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PERSPECTIVE

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Towards integrated wind farm control: Interfacing farm flow and power plant controls

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Abstract

Concepts for control of wind farms (WFs) can be clustered into two distinct concepts, namely, wind power plant control (WPPC) and wind farm flow control (WFFC). WPPC is concerned with the connection to the power system, compliance with grid codes, and provision of power system services. This comprises the traditional way of operating a WF without consideration of aerodynamic turbine interaction. However, flow phenomena like wake effects can have a large impact on the overall performance of the WF. WFFC considers such aerodynamic phenomena in the WF operation. It can be viewed as a new feature that shall be integrated with the existing control functions. The interaction of these different control concepts is discussed in this article, leading to an identification of the challenges whose solutions will contribute to a successful integration of electrical system and aerodynamic aspects of WF control.

KEYWORDS

active power reserves, power system services, wake control, wind farm control, wind farm flow control, wind power plant control

Abbreviations: ENTSO-E, European Network of Transmission System Operators for Electricity; FCR, frequency containment reserves; FFR, fast-frequency reserves; FRR, frequency restoration reserves; FRT, fault-ride-through; IEA, International Energy Agency; IPC, individual pitch control; MPPT, maximum power point tracking; OEM, original equipment manufacturer; O&M, operation and maintenance; PCC, point of common coupling; PI, proportional integral; RR, restoration reserves; TSO, transmission system operator; WF, wind farm; WFC, wind farm control; WFFC, wind farm flow control; WPPC, wind power plant control; WT, wind turbine; WTC, wind turbine control.

1 | INTRODUCTION

Offshore wind farms (WFs) with installed capacities of gigawatts will have significant impact on the operation of power systems and the adaptation of electricity markets.[1] With increasing wind power shares, the operational focus is shifting from maximizing the power output to maximizing the profit, which adds complexity to the operation and control regimes. Wind farm control (WFC), the coordinated operation of wind turbines (WTs) within a WF, is gaining relevance for successful operation as the size of WFs increases. WFC encompasses both the more traditional wind power plant control (WPPC), addressing electrical aspects, and the newer concept of wind farm flow control (WFFC), addressing aerodynamic aspects. This separation of WFC into WPPC and WFFC follows the nomenclature suggested by Eguinoa et al..[2] Wind turbine control (WTC), the control of a single WT represents the inner module of the control structure, while the wind energy management system (WEMS) represents the outer layer, where several WFs are managed together. The different modules of operation and control of wind power are visualized in Figure 1.

WFFC is not yet common practice in industry. However, a survey conducted as part of the present work confirmed that WF operators are in general interested to apply WFFC. Operating a WF with consideration of the aerodynamic turbine interactions can contribute to an increased power output, but it can also improve the provision of power system services like power boosting, power reference tracking, and power reserves. Moreover, structural load management by WFFC can likely extend the lifetime and lower operation and maintenance (O&M) costs. The reasons for not adopting WFFC in the industry span from missing validated evidence for performance benefits to warranty issues and unavailable communication interfaces with the WT. The latter was also confirmed in the survey by researchers that implemented WFFC in field tests.

An expert elicitation[3] showed that WFC could benefit from a closer collaboration of the involved research disciplines. Eguinoa et al.[2] represent the initial attempt within FarmConners project[4] to integrate WPPC and WFFC. It aims at approaching the fields of wind flow modeling and aerodynamic turbine interaction from WFFC on one side, and electricity markets and grid integration on the other. Therefore, WFFC is analyzed with respect to other control functions which are (or could be) present in a WF, highlighting potential interactions and opportunities for improvement. The present article looks into the interactions between conceptual control functions in WFs and identifies challenges toward well integrated WFC. Further details like different WFC algorithms are out of the scope here but provided in recent reviews.[5,6]

The remainder of this article is structured as follows: Section 2 introduces active power provision and connects their timescales with aerodynamic WF phenomena. Section 3 differentiates conceptual modules of the WFC system. Section 4 gives an example of interactions between electrical and aerodynamic aspects. Section 5 highlights the identified challenges of integrating WFC. Section 6 concludes the article.

2 | ACTIVE POWER PROVISION IN POWER SYSTEM OPERATION

WFs have the main purpose to capture energy from the wind. The variable that both WPPC and WFFC seek to influence is the active power provided by the WF at the point of common coupling (PCC). Therefore, the present

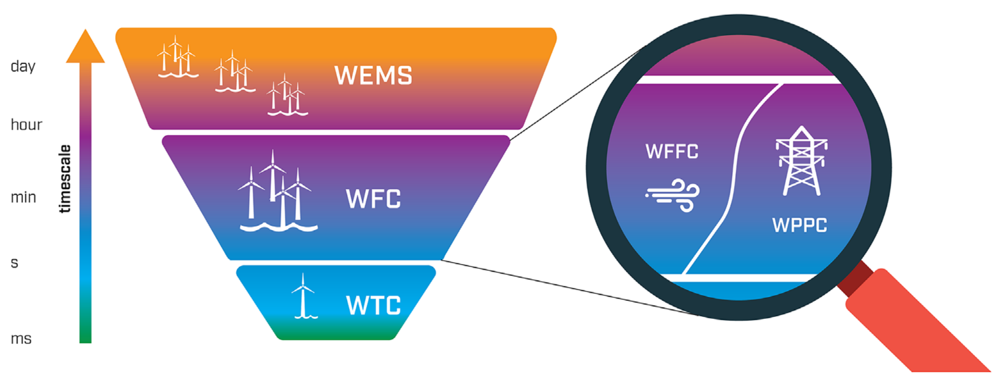

FIGURE 1 Generic overview of the modules for operation and control of wind farms. WEMS, wind energy management system; WFC, wind farm control; WFFC, wind farm flow control; WPPC, wind power plant control; WTC, wind turbine control.

article focuses on the provision of active power by WFs and general control functionalities for this. Figure 2 places the provision of active power reserves in relation to the timescales of power system operation and phenomena in wind energy systems. Electromagnetic transients represent phenomena such as transient overvoltage and switching, which are considerably faster than WT dynamics and the aerodynamic interactions at the WF. Inertia is provided by all directly grid-connected rotating electrical machines. Most WTs are operated with variable rotor speed and interfaced to the grid through power electronics. Thus, the rotor speed is not synchronized with the network frequency and inertia is not provided by WTs.[7] Active power reserves (FFR, FCR, FFR, RR) are provided in time frames of sub-seconds to hours, and are in focus here. Electricity markets link to WFC through the electricity prices. WFC considering flow effects in scenarios with variable electricity prices has recently been studied[8] but this is out of the scope of this work.

Following the terminology of References 9 and 10, three traditional reserve levels contribute to stabilizing the grid frequency in case of significant imbalances between generation and consumption:

1. Frequency containment reserves (FCRs) are typically activated automatically through the power-frequency droop control loop of generating units, a few seconds after a major disturbance has occurred in the system. Their aim is to stabilize the frequency at an acceptable value by quickly balancing generation and consumption.
2. Frequency restoration reserves (FRRs) are typically activated in time-frames of 30 s to 15 min after the disturbance, either automatically or manually at the control center of the transmission system operator (TSO). The aim is to restore the rated frequency and to release the FCRs, as well as to restore active power set-points interchanged between control areas in large interconnected systems.
3. Replacement reserves (RRs) are commonly activated in time-frames of 15 min up to hours after an imbalance. They are activated manually at the TSO control center to replace FRRs and to restore the rated frequency if FRRs were not sufficient. They can also be activated to counteract anticipated imbalances.

In addition, fast frequency reserves (FFRs) have been recently introduced in some regions as a mitigation measure to low-inertia situations. The aim is to assist the FCRs by providing a fast response of short duration (only until the FCRs respond).[10] For example, in the Nordic synchronous area, the FFR is fully activated within 0.7–1.3 s when the grid frequency falls below a certain value, and the duration of the support by FFRs can be short (at least 5 s) or long (at least 30 s).[11] In the new fast frequency response service in Ireland,[12] a reserve should be activated in time-frames of 150 ms to 2 s following a frequency event and last until 10 s after activation.

The timescales of active power reserves from subseconds to hours coincide with those relevant for the aerodynamics of wind energy systems as depicted by the turbine and wind icons in Figure 2. Power system services by means of FFR, FCR, and FRR are usually provided by WTC and WPPC. However, WFFC has the potential to support the provision of FCR, FRR and RR. Power maximization is typically implemented at the turbine level but WFFC can lift the power output by optimizing the wake interactions for the whole WF. Moreover, each conceptual module can address structural

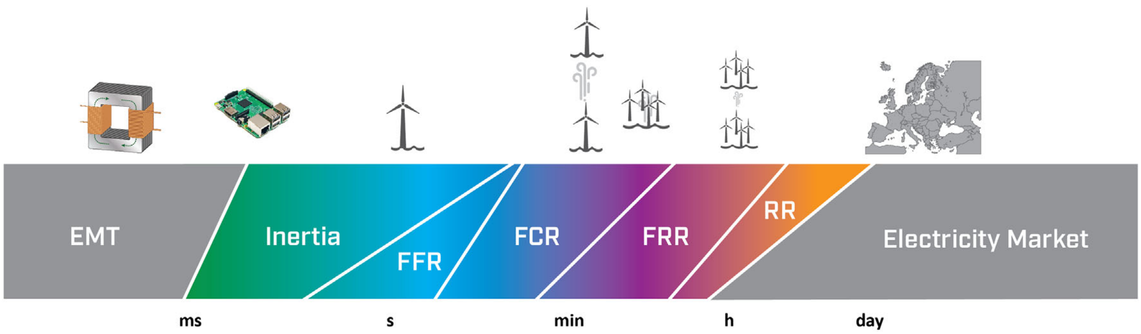

FIGURE 2 Timescales of power system operation underlining the provision of active power reserves. From left to right, the timescales are representative of electromagnetic transients (EMT), inertia, fast frequency reserve (FFR), frequency containment reserve (FCR), frequency restoration reserve (FRR), replacement reserve (RR), and electricity market.

load reduction and/or redistribution. These overlapping control objectives and timescales illustrate the importance of the integration of the control modules.

3 | ELEMENTS OF WIND POWER OPERATION AND CONTROL

Control systems ensure that WFs provide active power to the power system within the given national/regional framework. Figure 1 divides the control system into different control elements or modules where the vertical position illustrates the timescales of the phenomena that are handled by the given controller. The timescale of control actions increases from WTC to WEMS. Within WFC, WPPC acts on lower timescales and is state of the art in present control systems whereas WFFC is an emerging technology to be integrated. The sketched controllers (Figure 1) should not be considered as separate and independent modules in future control systems, but rather as conceptual elements that fulfill a certain functionality as described below.

3.1 | Wind turbine control

WTC is implemented at each WT to regulate and optimize its power production. It has many functions which can be roughly classified into two parts: the normal power production control and the supervisory control functions.

The power production control is active in normal conditions when the WT state is within the operational envelope. Its main objective is to regulate the electrical power output which is typically separated into two different regions depending on the wind speed. In partial load operation below rated wind speed, the WT is operated at the design tip speed ratio when possible, to maximize the power extraction, and the generator torque is used to control the rotor speed. In full load operation above rated wind speed, the generated power is restricted to its rated value using the blade pitch actuators while the generator torque is either constant or inversely proportional to the generator speed. Moreover, modern turbines accept additional set-points for the rotor speed and blade pitch controllers to enable operation at lower than available power. This allows to down-regulate to a power command required by, for example, the WPPC.[13] Down-regulation influences also the structural loading.[14] Additionally, OEM's have started offering the option of power boosting which allows to increase the nominal rating by 5%–10% in certain environmental conditions.[15]

The supervisory control functions are dedicated to the safe operation of the turbine. They are responsible for determining the operational state, deciding when the turbine should start-up or shut-down. Also, using signals relevant to condition monitoring (rotor speed, temperature, actuator motion, nacelle acceleration, etc.), they detect faults and trigger alarms for emergency shut-downs. The main actuators employed by the supervisory control functions are the blade pitch (aerodynamic brake), the generator torque, and the mechanical brake.

A secondary objective of WTC is to reduce the structural loading and vibrations of the WT. Standard input signals are the generator speed, the blade pitch angles, and acceleration sensors while relevant actuators are the blade pitch actuators and the generator torque. Another objective, often implemented in a decoupled control loop, is to align the turbine nacelle with the wind direction. Using a low-pass filtered wind direction signal from the wind sensors (nacelle mounted sonic anemometers and/or wind vanes), a yaw angle or yaw rate is commanded to the yaw actuator to assure optimal inflow conditions.

In terms of timescales, the pitch actuators have a maximum rate of 8–10°/s and an inherent delay due to the electro-mechanical or hydraulic systems employed. The generator torque actuator is faster, in the sub-second scale, with negligible delays and is bounded by the upper limit of the specific design (usually designed for a maximum overshoot of 10%–15% above the rated value). The aerodynamic design and the size of the rotor are also impacting the aeroelastic response of the turbine to the control inputs, with the delays increasing proportionally to the rotor size. For modern WTs, the time to respond to control inputs for power regulation is only a fraction of a second, as the generator torque can quickly increase to increase the active power output. However, this additional power is initially drawn from the inertia of the rotor, as the energy capture cannot be elevated that fast. The corresponding response time is in the order of a fraction of a second for generator torque and power, and a few seconds with the limits defined by the design of the actuators and the rotor. The yaw actuator dynamics are much slower due to the large moment of inertia of the nacelle-rotor assembly.

3.2 | Wind power plant control

WPPC provides control and supervision for the entire WF regarding the electrical aspects while guaranteeing compliance with grid code requirements at the connection point to the power system.[16] The WPPC comprises the conventional way of operating a WF without consideration of the aerodynamic interactions between the turbines. The most common functionalities of WPPC include active power control and frequency support, reactive power and voltage control, as well as fault ride-through capability.

WFs have proven capabilities to provide frequency support to the grid services on timescales from 2 s to 5 min,[17] which coincides with the timescales of FFR, FCR, and FRR. Maximum power tracking is an operational mode in which each WT produces as much as the available aerodynamic power allows. In balance control mode, the power output is limited to a specified maximum level, while in delta control mode, a fixed amount of the available power is produced, creating a certain constant reserve capacity in order to provide frequency services. During either of the above-mentioned control modes, ramp rate control is always activated to regulate the gradient of power production adjustment upwards and downwards.[18]

The feedback of the closed-loop power-frequency droop control includes active power and frequency measurements collected at plant point of connection and available power obtained from the WTC. Functions of WPPC and WTC have been used together for 20 years.[19-21] The measurements for WPPC are sampled with a frequency ranging from 100 to 1 Hz, while available power sent from WTC is at a rate lower than 1 Hz. The interface between WPPC and WTC is described in detail in Figure 3. This interface design allows WFs to provide frequency regulation such as FCR, FRR, and RR, shown in Figure 2. In order for WFs to provide frequency services in shorter timescales, such as FFR and inertia response, the corresponding frequency-supporting active power response might need to be implemented at the WTC to avoid the effect of communication latency. However, control counteraction might arise between WPPC and WTC during the provision of fast frequency services.[22]

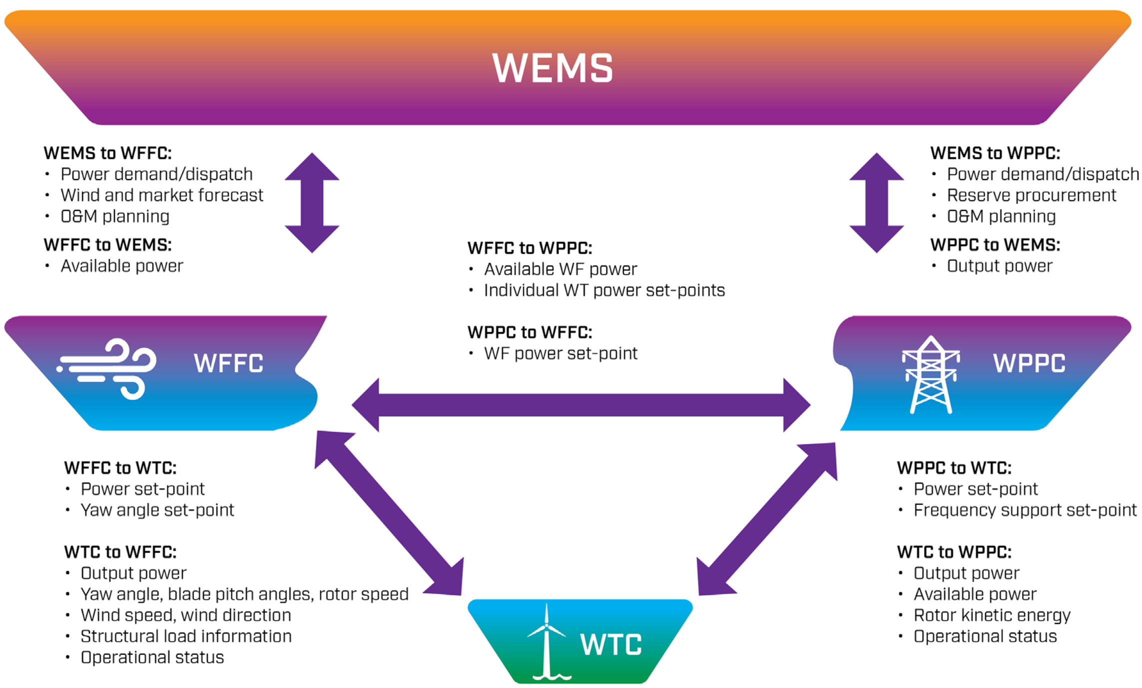

FIGURE 3 Potential interfaces by means of information that is exchanged between the conceptual control modules. WEMS, wind energy management system; WFFC, wind farm flow control; WPPC, wind power plant control; WTC, wind turbine control.

3.3 | Wind farm flow control

WFFC considers the aerodynamic turbine interactions to define the set-points for individual turbines in a WF. Focusing on mitigating the wake effects, WFFC can have several control objectives such as increased energy capture, structural load alleviation, improved provision of system services, and beyond.[23] Despite its promises and years of research on the topic, WFFC is still not a standard functionality in WF operation.

Most WFFC strategies are based on flow information obtained from an underlying flow model of the aerodynamic turbine interaction. To mitigate the wake effects within the WF, WFFC strategies define set-points for the yaw misalignment or the power output, or use cyclic blade pitching of individual turbines by sending the desired values to the WTC. The yaw misalignment can be introduced to steer the wake away from the downstream turbines. For changing the power output of individual turbines, the WFFC typically sends a power set-point to the WTC which implements it using a certain down-regulation strategy. Finally, cyclic collective or individual blade pitching could be used to promote the wake mixing for faster recovery of the wake at the downstream locations, however, no field implementation is reported up to date.

Depending on the control objective(s) and controller complexity, WFFC could be based on different input signals. In addition to the information collected from WTC and WPPC systems as listed in Figure 3, in-situ observations of the wind conditions (e.g., meteorological masts or remote sensing devices placed in the WF) can be fed into WFFC.

Considering typical times needed for wakes to propagate between two turbines in a WF, suitable sampling times for control algorithms dealing with flow aspects range from approximately 30 s to several minutes. However, especially for closed-loop implementations, estimators and algorithms might need even higher sampling rates, although typically not faster than 1 s.

3.4 | Wind energy management system

WEMS coordinates the operation of several WFs and works on timescales of minutes to hours or even days. It is therefore concerned with managing the energy (power × time) rather than the short-term power output. Here, the energy management system refers to the operation scheduling considering, for example, external signals like electricity prices but also O&M constraints like planned maintenance activities.

3.5 | Interactions within WFC

The outlined control modules exchange measurements and determined set-points. Figure 3 shows possible variables passed between them to illustrate potential synergies and conflicts of their interaction.

In the illustration, WPPC and WFFC are separated but exchange information with both WEMS, WTC, and each other. The WEMS would demand a farm power and provide external information to the WFC (WPPC and WFFC). The WTC sends information about its operational status (shut-down, fault, etc.) and local measurements to the WFC modules. The WPPC receives measured variables relevant for the electrical aspects, the WFFC for the aerodynamic. Conflicts may arise, for example, because both WPPC and WFFC define power set-points for the WTC, or because the WPPC receives estimates of available power from both WTC and WFFC. It is important that WFC integration prevents such conflicts between WPPC and WFFC, and makes best use of the available information. The next section illustrates the effect of unconsidered dynamics on WPPC through a simulation example.

4 | SIMULATION EXAMPLE OF INTERACTIONS WITHIN A CONTROLLED WIND FARM

A simulation example illustrates possible interactions between WPPC and the farm flow. Figure 4 shows a simplified block diagram of a MATLAB Simulink model that can be used to simulate WFC interactions.[24] The wind-farm-dynamics block substitutes a real controlled WF by modeling (low-fidelity) the dynamics that a WFC system would experience. It has two main sub-blocks: the farm flow and the WTs. The farm-flow-dynamics sub-block simulates the local wind conditions at each turbine using FLORIS[25] to model the farm flow. It receives the ambient wind condition (wind speed, wind direction, turbulence intensity) and individual turbine properties (e.g., nacelle orientations and thrust coefficients) as input and returns the local wind condition (wind speed, wind direction) at each turbine as output. The underlying wake generation model calculates local wind conditions, while the wake propagation model imposes a variable time delay on the relevant turbine properties. The wind-turbine sub-blocks contain the turbine dynamics, respective turbine level controllers and corresponding actuators. Both the dynamical WT model and the WTC receive local wind speeds and wind directions for the respective turbine as calculated by the farm-flow sub-block.

Note that the WTC is considered here as part of the WF (dynamics) which is controlled by WFC. The WTC in Figure 4 can receive power and yaw angle set-points as inputs from the integrated WFC composed of WPPC and WFFC. The inputs to the WFC are the produced and available power at each individual WT, as well as local wind speed and direction.

The interaction between WPPC and farm flow dynamics is illustrated in a test case where the WPPC operates the WF in three different control modes, namely (1) balance control (tracking specified power reference), (2) delta control (maintaining specified power reserve), and (3) maximum power point tracking (MPPT; generating maximum power). WFFC is inactive to focus on the interactions between WPPC and flow dynamics.

A row of four IEA-15MW-RWT reference wind turbines (RWTs)[26] with a spacing of five rotor diameters (5D) is simulated without yaw misalignment. In Figure 5A, the applied WFC modes are shown in the first subplot, where balance control at 40% of the rated power is applied for the first 30 min, followed by delta control with 20% of available power for the next 30 min, and MPPT for the last 60 min. The balance control reference value represents the percentage of its rated power that the WF should generate. The delta control reference value represents the percentage of available power that should be kept as reserve. Thus, a balance control reference of 1 together with delta control reference of 0 represents the MPPT mode. The remaining subplots of Figure 5A detail the investigated ambient wind conditions into wind speed, wind direction and turbulence intensity. They represent a case where the ambient wind speed fluctuates from below rated to rated conditions, while the wind direction is aligned to the WT row (corresponding to $0° \pm 5°$), resulting in full wake conditions. The resulting power dispatch set-point from the WPPC, the simulated available power and the simulated output power are shown in Figure 5B. The gray dashed curve shows the case without consideration of flow dynamics in the WF simulation. The solid black curve shows the integrated output. In both cases, the WF is controlled with the WPPC only, that is, not using the WFFC. The difference is that the WF is simulated either as uncoupled WTs (gray dashed curve) or including the farm flow (solid black curve). The latter including flow dynamics is a more accurate representation of the WF.

A clear observation from Figure 5 is the over-prediction of the available power when farm flow effects are not considered (gray dashed curve). Such a simulation results in a falsely higher power output. Including the farm flow (black solid curve), the simulated available and output power are lower due to the wake shed by the upstream turbine(s) on the

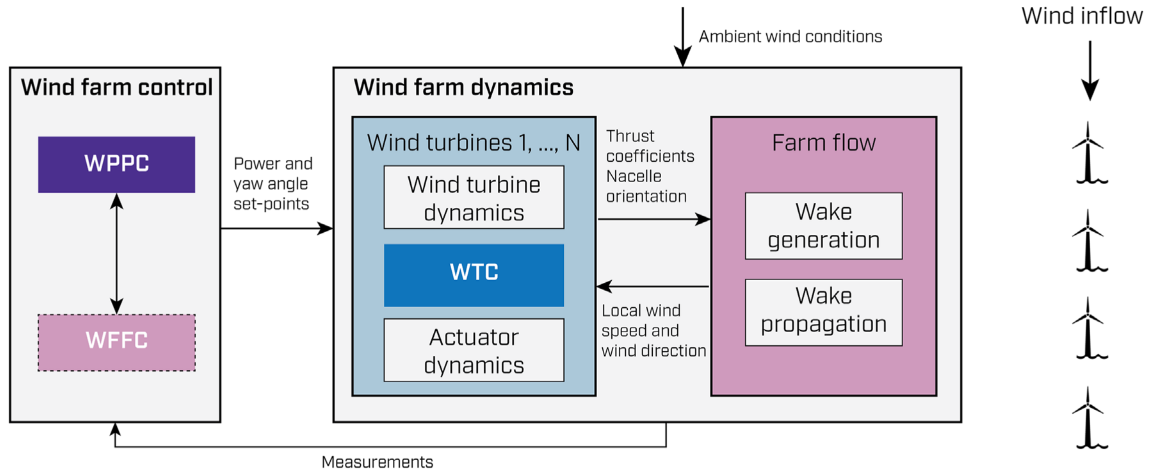

FIGURE 4 Simplified block diagram of the MATLAB Simulink model used to simulate a controlled wind farm.[24] The simulated farm with four wind turbines in a row is indicated on the right.

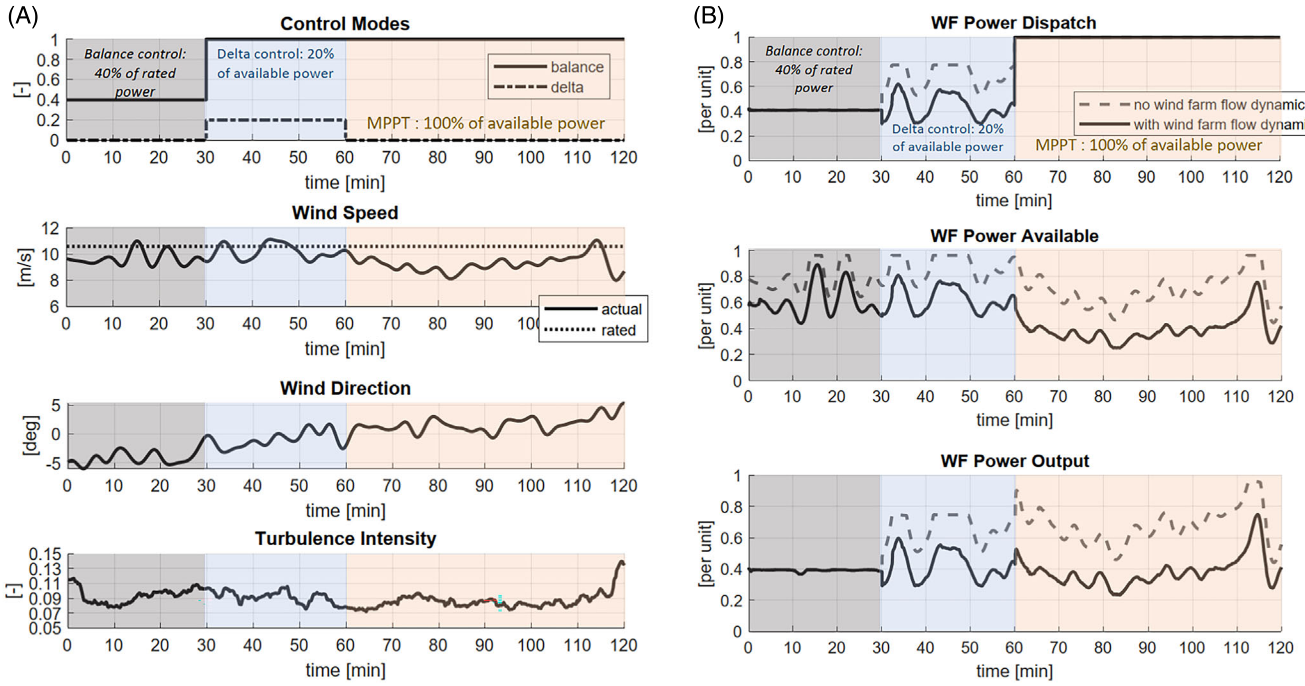

FIGURE 5 Simulation set-up and output of example test case of integrated wind farm simulation. (A) Control modes of WPPC and ambient wind condition as input to WF in simulations. (B) Power dispatch set-point, simulated available power, and simulated power output of the WF for simulations with and without farm flow model.

downstream turbines. The power production in the WPPC delta control mode is even a function of these wake effects varying with the changing inflow conditions.

5 | CHALLENGES AND RESEARCH GAPS

The test case in Section 4 highlighted the interaction between WPPC and the farm flow, demonstrating the importance of considering WF flow effects in an integrated WFC setting. Furthermore, an anonymous survey about the implementation of WFFC was sent to representative WF operators and researchers with different levels of experience with WFFC and field tests. Although the number of participants only included four industry partners and four researchers, the answers gave valuable input about the challenges of implementing WFFC in the field. They also indicated a diversity in the taxonomy and terminology used. However, they clearly stated that integrating WFFC and WPPC can be challenging.

The following challenges were identified:

Integrity of safety and protection functions: Means to provide electrical and mechanical protection to WFs is typically implemented at the turbine level. The WTC implements the set-points from the WFC if they do not interfere with the integrity of safety functions. This may not be possible in cases of extreme events, exceedance of operation limits or component failures. The control structure must ensure that WFC does not and cannot interfere with these essential functions.

Activation of WFFC: Grid compliance is a prerequisite when operating a WF making WPPC essential. Indeed, in some operation modes such as FCR, only typical WPPC is relevant due to the involved dynamics. However, WFFC can increase the profitability depending on the wind inflow and operational objectives. When it is activated though, potential interactions of the WPPC and WFFC at lower frequencies should be considered.

Increased number and types of sensors: Novel control functions and emerging technologies like WFFC introduce new sensors and increase the amount of monitoring data that needs to be handled, and which can potentially fail. An example of sensing technology that is today not commonly installed at WTs is light detection and ranging (LiDAR) devices scanning the incoming wind field.

Actuators and update rates: Conflicting input signals should be avoided to prevent the WTC from switching between control modes which would create unnecessary transients. WPPC and WFFC may request to adjust the same variables, for example, the power set-points. A possible implementation is that WPPC and WFFC functions define delta signals instead of absolute power set-points, and the integrated WFC evaluates their combination.

Balancing control objectives: The definition and observability of appropriate control objectives is particularly important when considering a system that integrates various control functions. With the major purpose of power production, WFC will dispatch power set-points balancing different objectives. Providing downward reserves as grid service, for example, contradicts with general power maximization. Structural load reduction as control objective must be weighted against those concerning the power production. The successful integration of such control objectives depends also on the external inputs to the control system linking it to sensors, electricity market conditions (for revenue objective), and structural loads for lifetime estimation or O&M costs.

Overall system dynamics and model fidelity: Present WFC focuses on WPPC, whereas WFFC will be a new functionality that must be integrated in the control system. The control logic managing both WPPC and WFFC must consider the interactions outlined in Figure 3 and overall system dynamics. Models used to design the control system describe subsystems with different fidelities. When designing the WPPC, for example, the WF flow is typically neglected or extremely simplified. Flow dynamics, however, might impact the typical WPPC functions, as demonstrated in Section 4.

Programming languages: Interactions of different control modules in the control design phase require smooth communication between several models/modules that might be written in different programming languages. Proper wrapping of such tools is another challenge to develop generic frameworks.

Access to WTC by WFC: In practice, the main technical challenge for interfacing WFC with WTC is the actual implementation of required modifications to the system. As WTC is proprietary of the OEM's, currently the farm operators can use it as a black box with the only option being the predefined down-regulation set points. For example, the yaw actuator command has to allow for deviations from the nominal WTC value and alternative down-regulation set-points might be required to reduce the thrust which cannot be applied without direct access to the controller software. Hence, in order to integrate WFFC and WPPC with WTC, OEM's have to be actively involved or supply interfaces allowing farm operators to apply the relevant strategies independently. Establishing an extended two-way communication between WFC and WTC, cybersecurity risks become even more important.

Standardization: Standardization of control interfaces, in particular between WTC and WFC, could facilitate and promote an integrated control approach, making the most of the different control functionalities at hand and improving interoperability. The international standard IEC 61400-25 "has been developed to provide a uniform communications basis for the monitoring and control of wind power plants. It defines wind power plant specific information, the mechanisms for information exchange and the mapping to communication protocols."[27] The use of the standard for control of WFs to support power system stability was outlined,[28] and a user group (https://use61400-25.com/) is formed. Nevertheless, there is not a single or prevailing way of integrating WFFC and WPPC.

Certification of WFC including WFFC: Current practice is to certify WTs according to internationally accepted standards. OEM's achieve a type certification by a third party or certification body for a specific rotor-nacelle assembly type which complies with safety requirements, structural reliability (typically for 20 years life time) and certain structural load envelopes. The control system is tested in scenarios to confirm that the system remains within these envelopes. Building on this existing procedure to get a certification for WFFC, it has to be shown that the WFFC algorithm does not lead to higher loads on the structures. Possible risks for the structural integrity could occur, for example, by reduced power set points that would drive the turbine to unusual operating points.

The above challenges fully focus on the control integration problem itself. They add to other more general challenges, such as warranties for the integrated system, which also become relevant for the commercial uptake of the technologies.[29] Here, certification activities could provide additional confidence for WF operators and OEM's that the WFFC strategy in place does not collide with existing safety standards. Relevant load cases for WFFC are currently being defined for the TotalControl publication D4.7 "Design guidelines and standards."[30] Moreover, the certification body DNV plans to update its load standard DNVGL-ST-0437 "Loads and site conditions for wind turbines" within 2022 including a proposition for the certification of WFFC as part of the control system.

6 | CONCLUSION

Two distinct concepts of WFC have developed in research: (1) WPPC that deals with the compliance to grid codes and the provision of power system services, and (2) WFFC that focuses on the aerodynamic turbine interaction to improve the WF operation. Poorly integrated WFC can lead to switching between different control modes to address conflicting interests regarding electrical and aerodynamic aspects. In contrast, well integrated WFC must avoid such switching by continuously regarding WPPC and WFFC.

Although many control functions can be separated based on frequency ranges, possible interactions have to be considered and potentially contradictory control objectives must be carefully balanced when integrating WFC.

The main achievement of this article is identifying the challenges of integrating the different concepts in a holistic WFC system. They indicate directions for future work that depend on the effort of various disciplines. In a nutshell, a successful integration of WFC is all about communication, both between the different control functions and among the researchers/institutions of various disciplines within wind energy.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available upon registration in the repository at https://doi.org/10.5281/zenodo.6241565 and https://gitlab.windenergy.dtu.dk/farmconners/simulink-wfc-platform/.

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