Hierarchy and complexity in control of large offshore wind power plant clusters

Kavimandan, Anup; Das, Kaushik; Hansen, A. D.; Cutululis, Nicolaos Antonio

Published in:
Proceedings of the 16th Deep Sea Offshore Wind R&D conference

Link to article, DOI:
10.1088/1742-6596/1356/1/012038

Publication date:
2019

Document Version
Publisher’s PDF, also known as Version of record

Citation (APA):
Kavimandan, A., Das, K., Hansen, A. D., & Cutululis, N. A. (2019). Hierarchy and complexity in control of large offshore wind power plant clusters. In Proceedings of the 16th Deep Sea Offshore Wind R&D conference (1 ed., Vol. 1356). [012038] IOP Publishing. Journal of Physics: Conference Series (Online) https://doi.org/10.1088/1742-6596/1356/1/012038
Hierarchy and complexity in control of large offshore wind power plant clusters

To cite this article: A Kavimandan et al 2019 J. Phys.: Conf. Ser. 1356 012038

View the article online for updates and enhancements.
Hierarchy and complexity in control of large offshore wind power plant clusters

A Kavimandan, K Das, A D Hansen and N A Cutululis
Department of Wind Energy, Technical University of Denmark, Roskilde, Denmark

Email: anuk@dtu.dk

Abstract. The scope of this paper is to review the hierarchical control architectures for offshore wind power plants (OWPPs) described in the state-of-art literature. A typical WPP control architecture consist of three levels: local wind turbine control level, WPP control level and control of group of WPPs. With more and more OWPPs development in close proximity and integration with the grid, future trends are favourable for large OWPP cluster formations, resulting in the growing need to better outline and interpret the WPP control strategies and propose means to establish coordination between the WPPs within large OWPP clusters. Coordination is essential for large WPP clusters to ensure the variable and stochastic wind power production does not adversely impact the overall grid stability and fulfil the requirement at PCC with optimised operation. Additionally, the paper also highlights the complexities associated with the hierarchical and coordinated control of large OWPPs and recommends ways to address them.

1. Introduction

There is a growing trend and demand of integrating large MW capacity wind power plants (WPP) to the transmission system throughout Europe. Based on the analysis of potential conditions determining wind energy deployment assuming favourable market and policy conditions, 397 GW of cumulative wind energy capacity is expected to be installed in the EU by 2030, 298.5 GW onshore and 99 GW offshore [1], which would be around 23% more capacity than in the central scenario currently installed in the EU. Among the EU countries, Denmark has set the most ambitious target of producing 50% electricity from wind power by 2020 [2]. Such a high wind power penetration calls for WPPs to be compliant with the guidelines and technical requirements of the international grid codes.

The electric power system tends to become more susceptible and dependent on wind power with increased penetration. This necessitates the large wind farms will have to behave as active controllable components in the power system, meaning they are expected to demonstrate controllability similar to the conventional power plants with respect to performing active and reactive power regulation, frequency and voltage control in the power system [3]. Wind power was considered as a non-controllable energy source fully dependent on fluctuating weather conditions around three decades ago. But the existing European grid codes indicate that nowadays wind power can be regarded as a controllable power source. The regulatory mechanisms are driving the development of novel strategies in order to utilise the existing technologies and fulfil the grid code requirements.

The scope of this paper is to review the different control strategies and architectures employed for large offshore WPPs, the control objectives and the typical complexities associated with such large
control architectures. In the past, there were single wind turbine generators which were aggregated under a wind power plant. Nowadays, WPPs are being grouped together resulting in the formation of a ‘cluster’. A wind power plant cluster is thus a logical (and of course electrical) aggregation of independent physical offshore WPPs geographically existing in close proximity which are connected to the same grid node. The aim of such a ‘cluster’ formation is to allow the wind energy to better fulfil the TSO requirements, increase its grid integration capabilities, admit more wind energy into the grid, allow TSOs to govern wind energy as a conventional source of power despite the stochastic nature of the wind, the distributed location of the wind farms and the existence of different generator technologies. The aggregation of WPPs by means of a cluster also increases the capacity to maintain the accuracy of wind power feed-in forecast and balance the forecast errors / respective deviations within the cluster. Additionally, it also supports and brings about the coordination between TSOs, dispatch centers, wind power producers and energy markets [4]. The individual WPPs could be owned by same or separate owners and they could be AC connected or connected through an HVDC link to the shore. For instance, consider the Dogger Bank project [5] spread across UK, Denmark, Germany, Netherlands and Norway consisting of four OWPPs with a size of 1200MW each connected to the shore via HVDC converter links. But it involves a high degree of complexity due to multiple countries and stakeholders involved, cooperation across borders of member states to find optimal solutions, coordination challenge as the four OWPPs are at different stages in the respective countries, regulatory and financial decisions.

In order to efficiently perform the real time monitoring and control of large OWPP clusters, a multilayer hierarchical control structure can be adopted so that the control responsibilities are assigned to the different hierarchical control levels. A typical OWPP cluster control architecture consist of three levels: local wind turbine control level, WPP control level and control of group of WPPs to regulate the WPP cluster power production to the reference power ordered by the system. The individual WPP control level controls its own power production by sending out reference signals to each individual wind turbines within the WPP. The local wind turbine control level ensures the reference power signals sent by the WPP control level are followed [3]. The highest level in the control hierarchy i.e., control of group of WPPs may perform the strategic adjustment of the WPP reference power set points with respect to the power demand specified by the system operator based on certain control objectives. The control architecture could typically be based upon one of the three types of control – centralized, distributed and decentralized, each of them being characterized and differentiated by the flow of information between the site of data acquisition, the location of decision making and the location of final action being performed.

The paper is organized as follows: First the desired control objectives to be achieved in large OWPP clusters is discussed. This is followed by state-of-the-art literature existing in the control of large OWPPs. Then, a survey of various control architectures – centralized, distributed, decentralized – is presented highlighting their applicability in case of large OWPP clusters. Thereafter, the complexities associated with the hierarchical and coordinated control of large OWPP clusters is assessed and described considering a reference OWPP cluster as a base case, recommending ways to address them. Finally, the review is summarized with concluding remarks and discussion on suitable hierarchical control architectures for large OWPP clusters.

2. Control Objectives

Wind farm controller have several possible functions, objectives, and implementations, depending on the physical design aspects as well as the operator and grid code requirements. The wind turbines equipped with power electronic converters (Type 3 and Type 4) not only can control their active power output according to an external set-point, but can also control their reactive power output independently. The control limitations are, however, posed by the voltage and current rating of the power-electronic converter, aerodynamic torque and rotor speed control limitations and wind turbine operational range. Main objectives of wind farm active power control [3],[14],[15] can be as follows:

- To maximize the total wind power extraction from the WPP.
To regulate the wind farm power output according to an external set-point, which ensuring gradient control, power limitations, maintaining a certain balancing reserve, frequency control etc.

- To mitigate fatigue loads on the wind turbine due to high turbulence intensity of the wakes.

The reactive power control objectives can be as follows:

- To keep the voltages in the wind farm collection grid and in the transmission grid within the normal operating ranges.
- To minimize transmission losses and optimize transmission capacity, e.g. through contributing to the reactive power compensation.
- To control the reactive power and improve the power factor at the grid connection point according the grid operator set-point.

The active and reactive power set points can be directly ordered by the network operator or indirectly obtained through a look-up table based on measured grid frequency or the measured grid voltage at the PCC respectively. In some cases though, coordinated reactive power control may be required, as the reactive power produced by other components in the transmission line may also need to be controlled.

As shown in Figure 1, a wind farm controller typically consists of the following main components:

- **Farm power reference**: It computes the reference signal for the active and reactive powers for the whole wind farm. These references are determined so as to comply with the constraints and set-points received from the System Operator [15]. The power could be limited to maximum production or to a small portion (delta) of the available power or controlling the gradient (ramp) or maintaining a balance power reserve or controlling the inertia by extracting up to typically 30% of the rotor energy in case a big power plant fails.

- **Active power control**: This controller acts on the difference between the measured and reference active power command [3],[15]. The feedback loop is important in order to achieve the desired active power in the presence of measurement errors and electrical losses in the farm. It should also include proper anti-windup limitation of its output to ensure it does not exceed the maximum available power.

- **Reactive power control**: This feedback controller (typically a PI) acts on the difference between the measured (at PCC) and reference reactive power command. Similar to the active power control, this also requires proper anti-wind up limitation. It must be noted, since the reactive power generation capability depends on the active power produced, it is fed as an input to this block in Figure 1.

- **Voltage control**: This control adds up an additional reactive power demand to the farm power reference, in order to provide voltage support to the system operator. The TSO specifies the voltage droop and dead-band. It receives the measured voltage at the PCC as an input. It is desirable that the voltage control should be coordinated in the wind farm and all voltages in the wind farm should be kept within the normal operating limits. In case of HVDC connection, the offshore grid voltage is traditionally controlled by the HVDC converter, both in normal and fault conditions. Additionally, the tap changers in substation transformers also assist in the voltage control alongwith other compensation devices, if any.

- **Frequency Control**: This control adds up an additional active power demand (either positive or negative) to the farm power reference based on the measured frequency, aiming to support the operator in controlling the grid frequency on short time scales (primary frequency control). Typically, the TSO provides the frequency droop and dead-band (as per the grid code). It is usually in cascade with the active power control.

- **Active power dispatcher**: This block distributes the wind farm active power set-point proportionally to the turbines available power [3],[14],[15]. However, depending on the
objective (maximizing the farm power production and/or minimizing the fatigue loads) the algorithm could be much more elaborate.

- **Reactive power dispatcher**: This block distributes the reactive power set-points among the wind turbines.

![Schematic representation of a typical wind farm controller](image)

**Figure 1.** Schematic representation of a typical wind farm controller [16].

The active and reactive power control loops are typically designed to operate independent of each other with different time scales: while the active power loop is more dynamic as it requires pitching of the blades of the turbine, the reactive power is controlled by the turbine power electronics and is therefore much faster. Besides, the active and reactive current are orthogonal vectors and can be controlled independently using power electronic converters, as shown in **Figure 1**. The relation between active and reactive power is the limitation of the current amplitude.

### 3. State-of-the-art in control of large offshore wind power plants

The operation and controllability of large offshore wind power plants is a key research domain for the grid integration of large OWPPs considering their active participation in fulfilling the grid code requirements. The system operators are now demanding similar grid connections, operating conditions and services provided to support the grid, as for conventional power generation sources. The conventional wind turbines connected directly to the grid work autonomously producing maximum possible power in normal operation and disconnect in case of grid faults. They cannot regulate their power produced and do not have much control capabilities. With the development of variable speed wind turbines and presence of power electronics interfacing the wind turbines to the grid, the control capabilities have enormously increased. Wind turbine controllers today are fully developed and most of
them are optimized from a control perspective as a single wind turbine. The main objective of most wind power plant controllers (WPPCs) is to make the WPP act as a single production unit instead of several individual units, like Horns Rev wind farm [6]. Horns Rev was the one of the first large offshore WPP built in Denmark with 160 MW rated power capacity, using DFIG based variable speed wind turbines and equipped with advanced control functions providing power (both active and reactive) reference for the WPP and distribution functions converting the WPP level power reference to set points for the individual turbines as shown in Figure 2.

![Figure 2](image-url)  
**Figure 2.** The control block diagram of the Horns Rev wind farm [6].

A hierarchical modular wind farm control architecture is designed and implemented by A D Hansen et al. [3], consisting of a central wind farm controller to generate reference signals (active and reactive power) for each local wind turbine controller, based on several measurements in the PCC and on the available power. The main objective of the controller is to perform the power/frequency (primary control) and reactive power/voltage control and regulate the WPP production (secondary control). Fault ride through capability is existing at the wind turbine controller level rather than the WPP controller level. Even the local wind turbine controller is built-up with a hierarchical structure, composed of a slow dynamic control level for control of speed and power and a fast dynamic control level for the electrical control of generator currents, as shown in Figure 3.

![Figure 3](image-url)  
**Figure 3.** The wind farm control level consists of two control loops: (i) an active power control loop with a subordinated frequency control loop to adjust the reference signal with some correction $\Delta P_{freq}$ and assure that frequency limits are not violated in PCC, and (ii) a reactive power control loop with a subordinated voltage control loop to adjust the reference signal with some correction $\Delta Q_{volt}$. Each loop consist of a PI controller with antiwind-up to ensure an accurate power production. It computes the error and sets up the power reference ($P_{out}^{wfc}$, $Q_{out}^{wfc}$) for the entire wind farm. They are further used by the dispatch function block which converts them into power reference signals for each individual wind turbines based on a proportional distribution of the available active and reactive power.

M Soleimanzadeh [7] has developed control algorithms to optimize the power production and enhance the lifetime of the turbines in wind farms. The reference signals for the wind turbine controllers are provided such that the demanded power for the whole farm is satisfied and structural loads on the turbines are minimized. Three different strategies are proposed: two centralized controller with two different strategies and one distributed controller considering wind turbines as subsystems of the distributed system (coupled through wind flow), formulating an H2 control problem, with the objective to minimize structural loads on the turbines. V Spudić [8] presents the design of an optimal wind farm controller for tracking the power reference while achieving reduction of the wind turbine structural loads. The designed controller is based on model predictive control (MPC) methodology using dynamic feedback from wind turbine measurements. A hierarchical control design approach is used – controllers with different sampling times are designed for the slow and the fast processes. A supervisory wind turbine controller is designed with a goal of reducing the wind turbine loads. It does not interfere with
the local control algorithms, though, for plant safety. The wind farm controller essentially coordinates the individual wind turbine supervisory controllers in a manner such that the power perturbations are synchronized. C J Spruce [9] designed supervisory controllers for windfarms with the objective to maximize the financial income from the generated electricity and minimize the turbine fatigue loads. Two possible control strategies are proposed: hierarchical control and multivariable control. The multivariable control is a centralized dynamic control strategy taking inputs from all turbines while hierarchical control has a plant control and supervisory level control, providing references and making strategic adjustments of the set-points for the plant level controllers in steady state. Alejandro J Gesino [10] defines control strategy with the aim to receive a command sent by the TSO to a certain WPP cluster and calculate the set points to be sent to each WPP within the cluster in order to fulfil the grid requirements of the TSO. The control strategies are mainly focusing on active and reactive power regulation, congestion management, gradient control, voltage control as well as power factor control in order to meet the operation flexibility and security requirements of the grid operators.

Figure 3. (a) The overall wind farm hierarchical control system (b) Wind farm control level [3].
The WPPs are grouped in ‘clusters’ aggregated physically, connected to the same transmission grid node and controlled from an ‘upper’ level in the hierarchy in [11]. As a part of German R&D project “Integration großer Offshore-Windparks in elektrische versorgungssysteme”, a ‘Wind Farm Cluster Management System’ (WCMS) was developed to aid the TSO by operating the cluster according to the needs of the power transmission system. This is shown in Figure 4. Making use of wind farm control strategies and wind energy forecast technologies, WCMS is able to perform active and reactive power control, congestion management, voltage as well as power factor control. The architecture, consisting of two layers, namely the ‘TSO layer’ and the ‘dispatch layer’, allows to efficiently monitor all wind farms operating in their control zones as well as reliably distribute control commands to all wind farms in the cluster:

- **TSO layer**: This layer is mainly responsible for grid security and decision making regarding control commands for the wind farm cluster, based on real time information at wind farm level as well as forecasting. Before the control command is sent to a wind farm, it is forwarded to the connected dispatch centre, which re-transmits it to the wind farms under their control.

- **Dispatch center layer**: This layer is responsible to supervise and control the power production of all wind farms. It forwards the control commands sent by the TSO to each wind farm and also sends the monitoring values at wind farm level to the TSO (to monitor the generation status). The dispatch centre collects information and measurements from the control units of each wind farm such as active and reactive power, voltage, connectivity, temperature, wind speed taken from each wind farm every second.

![Figure 4](image)

**Figure 4.** Wind Farm Cluster Management System (WCMS) (a) Overview of a ‘cluster’ definition (b) WCMS architecture showing the command data flow and monitoring [11].

The WCMS control strategies [12] are mainly focussed on:

A. **P/Q Availability Calculation**: The active power availability is obtained through wind power forecast for each turbine, while the reactive power range is strongly dependent on the P/Q
characteristics of the wind turbine, as provided by the manufacturer. This is shown for 3 different turbines with different P/Q characteristic curves in Figure 5 (b).

B. **Active Power Control:** With the forecasted (day ahead/short-time) and current power information and the grid situation, it is possible to perform active power control at cluster level. It is also important to consider the gradient so that the grid is not affected by sudden increase or decrease of wind power. This is shown in Figure 5 (c).

C. **Reactive Power Control:** It is crucial to provide available reactive power range information for the next time interval. The possibility to forecast and control the generated reactive power within the cluster can enable to operate the cluster without reactive power consumption by controlling the wind turbine power factor. This is shown in Figure 5 (d).

![Figure 5](image)

Figure 5. (a) WCMS control strategies (b) Available P/Q calculation (c) Active power control based on forecasting (d) Reactive power range forecast [12].

The control strategies, as discussed above, can be realised by using the four WCMS operating modes [13]:

1. **Active Power Limitation** (which combine the strategies “Reduction of gradients”, “Generation Management” and “Congestion Management”)
2. **Supply of Reactive Power**
3. **Supply of Balancing Power**
4. **Scheduling**
The controllability of the DFIG to fulfill the grid requirements and thus to assist the power system can be enhanced using its ability to control independently their active and reactive power. A co-ordinated voltage control strategy is designed and implemented by A D Hansen et al. [17] based on the idea that both the converters of the DFIG (i.e., rotor-side and grid-side converters) participate in the grid voltage control. The primary focus is on the voltage control strategy where the reactive power contribution is performed by both the converters in a co-ordinated manner. The coordinated control of WPP clusters with wind turbines of different technologies i.e., fixed speed and variable speed is described in [18] in three levels: individual turbine control, WPP control and central control. A hierarchical and robust control structure is designed and implemented through the three levels i.e., Point of Interconnection (POI), wind farm output and wind turbine terminals, with two separated loops of active and reactive power in each level as shown in Figure 6. The POI is the highest level in the control hierarchy, where the TSO assigns limits for active and reactive power injected by the whole generation. The POI controller then computes the power references for each wind farm according to a dispatch function block, based on the TSO power demand and power measurements from each wind farm. The wind farm controller is the next level in the hierarchy, which controls the power production of the wind farm by sending the power references to the wind turbine control level. The wind turbine control level is the lowest in the control hierarchy, which ensures that the references sent from the wind farm control level are followed. The proposed concept is able to contribute to grid operation and demonstrated the possibility to control wind farms of different technologies together.

![Figure 6. Schematic of hierarchical control scheme as explained in [18].](image)

A hierarchical and consensus-based distributed control scheme is proposed in [19] to coordinate the reactive power among clustered wind farms as shown in Figure 7. Considering the vast distribution topology of large WPP clusters, the distributed control scheme is more practical and tractable. The consensus-based distributed control scheme is the upper level of the hierarchy, while in the lower level, considering the characteristics of the collector system, the reactive power capability of the wind turbines is utilised and they are coordinated with the compensating devices such as STATCOM to provide reactive power under centralised control. The flowchart in Figure 7 (b) explains the steps involved in
formulating the Qref, communicating it to the WPP clusters, dispatching it to the distributed controllers and finally assign the required reactive power to each wind turbine and compensating devices.

Figure 7. Coordinated reactive power regulation scheme (a) Structure of the proposed consensus-based coordinated control scheme for wind farm reactive power regulation (b) Flowchart of the proposed scheme [19].

The state-of-the-art for reactive power control strategies has been divided into control at the PCC and control at the wind turbine by [20]. At the PCC, the control strategies could be designed with the objective to control the (1) power factor, (2) reactive power or (3) voltage. Power factor control can supply reactive power as soon as the active power production changes. But the drawback of this control is that the changes in active power result in a change in the power factor at the PCC due to the transformer and cable inductance. Reactive power control at the PCC is common, but it requires a fast control of the setpoint to avoid undesirable effects on the voltage, due to sudden changes in wind speeds. Voltage control at the PCC can offer a more reliable and robust control to reduce the effects of changes in active power supply without requiring a fast control of setpoint. But due to communication delays, small changes in voltage are unavoidable. The alternate way described is to control at the wind turbine, where the reactive power setpoints for each turbine are received as an input from the wind farm controller. It is also possible to influence the reactive power output at the wind turbine with the measured voltage as an input to the turbine in case of a grid fault. Consequently, during grid faults the operation mode is switched from reactive power control to voltage control.

A coordinated voltage control scheme for a cluster of offshore VSC HVDC connected WPPs is presented in [21] using an optimization algorithm, aiming to minimize the active power losses in the offshore grid, to generate the reference voltage for the Pilot bus having the highest short circuit capacity. The proposed scheme considers the network sensitivity and effectively utilizes the available reactive power sources, by sending reactive power reference to WPPs based on their available reactive power and participation factors. A coordinated control for cluster of offshore WPPs connected to the same HVDC connection is implemented in [22]. The study mainly focuses on coordination of reactive power flow between HVDC converter and WPP cluster while providing offshore AC grid voltage control as shown in Figure 8 and coordinated closed loop control between the HVDC and the WPPs while the cluster is providing power oscillation damping (POD) via active power modulation. It is shown that coordinated cluster control helps to improve the steady-state and dynamic response of the offshore AC grid.
Control architectures for large offshore WPP clusters: A Survey

A wind farm can be regarded as a constrained multiple input and multiple output (MIMO) system whose order drastically increases with increasing number of WTs [23]. Traditionally a wind farm control is implemented in a computer, which receives and sends information from all the turbines and system operators. This is commonly known as centralized control scheme, implemented in conventional networks. But for large-scale OWPPs with hundreds or even thousands of WTs, the centralized controller may be impractical owing to the heavy computation burden in order to process the information. The conventional control schemes such as droop-based or PI with/without optimization might fail to obtain optimal performance for large-scale OWPPs [23].

So from a control perspective, the control of large-scale WPPs consisting of a large number of distributed generation units has been historically handled by separating the control into the control at single WT level and control at the WPP level [24],[25]. There is a need to breakdown the given control problem into manageable subproblems, which may be weakly related, such that the overall plant is no longer controlled by a single controller but by several independent controllers [26]. Instead of a fast powerful computer centralizing the control of the entire WPP, the responsibility can be shared among the wind turbines. This gives rise to two more control structures besides centralized control: distributed and decentralized control.

4.1. Centralized Control

In a centralized control scheme, all the information available about the system, the calculations based upon this information, decision making and the enhancement of the decisions are all centralized i.e., concentrated in a single location. The data from all parts of the controlled system are sent to the central
control unit for processing [10]. An illustration of a centralized control architecture for a large OWPP cluster with multiple WTs is shown in Figure 9. The computers monitor and coordinate the operation of each turbine in order to minimize the impact of power fluctuations on the grid. The control algorithms, the turbine controller, the WPP controller and the central controller receive information about the system from many sensors. The feedback process helps to ensure that the system can adapt to different conditions, but also makes it vulnerable to loss or corruption and interruption of information which can have detrimental impact on the overall system.

4.2. Distributed control
Modern WPPs can be seen as smart grids with many intelligent agents (wind turbines) exchanging information with their neighbours to produce a desired power profile. The turbines talk to each other in order to agree on a global outcome. In the automatic control field, this is commonly known as distributed control. It refers to a control scheme that consists of a number of local controllers, each of which controls a subset of the system, with capability of communication between the controllers. The algorithms running in each agent take decisions with partial information about the system state provided by the other agents. This is shown in Figure 10 (a), where the solid lines indicate mandatory communication between the controllers while the dashed lines indicate the presence of a possible interaction or information exchange. In a distributed controller, data may be processed locally or remote-controlled by a central controller (hence shown as dotted box in Figure 10 (a)). In a way, it is similar to the structure between TSOs and dispatch centres where the information flows bidirectionally: TSO – Dispatch Centre – TSO i.e., the main information is supervised by the TSO while the dispatch centres have local independency with regard to management and monitoring from their WPPs.

![Figure 10](image-url)  
**Figure 10.** Structure of a typical (a) distributed and (b) decentralized control architecture for a large OWPP cluster

As large OWPPs network is spread over a large geographical area, having distributed control units also improves cybersecurity and resilience of the network with respect to failure of some parts of the network.
For instance, in case any of the local controllers or components fail, it will affect only a small part of
the network instead of the entire network. Additionally, it may also provide a certain degree of privacy
since not all information is communicated. However, it also presents some challenges such as the proper
design of a distributed algorithm, the reliability of the communication network and coordination of the
agents to achieve the desired power regulation with limited information exchange. The first challenge
can be addressed with system and control problem decomposition where a local controller is assigned
to every sub-system/problem. While dealing with the second challenge, it is imperative to consider the
possible communication issues such as delays, data packet drops, communication link failures etc. as
they can disrupt the computation process in a distributed scheme. Therefore, techniques must be
incorporated in the controller to solve these issues. In the last few years, some encouraging progress has
been reported in the area of distributed control [27],[28]. A two-step distributed Kalman filtering is
proposed in [29]. In [24], a centralized controller paradigm is derived based on “model predictive
control” in parallel with a distributed controller where the turbines essentially only communicate with
their neighbours.

4.3. Decentralized Control
For a large-scale system such as an OWPP cluster, it may be necessary to partition the given analysis
into manageable sub-problems. As such, the overall plant is no longer controlled by a single controller
but by several independent controllers which all together represent a decentralized controller [26]. Here
the local regulators are designed to operate in an independent fashion [28]. However, the information
could be shared between the local decentralized control centres to solve the larger problem, as shown in
Figure 10 (b). This structure is similar to the one existing at ENTSO-E level. Each TSO could typically
be considered as a “Decentralized Control Centre”, with their own control rules and have
communication with its neighbour. ENTSO-E coordinates this structure and receives relevant
information from the TSOs [10]. Many efforts have been devoted to develop design methods
guaranteeing stability and performance of decentralized control. Among them are few based on
Lyapunov functions [30], sequential design [31], optimization [32] and overlapping decompositions
[33]. A decentralized coordinated voltage control scheme for VSC-HVDC connected OWPPs is
proposed in [23] to regulate voltages within the feasible range by optimally coordinating the WPP side
VSC and WTs based on Model Predictive Control (MPC). A novel decentralized control of offshore
WPPs connected to onshore grid through a HVDC by means of a diode rectifier is proposed in [34]. The
design of local regulators is trivial when the interactions among the inputs and outputs of different
regulators are weak, but strong interactions can even prevent one from achieving stability [35].

5. Control complexities in large offshore WPP clusters
With increasing number of WPPs development (or planned) in close proximity and integration with the
grid leading to potential cluster formations, the WPPs become closer in size to conventional power
plants, thus reducing the operating costs, but it also introduces problems in the electrical grids and
disturbances in the air flow that can affect the power generation. Some of the complexities associated
with the operation and control of such large OWPP clusters are:

1. Control Coordination: It is known that an OWPP cluster consists of many control layers in the
system i.e., WT converters, WPP controller, HVDC converter (if HVDC connected), supervisory
control and each of them have different dynamics and characteristics individually. So the
coordination between them is going to be a challenge. When there are multiple tap changers for
individual WPPs trying to control the voltage along with the converter, the way they interact with
each other might play a bigger role. Controlling multiple tap changers is a complex task (it is
generally not done) as it will start hunting against each other with high in rush current. Similarly
there is pitch controller (very slow), converter control (non linear still quiet continuous and very
fast), tap changer (discrete and slow) control they are all controllable elements that have to be
controlled using some kind of a ‘supervisory’ control. Otherwise they can start to conflict and
interplay against each other, in an attempt to control the same voltage with two (or more) different controllable elements.

2. **Communication Requirements**: A WPPC has access to extensive information from the controllers of the individual wind turbines. The amount of data handling requirements with large number of assets and the ability to continue operation in the absence of communication are some of the aspects that define the control complexity for an OWPP system. Some of the possible communication issues that might appear during the operation of the system are inherent latency/delays, data packet drops or communication link failures. They can have a detrimental impact on the controller by interrupting the computation process in the system. Control techniques based on parameter optimisation or adaptive control could reduce the communication requirement, as then the control is designed for different operating conditions for a non-linear system which is linearized for those points and pick up the set of parameters to be used for those points – that’s typical of a gain scheduling control. In order to get a sense of the complexity in terms of the volume of data required to be communicated, let us try to exemplify them with real parameters in a real case:

Consider the Dogger Bank project [5] planned across UK, Denmark, Germany, Netherlands and Norway split into four OWPPs (Dogger Bank Creyke Beck A/B, Teesside A/B each 1.2 GW owned by Statoil, SSE and Innogy) each will be connected to the shore via HVDC converter links as shown in Figure 11. It involves a high degree of complexity due to multiple countries and stakeholders involved. Considering each WT with a power rating of 10 MW [37], there would be around 120 WTs in each WPP (each WPP will be 1.2 GW in size). Therefore, the total number of WTs all the four WPPs will be around 480. It is well known that certain delays or latency are always inherently present in any communication infrastructure. The network architecture will determine if the signals sent from one communicating entity to the other will reach its destination in one or more hops. This will directly affect the latency, which also depends on the traffic condition.

![Figure 11. Dogger Bank OWPP Cluster profile](image)

The transmitted set-points typically consist of signals of interest such as voltage, active and reactive power demands, frequency, wind speeds etc. Depending on the communication
infrastructure with the central/supervisory controller, there could be different modes of communication. This is explained below and summarized in Table 1, considering a delay of 500ms corresponding to each WT:

**Case 1:** Serial communication with all WTs within each WPP (120 WTs) with four WPPs communicating in parallel. The delays will add up in a cascaded manner (serially) for 120 WTs within each WPP.

**Case 2:** Serial communication with all WTs (480 WTs). The delays will add up in a cascaded manner (serially) for all 480 WTs within the cluster.

**Case 3:** Parallel communication with all WTs within each WPP (120 WTs) with four WPPs communicating serially. With parallel communication, the delay in one WPP will be same as the delay corresponding to communicating with one WT. They will add up serially for four WPPs.

**Case 4:** Parallel communication with all WTs (480 WTs). Since all WTs will be communicating in parallel, the delay will be same as the delay corresponding to communicating with one WT. This case, however, may not be practically feasible as the volume of information at any point of time will be huge, thus increasing the computational burden by manifold.

As it can be seen from Table 1, for big OWPP clusters with large number of assets, the cumulative delays can go as high as 240s (Case 2) for the entire cluster, to 60s (Case 1) for every WPP. The delays will increase if more signals are required to be transmitted for every WT or due to other delays as well like measurement filter delay, scada computation delay etc., which can further make the response of the system slower.

| Mode of Communication | Case 1 | Case 2 | Case 3 | Case 4 |
|-----------------------|--------|--------|--------|--------|
| **Serial – 120 WTs**  | 500    | 500    | 500    | 500    |
| **Parallel – 4 WPPs** |        |        |        |        |
| **Action**            | Delay (ms) | Action | Delay (ms) | Action | Delay (ms) |
| Send to WT1           | 500    | Send to WT1 Read Inverter1 | 500 | Send to WT1 Read Inverter1 | 500 |
| Read Inverter1        |        | Send to WT1 Read Inverter1 | 500 | Send to WT1 Read Inverter1 | 500 |
| Send to WT2           | 1000   | Send to WT2 Read Inverter2 | 1000 | Send to WT2 Read Inverter2 | 1000 |
| Read Inverter2        |        | Send to WT2 Read Inverter2 | 1000 | Send to WT2 Read Inverter2 | 1000 |
| ……                   | ……    | ……    | ……    | ……    |
| Send to WT120         | 6*10^4 | Send to WT1480 Read Inverter480 | 24*10^4 | Send to WT1480 Read Inverter480 | 2000 |
| Read Inverter120      |        |        |        |        |

The delay requirements are determined by the type of measurements transmitted. According to [38], when the messages are used for periodic maintenance measurements, a maximum network delay of about 1s is allowed. When the messages convey real-time monitoring, control information of important working states (such as voltage and frequency), the network delay should be limited to around 10ms. In case that the messages carry urgent equipment fault information (reporting failures), the delivery to the control station should be within 3ms.

3. **Control during faults:** Coordination between the ‘supervisory’ controller and the HVDC converter (for an HVDC connected system) is critical to support the system during faults and demonstrate the fault ride through capability of the system. The supervisory controller, though, can only support during post fault conditions, depending on the requirements post fault and the priority (active power or reactive power). But during faults there will be very short time and probably the recovery will be dependent on the individual controllers. There might be communication with the supervisory control.
post fault, but during faults it remains to be seen as it depends on the duration of the fault, post fault requirements and the speed of communication in the system.

4. **Assets owned by different operators**: It is highly possible that the individual assets (WPPs) could be owned by separate owners/operators in a large OWPP cluster. Although the owners agree as to how and what to exchange at the point of common coupling, but there is lack of communication between the individual WPPs. The lack of regulatory, operational and technical framework for a cluster controller that will operate on several assets with different legal owners prohibits its existence today. This will add further constraints to the operation and control of such a system.

5. **HVDC Connected System**: In case of an HVDC connected OWPPs there is an additional active controllable component, the offshore HVDC converter, adding to the control complexity. It could be a possibility that the HVDC converter control itself could have the cluster supervisory control functionality embedded in it. The HVDC controller could coordinate with the WPP controller in addition to offshore grid voltage and frequency control, to alleviate the control complexity.

6. **Summary**
The paper attempts to review the control objectives and the state-of-the-art literature existing with regards to the control of large OWPPs, a survey of control architectures – centralize, distributed, decentralized for large OWPPs and highlighting the control complexities associated with the operation and control of such large-scale networks. The sharing of responsibility can make the system more resilient and reduce the high computational demand. Distributed control approaches are suitable for future electrical networks and offer the capability to distribute the computational burden on the system, besides improving the cybersecurity. However, they also possess certain challenges that must be overcome. With the existing industrial practises and communication standards the delays can reach very high values for large OWPP clusters with hundreds of assets. Appropriate techniques must be implemented in the controller to solve these issues.

7. **Acknowledgement**
This work is a part of InnoDC project that has received funding from European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 765585.

8. **References**
[1] WindEurope, “Wind Energy in Europe: Scenarios for 2030,” Technical Report September 2017, [Online]. Available: https://windeurope.org/about-wind/reports/wind-energy-in-europe-scenarios-for-2030/
[2] Valentine S 2014 Wind Power Politics and Policy. Oxford University Press.
[3] Hansen A D, Sørensen P, Iov F and Blaabjerg F, 2006, Centralised power control of wind farm with doubly fed induction generators, *Renewable Energy* 31; 935-951, Elsevier.
[4] Braun M et.al. 2009, Wind power plant capabilities – Operate wind farms like conventional power plants. *European Wind Energy Conference 2009*, Marseille, France, 16-19 Mar.
[5] http://www.forewind.co.uk/projects/projects-overview.html
[6] Kristoffersen J R and Christiansen P, 2003, Horns Rev offshore windfarm: its main controller and remote control system. *Wind Engineering*, vol. 27, no. 5, pages 351–359.
[7] Soleimanzadeh M, 2012, Wind Farms: Modeling and Control. PhD thesis, Aalborg University.
[8] Spuđić V, 2012, Coordinated optimal control of wind farm active power. PhD thesis, University of Zagreb.
[9] Spruce C J, 1993, Simulation and Control of Windfarms. PhD thesis, University of Oxford.
[10] Gesino Alejandro J, 2010, Power reserve provision with wind farms. PhD thesis, Fraunhofer IWES, Kassel University.
[11] Gesino A, Quintero C, Mackensen R, Wolff M, Lange B and Rohrig K, 2008, Wind farm Cluster Management System, *XV Energie Symposium*, Fachhochschule Stralsund, Nov 6th – Nov. 11th.
[12] Quintero C, Gesino A, Lange B, Rohrig K, Mackensen R and Wolff M, 2008, Reactive Power Management and Voltage Control with the Wind Farm Cluster Management System, 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms; 26-27 May; Madrid, Spain.

[13] Wolff M et. al. 2006, Advanced Operating Control for Wind Farm Clusters, Sixth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, 26-28 October, Delft, The Netherlands.

[14] Guan X and Gerrit M van der Molen, 2009, Aeolus project deliverable d3.1: Control strategy review and specification (part 1). Technical report, Industrial Systems and Control.

[15] Sørensen P, Hansen A D, Iov F, Blaabjerg F, and Donovan M H, 2005, Wind farm models and control strategies, Technical Report ISBN 87-550-3322-9, Risø.

[16] Kanev S, Savenije F, Soleimanzadeh M and Wiggelinkhuizen E, Dec 2013, Wind farm modeling and control: an inventory.

[17] Hansen A D, Michalke G, Sørensen P, Lund T and Iov F, 2007, Co-ordinated voltage control of DFIG wind turbines in uninterrupted operation during grid faults, Wind Energ.; 10:51-68, Wiley Interscience.

[18] Rodríguez-Amenedo J L, Arnaltes S and Rodriguez M A, 2008, Operation and coordinated control of fixed and variable speed wind farms, Renewable Energy, vol. 33, no. 3, pages 406-414.

[19] Yuan L, Meng K and Dong Z Y, 2018, Hierarchical control scheme for coordinated reactive power regulation in clustered wind farms, IET Renewable Power Generation, vol. 12, no. 10, pages 1119-1126.

[20] Fortmann J, Wilch M, and Koch F W, 2008, A novel centralised wind farm controller utilising voltage control capability of wind turbines, 16th Power Systems Computation Conference (PSCC), July 14-18.

[21] Sakamuri J N, Rather Z H, Cutululis N A, Rimez J, Oct. 2016, Coordinated Voltage Control in Offshore HVDC Connected Cluster of Wind Power Plants, IEEE Trans. on Sustainable Energy, vol.7, pp.1592-1601.

[22] Göksu Ö, Sakamuri J N, Rapp C A, Sørensen P, Sharifabadi K, 2016, Cluster Control of Offshore Wind Power Plants Connected to a Common HVDC Station, 13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind’2016, 20-22 January, Energy Procedia, Vol. 94, Sep 2016, Pages 232-240, ISSN 1876-6102.

[23] Guo Y, Gao H, Xing H, Wu Q and Lin Z, 2018, Decentralized Coordinated Voltage Control for VSC-HVdc Connected Wind Farms Based on ADMM, IEEE Transactions on Sustainable Energy.

[24] Knudsen T, Bak T and Soltani M, Distributed Control of Large-Scale Offshore Wind Farms, Aalborg University, AEOLUS Project, http://www.iet-aeolus.eu/pub/246_EWEC2009presentation.pdf.

[25] Hansen A D, Sørensen P, Iov F, and Blaabjerg F, 2006, Grid support of a wind farm with active stall wind turbines and ac grid connection. Wind Energy, 9:341–359.

[26] Bakule L, 2007, Decentralized control: An overview, 11th IFAC/IFORS/IMACS/IFIP Conference on Large-Scale Systems: Theory and Applications, Gdansk, Poland.

[27] Bamieh, Bassam, and Voulgaris P G, 2005, A convex characterization of distributed control problems in spatially invariant systems with communication constraints, Systems & Control Letters, pages 575–583.

[28] Scattolini R, 2009, Architectures for distributed and hierarchical Model Predictive Control – A review, Journal of Process Control 19, 723-731.

[29] Alriksson P and Rantzer A, 2006, Distributed kalman filtering using weighted averaging, Proceedings of the 17th International Symposium on Mathematical Theory of Networks and Systems.

[30] Siljak D D, 1991, Decentralized Control of Complex Systems, Academic Press, Cambridge.
[31] Hovd M and Skogestad S, 1994, Sequential design of decentralized controllers, *Automatica* 30 1601–1607.

[32] Scattolini R and Schiavoni N, 1985, A parameter optimization approach to the design of structurally constrained regulators for discrete-time systems, *International Journal of Control* 42, 177–192.

[33] Ikeda M, Siljak D D and White D E, 1981, Decentralized control with overlapping information sets, *Journal of Optimization Theory and Application* 34, 279–310.

[34] Cardiel-Álvarez M Á, Arnaltes S, Rodríguez-Amenedo J L and Nami A, Sep. 2018, Decentralized Control of Offshore Wind Farms Connected to Diode-Based HVdc Links, *IEEE Transactions on Energy Conversion*, vol. 33, no. 3, pp. 1233–1241.

[35] Davison E J and Chang T N, 1990, Decentralized stabilization and pole assignment for general proper systems, *IEEE Transactions on Automatic Control* 35, 652–664.

[36] https://www.power-technology.com/features/dogger-bank-profiling-true-titan-wind-power/

[37] Kirkeby H and Tande J O, 2014, The NOWITECH Reference Wind Farm, *EERA DeepWind’2014, 11th Deep Sea Offshore Wind R&D Conference*, Energy Procedia 53, 300 – 312.

[38] Wang W, Xu Y and Khanna M, Oct. 2011, A survey on the communication architectures in smart grid, *Comput. Netw.*, vol. 55, no. 15, pp. 3604–3629.