Wind Power Plant Control - An Overview

Mufit Altin, Remus Teodorescu, Birgitte Bak-Jensen, Pedro Rodriguez, Florin Iov, Philip C. Kjær

***Abstract*-- Recent developments in wind turbine technology go towards installation of larger Wind Power Plants (WPPs). Therefore, power system operators have been challenged by the WPP penetration impacts in order to maintain reliability and stability of the power system. The revised grid codes have concentrated on the WPP connection point and as a result a WPP is considered as a single power plant. Nevertheless, compared to conventional power plants, WPPs have different inherent features such as converter-based grid interface technology, internal electrical layout, and asynchronous operation of turbines. Taking these into account, a WPP controller is the key factor in order to satisfy the grid code requirements. This paper presents a comprehensive overview of various WPP controller strategies comprising active power, reactive power, voltage, frequency, and emulated inertia control. The WPP control architecture composed of WPP control level and wind turbine control level is also discussed considering the hierarchy and coordination of these levels.**

***Index Terms*— active and reactive power control, emulated inertia control, frequency control, wind power, wind power plant control,**

I. Introduction

BEFORE the rapid increasing of the wind power generation, wind turbines had been considered as distributed energy sources in medium and low voltage distribution systems. The wind turbine technology was not adequate to participate in power system control in response to voltage or frequency disturbances [1]. Common practice during a system disturbance was to disconnect the wind turbines and reconnect them after the fault clearance. However, recent developments in wind turbine technology have changed this picture and TSOs have revised their grid codes for connection and operational requirements to reduce the impacts of the large WPP installations. Denmark and Germany have led these grid code revisions among the other countries due to their high wind power capacity [2], [3]. In Spain, the TSO has also revised the grid code including future requirements that are introduced for planned wind power installations in order to maintain stable and reliable integration [4]. Technical analyses and comparison of the most recent available grid code editions with the wind turbine technologies are surveyed in the literature [5], [6]. All these studies with the experiences from recent years have pointed out that WPPs should be treated like conventional power plants. Accordingly, grid codes have concentrated on the WPP connection point rather than the wind turbines connection points.

Furthermore, in a conventional power plant, generating units usually have identical controllers, i.e. governors and excitation system, with similar controller settings. They are connected to the same bus through common or individual step-up transformers. Thus, the general approach for modeling and evaluating the performance of the power plant is that one synchronous generator with its controllers can represent the overall power plant response. In some applications, conventional power plants are equipped with joint control functionality which provides the power plant operator to control the generating units as a group, working together on the basis of single active and reactive power generation set points [7]. As a result, the power plant control features are implemented with a single generating unit and should satisfy the grid code requirements.

WPPs have completely different aspects from the above discussion which bring additional considerations to the control system. The control structure is not straightforward as in the conventional power plant case mentioned above. The characteristic aspects of the WPPs can be summarized as follows [8]:

- WPPs have wind turbines with converter-based grid interface technology (permanent magnet synchronous generators and squirrel cage induction generators with full-scale converters or doubly-fed induction generators with partial-scale converters).
- The rotor speed of the wind turbines is varying and fluctuates due to the wind (variable wind speed turbines). In other words, wind turbines rotor speed is eventually decoupled from the frequency of the transmission system due to the usage of the induction generators and full-scale converters.
- In WPPs, the typical size of the wind turbines is much smaller with respect to conventional units (from kW to MW range).
- WPPs are not simply collections of individual wind turbines, they have collector systems and other devices (energy storage, FACT, etc.) with controllers. This means each individual wind turbine terminals face different operating

This work was supported by Vestas Wind Systems A/S.

M. Altin is a PhD student at Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: mua@et.aau.dk).

R. Teodorescu is with Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: ret@et.aau.dk)

B. Bak-Jensen is with Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark (e-mail: bbj@et.aau.dk).

P. Rodriguez is with the Technical University of Catalonia, Spain. (e-mail: pro@et.aau.dk).

F. Iov is with Vestas Wind Systems A/S, 8200 Århus, Denmark (e-mail: fliov@vestas.com)

P. C. Kjær is with Vestas Wind Systems A/S, 8200 Århus, Denmark (e-mail: pck@vestas.com)

conditions from the point of connection during the steady-state and the transient situations.

- Each individual wind turbine has its own electrical and mechanical control systems (wind turbine control level).
- Active and reactive power controls are decoupled in the converter-based wind turbines.

Therefore, in large WPPs wind turbines have to be managed from a higher and centralized control level, here called as WPP control level. The WPP control level is an interface between the WPP (wind turbines and if available, reactive compensation or energy storage devices) and the transmission system, and therefore, also the WPP operator and TSO. The WPP control usually regulates the production of the WPP based on the TSO demands and the connection point measurements. Additionally, the WPP control level is a key factor to control the wind turbines centrally in an efficient and hierarchical way while satisfying the grid codes.

To be able to implement the WPP control level, aggregated models are used in the literature [9]-[11] for the overall WPP, which is represented as a single wind turbine without losing the wind and collector system characteristics. Another approach is to model the WPP as individual wind turbine and the WPP control functions are implemented at this wind turbine control level. This approach aims to gain wind turbines the required WPP functionalities. After implementing the control structure, evaluation is performed for the proposed controller in order to fulfill the grid code requirements [12], [13].

So far, the mentioned approaches are based on a single control level without a hierarchical architecture or distribution of the control functions among several control levels (i.e. WPP and wind turbine control levels, if available FACTs and energy storage controllers). But, in this paper, a comprehensive overview of WPP control strategies [14]-[19], which are implemented at the WPP control level in the WPP two-level control architecture, is presented regarding active power, reactive power, voltage, frequency, and emulated inertia controls. Moreover, WPP and wind turbine control level functions are discussed considering the hierarchy and coordination of these levels.

II. Grid Code Requirements for WPPs

Grid codes define the connection and operational requirements for all parties such as power plant owners, large consumers, and ancillary service providers, connected to the transmission system. Recent grid codes for the power plants were specified in terms of synchronous machines. However, wind turbines are based on different technologies which have significant impacts on the conventional transmission system [20]. TSOs have revised their grid codes to sustain reliable and stable power generation to the loads while enabling the large scale integration of wind power generation [2]-[4]. Although the requirements depend on the inherent characteristics of each transmission system, structural harmonization study of the grid codes has been intended to establish a generic common grid code format where the general layout and specifications, not the values, are fixed and agreed upon by all the TSOs, WPP developers, and wind turbine manufacturers [21]. The most common requirements comprise:

- Active power and frequency control,
- Reactive power and voltage control,
- Fault ride through (FRT) capability,
- Frequency and voltage operating ranges.

The given requirements and more detailed discussions have already been made in the literature [5], [6], [20], [21]. Here a brief review of the mentioned common requirements is included for the WPP control functions.

A. Active Power and Frequency Control

WPPs have to dynamically participate in the grid operation control by regulating their active power output. Active power regulation in the grid codes include active power control functions, which limit the maximum active power, balance the active power output, and define the ramp rates upward or downward direction.

The control functions provide TSOs to control WPPs in a predictable way reducing the uncertainties caused by the wind. They might also be the supervisory tools to integrate WPPs into existing transmission planning and market operations. Additionally, reserve power can be maintained through using these functions for the frequency control. Active power reference update rate, start-up ramp rate, shut down ramp rate, and system protection functions are the additional requirements specified under the active power control title in the grid codes [2]-[4], [21], [23], [24].

Frequency control is performed by the power plants under the supervision of TSO in different stages which depend on each other [22]. Primary frequency control is one of the stages and allows a balance to be re-established between generation and consumption at a frequency other than the system frequency reference (50 or 60 Hz) in response to a frequency deviation.

In the WPPs, the wind turbines don't have a synchronously rotating rotor like in conventional power plants, and they are therefore following the system frequency. If there is a frequency excursion, they can change their active power output by the additional converter or the wind turbine controllers according to the grid code requirements [8]. The grid codes generally demand active power curtailment for frequencies above the normal operating limits (i.e. higher than 50.2 Hz in [3]) and immediate disconnection for lower frequencies (i.e. lower than 47 Hz in [3]). However, these limits can vary according to the bilateral agreements between the TSO and WPP owner. If the TSO demands same primary frequency control performance as for the conventional power plants, active power reserve should be deployed in the turbine kinetic energy, energy storage equipments or by de-rated operation of the wind turbine.

Moreover, emulated inertia control is another form of active power control for WPPs. This control idea comes from the conventional power plant natural response to the load changes in the grid operation. However, in WPPs wind turbine rotor speed is decoupled from the system frequency. The controller for inertia emulation should increase or decrease the active power output proportional to the derivative of the frequency, and as a result reduces the drop/rise of the frequency deviations. But, specifications for the emulated inertia control rely on the power system characteristics, such as the overall inertia of the system and the wind power penetration level in the transmission system. This controller structure is not a common requirement now in the grid codes, but is defined for a future implementation in the Spanish grid code [4].

B. Reactive Power and Voltage Control

WPPs have to regulate their reactive power output in response to the voltage deviations at the grid connection point and the reactive power references sent by the TSO. The reactive power requirements depend on the grid connection point characteristics, which include short-circuit power of the connection point, X/R ratio, and wind power penetration level. For the grid operation, there are three different possibilities for reactive power references set by the TSO; reactive power, power factor and voltage references. Grid codes have stated these reactive power operating conditions, such as P/Q and V/Q curves or voltage slope characteristics. Additionally, the reactive power ramp rate, reactive power control and measurement accuracy, settling and rise times for reactive power change are specified in the grid codes [2]-[4], [21], [23], [24].

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, support to the voltage recovery by injecting reactive current and active power restoration after the fault clearance with a limited ramp values. All these features are defined as FRT capability of the wind turbines and described by the FRT voltage profile given in the grid codes. During the fault, the reactive current injection is defined by another figure, and in addition to these capabilities, reactive current injection, dead, rise, and settling time with the post fault support time are specified correspondingly in the grid codes [2]-[4], [23], [24].

III. WPP CONTROL

In order to satisfy the mentioned grid codes, the WPP control level is responsible for the active and reactive power dispatch for the wind turbines. In addition to the steady state performance, the WPP control level can dynamically provide stability, or if it is not possible to react due to the response time of the WPP controller and WPP communication system, it should not affect the transmission system operation adversely during the transient conditions (i.e. faults, switching operations, and load/wind variations). The challenge increases further when there are other components, such as energy storages, capacitor banks, and FACTs in the WPP. Therefore, the WPP control architecture should be structured in a hierarchical and coordinated way for efficient, reliable and stable grid operation as a single generating unit.

Generally, two-level control, which comprises the WPP control level and the wind turbine level, has been implemented as a benchmark of WPP control architecture in the literature and industry [14]-[19]. In this architecture, the WPP control level determines the active and reactive power set points for each wind turbine based on the grid connection point measurements and TSO demands.

The wind turbine control level on the other hand, ensures that the sent out references from the WPP control level are reached. Moreover, if any operational changes occur, such as available wind power or fault situations, the WPP control level should be acknowledged through a SCADA (Supervisory Control and Data Acquisition) system. In the following subsections, the WPP control level is described in more details.

A. WPP Active Power Control

In the WPP control level, the active power control main purpose is to control the injected active power at the point of connection into the transmission system. Therefore, the WPP active power controller calculates the active power set points of each wind turbine in the WPP with respect to the active power reference received from the TSO. As illustrated in Fig. 1, the inputs of the active power control are the received power reference, measured active power at the connection point, available active power values from each wind turbines, and the outputs are the reference signals to each wind turbine. The WPP active power control typically contains an active power control functions block, main controller block and dispatch function block as shown in Fig. 1.

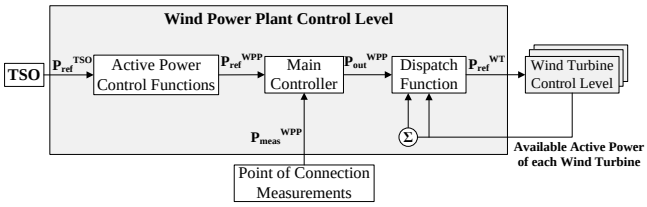

Fig. 1. WPP level active power control [16]

1) Active Power Control Functions

In Danish grid code [2], active power control functions are clearly defined, thus in Horns Rev I all the functions are implemented and in operation [17]. The active power control functions block in Fig. 1 can decide which control function will be active for the WPP. For instance, balance control or delta control can work at the same time with the power rate limiter function. These control functions are simulated in [16] and the results are given in Fig. 2.

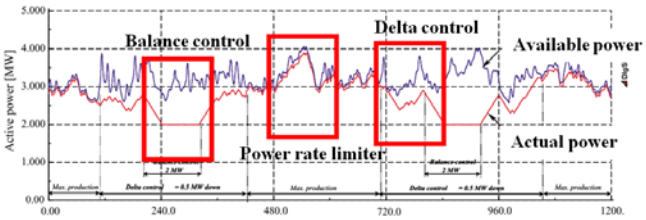

Fig. 2. WPP active power control functions [16]

2) Active Power Main Controller

The main controller block, illustrated in Fig. 3, is a simple PI controller with anti wind-up limiter that calculates the active power error and decides the overall WPP active power reference (P_{out}^{WPP}).

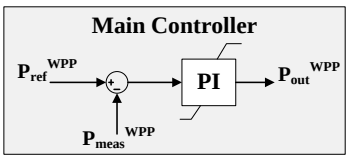

Fig. 3. WPP active power main controller based on [16]

3) Active Power Dispatch Function

There are various ways in order to distribute the active power reference signals to individual wind turbines (P_{ref}^{WT}) as a dispatch function. The simplest algorithm directly sends the input signal (P_{out}^{WPP}), which is expressed in per unit (pu), to all wind turbines. It should be noticed that if the power reference signal sent to a wind turbine exceeds the maximum available power of the wind turbine, in the next error computation step the rest of the wind turbines will automatically increase their outputs in order to reset the active power error. However, this algorithm does not check the available power of the overall WPP, thereby a steady state error may remain [19], [25].

Another strategy, which is mentioned in [16]-[18], calculates the wind turbine active power set points based on a proportional distribution of each wind turbine available active power. Equation (1) is simply formulated as a proportional distribution of the available active power by dividing each wind turbine available active power to the total available active power, where P_{av}^{WTi} is the available active power of ith wind turbine and P_{av}^{WPP} is the total available active power of the WPP.

$$P_{ref}^{WT_i} = \frac{P_{av}^{WT_i}}{P_{av}^{WPP}} \times P_{out}^{WPP}, \quad P_{av}^{WPP} = \sum_{i=1}^{n} P_{av}^{WT_i} \qquad (1)$$

Further, an optimized dispatch control strategy is implemented that defines the active power set points of each wind turbines and closely follows the TSO active power reference taking the WPP internal active power losses and availability of the wind power into consideration [14]. This optimization problem defined in (2) is composed of three sub-objective functions: the first and second part aim to decrease the deviation between the WPP active and reactive power outputs and the TSO reference value respectively, and the last part seeks to reduce the active power losses in the collector system.

$$\min \begin{Bmatrix} p_1(P_d - P_{total})^2 + p_2(Q_d - Q_{total})^2 + \\ p_3\left[(P_{out1} - P_d)^2 + \sum_{i=2}^{n}(P_{outi} - P_{s_{i-1}})^2\right] \end{Bmatrix} \qquad (2)$$

,where P_d and Q_d is active and reactive power demand received from the TSO, P_{total} and Q_{total} is the total active and reactive power of the WPP, P_{outi} is the sending side active power flow of branches and P_{Si} is the receiving side active power flow of branches from the wind turbine side to the connection point. For this objective function a primal-dual predictor corrector interior point optimization method is used in [14].

As a result, using the above active power control the WPPs can operate at the maximum power or at a de-rated power that would be used for the primary and secondary frequency control purposes or to support voltage stability in contingency situations (curtailment of the active power).

B. WPP Reactive Power Control

The grid codes demand reactive power support in several ways; reactive power, power factor or voltage control specified as set points sent by the TSOs. Among these control strategies, the appropriate strategy is selected by the TSO and WPP developer with respect to the short-circuit ratio, X/R ratio at the connection point and the currently installed reactive compensation in the vicinity of WPP connection point.

The WPP reactive power control structure is similar to the active power control mentioned above. It is briefly shown in Fig. 4 that possible set points from the TSO are reactive power, power factor or voltage. The inputs of reactive power control are the set points (Q_{ref}^{TSO}, V_{ref}^{TSO}, pf_{ref}^{TSO}), the measurement of the related signal (Q_{meas}^{TSO}, V_{meas}^{TSO}, pf_{meas}^{TSO}) according to the set point, and in some cases the available active power of the wind turbines, are needed in order to calculate the individual reactive power or voltage reference of the wind turbines (Q_{ref}^{WT}, V_{ref}^{WT}) [16].

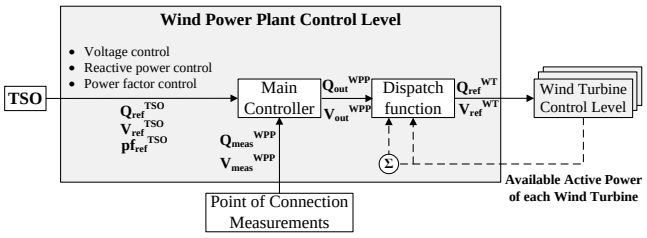

Fig. 4. WPP level reactive power control [16]

1) Reactive Power Control Strategies

Power factor control is a passive reactive power control related to the active power output of the WPP. In other words, when the active power output is increased, the power factor control will also increase the reactive output. The significant disadvantage is that when the active power changes due to wind or TSO reference, these changes will lead to reactive power changes at the connection point [15].

Another strategy is the reactive power control which receives the reactive power reference signal from the TSO. Same disadvantage can take place, if the wind power

change is very rapid. Thus a very fast reactive control will be required from both the TSO operator and the WPP reactive power controller in order to sustain the voltage constraints.

On the other hand, the voltage control strategy is more robust and active power changes do not affect the set points coming from the TSO as in the previous strategies. But practical drawbacks, such as communication delays, should be carefully handled. However, undesired voltage changes cannot be avoided at the point of connection [15].

2) Reactive Power Main Controller

The main controller, which is illustrated as a block in Fig. 4, is a simple PI controller with anti wind-up limiter that calculates the reactive power or voltage error and decides the overall WPP reactive power reference (Q_{out}^{WPP}) or connection point voltage reference (V_{out}^{WPP}). In addition to this structure in reactive power control strategy, the reactive power reference can be modified by adding output of the voltage control as a reactive power correction. It is shown in Fig. 5 and the additional voltage loop is realized to assure the voltage constraints at the connection point [16]. Similar control structure with the reactive power additional loop can also be implemented in the voltage control strategy. Another similar main controller structure, which is based on reactive power control and a subordinated voltage control loop, is illustrated in Fig. 6 [25]. The implementation of the subordinated loop is to enable the voltage constraints while following the reactive power reference. In other words it s a protection to sustain the WPP availability such that the WPP connection point voltage remains between the voltage limits.

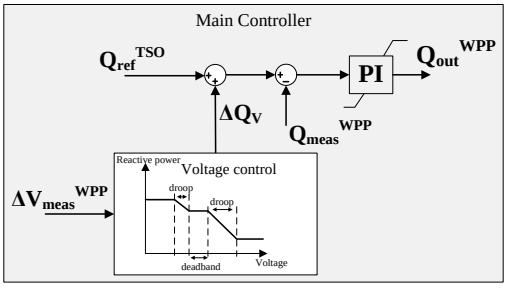

Fig. 5. WPP reactive power main controller [16]

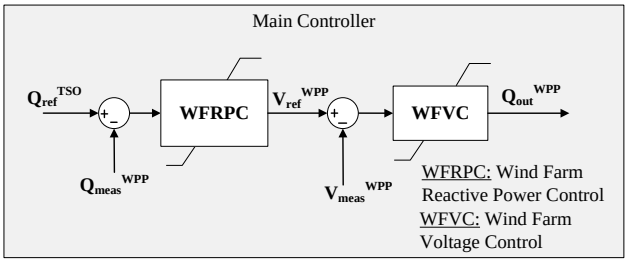

Fig. 6. WPP reactive power cascaded main controller [25]

3) Reactive Power Dispatch Function

Similar to the active power dispatch function, there are various ways in order to distribute the reactive power/voltage reference signals to individual wind turbines (Q_{ref}^{WT} or V_{ref}^{WT}) similar to active power control as a dispatch function. The simplest algorithm directly sends the input signal that is reactive power reference (Q_{out}^{WPP}) to all wind turbines. It should be noticed that in the voltage control strategy, the voltage reference (V_{out}^{WPP}) must be converted to reactive power set point, and then it can be distributed as the reactive power references (Q_{ref}^{WT}) [25]. However, the disadvantage of the reactive control strategy with this distribution function is that the identical reactive power set values sent to each wind turbine would cause excessive voltage variations within the collector feeders. In case of high voltage profile, there could be trip of the wind turbines because of the voltage instability and equipment voltage ratings [19].

Another strategy, which is mentioned in [16]-[17], calculates wind turbine reactive power set points based on a proportional distribution of each wind turbine available reactive power. Equation (3) is simply formulated as a proportional distribution of the available reactive power by dividing each wind turbine available reactive power to the total available reactive power, where P_{av}^{WTi} and Q_{av}^{WTi} is the available active and reactive power of ith wind turbine respectively, Q_{av}^{WPP} is the total available reactive power of the WPP, and $S_{gen\_rate}^{WTi}$ is MVA rating of the ith wind turbine.

$$Q_{ref}^{WT_i} = \frac{Q_{av}^{WT_i}}{Q_{av}^{WPP}} \times Q_{out}^{WPP}, Q_{av}^{WPP} = \sum_{i=1}^{n} Q_{av}^{WT_i}, Q_{av}^{WT_i} = \sqrt{\left(S_{gen\_rate}^{WT_i}\right)^2 - \left(P_{av}^{WT_i}\right)^2} \quad (3)$$

Further, an optimized dispatch control strategy is implemented that defines the reactive power or voltage set points of each wind turbines and closely follows the TSO active power reference taking the WPP internal active power losses and availability of the wind power into consideration [14]. This optimization problem is defined in (2) and the details are mentioned in the active power dispatch function part.

Another optimization algorithm focuses on the WPP collector system losses which are the sum of no-load and load losses in the collector system [26]. In (4), the total loss (P_{LOSS}) is formulated in two parts; the first part is the load loss at any operating point in terms of total power (S) and voltage (V) which is related to the load loss ($P_{LL\text{-}rated}$) at the rated power (S_{rated}) and nominal voltage (V_{rated}). The second part is the no-load loss of the collector system transformers at any V which is also related to the no-load loss ($P_{NL\text{-}rated}$) at the nominal voltage (V_{rated}).

$$P_{LOSS} = \left(\frac{V_{rated}}{V}\right)^2 \left(\frac{S}{S_{rated}}\right)^2 P_{LL-rated} + \left(\frac{V}{V_{rated}}\right)^2 P_{NL-rated} \quad (4)$$

4) WPP Coordinated Reactive Power Control

The WPP reactive power control level is surveyed as a single central unit in order to satisfy grid codes reactive power and voltage requirements. Likewise, the wind turbine control level has reactive power and voltage control strategies, which affect the overall performance of the WPP. The coordination of these two control levels is very important. For instance, reactive power control can be implemented as a slow control loop on the WPP control level and a fast voltage control loop, which is able to

operate in the wind turbines (Fig. 7). Another possible structure is that both WPP control and wind turbine control level have the voltage control capability. The voltage control on the WPP level can stabilize the connection point voltage within the limits regardless the active power variations. On the other hand, voltage controllers at the wind turbines are able to reduce the fast voltage variations in the collector system and the grid (Fig. 8) [15], [27]. On the contrary to this control structure, there has been an implementation where the voltage control loop is the inner control and the relatively slower reactive power control loop is the outer control loop [28]. The claim for this structure, which is depicted in Fig. 9, is that it is more stable than the reactive power control loop inside of the voltage control loop. However, if the wind turbines react with their very fast voltage control with respect to the disturbances, there might be some intra-plant stability problems due to the WPP collector system and interaction of these controllers.

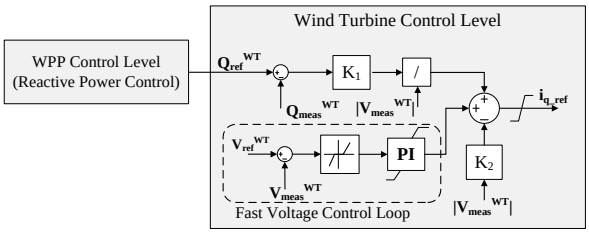

Fig. 7. WPP reactive power control with voltage control at the wind turbine [15]

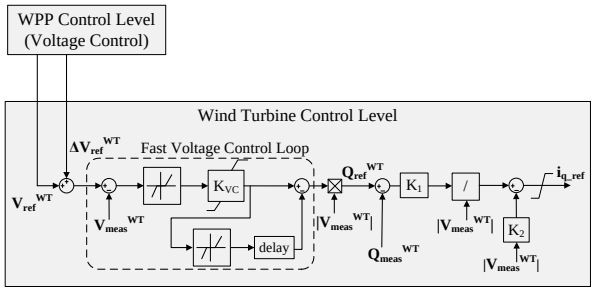

Fig. 8. WPP voltage control with voltage control (inner reactive power control loop) at the wind turbine [15]

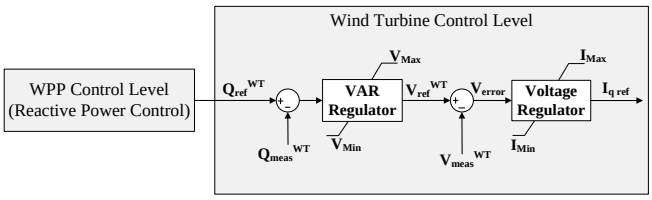

Fig. 9. WPP reactive power control with reactive power control (inner voltage control loop) at the wind turbine [28]

C. WPP Frequency Control

In the power system, the active power generated and consumed must be in balance during steady state conditions. When a disturbance has occurred, the system frequency will deviate with respect to the angular momentum of the synchronous machines and spinning loads connected to the system. For these frequency excursions, power plants are required to provide frequency response which is specified in the grid codes by the TSOs.

The primary frequency control is the response of the power plant during the frequency deviation by changing its active power output in order to stabilize the frequency at a level different than the nominal frequency (50 Hz or 60 Hz) within 10 sec. – 30 sec. (BC period in Fig. 10).

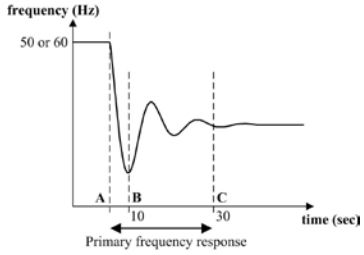

Fig. 10. Primary frequency control

In the last 5 years, there have been a lot of studies about primary frequency control both implemented on the WPP control and wind turbine control level. Most of the studies have implemented the primary frequency control in the pitch control system or active power control loop of the converters by either using the inertial response of the rotor, reserve power of the wind turbine (de-rated operation mode) or energy storage devices. In [16] and [17], the primary frequency control is implemented on the WPP control level and the reason is stated to avoid that WPP can counteract the frequency controllers in the wind turbines. This control structure is illustrated in Fig. 11. On the other hand, in [14] and [17], all the all the wind turbines are able to response to frequency deviations and they can change their active power autonomously regardless of the WPP controller.

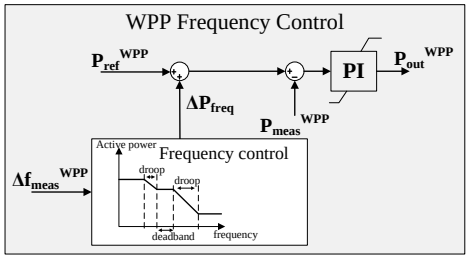

Fig. 11. WPP frequency control [16]

D. WPP Emulated Inertia Control

As mentioned in the frequency control, any imbalance such as the difference between generation and consumption leads to deviations in the system frequency. The frequency drop during the AB period (in Fig. 10) depends on the total inertia of the system, which can be described as the available stored energy in the rotor of the conventional power plants. This stored energy is instantaneously released to cease the frequency drop.

If the wind power penetration level is expected to increase with the converter based wind turbines, the system inertia response will be reduced. As a result, the system frequency drop during an imbalance will drop very rapidly to lower values than the previous case. Therefore, TSOs let WPPs contribute to system inertia by emulating synchronous machine inertial response [4]. In [29], the active power output of a WPP is controlled by an algorithm in order to contribute to the system frequency. This control

is emulating the inertia response behavior of the synchronous power plant. It detects the frequency of the power system and then calculates a variation rate in the detected system frequency. Afterwards, an active power output change of the WPP is calculated based on a value of the WPP overall inertia and the previously calculated frequency variation rate. The calculated active power change for the overall WPP is distributed with respect to two embodiments, the first one is just by dividing the number of the wind turbines, and the second approach is by taking account of the WPP equivalent rotational speed and every individual rotational speed of the wind turbines. Furthermore, the method comprises the detection of the incoming wind speed at the WPP, and the calculation of the energy residing in the rotational masses of the WPP from the detected wind speed. Fig. 12 illustrates the whole detection and calculation steps of the control methodology.

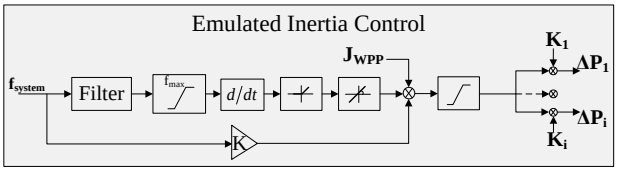

Fig. 12. WPP emulated inertia control based on [29]

IV. Discussion and Conclusion

The installation of larger WPPs at both onshore and offshore are rapidly increasing by virtue of the recent developments in wind turbine technology and the incentives provided by the governments. According to the wind integration studies performed by the TSOs and organizations from academy and industry, the grid code requirements have been revised, wind turbine manufacturers have been implementing new developments to the market, and the WPP developers have been conducting the connection studies considering grid codes and wind turbine technology. In this paper, a comprehensive overview of WPP control strategies is presented regarding active power, reactive power, voltage, frequency, and emulated inertia controls.

The WPP control level is the key factor for steady state and dynamic operational performance of the WPP. The WPP control architecture as a usual concept consists of mainly two levels, the WPP control level and the wind turbine control level. The general functions of the WPP control level are discussed in the related part of the report that comprises the following functions required from the system operator; active power, frequency, emulated inertia, and reactive power (voltage control, pf control).

FRT control function is much more related to the wind turbine level with respect to the response time and elimination of the disturbances. In the literature the functions of each WPP control level and the coordination of these levels haven't been covered in detail. Furthermore, more detailed WPP models including the communication latency and sampling time should be developed. According to the grid code requirements and wind turbine technology a brief provision of the functions for the each level can be classified as follows:

<u>WPP Control Level Functions:</u>

- Active power control of WPP
- Secondary frequency control
- Primary frequency control
- Reactive power control (or Voltage control) of WPP

<u>Wind Turbine Control Level Functions:</u>

- Active power control of wind turbine
- Reactive power control of wind turbine
- Emulated inertia control
- FRT control

On the other hand, AGC (Automatic Generation Control) for the secondary frequency control and secondary voltage control functions utilized in conventional transmission systems can be implemented to improve the WPP control algorithm which includes optimization of the active and reactive power control considering the collector system layout, wind prediction, and availability of the generation.

Finally, communication time delays between the control levels should be taken into account for the WPP control architecture. For instance, the arrival time of the available wind power information from the wind turbine to the WPP controller will affect the primary frequency control performance.

V. Acknowledgment

This work was supported by Aalborg University-Vestas Wind Systems A/S partnership under Vestas Power Program. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of Vestas Wind Systems A/S.

VI. References

[1] T. Ackermann, *Wind Power in Power Systems*, Chichester: Wiley, 2005.

[2] Eltra and Elkraft System, "Wind turbines connected to grids with voltages above 100 kV, Regulation TF 3.2.5", Dec. 2004.

[3] VDN, "TransmissionCode 2007, Network and system rules of the German transmission system operators", Aug. 2007.

[4] Red Electrica, "Offprint of the outline of O.P. 12.2 Restricted to the technical requirements of wind power and photovoltaic facilities", 2008.

[5] I. Dealegria, J. Andreu, J. Martin, P. Ibanez, J. Villate, and H. Camblong, "Connection requirements for wind farms: a survey on technical requirements and regulation," *Renewable and Sustainable Energy Reviews*, vol. 11, pp. 1858-1872, 2007.

[6] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renewable Power Generation*, vol. 3, p. 308, 2009.

[7] L. O. Long, "Joint control of electric governors for hydraulic turbines," *IEEE Transactions Power Apparatus and Systems*, vol.PAS-87, no.9, pp.1754-1762, 1968.

[8] O. A.-Lara, N. Jenkins, J. Ekanayake, P. Cartwright, and M. Hughes, *Wind Energy Generation, Modelling and Control*, Chichester: Wiley, 2009

[9] M. P. and S. Achilles, "Aggregated wind park models for analyzing power system dynamics," in *4th International Workshop on Large Scale Integration of Wind Power and Transmission Networks 2003*.

[10] L. Fernandez, C. Garcia, J. Saenz, and F. Jurado, "Equivalent models of wind farms by using aggregated wind turbines and equivalent winds," *Energy Conversion and Management*, vol. 50, pp. 691-704, 2009.

[11] E. Muljadi, C. P. Butterfield, A. Ellis, J. Mechenbier, J. Hochheimer, R. Young, N. Miller, R. Delmerico, R. Zavadil, and J. C. Smith, "Equivalencing the collector system of a large wind power plant, " in *Proc. 2006 IEEE Power Engineering Society General Meeting*.
[12] J. Morren, J. Pierik, S. W.H. de Haan, "Inertial response of variable speed wind turbines," *Electric Power Systems Research*, vol.76. Issue 11, pp.980-987, 2006.
[13] J.G. Slootweg, S.W.H. de Haan, H. Polinder and W.L. Kling, "Voltage control methods with grid connected wind turbines: a tutorial review," *Wind Engineering*, vol.25. no. 6, pp.353-365, 2001.
[14] R. deAlmeida, E. Castronuovo, and J. PecasLopes, "Optimum generation control in wind parks when carrying out system operator requests," *IEEE Transactions on Power Systems*, vol. 21, 2006.
[15] J. Fortmann, M. Wilch, F. Koch, and I. Erlich, "A novel centralised wind farm controller utilising voltage control capability of wind turbines," in *Proc. 2008 Power System Computation Conf.*, pp. 1-7, 2008.
[16] A. Hansen, P. Sorensen, F. Iov, and F. Blaabjerg, "Centralised power control of wind farm with doubly fed induction generators," *Renewable Energy*, vol. 31, pp. 935-951, 2006.
[17] J.R. Kristoffersen and P. Christiansen, "Horns Rev offshore windfarm: its main controller and remote control system," *Wind Engineering*, vol. 27, pp. 351-359, 2003.
[18] B. Liu, X. Peng, and T. Undeland, "Centralized power control strategy of offshore wind farm with permanent magnetic generators," in *Proc. 2009 IEEE 6th International Power Electronics and Motion Control Conference*, vol. 3, pp. 1075-1079.
[19] J. Rodriguez-Amenedo, S. Arnaltes, and M. Rodriguez, "Operation and coordinated control of fixed and variable speed wind farms," *Renewable Energy*, vol. 33, 2008, pp. 406-414.
[20] J.C. Smith, M.R. Milligan, E.A. DeMeo, B. Parsons, "Utility Wind Integration and Operating Impact State of the Art," *IEEE Transactions on Power Systems*, vol.22, no.3, pp.900-908, Aug. 2007.
[21] European Wind Energy Association (EWEA) Working Group, "Generic Grid Code Format for Wind Power Plants,"Nov. 2009.
[22] UCTE Operation Handbook, 2009: http://www.entsoe.eu/index.phpid57
[23] EirGrid, "Grid Code," ver.3.1 3, Apr. 2008.
[24] NGET, "The Grid Code," Issue 4, June 2009.
[25] J. Rodriguez-Amenedo, S. Arnalte, and J. Burgos, "Automatic generation control of a wind farm with variable speed wind turbines," *IEEE Transactions on Energy Conversion*, vol. 17, pp. 279-284, 2002.
[26] General Electric Company Patent, "Windfarm collector system loss optimization", EP2108828 A2.
[27] Repower Systems AG, "Wind park with robust reactive power adjustment system and method for the operation thereof", US2008/0073912 A1
[28] Einar V. Larsen, "Voltage Control for Wind Generations", US 2006/0012181 A1.
[29] Vestas Wind Systems A/S, "Method and system for controlling a wind power plant comprising a number of wind turbine generators", PCT/EP2009/057943828.

VII. BIOGRAPHIES

Mufit Altin (S'09) was born in Denizli, Turkey, 1982. He received B.S. and M.S. degrees in electrical and electronics engineering from Middle East Technical University (METU), Ankara, in 2004 and 2009, respectively. He was a research engineer with Power System Group in the Scientific and Technological Research Council of Turkey (TUBITAK), from 2004 to 2009. He is currently working toward the PhD. degree in the Department of Energy Technology, Aalborg University, Denmark. His research interest includes distribution automation, wind power plant control, wind energy, and power systems.

Remus Teodorescu received the Dipl.Ing. degree in electrical engineering from Polytechnical University of Bucharest, Romania in 1989, and PhD. degree in power electronics from University of Galati, Romania, in 1994. In 1998, he joined Aalborg University, Department of Energy Technology, power electronics section where he currently works as full professor. He is the co-recipient of the Technical Committee Prize Paper Awards at IEEE lAS Annual Meeting 1998, and Third-ABB Prize Paper Award at IEEE Optim 2002. His areas of interests are: design and control of power converters used in renewable energy systems, distributed generation mainly wind power and photo-voltaics, computer simulations, digital control implementation. Remus Teodorescu is the coordinator of the Vestas Power Program.

Birgitte Bak-Jensen (M'88) received the M.Sc. degree in electrical engineering in 1986 and the Ph.D. degree in "Modeling of High Voltage Components" in 1992, both from the Institute of Energy Technology, Aalborg University, Aalborg, Denmark. From 1986 to 1988, she was with Electrolux Elmotor A/S, Aalborg, Denmark as an Electrical Design Engineer. She is currently an Associate Professor in the Institute of Energy Technology, Aalborg University, which she joined in August 1988. Her fields of interest are modeling and diagnosis of electrical components and power quality and stability in power systems. During recent years, integration of dispersed generation to the network grid has become one of her main fields, where she has participated in many projects concerning wind turbines and their connection to the grid.

Pedro Rodriguez (S'99-M'04) received the M.S. and Ph.D. degrees in electrical engineering from the Technical University of Catalonia (UPC), Barcelona, Spain, in 1994 and 2004, respectively. In 1990, he joined the faculty of UPC as an Assistant Professor, where he is currently an Associate Professor. In 2005, he was a visiting researcher in the Center for Power Electronics Systems, Virginia Tech, USA. He is now the Head of the Research Group on Renewable Electrical Energy Systems at the UPC and co-Supervisor of the Vestas Power Program in partnership collaboration with the AAU. His research interest is focused on applying power electronics to distributed energy systems and power quality. Dr. Rodriguez is a Member of the IEEE Power Electronics, IEEE Industry Application, and IEEE Industrial Electronics Societies. Currently, he is a member of the IEEE IES Technical Committee on Renewable Energy Systems and the chair of the IEEE Industrial Electronics Student Forum.

Florin Iov was born in Galati, Romania, in 1968. He received the Dipl. Eng. degree in electrical engineering from Brasov University, Brasov, Romania, in 1993. He served as a faculty member in the Department of Electrical Machines and Drives, Galati University, Galati, Romania, from 1993 to 2000. In November 2000, he joined the Department of Electrical Energy Conversion, Aalborg University, Denmark, where he worked on the Low Inductance IGBT Fuse Project in cooperation with Cooper Bussmann, Inc. Currently, he is with Vestas Wind Systems. His fields of interest are electrical machines, power electronics and drives, wind turbines, modeling, and simulation.

Philip Carne Kjaer received the M.Sc. degree in electrical engineering from Aalborg University, Aalborg, Denmark, in 1993, and the Ph.D. degree from the University of Glasgow, Glasgow, U.K., in 1997. From 1993 to 1998, he was a Research Assistant at the University of Glasgow, working with advanced control of switched reluctance machines and drives. From 1998 to 2003, he was with ABB Corporate Research, Vasteras, Sweden, where, as a Development Engineer, he worked on servo-motor-based high-voltage circuit breaker drives, factory testing of synchronous machines, power converters for HVDC power transmission, and multi-megawatt variable-speed drives. Beginning in 2000, he also functioned as Deputy Department Manager and, most recently, as Group Manager for a team of 18 scientists. In October 2003, he joined Vestas Wind Systems, Arhus, Denmark, where he currently holds the position as Chief Specialist for power plants. His research covers control and application of electrical machines and power electronic converters. Dr. Kjaer is a Chartered Engineer in the U.K., a Member of the Institution of Electrical Engineers, U.K., and the recipient of the 2004 Richard M. Bass Outstanding Young Power Electronics Engineer Award.