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Provision of enhanced ancillary services from wind power plants – Examples and challenges

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ABSTRACT

Emphasis in this article is on the power system impact of wind power plants capability to provide enhanced ancillary services, i.e. temporary frequency response (TFR) and power oscillation damping (POD). The main objective of the article is to analyze and justify the challenges in the use of TFR and POD from wind power plants (WPPs). The study is conducted with an aggregated wind power plant model which is integrated into a generic power system model, specifically designed to assess the targeted ancillary services in a relatively simple, but still relevant environment. Various case studies with different wind power penetration levels are considered.

The study shows that WPPs can provide additional control features such as TFR and POD to enhance the stability of power systems with large share of wind power. Nevertheless, the results illustrate that the power system stability can be potentially degraded without careful coordination between WPPs, simultaneously providing TFR or POD in power systems with large displacement of conventional power plants by WPPs. The article provides to TSO new insights into the need for service coordination between WPPs into future power systems.

1. Introduction

Across the globe, power systems are continuously changing and expanding through new interconnections and an increased number of wind power installations. As a result, power systems are getting increasingly complex, but also more vulnerable and dependent on wind power production. Moreover, conventional power plants may be replaced by wind power in the future. This aspect raises concerns about the operational security and stability of the systems. One way of ensuring that WPPs are not detrimental to the power system stability and security is to require control functionalities (e.g. reactive power, voltage control, fault ride-through, up-/downregulation of active power, primary reserve, power system stabilization) from WPPs which resemble those traditionally offered by conventional power plants, namely ancillary services (AS).

During the past decade, this concern has led to an intensified research interest from both academia and industry for developing AS for WPPs, i.e. Refs. [1–38], to name but a few. Initially focus was on investigating the capabilities of individual wind turbines (WTs) to provide a given service e.g. Refs. [2–6,8–10], while in the recent years more research is analyzing provision at plant level [7,11,15,19,20,27,30–36], including also operation in isolated power systems [24–26,34]. The frequency stability support in terms of inertia and primary frequency control [4–6,8,13,15,21–23] and the small-signal stability support as the damping of power oscillations [21,32–36] have been investigated thoroughly. Some research is focuses only on particular WT topologies e.g. doubly-fed induction generator or full scale power converter based WTs e.g. Refs. [2–4,8–10,16,17,29] while other address generic variable speed topologies e.g. Refs. [6,8,22,27,31,49]. Little research is dedicated to provision of AS from multiple assets e.g. wind and solar generation combined with energy storage [23]. The coordination of services is barely treated in recent years [12,24,34,38] and without a thorough insight on the need for service coordination between WPPs to avoid instability in the power system. This paper shows how the power system stability can be potentially degraded without careful coordination between WPPs, simultaneously providing services in power systems with large displacement of conventional power plants by WPPs.

As revealed in the European synthesis project *ReServices* [44], most of the research today confirms the technical and operational

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capabilities of WPPs to provide services such as frequency support, voltage support and fault ride-through. These capabilities, available from WPPs and reported in the literature [1–43] for years, have made their way into different technical connection requirements from transmission system operators (TSOs).

As mentioned previously, in the past years several research studies have started focus on development of new control features, such as Temporary Frequency Response (TFR) e.g. Refs. [15,19,24] and Power System Stabilizer like functionality, i.e. Power Oscillation Damping (POD) [20,32–36] at plant level to enhance even more WPP's capabilities to support the power system. TFR and POD delivered by WPPs might become attractive in the context of large displacement of conventional power plants by WPPs in the future. According to [12,20], the consideration of TFR and POD as AS should proceed cautiously and with emphasis on functional systematic needs, as WPPs' contribution is temporarily dependent on wind conditions, mechanical/electrical limitations, control strategies and availability of WPPs. So far, TFR and POD have only been prioritized by few research groups including partners from WT industry [21,39,40]. This is due to the fact that these services normally need temporary power reserve, i.e. prior curtailment of the WPPs with a resulting loss of energy. Meanwhile, discussions on enhanced AS have also been started in several working groups where TSOs are involved. For instance, Hydro-Quebec and Electricity Reliability Council of Texas (ERCOT) have analyzed the possibility to request emulated inertia/synthetic inertial response to be incorporated into future WPPs [13,14,18,19], while the TSO in Great Britain (NGET) has investigated the possibility to include the fast frequency control into their grid code requirement [20]. Power oscillation damping is also required by NGET [20] and recommended by ENTSOE [45]. However, in this respect, the present grid codes (GC) do not formulate clear requirements that enable WT manufactures to translate and implement them into their commercial products, yet [46].

Emphasis in this article is on the power system impact of WPPs capability to provide TFR and POD. The TFR of WPPs refers to the short-term additional active power contribution that can temporarily be released by using the stored kinetic energy in the rotating mass of variable speed WTs. However, as indicated e.g. in Refs. [12,13] unlike the inherent response of synchronous generators (SGs), the capability of WPPs of injecting short-term additional active power into the grid is strongly dependent on wind speed conditions, mechanical/electrical limitation and proprietary control strategy of the turbines.

The POD provision from WPPs refers to the damping of electromechanical oscillations which are typically undesirable in the power system as they limit power transfers on transmission lines, in some cases may even induce stress in the mechanical shaft of SGs [20], and ultimately may lead to system collapse in extreme situations. The POD provision from WPPs has found room for investigations on control strategy design in several recent publications [32–36]. As indicated in Refs. [33,34], the location of WPPs may be a physical limitation in respect to their capability to damp the power system oscillations.

The capability of WPPs to provide TFR and POD have thus been studied in details so far. Nevertheless, the detailed review of the previous research work in the area of AS provision from WPPs [1–45] shows knowledge gaps and needs for further research. The results underline the potential need for further research for better understanding of the main factors influencing the impact of large scale wind power integration on power system stability. Furthermore, to the author's knowledge, the impact of simultaneous provision of ancillary services like TFR and POD from WPPs without any coordination have not been investigated so far for power systems with various wind power penetration scenarios.

According to the synthesis European report [44] further investigations strengthening system reliability are necessary regarding the need for coordination of WPPs in providing AS. Many aspects, such as real limitations imposed by WPPs, the role of the power system characterizations on the implementation of POD, impact of TFR and POD, location of WPPs and the variability of WPPs' output on the power system performance could still be enriched.

The goal of this article is primarily to demonstrate that WPPs can support the power system with TFR and POD. Consequently, an adequate simple power system model should be relatively weak in order to be able to stress and push the system close to its stability limit. In this respect, a generic island power system model instead of a large interconnected power system has been therefore used to generate relevant case studies. Furthermore, an assessment of the entire European grid through simulation studies may be a tremendous task due to the necessary level of information which is not typically available for academia. By studying a small but representative power system that has characteristics and properties similar to continental European is therefore more feasible as long as the proposed solutions are scalable and replicable. Moreover, this small generic power system model is developed with various wind power penetration scenarios [24,34], and therefore the conclusions of this work on the impact of the provision of TFR and POD services from WPPs on a power system with large displacement of conventional power plants by wind power can be approached in a future ENTSO-E network with large wind power penetration. Furthermore, a perfect knowledge of instantaneous available wind power has been assumed. The impacts of available power uncertainty and communication delays on providing AS are out of the scope of this work, as they are considered in details in a new research project [48]. The article does not focus on the design of TFR and POD controllers and parameter tuning, as this has been addressed in many publications over the past years [8–35]. By expanding previous work started in Refs. [24,34] within the frame of research work [43], this article rather focuses on emphasizing the need for coordination between WPPs in TFR and POD provision, in order not to lead towards unstable power system operation. With this aim, it is believed that the work presented in this article provides to TSOs new insights into the need for AS coordination between WPPs in power systems with large displacement of conventional power plants by wind power.

The article is organized as follows. Section 2 briefly presents the enhanced AS from WPPs. Section 3 focuses on the WPP model and its control architecture. A set of simulations, considering different wind power penetrations levels and WPPs' locations, is carried out to reflect how power system stability may be affected when WPPs are required to simultaneously contribute with specific AS. The results show that it is not enough only to require WPPs to exhibit technical capabilities to provide enhanced services, but it is also crucial to coordinate the AS's provision between WPPs in order to ensure a future resilient power system. Finally, conclusive remarks are reported.

2. Enhanced ancillary services from WPPs

The technical capabilities required today in the GC are active/reactive power control, frequency/voltage control and fault ride-through control. In general, the active and reactive power control at the point of common coupling (PCC) is guaranteed at the WPP level by a dedicated controller. Fault ride-through is typically provided at the WT control level due to the fast response times e.g. Refs. [3,9], while voltage control at PCC is usually performed at WPP level [38]. The frequency control can be performed either in the WT level [6,8,16] or in the WPP level [12,15,24]. Today, the above

mentioned features are commercially available from major wind turbine manufactures, e.g. Refs. [51–53].

As previously stated, WPPs' capabilities to provide TFR and POD might be attractive in the context of large displacement of conventional power plants by wind power and therefore possibly required in future GC.

2.1. Temporary frequency response (TFR)

The TFR support from WPPs might be used to compensate for the loss of inertia in power systems e.g. when conventional power plants are displaced by WPPs. The TFR from WPPs refers to the first two sequential reactions of conventional SGs to a frequency deviation following e.g. a disconnection of a generating plant:

1. *Inertial response* – is the response of the SGs inherently delivered through their inertia in the first few seconds of a frequency deviation, as result of the electromechanical imbalance between the mechanical and the electric power. The power system inertia determines the sensitivity of the system frequency following a power imbalance and indicates how fast the system frequency deviates, namely its rate of change (ROCOF).
2. *Primary frequency control* – is automatically activated by the frequency droop controllers of the conventional generators after a few seconds in order to bring the frequency at a certain steady state level. The frequency droop controller has a large impact on the frequency Nadir and on the new steady state level of the frequency.

Fig. 1 depicts the principle of TFR from WPPs, i.e. first a power injection, then a power decay and finally a power recovery where the turbines are returning to the pre-event operational conditions.

Various control strategies of inertial response and primary frequency control have been suggested in the literature [12–19,24–29]. Thanks to the fast response time of WT controllers and the energy stored in the aerodynamic rotors [12], it is technically feasible for WPPs to provide rapid power injection to limit both frequency nadir and ROCOF in a way similar to the primary frequency control of SGs. Notice, however, that their power injection is only temporary, otherwise the WTs would lose drastically rotational speed and aerodynamic torque.

2.2. Power oscillation damping (POD)

POD is typically an embedded feature in the power system stabilizer of conventional power plants which damps the low-frequency oscillations in the power system. This feature may be lost when some conventional power plants are replaced by WPPs. In this context, modern WPPs should contribute with POD support since they typically have a decoupled control of the active and reactive power and can provide a specific desired power delivery to the grid.

Fig. 2 depicts the principle of POD, i.e. to modulate either the WPPs' active power (ΔP_{POD}) or reactive power (ΔQ_{POD}) output in an appropriate phase that supports the damping torque induced in the generator units.

Several POD controller designs that are able to damp power system oscillations based on the power output modulation of the converter are proposed in the literature [32–36]. Any signal reflecting the power system oscillations, being representative of a measured or estimated network state (i.e. line current, power flow) can be used as input to the POD action. The effectiveness of which input/output to use depends on the network characteristics and where the WPP is connected to the network [32–36].

3. Wind power plant model and control architecture

Fig. 3 sketches an overview of WPP architecture used in this article, including WPP controller and WPP model. The WPP controller

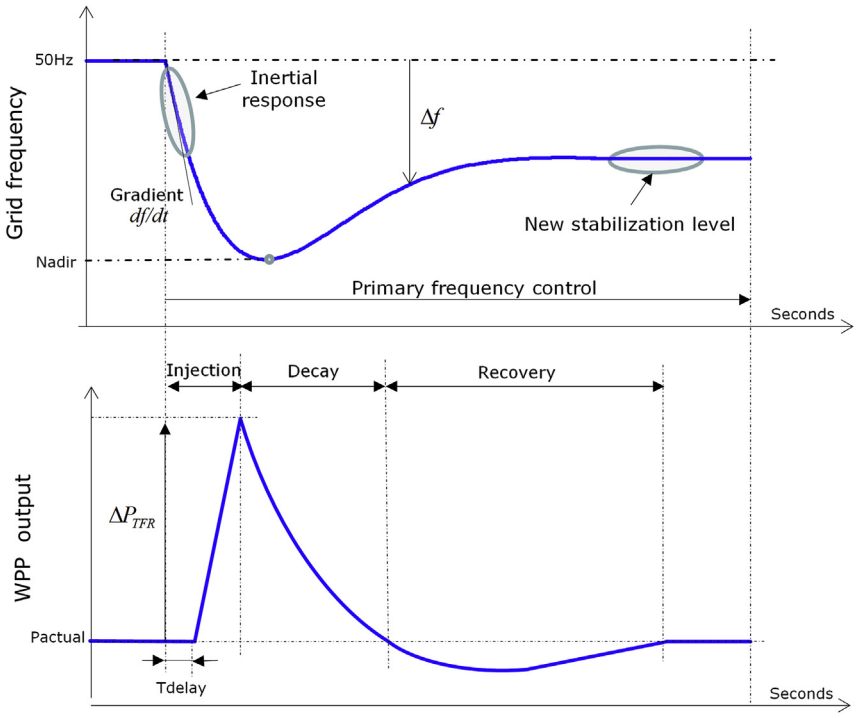

Fig. 1. TFR signal time traces.

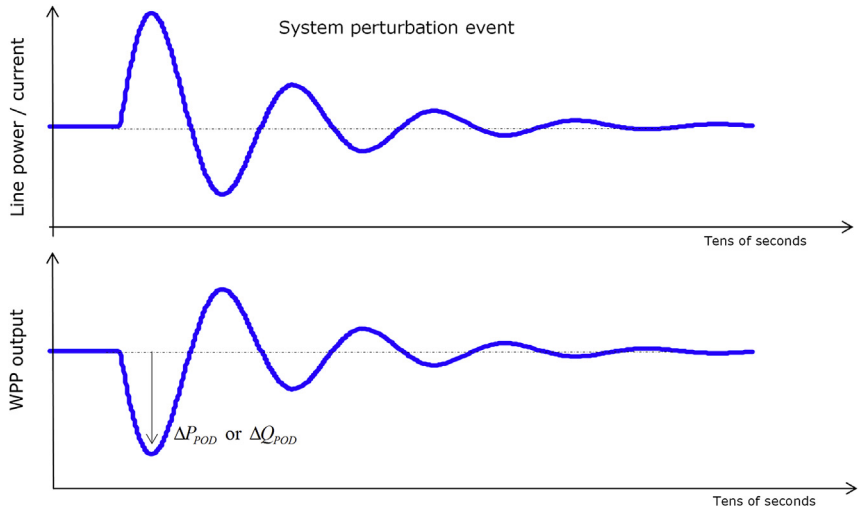

Fig. 2. POD controller and input/output waveforms [43].

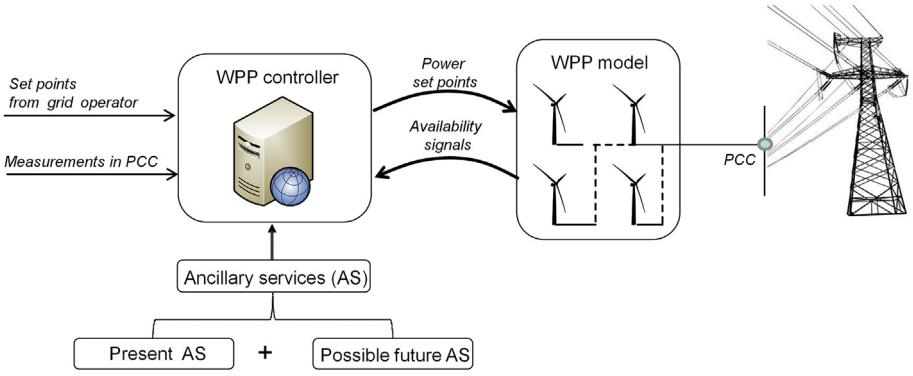

Fig. 3. Overview – WPP control topology.

controls the power production of the whole wind farm and, if required, provides AS, by generating power setpoints to the WPP, based on the TSO's demands, measurements in the point of common coupling (PCC) and availability signals from individual WTs.

Notice that, AS are typically integrated in WPP control level. Besides the present AS in the GC (i.e. active power/frequency control, reactive power/voltage control), the WPP controller can also contain possible upcoming AS in GC i.e. TFR and POD.

3.1. WPP model

In power system stability studies, WPP is typically represented by an aggregated model which, without too high complexity, should reflect correctly the dynamic features of interest.

Nowadays, the new large offshore WPPs are commonly based on full scale power converter WTs (Type IV) [2]. These plants can offer more flexibility in providing POD compared to the Type III (double-fed induction generator based ones) due to the complete decoupling of generator in terms of active and reactive power control. In this research, an aggregated WPP model, based on the generic Type IV WT standard model proposed in IEC 61400-27 [49] and adjusted to reflect the dynamic features of WTs relevant for TFR and POD studies, is therefore used. The aggregated model includes representation of instantaneous wind speed, aerodynamics, pitch actuation, drive-train kinetics, and a dynamic estimation of the turbine's available power based on wind speed and on active power reference gradient [43].

In the aggregation method, illustrated in Fig. 4, an equivalent wind speed is fed into a single up-scaled power WT model to further calculate an equivalent aggregated WPP power. The equivalent wind speed is an average wind speed of all individual turbine wind speed time series, generated by the CorWind model [50] taking into account the spatial and temporal correlation of wind speeds across the n turbines in WPP.

The WPP aggregation method is evaluated in Ref. [43] for several WT operational conditions. The evaluation shows that the aggregated WPP model fed by the equivalent wind speed can correctly represent the behavior of a WPP in power system studies related to TFR and POD provision from WPPs.

3.2. WPP control architecture

A representative WPP control architecture[1] is suggested in Fig. 5. The WPP controller is responsible for hosting all control functionalities, as well as for measuring relevant quantifies at PCC, and performing closed-loop control on plant active and reactive power. It consists of:

[1] The control architecture might also include a power dispatch block, if no aggregated WPP representation is used.

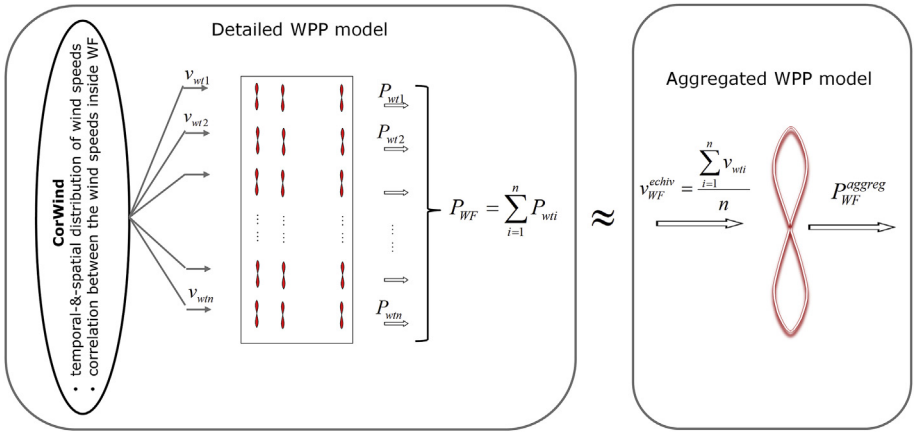

Fig. 4. WPP aggregation method.

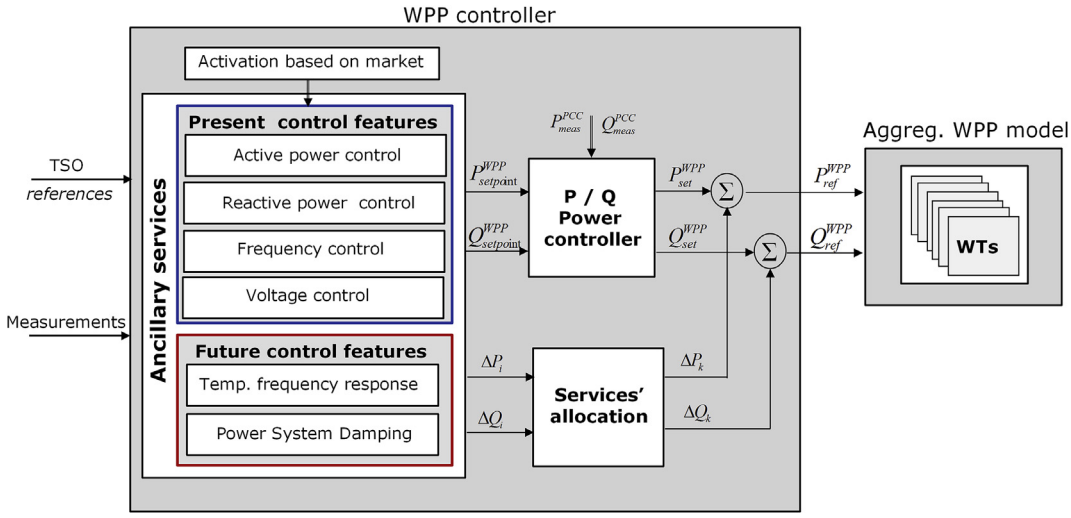

Fig. 5. WPP architecture.

- **Ancillary services block** – includes the present and the possible upcoming AS in the GC.
- **Power controller block** – is responsible for controlling the WPP power production. The power controller generates active and reactive power setpoints for the aggregated WPP, based on specific activated AS controllers, measurements and operation conditions of the WPP.
- **Services' allocation block** – makes it possible to select and, if enabled, even combine simultaneously multiple control functionalities with a specific weighting. In this work, the attention is drawn on individually enabled control features of WPP per time. Notice that in the WPP control architecture depicted in Fig. 5, the power outputs ΔP_k and ΔQ_k corresponding to the new control features, i.e. TFR or POD, are added to the power setpoints, bypassing the power controller in order to make sure that the active/reactive power setpoints from the WPP controller to the WPP are within the plant's capability limits.

It is worth mentioning that the activation of the present control features in GC in the WPP is assumed to be handled through dedicated markets, which is outside the scope of this paper.

4. Impact of WPP's enhanced services on the power system

The power system impact of WPPs capability to provide TRF and POD is analyzed based on a set of test cases which address aspects related to different wind power penetrations levels and to conventional SG's displacement by WPPs in the future.

4.1. Power system model

This research is performed using the power system model and configurations described in Refs. [24,34], specifically adapted to reproduce the necessary grid characteristics for actuation and impact assessment of TFR and POD from WPPs. Power system parameters are provided in the Appendix. According to [24], the grid characteristics of this power system model could for instance resemble the UK power system in a simplistic form. This does not mean that this model intends to represent the UK grid, but rather demonstrates the flexibility of this generic test system, which is small enough to be able to keep a good track of the system characteristics, while at the same time appropriate to display phenomena of interest for power system stability. The development of generic parameter tuning rules is out of the scope of this research and therefore the recommendations presented in Refs. [24,34] for

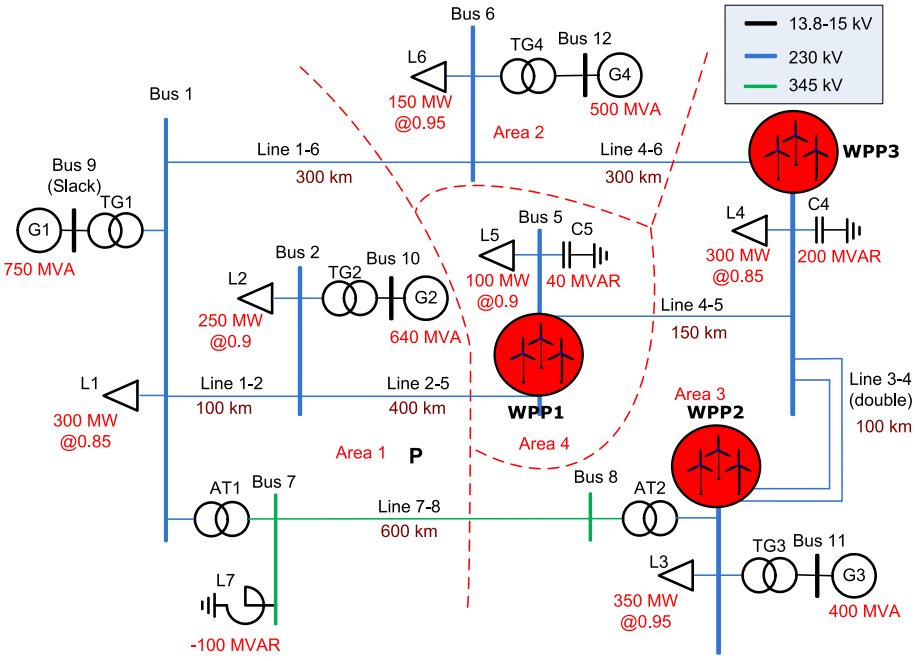

Fig. 6. Test system with location of WPPs.

the design and tuning of TFR and POD controllers are used as a starting point. Three aggregated WPPs are connected in three different locations in the test system, as depicted in Fig. 6.

The model is adapted to reproduce the grid characteristics necessary for actuation and impact assessment of TFR and POD, namely:

1. significant frequency excursions following the loss of the largest generator unit (N−1 contingency).
2. large electromechanical oscillations following short-circuit faults and clearing.

For analysis convenience, yet without loss of generality, it is assumed that the WPPs do not enter into the fault ride-through mode during short-circuit events.

The following wind power penetration[2] test scenarios are investigated:

- *0% penetration* – where no WPPs are connected into the system. This scenario is defined as baseline for power system security and stability assessment.
- *up to 20% penetration* – where increasing demand from loads is covered by WPP installations while the installed capacity of conventional power is kept at the same level. No conventional plants are displaced by wind power. This scenario is typical for countries such as Denmark, Germany and the UK where power systems have enough reserve to accommodate the new generation without major network reinforcements.
- *above 20% and up to 50% penetration* – where old conventional generation units are decommissioned and replaced by new WPP installations while the load demand is kept as in 20% penetration scenario. This scenario is typical for countries where wind power is reaching a relatively high penetration level, e.g. Denmark.

[2] The wind power penetration is understood as the amount of the load demand which is provided by online wind power capacity.

Table 1 summarizes events necessary for actuation of TFR and POD, as well as the test scenarios characteristics, i.e. the amount of wind generation, load and conventional generation.

The 20% scenario is conducted with only one WPP, i.e. WPP1, connected into the system, reflecting a typical situation where good wind conditions are concentrated in a remote rural area. The 50% scenario is conducted by decommissioning large conventional units and connecting additional WPPs into the system, namely three WPPs in three different locations, as depicted in Fig. 6.

4.2. Case studies

In this section, sample results from the test scenarios, listed in Table 1, are presented. The AS provision from a single or multiple WPPs in the power system is analyzed in comparison to the baseline, assuming, as mentioned earlier, that only one control functionality is enabled per time. It is furthermore assumed that WPPs operate curtailed, i.e. they have enough power reserve prior to each network event.

4.2.1. WPPs providing TFR

For each scenario defined in Table 1, Fig. 7 illustrates how the frequency excursion following the loss of largest generation

Table 1
Test scenarios.

AS	Network event	Network behavior of interest	
TFR	Loss of largest generator unit	Frequency excursion	
POD	Short circuit	Electromechanical oscillations	
Case	0%	20%	50%
CPP (GW)	2.00	2.00	1.65
Load (GW	1.45	1.85	1.85
WPP (GW)	0.00	0.40	1.00

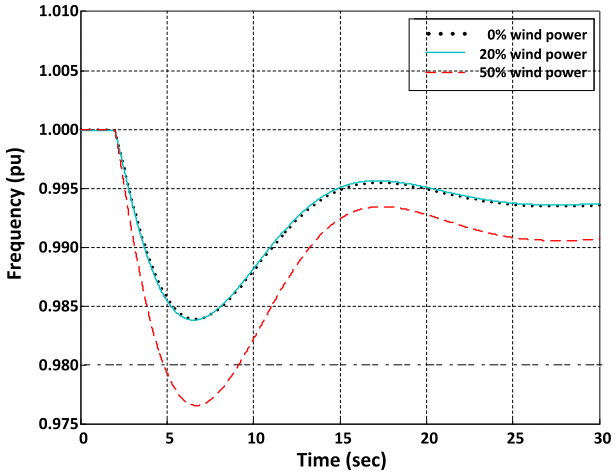

Fig. 7. System frequency following loss of largest generator for different scenarios and no TFR from WPPs.

increases with the increase in wind power penetration when WPPs do not provide TFR. The frequency excursion in the 20% scenario, namely when no conventional power plants are displaced by wind power, is almost the same as in the baseline scenario and does not exceed the load shedding limit. Notice, however, in the 50% scenario, the decrease of system inertia due to the displacement of conventional power plants by WPPs, as well as the frequency excursion which exceeds the load shedding limit.

Fig. 8 illustrates the comparisons to the baseline of the system frequency excursion in the 20% and 50% scenarios, with or without TFR provision, respectively. As depicted in Fig. 8a, the frequency excursion is clearly improved in the 20%, scenario when WPP provides TFR, i.e. the frequency nadir is improved compared to the baseline scenario.

Fig. 8b depicts the frequency excursion for 50% scenario in different cases, i.e. firstly without any TFR provision, then with TFR enabled in one, two or three WPPs, respectively. The results in Fig. 8b are consistent with those depicted in Fig. 7, namely that the displacement of conventional units by accommodation of 50% wind power without any TFR provision, decreases the system inertia and the frequency nadir, easily exceeding the load shedding limits. Notice also that WPPs with TFR provision improve both system inertia and frequency nadir, and that the frequency nadir, when all WPPs simultaneously provide TFR, is improved compared to the baseline scenario.

The displacement of conventional power plants by WPPs, reflected in this work through the 50% scenario, may increase drastically the complexity of the power system operational characteristics. As depicted in Fig. 8b, the power system performance might be degraded if, without detailed insight and understanding of this complexity, all WPPs in the system simultaneously provide TFR. For example, Fig. 8b shows how a double dip may occur in the frequency excursion when more than one WPP simultaneously provides TFR. This double dip, typically not preferred by power system operators with few exceptions [18,47], shows that it might not be necessary that all WPPs simultaneously provide TFR – as for example shown in Fig. 8b, the frequency excursion in the scenario with TFR only enabled in WPP1 and WPP2 is almost the same, except the double dip in the frequency, with that with TFR enabled in all three WPPs.

Hence, this result shows that the simultaneous TFR provision from multiple WPPs in a system should not be directly stated as a general requirement in the grid codes without thorough analyzes. A careful coordination of the TFR provision between WPPs, considering for example different activation times and parameter tuning, might be necessary for each particular network. However, such coordination might be a regulatory challenge in practice when different WPP owners might be involved.

4.2.2. *WPPs providing POD*

Power system robustness is challenged by network disturbances, such as short-circuits or loss of generators. These events are typically manifested through rapid changes in power system states (i.e. voltage amplitude, frequency, voltage angle, line current flow). As result of such events, low frequency power swings can appear due to the electromechanical nature of SGs interconnected by long transmission lines which altogether form an electrical equivalent to mechanical spring-mass-damper systems. Some of the power system states of relevance can be measured locally at the power plant point of connection, but in general there is a benefit and a need to measure quantities at remote locations in the network.

The usefulness of remote measurements and state estimation has been intensively researched globally and non-specific to wind power [34,41,42]. The use of remote measurements is especially relevant in wind power applications due to the fact that WPPs locations, mainly defined based on energy capture possibilities and economic aspects, may be far away from power corridors prone to power system oscillations. This research work excludes solving optimally placement of remote measurements points, but merely assumes certain remote signals to be available to the WPP controller.

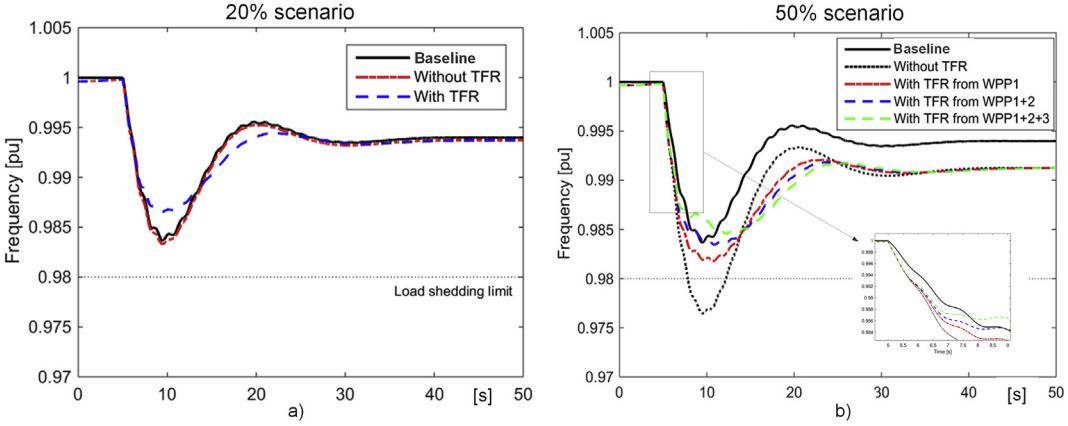

Fig. 8. System frequency excursion following the loss of largest generator unit for: a) 20% scenario, b) 50% scenario (WPPs with or without TFR).

A set of case studies has been carried out to test the performance of the POD provision from WPPs, based on assumed available remote measurements and across several degrees of freedom such as:

- 20% or 50% scenarios, as defined in Table 1.
- Single or multiple WPPs contribution
- Different input/output pairs for the POD controller, i.e.:
  - Current based POD (I& ΔQ): where the current and the reactive power ΔQ are used as input and output in the controller, respectively
  - Active power based POD (P& ΔP): where the active power P and ΔP are used as input and output in the controller, respectively

Fig. 9 illustrates the current and active power measured in a remote line in the system for the 20% scenario with and without POD from WPP. Notice that the POD from WPP has a positive damping effect on the current and active power signal.

The Prony signal decomposition method [34] is used to analyze the system oscillatory profile by translating the time series into modal quantities (i.e. the damped frequency and damping ratio), in the attempt to fit data by a series of damped harmonics. No significant deviations from 0.7 Hz are observed in the damped frequency with or without POD. Instead, the damping ratio of the power and current, displayed in Fig. 9, respectively, is affected, as shown in Fig. 10, depending on POD controller input/output pairs. Notice that a POD with active power modulation (i.e. POD – P& ΔP) has bigger damping impact on the power than on the current, that both POD controllers have the same impact on the current signal and that the damping ratio is more than doubled compared with the case without POD.

Fig. 10 shows that for the 20% scenario, any combination of POD controller input/output pair contribute almost equally to the damping of the oscillations of the current and active power measured in a remote line in the system. Thus, clear recommendations for selection of the measurement signal are difficult to formulate.

Fig. 11 illustrates the current and active power measured in a remote line in the system in the 50% scenario for two case studies:

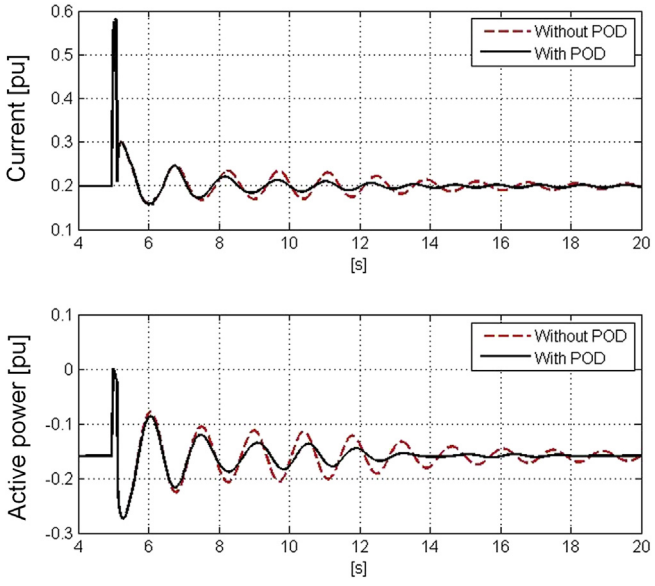

Fig. 9. 20% scenario – POD impact on line current and active power.

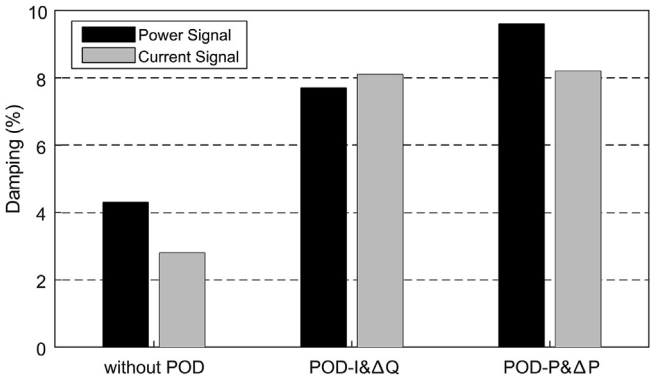

Fig. 10. 20% scenario – damping ratio of the power and current signal (with/without POD).

1) POD provision activated in only one WPP 2) POD provision simultaneously activated in all WPPs connected to the system. These case studies are carried out using the same POD parameters tuned for the 50% scenario and same input/output pairs in all three WPPs.

The damped frequency and damping ratio of the power and current are further depicted in Table 2 for the 50% scenario with single or multiple WPP contribution with POD, for two input/output pairs combination, i.e. active power based POD (P & ΔP) – and current based POD (I & ΔQ), respectively.

Both Table 2 and Fig. 11 indicate that the POD provision activated only in one WPP has a positive damping effect which is almost similar for the two POD input/output pairs configuration. Their results are consistent, i.e. the damping of the power and current gets worse when the active power based POD (P & ΔP) is simultaneously enabled in all three WPPs, compared to the case without POD. Moreover, no significant changes in the frequencies of natural modes occur while activating POD provision in all WPPs. The following remarks can be derived:

- In the 50% scenario, with a single POD plant contribution, the conclusions are as for the 20% scenario, namely the POD provision from WPP has a positive damping effect which strongly depends on input/output pair configuration. For example, for the considered network configuration the current based POD (I & ΔQ) has in general a better damping effect on remotely measured current and active power than the active power based POD (P & ΔP) configuration.
- In the 50% scenario, with multiple plants contribution, the choice of POD input/output pair might have a significant impact on the damping performance. The simultaneous POD provision from multiple WPPs may lead to a degradation of power system small-signal stability compared to the case when only one single WPP provides POD. In this respect, Table 2 shows that the active power based POD (P & ΔP) controllers, activated simultaneously in all WPPs, have a negative impact on the system stability.

More detailed investigations on POD provision coordination between WPPs, parameters tunings and choice of input/output pairs in the controller is likely to render better performance. This fact however might be difficult to implement in practice, as the WPPs might have different owners.

These results raise the question whether it is really necessary that multiple WPPs should contribute with POD in the system. The simultaneous POD provision from multiple WPPs in the system should not be directly stated as general requirement in grid codes as a careful coordination of POD provision between WPPs,

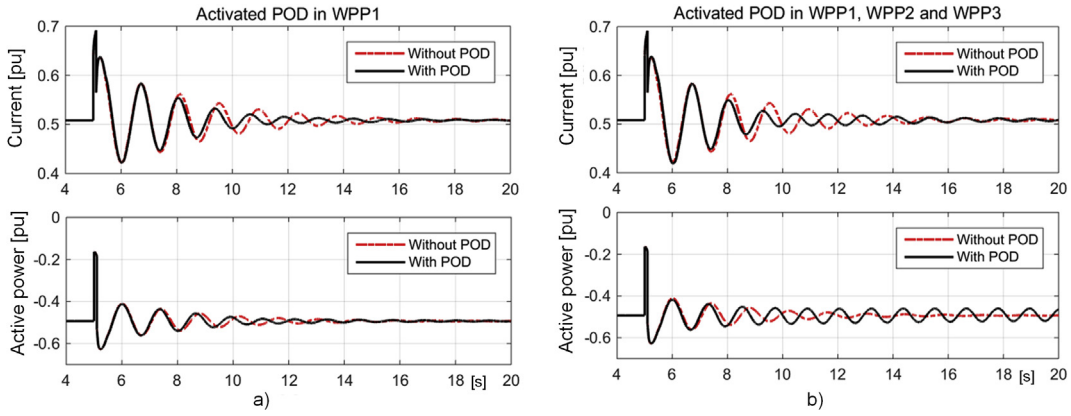

Fig. 11. 50% scenario – POD (P & ΔP) impact on line current and active power. a) POD activated in only one WPP b) POD activated in all WPPs.

Table 2
50% scenario – power system swing modes using Prony decomposition.

Without POD		With POD	POD – I & ΔQ		POD – P & ΔP	
Frequency [Hz]	Damping (%)		Frequency [Hz]	Damping (%)	Frequency [Hz]	Damping (%)
Current						
0.71	**6.1**	WPP1 only	0.74	**6.7**	0.76	**5.4**
		WPP2 only	0.72	**6.6**	0.74	**6.2**
		WPP3 only	0.72	**6.6**	0.74	**6.9**
		WPP1, WPP2, WPP3	0.76	**7.3**	0.82	**2.5**
Power						
0.71	**6.5**	WPP1 only	0.74	**7.4**	0.76	**6**
		WPP2 only	0.72	**7.1**	0.74	**6.9**
		WPP3 only	0.72	**7.1**	0.74	**7.5**
		WPP1, WPP2, WPP3	0.75	**8.2**	0.82	**2.8**

The bold values underline the damping ratio of power and current, respectivelly, and thus the contribution with POD from WPPs.

considering possible activation time and individual parameter tuning, might be necessary for each particular network. Despite this need, it is also important to underline that the implementation of such coordination might be a challenge in practice as WPPs might have different owners.

The results demonstrate that multiple and carefully coordinated WPPs can support with TFR and POD even an island power system, whose stability is more drastically affected during high wind power penetration scenarios compared with larger interconnected systems. Furthermore, these obtained results might be extended toward future interconnected power systems with large displacement of conventional power plants by wind power, when the system inertia and oscillation damping capabilities are reduced as results of the conventional power plants replacement by wind power. Moreover, there might also be situations, when interconnected power systems might enter an emergency operational condition due to cascade contingencies and even split into smaller areas as it was i.e. the situation at 4th November 2006 in ENTSO-E [54]. This means that careful service coordination between WPPs and even other renewable generations is crucial not only for N−1 contingencies but also for severe cascaded contingencies.

5. Conclusions

The power system impact of WPPs capability to exhibit TFR and POD has been assessed through a set of case studies on a generic power system with high share of wind power. Different factors concerning wind power generation such as wind power integration levels, WPPs location, large displacement of conventional power plants by WPPs as well as provision from single or multiple WPPs have been considered. Large aggregated WPPs are integrated into a generic power system model, specifically adjusted to suit and reproduce the necessary grid characteristics for realistic actuation and impact assessment of TFR and POD control functionalities. The attention in this work has been mainly on emphasizing the need for coordination between WPPs in TFR and POD provision, in order not to lead towards unstable power system operation.

The simulation results confirm that WPPs can provide TFR and POD control functionalities to improve the frequency and small-signal stability of power systems. However, it has been observed that the frequency and small-signal stability can be challenged and even potentially degraded when multiple WPPs are required to simultaneously contribute with TFR or POD for large shares of wind power scenarios. The results show that it is not enough only to require WPPs to exhibit technical capabilities to provide enhanced services, but it is also a clear need for thorough insight and understanding of the increased complexity of the power systems characteristics while replacing conventional power plants by WPPs while requiring provision of these AS through GCs from wind power. In this context, the possibility to exploit and coordinate multiple WPPs in the provision of ancillary services, considering for example different activation times and careful tuning of control parameters in each particular network, can likely offer better system stability performance.

Moreover, the results show that simultaneous provision of TFR and POD from multiple WPPs should not be directly stated as a requirement in the grid codes, at least not without further investigations. Tailoring the amount of AS provided by WPPs, developing algorithms for service allocation to manage multiple functionalities, individual control parameter tuning, service coordination and appropriate selection of the input/output pair for the controllers for a given network are likely subjects for further

investigation to offer improved power system stability performance and to minimize the needed wind power reserve allocation. Furthermore multi-input and multi-output control methods for the POD, as well as an adaptive TFR approach could be considered in the coordination and parameter tuning process, as possible solutions for the complex challenges faced by future power systems with large wind power penetrations. Another important aspect barely treated in recent years is related to coordinated control of multiple WPPs providing AS over different communication networks. The performance and characteristics of the communication networks have to be considered properly when designing and assessing AS, as they might have a crucial impact on the AS performance provision from WPPs. Typically, preliminary studies are only possible using control Hardware-In-the-Loop (HIL) architectures where these communication networks including performance and characteristics are properly captured using dedicated realistic models. These aspects will be addressed in the new on-going project RePlan [48], as a natural future step of the present investigation.

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Appendix

This appendix provides the main data of the power system model.

Table 3
Line data for 12-bus system base case scenario (100MVA base).

Line	Length [km]	R [pu]	X [pu]	B [pu]
1–2	100	0.01131	0.08998	0.18377
1–6	300	0.03394	0.26995	0.55130
2–5	400	0.0453	0.3599	0.7351
3–4	100 (×2)	0.0057	0.0450	0.3675
4–5	150	0.0170	0.1350	0.2757
4–6	300	0.03394	0.26995	0.55130
7–8	600	0.0159	0.1721	3.2853

Table 4
Transformer data for 12-bus system base case scenario.

From- to bus	Type	MVA capacity	UK (%)	Vector group
1–7	Autotransformer	500	13	Y_Ny_N
1–9	Step-up	800	12	Y_Nd_{11}
2–10	Step-up	700	12	Y_Nd_{11}
3–8	Autotransformer	500	13	Y_Ny_N
3–11	Step-up	400	10	Y_Nd_{11}
6–12	Step-up	500	11	Y_Nd_{11}

Table 5
CPP data for 12-bus system base case scenario.

CPP	# of units	Total MVA capacity	Generator type	Exciter type	Governor type
1	6	750	F6	H13	F10
2	4	640	F8	H13	F10
3	2	384	F9	F8	F10
4	3	474	H15	ST1A	H16

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