial speeds by decreasing their output power (Fig. 10). However, support is still preferred to mitigate the frequency

drop and this power lack period is mitigated by overall control of WPP controller, as proposed in [15], by starting recovery of WTs at different times; gradual turn-off of frequency support.

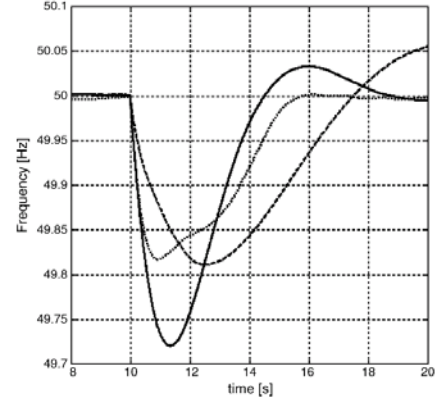


Fig. 9 Response to a frequency drop in the system; without WT contribution (solid), with inertia emulation (dashed), and with droop control (dotted) [13].

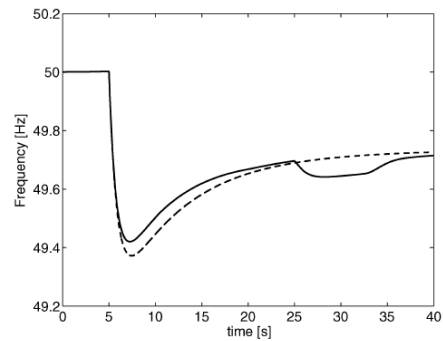


Fig. 10. Response to a frequency drop; without WT contribution (dotted), with WT frequency control (solid) [14].

In [15], frequency support when WT is operating at 100% rated power and has 120% available power (third method) is also analyzed. In this case, the extra power for frequency support is supplied from that excessive power and drop of active power after support period is not observed since WT is able to continue with 100% power.

In [16], second method, based on kinetic energy of WT, is utilized to obtain extra power from the WT while operating it in derated power and intentionally at high speed. Speed of the WT is reduced to a low speed point, where same derated power value can be provided after deceleration. Hence, only the stored kinetic energy is supplied during the support period and decrease of power level after support is avoided. However, WT is operated as derated and in order to provide the same support with kinetic energy again, WT has to be accelerated to the high speed point again.

In [17], first and second methods are combined such that power reserve (derated operation) is provided while keeping the WT at high speed. When power reference is increased to maximum available power value, both the reserved power and kinetic energy of the WT are utilized while decelerating to the optimum speed value. Hence, better frequency support is provided with more power increase, as shown in Fig. 11 below.

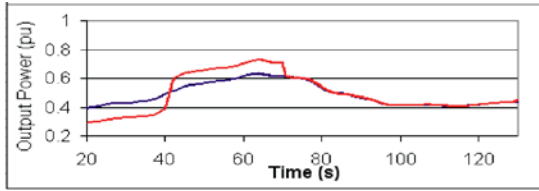


Fig. 11. Output power increase, utilizing both the reserved power and stored kinetic energy; available power (blue), output power (red) [17].

In [18], second method is analyzed for three different ways, as deceleration from point 2 to optimal; from point 2 to point 1; and from optimal to point 1, as shown in Fig. 12 below. Also, operating the WT with high rotor speed at low wind speed as a flywheel is proposed to provide frequency support for a short duration of time.

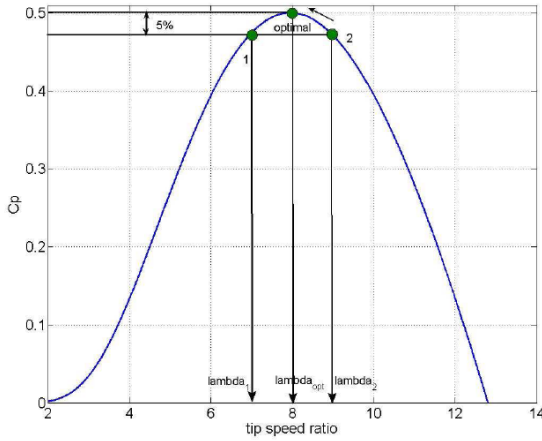


Fig. 12. C_p curve and the different operating points (under optimal speed-1, optimal speed-opt, and over optimal speed-2) [18].

In [19], inertia emulation is realized by the second method given above, decelerating the WT, where the WT was operating at maximum available power. The WT is decelerated by two different ways, first increasing the output power and updating it while considering the decrease of available power due to speed decrease and second; keeping the output power at a high constant value without considering the decrease of available power due to speed decrease. The second way results in a larger inertia support but more speed decrease and thus larger power loss after support period. It is stated that, appropriate way will be determined based on the characteristics of the power system, where the WT will contribute to frequency support.

In [20] and [21], POD function is implemented for full-scale WT with synchronous generator where the extra power is obtained utilizing the second method above. POD is implemented as a droop function and droop constant is continuously adapted depending on the rotational speed of the rotor since available kinetic energy is dependent on the speed. It is stated that, since the variable speed WT controls the power solely with its inverter, rapid and large power variations are easily supplied, which is advantageous for power system stabilization.

In [22] POD is implemented for DFIG WTs and it is shown that POD function of DFIG WTs can significantly contribute to the network damping. It is stated that, WTs, which include POD function, can perform the PSS action of

SGs, without degradation of voltage control, which occurs in case of SGs. Post fault voltage swings, which are caused by the coupling of PSS action in SGs, are avoided in case of POD action of DFIG WTs.

In [23], frequency stability is analyzed considering the load characteristics in the power system. It is stated that, voltage controlled WTs may have an adverse effect on frequency stability, and frequency dependent voltage control is proposed, which is able to contribute to frequency stability by utilizing the voltage dependency of the loads.

In [24], influence of wind power integration in Ireland's power system is analyzed. It is shown that effective inertia of the system decreases with installation of fixed speed or DFIG WTs. It is also shown that adding a frequency control function to the DFIG WTs improves the frequency stability of the power system.

In [25], contribution of energy storage (battery) system to frequency support is considered as an option.

E. Coordinated Control within Wind Power Plant

Up to this section, control of WT is considered as independent control of a single WT, where response is realized at the output of the WT. Interaction between WTs in a WPP, and control of WTs in collaboration with WPP controller are among the most important and practical issues to be dealt, in order to provide stability within the WPP, and compliance of grid codes at the PCC of WPP with high performance. In practical, when several WTs are connected, there can be the risk of interaction between WTs, such as oscillations against each other (intra-plant oscillations) or voltage instability within the WPP; and effect of communication delays needs to be analyzed.

In [26] it is pointed out that; control of frequency and voltage have to be realized at WPP level instead of local control at WT level, since frequency and voltage response are requested at PCC point of WPP. The reason for removing frequency control functions from WT level is stated to be the risk that the WPP controller can counteract the frequency control implemented in the individual WT. Regarding voltage control, it is stated that there is a risk of instability and a high flow of reactive power between the WTs, if voltage control is implemented locally at WT level.

In [27] a novel control structure comprising of WPP and WT level control is proposed for voltage control function, especially in cases of voltage deviations due to active power fluctuations and low voltage faults. The proposed structure is a cascaded system, where voltage control function is shared between WPP controller and WTs, as represented in Fig. 13. Local voltage control capabilities of WTs are utilized as fast inner control, while centralized slow control is implemented in WPP level. In this method, TSO does not need to rapidly change the setpoints of the WPP, hence aggressive controller settings and fast wind farm communication hardware are not needed, and local voltage stability within the WPP is provided by WTs.

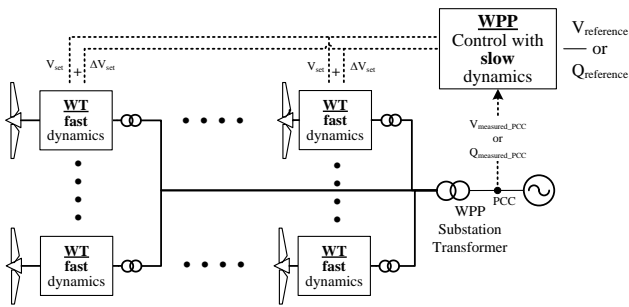


Fig. 13. Coordinated voltage/reactive power control based on voltage control of WTs [28].

In [4], interaction between full scale WTs is analyzed by simulation of a WPP (160MW) with eighty 2MW WTs during a short circuit fault, where voltage drops to 50%. In both cases, no interactions occur between WTs, such that they show coherent response. Also it is stated that, no interaction with dynamic reactive compensator device is observed. Author state that it may be expected in case of well-tuned converters, there is no mutual interaction between the converter controlled wind turbines, of full-scale or DFIG types.

In [28], reactive power or voltage output at the PCC of WPP is controlled in substation level, utilizing the tap changer of WPP transformer and voltage control capability of individual FSWTs. When tap changer is utilized in order to recover a voltage or reactive power drop at WPP output, voltage level within the WPP network decreases, which causes the WTs to produce more reactive power, thus contributing to the request at PCC of WPP. Also, response is improved by closed loop control of voltage (or reactive power or PF) at substation level by adjusting voltage setpoints of the WTs.

In [29], interaction of full-scale WTs with the grid is experienced as an oscillation due to the resonance between current control loops of converters and impedance seen, which includes transformers, filters and capacitance of the long cables to PCC of WPP. The interaction is shown to be solved by designing proper current control algorithms for converters of WTS.

IV. DISCUSSION OF CONTROL STRATEGIES

The control strategies developed in the literature and reviewed in this paper are partially implemented and continuously being improved by WT manufacturers in order to respond growing demands of the market. However, influences of the strategies have to be analyzed by simulations and field tests to see the expenses and benefits properly.

When the methods of obtaining extra power from WTs for frequency control are compared, there is a trade-off between expenses and benefits of each. When power is supplied by keeping a power reserve, then response would be effective without any loss after frequency support period; however, reserved power would be a loss regarding maximum productivity. For the second and third methods, where kinetic energy of the WT is utilized or it is overloaded more than rated, extra power would be supplied for a limited

time period which has to be analyzed whether it is effective or not for frequency support. Also, the resulting power level would be less than initial; and mechanical and thermal stress created on the WT by overloading would not be preferred, even there is no productivity loss. Employing energy storage would give superior results for providing extra power during frequency support, but with the highest economical cost. Hence, feasibility of the control strategies needs to be discussed between TSOs and WPP owners, and agreements have to be made on optimum solutions.

In summary, for proper contribution of WTs to reliable power system operation, analysis has to be made before; and characteristics of the power system, where the WTs will contribute, have to be considered to obtain superior results.

V. CONCLUSION

In this paper, control strategies for variable speed wind turbines (DFIG and full scale types) are reviewed. First, grid code requirements and wind turbine types are introduced briefly. Control strategies are given as separate functions, which are; active and reactive power control, fault ride-through, voltage control, and frequency control. Also, coordinated control approaches, based on hierarchical control structures in wind power plants are introduced. Finally, implementation and influence of control strategies are discussed.

VI. ACKNOWLEDGMENT

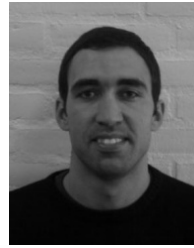
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VII. REFERENCES

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VIII. BIOGRAPHIES



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