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Aspects of Wind Power Plant Collector Network Layout and Control Architecture

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ABSTRACT

Recent developments in wind turbine technology go towards the installation of larger Wind Power Plants (WPPs) both onshore and offshore. As wind power penetration level increases, power system operators are challenged by the penetration impacts to maintain reliability and stability of power system. Therefore, connection topology and control concepts of large WPPs should be carefully investigated to improve the overall performance of both the WPP and the power systems. This paper aims to present a general overview of the design considerations for the electrical layout of WPPs and the WPP control strategy for optimum power generation while fulfilling the power system operators' requirements.

I. INTRODUCTION

As fossil fuel energy sources have dwindled and global warming increases, renewable energy sources attract more attention. Wind energy is one of the leading alternatives among these sources. The rapid growth of wind industry over the last decades brings along a lot of study and research for integration of wind energy to conventional power systems. In addition to technological and economical developments in wind turbine technology, governments have granted funds for research and support in renewable energy sources.

The important benefits of wind energy are reduced CO_2 emission, reduced operational cost (as no fuel is required) and adding capacity value to a power system (ability to contribute to peak demands). However, these advantages are available only when WPPs operate according to the regulations that are prescribed by power system operators for the stability and reliability of the system [1], [2]. Considering these regulations, WPP designers should design internal electrical system, as well as control structure of the WPP.

The main function of the internal electrical system is to collect power from each Wind Turbine Generator (WTG) spread over the entire WPP and to transmit it to the power system. Electrical collector systems can be designed using different topologies depending on the size, location (onshore or offshore), and terrain of the WPP [3], [4]. Because of the practical limitations, collector system design must be evaluated from economic and reliability point of view [5], [6].

Furthermore, the WPP control structure, which consists of centralized controller and individual WTG controllers, regulates the WPP power production [7]. WPP operators are able to control entire power plant by a centralized controller which is an interface between the power system operator and the WPP. The centralized controller should be implemented to satisfy the requirements of the power system operator in coordination with the WTG controllers [8], [9].

In this paper considerations for the collector system design regarding power loss optimization, reliability and economics are presented. Additionally, a hierarchical WPP control structure for optimum active and reactive power generation is introduced. Thereby, the overall WPP should be able to satisfy the power system operators' requirements.

In Section II, an overview of the grid codes of Germany and Denmark is briefly introduced as a general instance of common requirements. The collector system design considerations including optimization of power losses, economic and reliability evaluations are presented in Section III. Section IV introduces WPP control strategies in a coordinated and hierarchical structure. In the closing section, future work and milestones of the work is provided.

II. GRID CODE REQUIREMENTS

The transmission system operators (TSOs) are responsible for network operations in steady-state and transient conditions. According to TSOs' perspective, it must be proven for the power plants connected to transmission network that the reliability and stability of the grid should not be adversely affected. Thus the technical requirements, which are commonly referred to as grid codes, must clearly define the connection criteria of the WPPs into the transmission network. Recently there has been a lot of research and study on revising grid codes. However, it has to be considered, that every country has different connection criteria for the wind power and national regulatory frameworks require continuous changes due to the developments in the wind turbine

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technology.

The new grid codes treat the WPPs in such a way that they should contribute power system control similar to conventional power plants [1]. In the literature, technical analysis and overview of technical requirements regarding the connection of large WPPs to the transmission system are provided [10], [11]. In [11], the grid codes of several countries and comparison of their most recent available editions are presented. This paper narrows down the overview to Germany and Denmark grid codes, just to give an idea of the common requirements.

According to the grid codes, the technical requirements are defined for the connection and operation of WPPs connected to transmission system [1], [2]. These requirements cover:

- FRT requirements,
- Active power and frequency control,
- Reactive power control,
- Frequency and voltage operating range.

The FRT or low voltage ride through (LVRT) requirements are described in such a way that WPPs must withstand voltage dips to a certain percentage of the voltage level for a specified duration in the grid codes. These voltage characteristics depend on protection system of the network and fault location. The FRT requirements also include fast active and reactive output power restoration after a fault clearance.

The active power and frequency control requirements define the regulation of WPP active power output and the frequency response to control their active power outputs with respect to frequency deviations. Moreover, WPPs can actively participate in active power regulation using various control strategies [2]. This control should require ancillary services such as participation in primary and secondary frequency control.

Reactive power control capabilities are also required by the grid codes. It is performed either by setting a reactive power value or power factor value. Further, reactive power control should be extended for controlling voltage at the WPP grid connection point or at the distant node (secondary voltage control).

In addition to control and response capabilities, grid codes stated that WPPs must operate over an extended range of system voltages and frequency deviations from the nominal operating values. For these operating ranges, limited period of continuous operation and active power reduction is allowed.

A. Germany

1) FRT Requirements***Fejl! Henvisningskilde ikke fundet.***

According to the *Transmission Code 2007* [1], the FRT requirements are given in Fig. 1 for single, dual, and triple pole short circuits (with and without earth contact) or fault induced symmetrical and asymmetrical voltage dips. The curve characteristic represents the voltage magnitude associated with the time duration during which the WPP must remain connected.

The grid code defines the following FRT requirements:

- Above the borderline 1, voltage drops should not lead to WPP disconnection.
- The voltage dips within the shaded area between the borderline 1 and borderline 2 should not lead to instability or disconnection of the WPP. However, in case of WPP instability, short-time disconnection is allowed. The resynchronization must be completed at most 2 s and after fault clearance active power feed-in must be increased with a gradient of 10% of the nominal capacity per second.

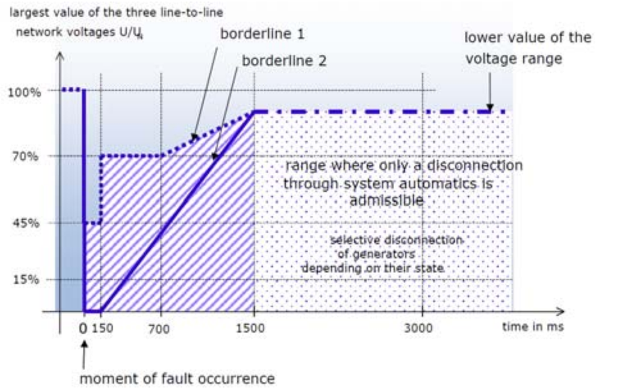

Fig. 1. Limit curve for the FRT requirements of the *Transmission Code 2007* [1]

- Below the borderline 2, disconnection of the WPP is allowed and also a short-time disconnection of the WPP from the network is always permitted (Resynchronization period may be more than 2 s and the active power gradient may be less than 10%).
- For all WPPs which are not disconnected during the fault, active power must be maintained immediately after the fault clearance and increased to the original value with a gradient of at least 20% of the nominal capacity per second.
- For reactive current feed-in for voltage backup, in the case of network voltage above the borderline 1, the requirements are shown in Fig. 2. *K* value should be in the range of 0 and 10 and it must be adjustable. Additionally, WPP disconnection time delays associated with voltage level are specified in *Transmission Code 2007*.

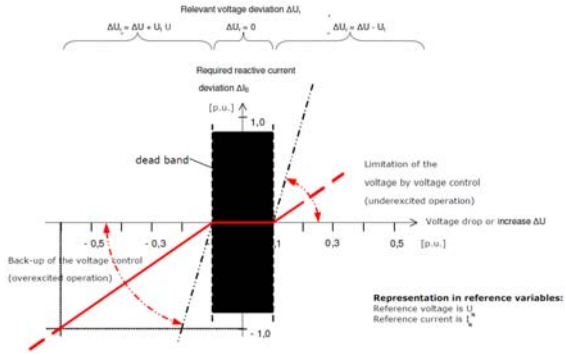

Fig. 2. Reactive output current during disturbances [1]

2) Active power and frequency control

The active power reduction must be satisfied with at least 10% of the network connection capacity per minute. And frequency response of the WPP is shown in Fig. 3 similar to the droop characteristic of a conventional power plant for over-frequencies. However, there is no limitation for the frequency band between 47.5 and 50.2 Hz. WPP is allowed to disconnect below 47.5 Hz and above 51.5 Hz.

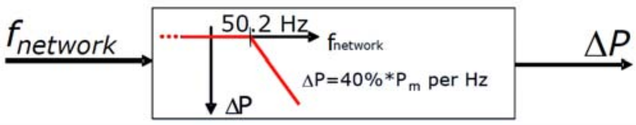

Fig. 3. Active power reduction of WPPs in the case of over-frequency [1]

3) Reactive power control

The reactive power control requirements are defined for various ranges of reactive power or power factor at rated active power. Each WPP must meet the requirements at the grid connection point to one of the variants of Fig. 4. The TSO shall select one variant with respect to the relevant network conditions. The reactive power output of the WPP must be able to reach the set value within 4 minutes.

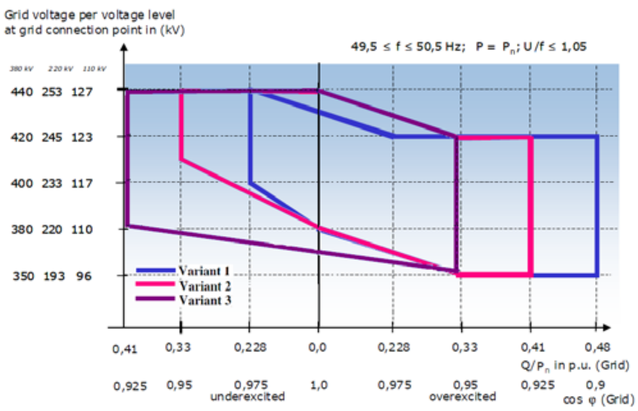

Fig. 4. WPP reactive power (or power factor) requirements at the grid connection point (Variants 1-3) [1]

4) Frequency and voltage operating range

WPP must operate continuously within certain voltage and frequency variation limits during the normal operation of the system. Further, they must remain in operation even in case of voltage and frequency disturbances outside the normal operating limits. Fig. 5 shows the operating voltage (at the grid connection point) and frequency limits for WPPs.

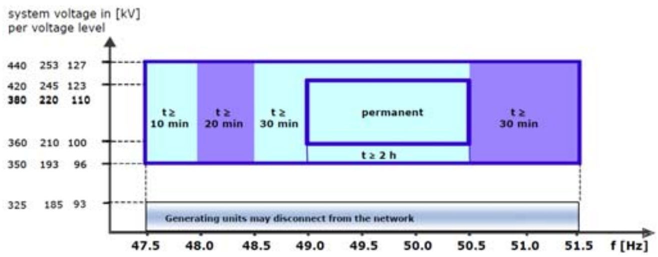

Fig. 5. Operating frequency and voltage limits for WPPs [1]

B. Denmark

The Danish requirements which are presented in this paper should apply to WPPs connected to grids with voltages above 100 kV (the transmission system) [2].

1) FRT Requirements ***Fejl! Henvisningskilde ikke fundet.***

The FRT requirements define that the WPP must remain connected after the faults or sequence of faults that are shown in Table I.

TABLE I
FRT REQUIREMENTS OF DANISH GRID CODE FOR WPPS CONNECTED TO THE GRIDS ABOVE 100 KV [2]

Type of the fault	Duration of the fault
Three-phase short circuit	Short circuit in 100 ms
At least two three-phase short circuits	Shorts circuits within 2 mins
Two-phase short circuit (with/without earth contact)	Short circuit in 100 ms followed by new short circuit 300-500 ms later, also with a duration of 100 ms
At least two two-phase short circuits	Shorts circuits within 2 mins
Single-phase short circuit to earth (earth fault)	Single-phase earth fault 300-500ms later, also with a duration of 100 ms
At least two single-phase earth faults	Shorts circuits within 2 mins

According to Danish grid code, behavior of the grid during a three-phase fault is illustrated in Fig. 6 for simulation purposes. Technical details are defined in the grid code [2].

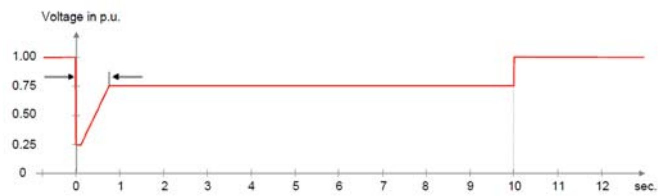

Fig. 6. Voltage profile for simulation of three-phase faults in Danish grid code [2]

Additionally, WPPs must have sufficient energy reserves in terms of emergency power, hydraulics and pneumatics for the following three independent sequences:

- At least six three-phase short circuits with 5-min intervals
- At least six two-phase short circuits with 5-min intervals

- At least six single-phase earth faults with 5-min intervals

2) Active power and frequency control

The grid code [2] demands WPPs to have ability of active power regulation speed (both upward and downward) with a ramp rate 10-100 % of rated power per minute.

By frequency regulation WPPs must change the active power production with respect to the grid frequency deviations. Fig. 7 shows two cases of frequency control. In case 1, the frequency control can only regulate the active power production in downward direction, whereas in case 2, it can also make upward regulation due to the previous downward regulation. The frequencies applied to this figure are depicted in the grid code [2].

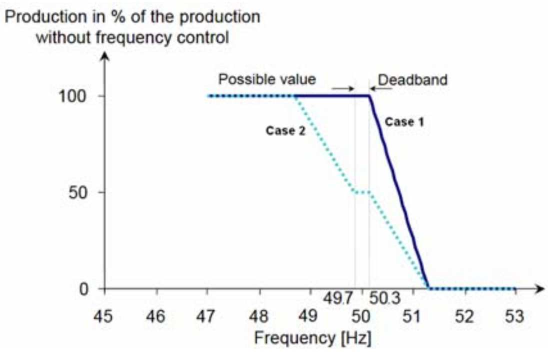

Fig. 7. Active power-frequency response [2]

3) Reactive power control

WPP must control its reactive power output that as a mean value over 10 seconds must be kept within the control band, as shown in Fig. 8.

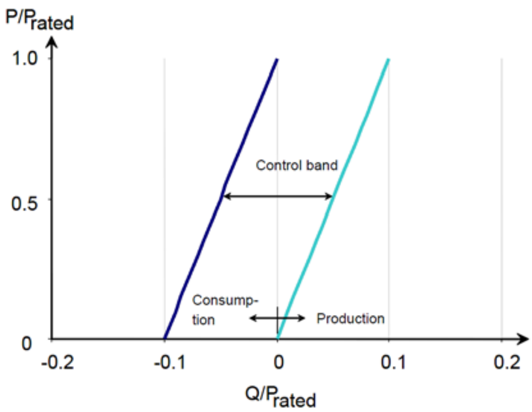

Fig. 8. Requirements concerning the WPP's exchange of reactive power at the grid connection point [2]

4) Frequency and voltage operating range

WPP must continue power production at voltages and frequencies that deviate from normal operating conditions. Fig. 9 indicates normal and time-limited operating conditions of the WPP. Abnormal voltages and frequencies will occur in less than ten hours per year.

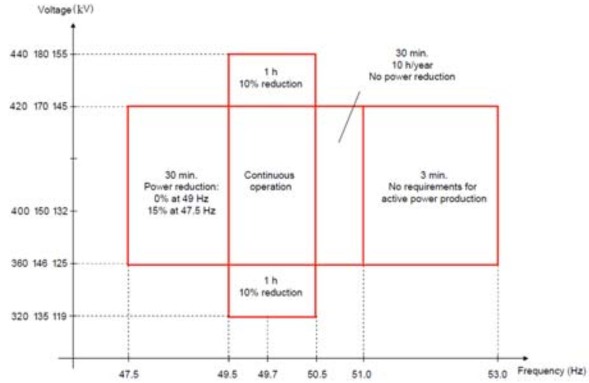

Fig. 9. Operating frequency and voltage limits for WPPs [2]

C. Comparison of German and Danish Grid Code Requirements

From the grid codes presented above, it can be clearly noticed that the interconnection requirements for WPPs have common concepts. However, they vary from country to country due to the inherent network structure.

In the German grid code, there are more options regarding FRT and reactive power control requirements for the WPP operator. In the Danish grid code, however, for the FRT requirement point of view, fault types and duration of the faults, which may occur in the transmission system, are clearly described. On the other hand, WPP operational voltage and frequency ranges are much flexible in Danish grid code. Active power control and frequency control requirements are very similar in both transmission codes, but they leave WPP primary and secondary frequency control issues to the bilateral agreements between the TSO and WPP operator.

III. WPP COLLECTOR SYSTEM DESIGN

The WPP collector system generally consists of WTGs, step-up transformers, network of cables which collect the power from each WTG, switching equipments, protection relays and collector substation where the collected power is transmitted to the transmission system. If WPP capacity increases, collector system performance becomes particularly important.

WPP location (onshore or onshore) and terrain are significant factors for designing collector system. Terrain characteristics determine whether the collector system consists of overhead lines, underground or subsea cables. Furthermore, WTG locations in the wind farm are optimized with respect to wind regime and site [12], [13]. Collector substation location and grid connection point can also be constrained by the terrain.

Once the WTG locations and grid connection point are decided, collector system layout, which is also referred to as feeder topology, must be configured by selecting and routing the cables. The number of WTGs located on a collection feeder is limited by the cable ampacity and the voltage level of the collector system. System reliability is another design consideration to maintain sustainable power. The reliability aspect covers redundancy, protection system, fault location, and service restoration systems. Typical configurations that have different levels of redundancy are illustrated in Fig. 10 [3]:

- Radial designed and radial operated feeder structure Fig. 10a ,
- Ring designed and radial operated feeder structure Fig. 10b and Fig. 10c,
- Star designed and radial operated feeder structure Fig. 10d.

The solutions that provide adequate reliability will increase capital investments and can increase power losses. A technique that translates power losses (fixed, variable losses and losses due to unavailability of the system) into initial capital investment should be used for economic evaluation of the collector system. By using expected financial return investment in the economic evaluation for WPP economic factors (fixed losses factor, variable losses factor, and system unavailability losses factor), design alternatives are shown to be favorable [5].

On the other hand, collector layout affects protection system design such that in some cases, it may be difficult to distinguish faults and make selective coordination of the layout. Therefore, in the early stage of the collector system design, protection scheme should be considered and protection evaluation factor may be introduced such as reliability assessment factor [14]. Short circuit current capacity, types and numbers of protection relays, additional switching equipment and relay cost, and selective coordination level (numbers of relays, which can be coordinated) can be the protection evaluation factors.

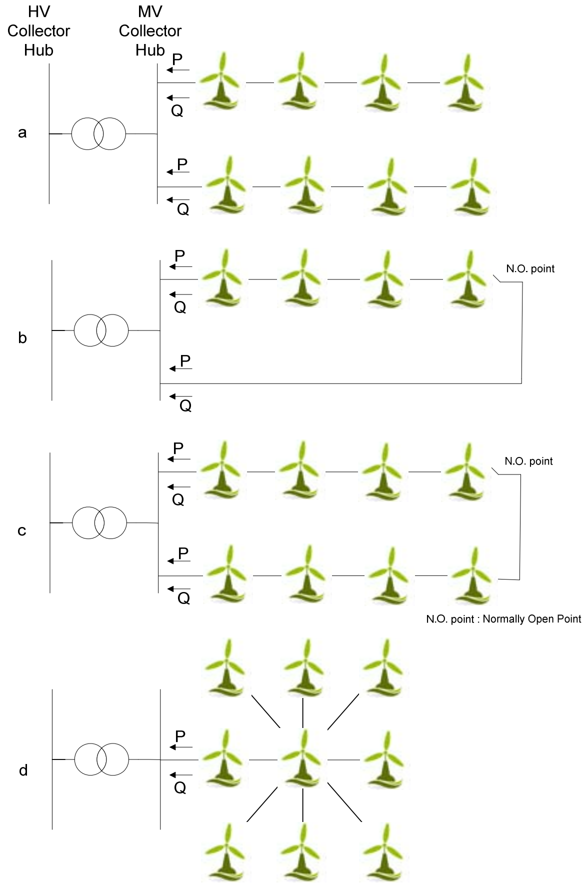

Fig. 9. Typical feeder configurations of WPPs.

IV. WPP CONTROL

The grid code specifications mentioned in Section II force the WPPs to participate in power system control similar to conventional power plants. WPP control structure should be designed including control of output power fluctuations (because of the intermittent nature of wind), primary frequency control, secondary frequency control, reactive power regulation, and secondary voltage control. To perform these control functions, the WPP must have a hierarchical structure such as a centralized (main) controller and WTG controllers. The main controller determines active and reactive power set points, which are ordered by the TSO, for each WTG. At the local control level, WTG controller ensures that the received set points are reached. In this scheme the main controller is responsible for the overall optimum power production of the plant considering the collector system power losses and availability of wind power [15]. In Fig. 10, an overall diagram of the centralized controller is shown [8].

The control functions mentioned above should be distributed among the main and WTG controllers in the following manner:

- Main controller functions:
    - Active power control of WPP,
    - Secondary frequency control,

- Reactive power control of WPP,
- Voltage control of WPP (at the grid connection point and a distance point).
- Wind Prediction

• WTG control functions:
  - Active power control of WTG,
  - Reactive power control of WTG,
  - Primary frequency control,
  - FRT control.

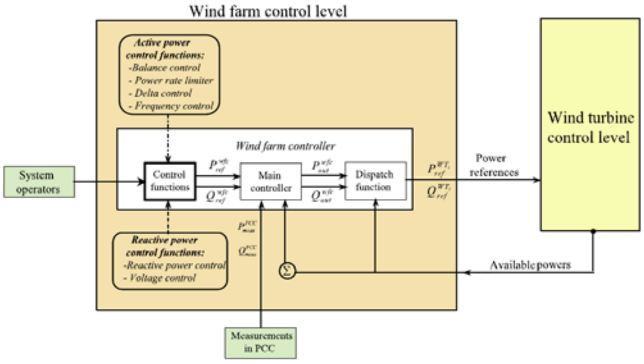

Fig. 10. WPP main controller [8].

Furthermore, the centralized controller should operate in coordination with each WTG controller to satisfy stability and robustness of the WPP, thus it is operated as a conventional plant. A *cluster controller* shown in Fig. 11 can be a novel option to satisfy this coordination. It can be basically described as a control level between the main controller and a group (cluster) of WTG controllers. The centralized controller shares its responsibilities with the distributed cluster controllers. These controllers are responsible for a group of WTGs (with respect to the collector layout) in a decentralized way. The cluster controller should include fault location and service restoration functions, which are automated processes, for the collector system, short-term wind forecasting function for optimum generation, and redundant control in case of emergency. Hereafter the centralized and WTG controller hierarchy is defined as 2-level control, and the centralized, cluster and WTG controller hierarchy is named as 3-level control structure.

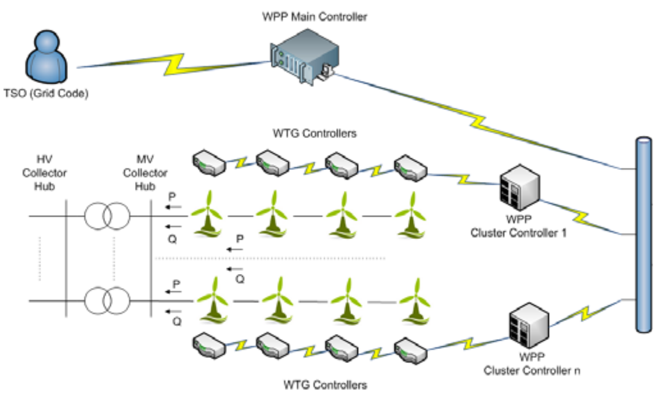

Fig. 11. WPP cluster controller concept.

In 2-level control structure, the centralized controller sends out set points, WPP operator commands to WTGs and gets related measurement data from the WTGs. All data should be processed in the centralized controller, thus there is a lot of network traffic in the WPP. However, the cluster controllers in 3-level control structure manage the network traffic and optimize the bandwidth of the network for faster communication. 3-level control structure is more reliable due to redundant control that during a communication failure between the cluster and centralized controller, the cluster control can perform the centralized controller's functions. In 3-level control structure, protection scheme will also have additional features such as group tripping of WTGs, faster fault detection and service restoration concerning a sub-area of the WPP not the whole WPP.

V. CONCLUSION

In this paper, an overview of German and Danish grid code requirements, the WPP collector system design considerations and the WPP control structure were presented. The objective of the grid codes is to specify WPPs' regulation and control capabilities for safe, reliable and economic operation of the power system. Grid codes may also be used for the modelling of the transmission system.

WPP collection system design decisions have been playing a critical role to efficient operation of the WPP. There are many challenges regarding power losses, economics, protection system and reliability. The tradeoffs between these challenges point out the importance of the design considerations and evaluation techniques to decide optimum configuration. Further study can integrate economic evaluation, steady state analysis (load-flow, loss calculation, short-circuit calculation), reliability assessment, protection and generation automation system analysis to develop an optimization platform.

To fulfill grid code requirements, the WPP control structure should have the functions presented in Section IV. The control strategy is similar to the Automatic Generation Control (AGC) concept of centralized dispatch centre in transmission system. For future study AGC experiences can be used to improve WPP control algorithm including optimization active and reactive power control due to the collector system layout and availability of the generation. Fast communication and redundant control are the primary drivers for the 3-level control structure. This structure should be required for redundancy, reliability, fault detection and service restoration functions in the WPP. To compare 2-level and 3-level control structure, communication time sensitivity and economic evaluation analyses should be required.

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