Capabilities and costs for ancillary services provision by wind power plants. Deliverable D 3.1

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REserviceS

ECONOMIC GRID SUPPORT FROM VARIABLE RENEWABLES

Capabilities and costs for ancillary services provision by wind power plants

Fraunhofer IWES, DTU Wind Energy, EWEA

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LIST OF ABBREVIATIONS

AGC	Automatic Generation Control
AS	Ancillary Services
BS	Black Start
Cluster	Wind Farm Cluster
CR	Contingency Reserve
DFIG	Doubly-Fed Induction Generator[1]
DS	Distribution system
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
FACI	Fast Active Current Injection
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FoR studies	The All Island TSO Facilitation of Renewable Studies (Eirgrid and SONI)
FRCI	Fast Reactive Current Injection
FRR	Frequency Restoration Reserve
FRT	Fault Ride-through
FSCG	Full Scale Converter Generator[2]
FSM	Frequency Sensitivity Mode
HV	High Voltage
HVDC	High Voltage Direct Current
I	Islanding
LFSM	Limited Frequency sensitive mode
MV	Medium Voltage
NC	Network Code, also called Grid Code
NC RfG	ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators
PMSG	Permanent Magnet Synchronous Generator
RoCoF	Rate of Change of Frequency
RM	Ramping Margin
RR	Replacement Reserve
SCIG	Squirrel Cage Induction Generators
SO	System Operator (indistinctly TSO or DSO)
SS	System Services
SSVC	Steady-State Voltage Control
TS	Transmission system
TSO	Transmission System Operator
TYPE 3	Variable speed, doubly-fed asynchronous generators with rotor-side converter[3]
TYPE 4	Variable speed generators with full converter interface[4]
VPP	Virtual Power Plant
WF	Wind Farm
WFC	Wind Farm Controller
WP2	Work Package 2
WP3	Work Package 3
WP5/6	Work Packages 5 and 6
WPP	Wind Power Plant
WRSG	Wound Rotor Synchronous Generator
WT	Wind Turbine

[1] According to WECC (WECC-Western Electricity Coordinating Council, 2010)

[2] *Id.*

[3] According to IEC 61400-27 standard draft.

[4] *Id.*

EXECUTIVE SUMMARY

A growing challenge to efficient integration of wind and solar photovoltaic (PV) energy technologies into the power system is the secure and economic provision of grid support services, commonly known as ancillary services. Network operators need ancillary services from generators connected to their grids in order to manage system frequency, voltage and to assist the system during and after faults. As increasing shares of power supplied by wind energy and PV is rapidly replacing conventional generation in Europe, its electricity system will certainly rely on the provision of grid support services from these renewable energy technologies.

Enhanced participation of wind and solar PV in delivering grid support services will reduce the need for curtailment of their power during network congestion and will increase the amount of renewable generation capacity that can be connected to existing networks, thus reducing the need for additional infrastructure expansion. At the same time, the provision of these services offers potential new revenue streams for the renewable generators in addition to the income from energy markets.

This report is the deliverable of the third work package of the REserviceS project and describes the technical options and related costs for the provision of ancillary services specifically from wind energy technologies. It is focused on the set of ancillary services defined in the previous work package 2, shown in table 1 below. The information from this deliverable will be used as input to the case studies in subsequent work packages, which are expected to provide additional insights to the actual provision of ancillary services in transmission and distribution networks.

Frequency support	Voltage support	System restoration
Frequency Containment Reserve FCR (<5, 10 or 30 sec) Frequency Restoration Reserve FRR (<15 min) Replacement Reserve RR (15 min to hours)	Normal Operation: control of power factor, reactive power or voltage	Black start
Fast frequency response (synthetic inertia) (< 2s) Ramping margin (1, 3, 8 hours ahead)	Fast reactive current injection	Islanding

Table 1. Ancillary services investigated in the REserviceS project

Added value: a forward looking study

Providing frequency and voltage support with wind power is not new. Technical capabilities for several types of ancillary services are prescribed in various ways in grid codes all over Europe. Wind farms are obliged to meet these requirements, however, as a rule without being paid for delivering the ancillary services. In some countries like, Germany and Spain, support schemes offer financial incentives for wind farms with enhanced capabilities. This practice remains, nevertheless, the exception rather than the rule in Europe.

The added value from the assessment of REserviceS is the provision of ancillary services from the perspective of an increased and proactive utilisation of enhanced capabilities of wind power technologies, enabling them to take over the current role of conventional must-run power plants. Moreover, the findings from this report can be considered to reflect adequately the present technology status and future expectations of the wind industry. By inventorying current experience and state-of-the art, supplemented by input from leading wind turbine manufacturers, REserviceS provides a framework to study and make cost estimations for the provision of relevant ancillary services in future transmission and distribution networks with large shares of wind.

Technical capabilities of wind power for ancillary services

The capabilities for the provision of ancillary services were broken down into detailed specific functionalities that need to be present in wind energy technology. REserviceS assessed the technical and operational state-of-art possibilities taking into account existing specifications in grid codes, standards and technical literature. The influence of the specific wind power conversion and control technology were considered at the level of wind turbine, wind farm and cluster of wind farms. Also, the technical limitations and other constraints for wind power technology to deploy or enhance the functionality were assessed.

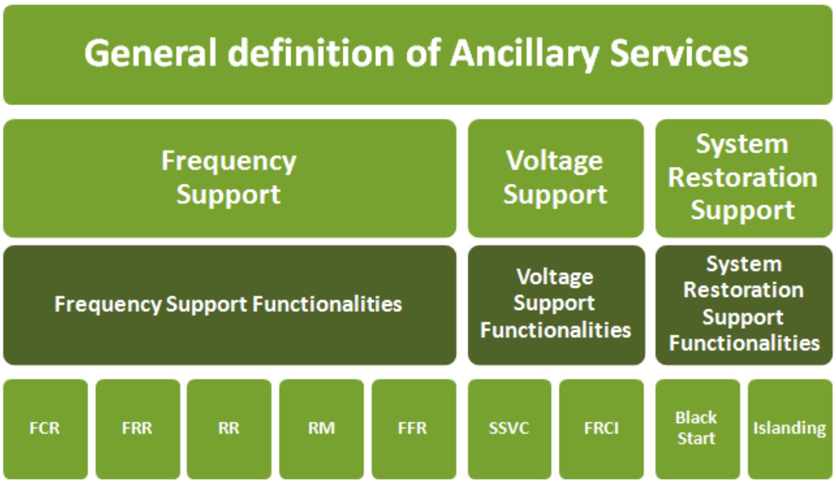

Figure 1: categories of Ancillary Services and Technical functionalities investigated.

Capabilities for frequency support

The detailed analysis per functionality of REserviceS shows that wind turbine technology, today, offers advanced capabilities for frequency support and only few technical constraints have to be overcome to deliver frequency services on a sustained basis. For existing ancillary services Frequency Containment Reserve (FCR), Frequency Restoration Reserve (FRR) and Replacement Reserves (RR) the essential wind power capabilities are in the area of active power control, sensing, wind power forecasting and communication. Also the proposed future Ramping Margin service essentially needs comparable capabilities as FCR, FRR and RR and can also be delivered with today's technology.

The analysis has also identified a number of aspects needing further efforts to enable an enhanced delivery of ancillary services by wind energy technology.

- For Frequency Containment Reserve (FCR) service: Improved TSO specifications for the active control mode of wind farms is needed. Also, wind turbine structural design may need adaptations to take into account increased mechanical loading of a sustained delivery of FCR. Finally, development of improved methods for defining and sensing system frequency at wind turbine and plant level, especially with respect to higher measurement resolution.
- For Frequency Restoration Reserves (FRR) and Replacement Reserves (RR) services: In addition to the wind turbine design challenges of FCR, improved forecasting through better

methods and by pooling wind farms into clusters is needed. Also, there is a need for reliable methods to estimate available power as input for active power control in wind farms.

- For the newly proposed Fast Frequency Reserve (FFR): It is needed improved TSOs specifications for the desired wind power plant control response. This is absolutely required to enable adequate design specifications for the wind turbine and control technologies. Such a specification has to be based on an in-depth analysis of the impact of 'inertia mimicking' response has on the power system. Finally, additional efforts are needed for developing reliable methods to detect and measure system frequency deviations at wind turbine and plant level, as well as for fast and reliable communication between plant and network operator.

Capabilities for voltage support

Similarly as for the frequency services, the detailed analysis per functionality shows that wind turbine technology offers adequate steady state and dynamic voltage support capabilities. However, the constraints to be overcome to deliver these services on a sustained basis depend on the wind turbine conversion technology and the grid requirements imposed, but these issues are mainly of economic nature:

- For the existing ancillary service Steady State Voltage Control (SSVC) the essentially needed capability from wind power is the controlled provision of reactive power, ranging from slow to fast and depending on network operator needs. Limits in reactive power provision imposed by wind power technology can be compensated either by oversizing the converters and/or installing additional equipment like STATCOM devices. Extending reactive power provision down to zero active power would imply extra costs. A particular economic challenge is the provision of reactive power at MV level where larger fluctuations in voltage can occur, leading to a higher need of oversizing electrical components.

- For the newly proposed ancillary service Fast Reactive Current Injection (FRCI) during network faults (i.e. during fault-ride-through, FRT), REserviceS confirms that current wind turbine design includes the capability for a controlled fast reactive current response and that limitations depend on the wind turbine conversion technology and the grid requirements imposed. When extending the capability towards very fast provision of a controlled response, technical challenges include the development of accurate voltage sensing, recognition of fault types and appropriate tuning of controllers. An important issue here is the need to develop a proper TSO specification that is based on a thorough quantification of the need for the fast reactive current in-feed, as well as on system stability studies about impacts of various in-feed strategies. Whereas the FRCI service is intended to provide a positive sequence voltage support to the network, the REserviceS analysis also made clear that there is scope for further development in the area of negative sequence support by wind power plants as synchronous generators gradually disappear from the network.

System restoration support

REserviceS also looked into the capabilities of wind power technology to participate in system restoration, should major failures occur in the power grid. This subject has remained largely unexplored until now and that there is a total absence of technical specifications in grid codes and standards. Whereas technically wind power offers capabilities for various required functionalities, any analysis for wind power to deliver system restoration support should start from the non-fully predictable nature of its prime mover. In a critical grid situation of system blackout, the reliability of supply is of massive importance.

Therefore, reliable participation of wind power in the restoration process, at least as one of the main suppliers of the service, is a subject that needs much further investigation. A suggested approach is for wind power not to constitute the first line of restoration, but to contribute in later stages of the restoration process, when there are already other generators online.

Influence of wind power variability on delivery of ancillary services

Wind power variability can significantly constrain the provision of ancillary services, especially from individual wind farms. A powerful way to deal with this limitation is making use of the smoothening effect that the geographical spread of a portfolio of wind farms offers. By doing this, the forecast error reduces in a linear way with the average 1 hour wind power gradients. Thus, appropriately spreading the portfolio allows wind power gradients to be reduced and to keep the forecast errors low.

When in addition advanced probabilistic forecast methods are used, the uncertainty on forecasted wind power can be reduced to a level where confidence intervals are similar to those of conventional power plants. Similar considerations apply on the provision of the voltage services. Thus, REserviceS recommends wind farm operators to use probabilistic forecasts and network operators to adopt plant pre-qualification methods adapted to the characteristics of wind power.

Costs for delivering ancillary services with wind power

Three categories of costs were considered, according to previous work package definitions, namely 1) costs for the capability (investment costs, CAPEX), 2)costs of readiness (opportunity costs) and 3) costs of utilisation (actual provision, wear and tear, OPEX).

Capability costs were defined as the additional CAPEX for the plant operator to provide a qualified and sustained service provision to the network operator – for example additional cost of a wind turbine with an enhanced load carrying capability or advanced control capabilities. These costs are based on estimations from manufacturers and developers coming from questionnaires and interviews and complemented by literature.

Readiness and utilisation costs generally constitute the value of wind energy not produced due to the delivery of the service. The report gives ballpark figures for all considered frequency and voltage services and for all cost categories, subdivided into different levels of technology: wind turbine, wind farm and wind farm cluster.

There is a significant difference in cost structure, when comparing voltage and frequency services. While additional CAPEX in wind power for enhancing frequency support capabilities FCR, FRR, RR and RM are almost insignificant (far below 1% of wind turbine capital costs), additional CAPEX for voltage services (per kW installed capacity) are a factor 2 to 8 higher than for frequency support services, mainly because of the high costs of power electronic devices. Conversely, readiness and utilisation costs are negligible for the voltage services but can be high for frequency services. The latter, however, depend on the reserve strategy applied, and on the design of the market where they are deployed.

Thus, favourable market conditions can reduce the costs for provision of frequency support by wind farms, while costs for provision of voltage support are largely dictated by technical requirements from network operators and cost recovery for plant operators is hardly conceivable on a market basis.

Finally, due to lack of data and practical experience it was not possible to assess the cost of system restoration services. It is recommended as an area for further research.

Concluding remarks

Few critical technology issues were found. Beside the limitations induced by the stochastic nature of wind, most of the functionalities necessary for delivering the considered ancillary services either already exist in wind farms, or are possible, although not used today. From a technical point of view, most of the necessary enhancements are related to communication – which needs to be fast and reliable – and controllers, that need to be developed and/or tuned for delivering the required performances.

Regarding reactive power support, where technological limitations were found, they could be overcome using hardware that is available today. Structural, mechanical and electrical design changes may also be required in wind turbines, depending on more exact specifications of the services.

In most cases, wind power meets the capability requirements for delivering the identified services, and where it does not; technical solutions exist but are not used today because there is no business case for them.

The lack of clear specifications and definitions of requirements by TSOs is an important obstacle to enhancing wind power plants technical capabilities for the provision of ancillary services. Detailed and clear specifications are of crucial importance when designing control strategies and tuning controllers for dynamic performances. It is recommended that requirements are defined in close cooperation between the TSOs and the wind energy industry.

The most compelling need is to develop clear procedures and methodologies for acquiring and delivering ancillary services that take into account the stochastic nature of wind power production. The methodology used today for proof of delivery or pre-qualification for frequency support services constitutes a big obstacle to competitive participation of wind power in ancillary services markets. Maintaining this approach will lead to wind power not being economically attractive to deliver frequency support services (FCR especially, but also FRR and RR) due to the need of curtailed operation over large time horizons. This could be overcome by adopting new methodologies and procedures.

Accurate wind power forecasting is a key element in increasing the utilisation of wind power in ancillary services markets. Significant improvements have brought the overall performances of the forecasting systems to very good levels, but the issue of how to use the forecasting information in the daily operation remains. Ultimately, a more proactive siting combined with pooling wind power production and high quality forecasting – will diminish the variability of the produced power and decrease uncertainty.

1 INTRODUCTION

With the continuously increasing penetration rate of variable generation (predominantly wind and solar power), the system needs are changing and so are the required types and levels of ancillary services. As variable generation is replacing thermal generation in the system, these generators are also required to participate in the provision of ancillary services. This report is the result of the work and findings done in the project work package WP3.

1.1 Objectives

WP3 provides the analysis of the technical capabilities and the associated costs for wind power to deliver ancillary services and it serves as an input to the case studies in further work packages.

The objectives achieved in this WP were:

- The definition of a framework of functionalities for the provision of ancillary services by wind energy technologies: The mapping between technical capabilities and services, as a list of generic characteristics of the different methods to provide ancillary services.
- The description of the technical capabilities already available in wind power plants: State-of-the-art survey of technical capabilities available in wind power plants so far.
- A gap analysis comparing the state-of-the-art and Grid Code requirements in order to identify the necessary developments and the required technology enhancements or modifications in operation and procedures.
- The description of impacts of variability and predictability in the provision of ancillary services.
- The estimation of the associated costs for the provision of ancillary services by wind power plants. An estimation of costs for each ancillary service, at Wind Turbine, Wind Farm and Wind Farm Cluster level, divided by connection level (TSO/DSO).
- The assessment of cost consequences of ancillary service oriented operation of wind turbines and wind plants.
- The evaluation of different Wind Farm Clusters concepts based on experimental data and cost estimations for providing ancillary.

1.2 Methodology

The approach for analyzing the provision of ancillary services with wind power is divided in four different levels:

- **Service Category Level:** ancillary services are grouped in frequency, voltage and system restoration support level as per WP2 definitions.
- **Ancillary Service Level:** each ancillary service is described and characterised as it has been identified in WP2.
- **Framework of Functionalities[5] Level:** for each ancillary service a set of minimum common and general functionalities enabling the service in combination is compiled.
- **Technical Capabilities Level:** all functionalities in the framework are characterized and described identifying the basic technical capabilities or requirements described in grid codes that wind power shall fulfil to provide a certain service.

[5] Please refer to the definition on page 11.

The focus of the analysis done in WP3 was the ancillary services identified in WP2 relating to wind power. The minimum technical capabilities required for the delivery of a specific service were identified and categorized through a combined approach of literature review and industry enquiries. The latter was done through a comprehensive questionnaire containing four sections: two were related to categories – frequency and voltage, one dealing with general questions and one was related to operational issues. The model of the questionnaire is presented in the annex.

Based on literature review, a basic framework of functionalities was developed. It contains a list of functionalities divided in three categories: frequency, voltage and restoration system support. A sub-set of functionalities are general technical capabilities, expressed mainly in grid codes[6] as requirements, described independently from the specific technical implementation or utilized technology. The other sub-set of functionalities contains operational capabilities, e.g. forecast capabilities, communication capabilities, etc. The combination of different functionalities enables each ancillary service.

Then, the answers obtained from the industry through the questionnaire were aggregated and analysed, the framework of functionalities were revised and the focus moved towards the challenges, both technical and economic, for wind power to deliver ancillary services in future power systems with a large penetration of renewable generation. This part of the analysis was done based on interviews with a selected number of wind turbine manufacturers and wind farm developers/operators. The interview included a part which was dedicated to system restoration, exploring the technical and economic challenges of black-start[7] and islanding[8] operation. The questions which were addressed during the interviews are listed in the annex. Questionnaires and interviews were transmitted anonymously to the WP leader in order to avoid proprietary right risks for respondents. The quality control was performed by the project coordinator.

In order to enable or improve certain functionality dealing with an ancillary service, the refined framework of functionalities was used to describe in detail all the required technical capabilities, to organize and summarize the gap analysis and to help gathering the costs of implementing or enhancing the technical capabilities.

For the cost analysis three different levels of aggregation were considered: First, wind turbine level, taking into account the two most important wind conversion technologies, namely Type 3 and Type 4 (please, refer to Chapter 1.3.1, Figure 1 and Figure 2). Second, wind farm level and third, wind farm clusters, based on the most common aggregations found in literature.

Identified in the framework of functionalities and as part of the qualitative and quantitative analysis of costs, the assessment of the influence of the wind power variability and predictability was investigated in order to describe how those phenomena are affecting the costs for providing ancillary services.

In this document the references to the mentioned questionnaire are marked as [q3.1], meaning question 3.1 from the questionnaire; the references to specific questions on the mentioned interviews are marked similarly as [i1.3], meaning question 1.3 from the interviews.

1.3 General definitions

1.3.1 Conversion concepts

This report follows the wind turbine conversion typology according to the new standard IEC 61400-27: Types 1, 2, 3 and 4; commented in (Margaris, Hansen, Bech, Andresen, & Sørensen, 2012). Complementary descriptions of the technology can be found in (Hansen, et al., 2001) and (Polinder, Bang, Li, & Chen, 2007).

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[6] A list of consulted grid codes is provided on page 11.

[7] For a description of Black Start and Islanding services please consult WP2 deliverable D2.2.

[8] *Id*.

These types were used in the questionnaire addressed to the industry. According to the received answers, the most implemented conversion types currently are Type 3 (in the 62% of the cases) and Type 4 (in the 38%) [q1.3].

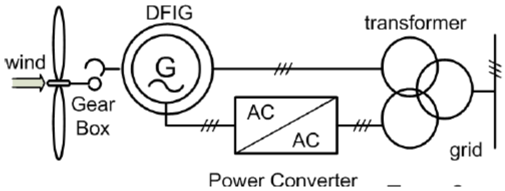


Figure 1: diagram of a Type 3 WT.

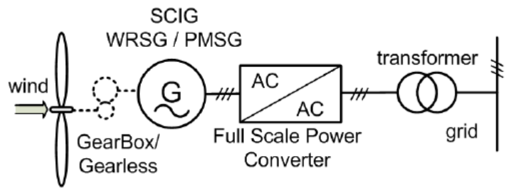


Figure 2: diagram of a Type 4 WT.

1.3.2 Wind Power Plant concepts and related concepts

Related topics with the WPP structure are:

- **Point of Interconnection (POI) or Point of Connection (POC)**: the point at which the Wind Farm's electrical system is connected to the public electricity system. The POI is shown in Figure 5.
- **Point of Common Coupling (PCC)**: the point on the public electricity network at which other customers are, or could be, connected. Not necessarily the same location as point of connection.
- **Wind Farm Controller (WFC)**: the management system that implements the control strategies and coordinates the operation of several wind turbines. The functions of a WFC are the control and supervision of the WT.
- **Voltage system:** symmetrical positive sequence three-phase voltage source.

The hierarchy of wind power technologies analysed in is this report is:

- **Wind Turbine (WT):** a single wind converter machine connected to the grid or to a wind farm controller that transforms the kinetic energy of the wind in mechanical energy and then, by means of an electrical generator, in electrical energy.

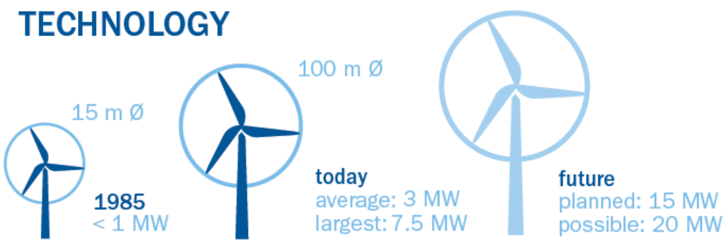


Figure 3: historical sizes of wind turbines and trends for the future (European Wind Energy Association - EWEA, 2013).

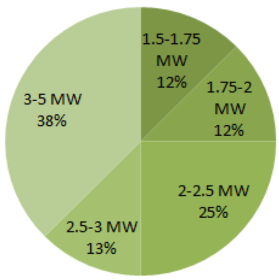


Figure 4: typical sizes of a WT according to the questionnaire [q1.1][9]

The average size of a wind turbine today and the trend for the future years is given in Figure 3. According to the responses of the questionnaire, manufacturers and developers consider the actual average wind turbine size as depicted in Figure 4.

- **Wind Farm (WF):** defines the aggregation of a number of WTs connected to the same substation (or collector system station), and controlled by only one autonomous WFC. A graphical description of a wind farm is presented in Figure 5. WF has only one POI and one WFC.

[9] All ranges presented in the graphics have closed lower intervals and open upper intervals.

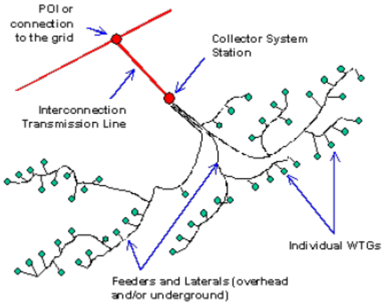


Figure 5: typical WF/WPP topology (WECC-Western Electricity Coordinating Council, 2010).

- **Wind Power Plant (WPP):** a set of independent WF controlled by a unique WFC which operates and manages the entire set of WF as a power plant. A WPP could have one or more POIs but only one WFC.

- **Wind Farm Cluster (Cluster):** set of independent WF/WPP controlled by their own WFC that are jointly managed by a special control system operating each single WF/ WPP in a coordinated manner through their own WFC. The pooling (aggregation) of several large wind farms to clusters up to the GW range facilitates the integration of large amounts of variable generation into electricity supply systems. Cluster management includes the aggregation of geographically dispersed wind farms according to various criteria, for the purpose of an optimized network management and optimized generation scheduling. The scope and size of a Cluster is mainly limited by the services provided, namely:

    - in case of frequency control, the WF/WPP integrating the Cluster could be dispersed and far away from each other;
    - when providing voltage control, due to the local character of the service, integrating WF/WPP must either be connected to the same POI or located nearby to effectively provide the intended service.

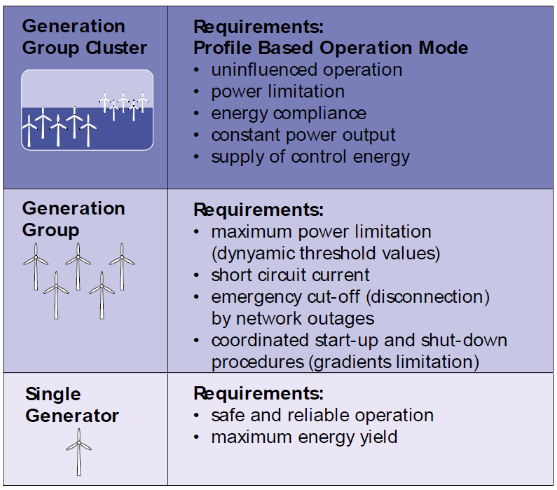


Figure 6: Wind Farm Cluster Management (Rohrig, et al., 2005).

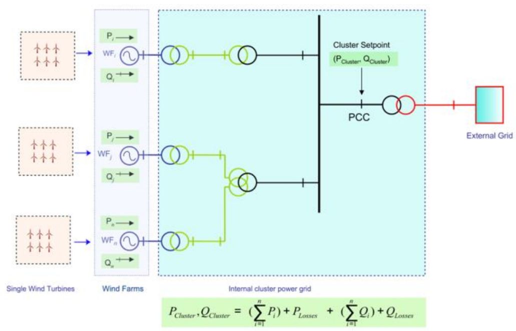


Figure 7: typical cluster layout, with the individual wind farms and the connecting grid until the POI (Source: Wind on the Grid Project, 2009).

Project related definitions:

- **Grid codes requirements:** technical performance requirements for generators imposed by network operators (TSO/DSO). Requirements are usually described as values, text or graphics defining the minimum expected capabilities. E.g.: Frequency response insensitivity = 10 - 30 mHz.

- **Technical capability:** technical means suitable to implement a specific functionality in the form of a response or a behaviour requested by the TSO/DSO as it is stated in a grid code under the predefined conditions. E.g.: Implementation of a PLL algorithm to compute the frequency deviations.
- **Functionality**: a single technical capability or a collection of them described independently from their technical implementation. E.g.: sensing the frequency deviations.
- **Framework of functionalities:** a tool for the analysis used in this WP3 that aggregates various related capabilities of wind turbines, wind farms and/or wind farm clusters in technical and operational general functionalities. These functionalities could be implemented, depending on the underlying technology, by means of different capabilities.
- **Ancillary services:** are all grid support services required by the TSO or DSO to maintain the integrity and stability of the transmission or distribution system as well as the power quality (EURELECTRIC, 2004). E.g.: Frequency Containment Reserve (please also refer to D2.2 of WP2 of REServiceS).
- **Service category**: a category comprising all related services. E.g.: Frequency Support, Voltage Support or System Restoration Support.
- **Detection time:** the time elapsed between the occurrence of a physical event on the network, e.g. frequency change or voltage change, and the moment control system detects this event. Most grid codes don't specify if this detection time is included into the response, rise and settling times or if they are calculated after the detection.
- **Response time:** defined as the time required providing 90% of the final response (as it is usually referred in the literature).
- **Full Response time:** idem before, but providing 100% response.
- **Rise time:** the time elapsed between the occurrences of a physical event and the time at which the response or the output intersects the lower limit of an interval or a deadband (see Figure 8). Grid codes usually don't specify if the rise time includes the detection time or not.
- **Settling time:** is the time elapsed between the occurrences of a physical event and the time at which the response or output intersects the upper limit of an interval or a deadband. Grid codes generally do not specify if it includes the detection time.

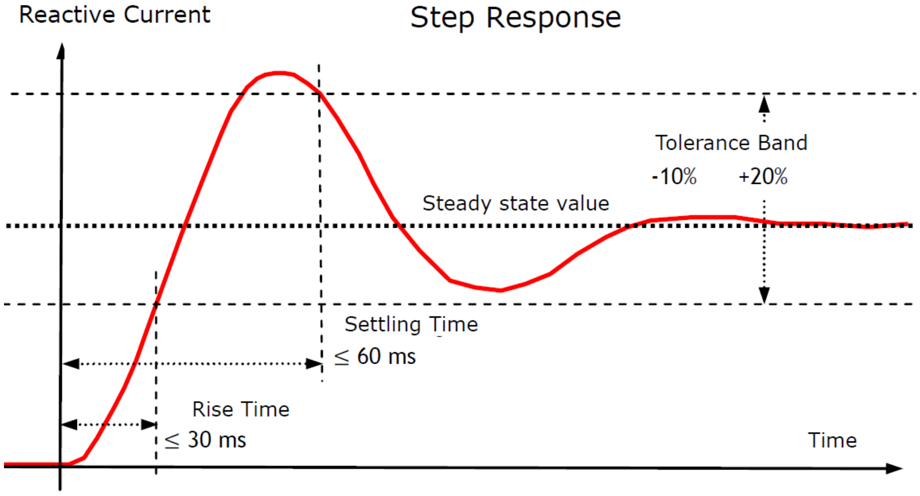


Figure 8: Graphic depicting the most important time parameters of the Fast Reactive Current Injection according to (VDE, 2013), including the Rise Time and Settling Time concepts.

1.4 Reviewed Grid Codes

In this report, the following grid codes were consulted:

- UK - National Grid (National Grid Electricity Transmission plc, 2013)
- Ireland - Eirgrid & SONI (EirGrid, 2011)
- Denmark - Energinet.dk (Energinet.dk, 2010)
- Spain - Red Eléctrica de España
- Germany - Transmission Code 2007 (Verband der Netzbetreiber VDN e.V. beim VDEW, 2007)
- EU - ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators (ENTSO-E, 2012).

2 FRAMEWORK OF FUNCTIONALITIES FOR PROVIDING ANCILLARY SERVICES

Defined in WP2 and presented here in the Table 1, the main ancillary services[10] offered today are related to Frequency support, Voltage support and System restoration.

Table 1: Ancillary Services defined in REServices Project (Source: WP2).

Frequency support	Voltage support	System restoration
Frequency Containment Reserve FCR (<5, 10 or 30 sec) Frequency Restoration Reserve FRR (<15 min) Replacement Reserve RR (15 min to hours)	Normal Operation: control of power factor, reactive power or voltage	Black start
Fast frequency response (synthetic inertia) (< 2s) Ramping margin (1, 3, 8 hours ahead)	Fast reactive current injection	Islanding

New services to reflect future needs are:

- **Fast Frequency Response** and **Ramping Margin** for frequency support;
- **Fast Reactive Current Injection** during voltage dips and for post fault voltage control;
- **Islanding** operation related to restoration (Table 1).

In order to assess the current technical capabilities for wind power to deliver those ancillary services, the framework of functionalities was defined, which incorporates the basic technical characteristics necessary to deliver a specific ancillary service.

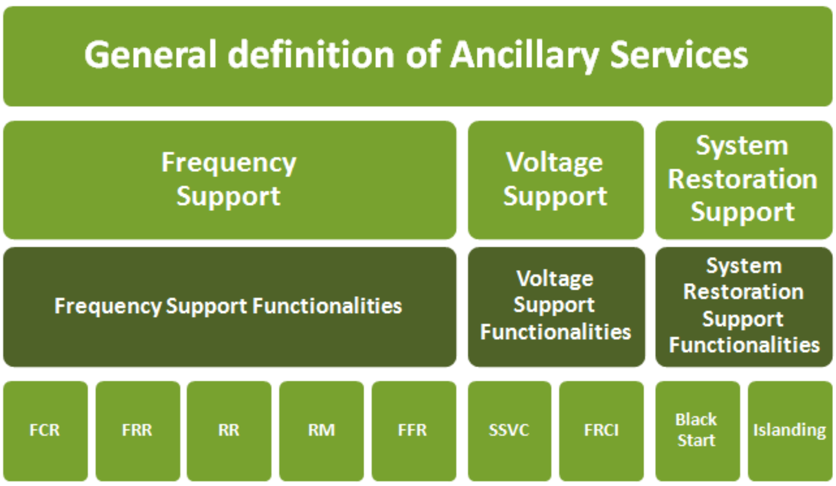


Figure 9: Four-level hierarchy describing the relation between the general description of ancillary services, the aggregated categorization, the framework of functionalities and the specified ancillary services.

[10] Frequency control, with three different time scales (the division proposed by ENTSO-E (ENTSO-E, 2012) has been chosen)

The analysis started using the three categories defined in Table 1, as it is presented graphically in the second layer of Figure 9, to describe the framework of functionalities. The framework is again divided in three sections and is describing functionalities that should be implemented by wind power to be able to provide ancillary services. Finally those functionalities are mapped to specific ancillary services, describing which functionalities are required to implement which ancillary service (fourth layer of Figure 9).

The introduction of the framework of functionalities in this context is useful as a tool in order to analyse category by category which kind of functionalities should be available and provided by wind power, to abstract the functionalities from the specific technological implementation of the capabilities (available or required in the future) and to perform a step-by-step gap analysis as well as the cost analysis.

Then, for each of the service categories (Frequency, Voltage and System Restoration), a table is presented showing which functionalities should be implemented to provide each specific ancillary service; this is the mapping process shown in Figure 10. At the same time, these functionalities are divided into technical and operational aspects, presented in tables for a better comprehension.

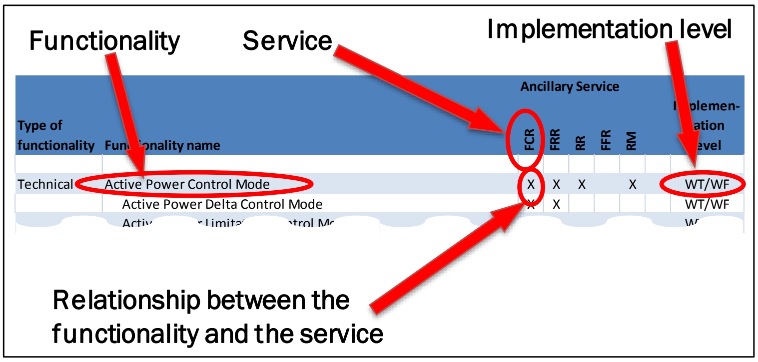


Figure 10: In the example, the functionality "Active Power Control Mode" is required (marked with and "X") for enabling the FCR ancillary Service at both, wind turbine (WT) and wind Farm (WF) levels.

This chapter presents the framework of functionalities divided in three categories (as showed in the third layer of Figure 9) as well as to briefly describe each functionality.

In Chapter 3, each functionality is mapped in specific capabilities already implemented or required by wind power and the technical solutions (available or required) are explained, providing information to Chapter 6, were the gap analysis is assessed.

2.1 Frequency Support Functionalities

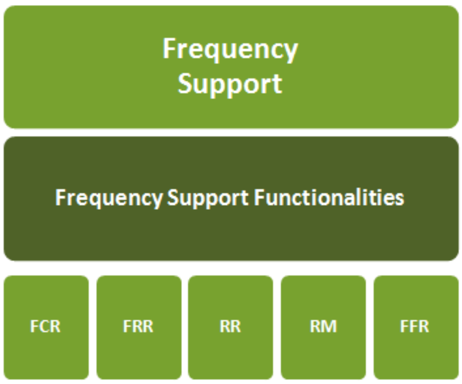


Figure 11: relation between Frequency Support Functionalities and AS.

1. **Active power control.** Probably the most important functionality that wind power plants need in order to deliver frequency support is active power control. The most common available methods for active power control are:
   a. **Active Power Delta Control Mode:** also known as *Delta Production Constraint* (sometimes referred as *spinning reserve*). Delta Control implies the ability of a WPP to reduce its power output by a desired power offset or percentage value compared to the possible production under present wind

conditions, creating a power output reserve. Graphically, the Delta Control is shown in Figure 12.

b. **Active Power Limitation Control Mode:** Also known as *Absolute Production Constraint. It* limits the current power production at the connection point to a maximum value. This constraint may be necessary to avoid overloading the grid.

c. **Active Power Gradient Control Mode:** also known as *Power Gradient Constraint* limits the maximum speed at which the power output of a wind power plant changes independently from wind speed variations. The definition of power gradient constraint is given in Figure 12.

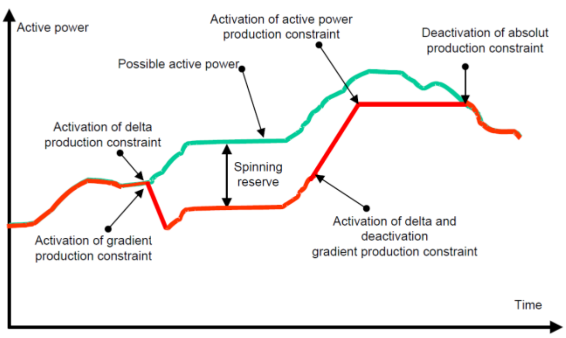


Figure 12: delta control mode – denoted with spinning reserve (Energinet.dk, 2010)

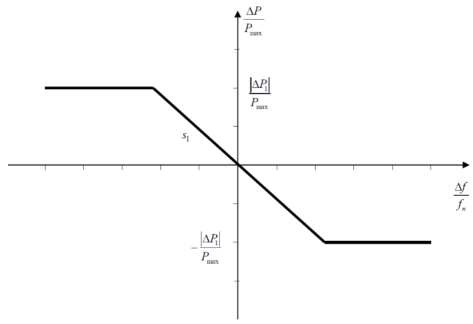


Figure 13: active power setpoint as a function of frequency deviation (ENTSO-E, 2012)

2. **Frequency Sensitivity Mode (or Droop Control).** The functionality is required for WPP to automatically modify the active power output depending on the frequency. A graphical representation is given in Figure 13.
3. **Frequency Sensing.** In order to react to deviations in the system frequency, the wind power plant needs to be able to sense the system frequency and its rate of change (df/dt) or Rate of Change of Frequency (ROCOF).
4. **Active Power Setpoint Processing**. Ability of the wind power plant to receive active power setpoints.
5. **Setpoint priority management**. Capability of the wind power plant to set priorities when receiving several setpoints (e.g. from a wind power plant operator, a TSO, etc.).
6. **Temporary Active Power Increase.** Functionality providing a temporary boost of active power on top of the possible active power output, affording a fast-acting response to changes in frequency.
7. **Ability to Calculate Actual Active Power Production.** Method for calculating the possible active power at WT and WF level. In practice, this would mean the magnitude of the *Delta* control band.
8. **Power Production Forecast.** Ability to calculate the available power output of a WF or a Cluster at different time scales and time horizons (from minutes up to several hours).
9. **Communication and Control Interface.** Physical link connecting the WF/WPP directly to its operator.
10. **Communication and Control Interface with the System Operator.** Dedicated link used by the TSO/DSO to send some control setpoints and control parameters to the WF/WPP.
11. **Wind Power Plant Management System.** Management system to coordinate or manage the behaviour of one or several WPP including external signals or capabilities based on control strategies. This management system could be an enhanced WFC or an external system, like a dispatch centre.

Table 2: Frequency Support related functionalities.

Type of functionality	Functionality name	FCR	FRR	RR	FFR	RM	Implemen-tation level
		Ancillary Service					
Technical	Active Power Control	X	X	X		X	WT/WF
	Active Power Delta Control Mode	X	X	X			WT/WF
	Active Power Limitation Control Mode	X	X	X		X	WT/WF
	Active Power Gradient Control Mode	X	X	X		X	WT/WF
	Frequency Sensing	X	X		X		WT/WF
	Frequency Sensitivity Mode (or Droop Control)	X	X				WT/WF
	Active Power Setpoint Processing	X	X	X	X	X	WT/WF
	Setpoint Priority Management	X	X	X	X	X	WF
	Temporary Active Power Increase				X		WT
Operational	Ability to Calculate Actual Active Power Production	X	X				WT
	Power production forecast		X	X		X	WF
	Communication and Control Interface	X	X	X	X	X	WT/WF
	Communication and Control Interface with the SO	X	X	X	X	X	WF
	Wind Power Plant Management System	X	X	X		X	WF

2.2 Voltage Support Functionalities

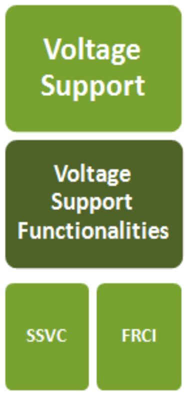


Figure 14: relation between Voltage Support Functionalities and AS

1. **Reactive Power Setpoint Processing.** Ability of a Wind Power Plant to receive reactive power setpoints for each Reactive Power Control Scheme.
2. **Reactive Power Provision.** Reactive Power can be supplied up to certain value.
3. **Reactive Power Control Scheme.** Defines a method to regulate the reactive power output of a wind power plant. Various methods can be used and selected independently.
    a. **Reactive Power Control.** Function controlling the reactive power based on a defined reference point.
    b. **Voltage Control.** Function controlling the reactive power depending on to the voltage at a defined reference point.
    c. **Power Factor Control.** Function controlling the ratio between active and reactive power at a defined reference point.
4. **Fast Positive Sequence Reactive Current Injection.** It is the capability of a WT to deliver a reactive power response in the range of tenths to hundreds of milliseconds.
5. **Fast Active Current Reduction Capability.** It is the capability of a generator/ converter to deliver active power at the same time as the Fast Reactive Current injection during a voltage dip. Some generators/ converters should/need to reduce the active current provision due to the prioritization of reactive current provision.
6. **Fast Negative Sequence Current Provision:** This is the ability of a WT / WPP to feed in an unbalanced (fault) current resp. to feed in a (fault) current comprising a negative sequence component.
7. **Communication and Control Interface.** Link connecting the WPP directly to its operator's control centre.

8. **Communication and Control Interface with the System Operator.** Dedicated link used by the TSO/DSO to send setpoints and control parameters to a WPP. This link could be technically the same as the "Communication and Control Interface"

The relation between those functionalities and the ancillary services is given in Table 3.

Table 3: Voltage Support related functionalities.

Type of functionality	Functionality name	Ancillary Service: SSVC	Ancillary Service: FRCI	Implemen-tation level
Technical	Reactive Power Setpoint Processing	X		WT/WF
	Reactive Power Control Scheme	X		WT/WF
	Reactive Power Control	X		WT/WF
	Voltage Control	X		WT/WF
	Power Factor Control	X		WT/WF
	Reactive Power Provision	X		WT/WF
	Fast Possitive Sequence Reactive Current Injection Capability		X	WT
	Fast Active Current Reduction Capability		X	WT
	Fast Negative Sequence Current Provision		X	WT
Operational	Communication and Control Interface	X	X	WT/WF
	Communication and Control Interface with the SO	X	X	WF

2.3 System Restoration Support Functionalities

The specific functionalities in this framework are:

1. **Ability to Energize the Grid.** Ability to start up a WT/ WPP without an external reference of frequency and voltage.
2. **Ability to start the auxiliary equipment of the plant.** Ability to start WT/WF/WPP auxiliary systems (**e.g. electronic devices for control, pitching system, et**c) and to move the blades into the wind without external power supply from the grid.
3. **Frequency Control Capabilities for Cell Operation.** Ability to balance the loads and the generation to operate within a cell. This can be done via an extended frequency control capability (please refer to WP2, D2.2).
4. **Voltage Control Capabilities for Cell Operation.** Ability to provide voltage control for a stable operation into a cell during isolated operation.
5. **Re-synchronization.** In order to synchronize with other networks running in islanding operation, a communication interface is necessary to handle and to coordinate the switching condition (equal voltage, equal frequency, and equal phase angle) at the connection point with the other networks.
6. ***Wind Power Plant Management System.***

Figure 15: relation between System Restoration Support Functionalities and AS

***The following functionalities, 7 t**o 13 were described in previous sections, but are also required for system restoration support.

7. ***Active Power Limitation Control Mode.***

8. *Frequency Sensing.*
9. *Frequency Sensitivity Mode (or Droop Control).*
10. *Reactive Power Control Scheme.*
11. *Communication and Control Interface.*
12. *Communication and Control Interface with the System Operator.*
13. *Power production forecast.*

Table 4: System Restoration Support related functionalities.

Type of functionality	Functionality name	Ancillary Service BS	Ancillary Service I	Implementation level
Technical	Ability to Energize the Grid	X		WT
	Ability to start the auxiliary equipment of the plant	X		WT/WF
	Frequency Control Capabilities for Cell Operation	X	X	WF
	Voltage Control Capabilities for Cell Operation	X	X	WT/WF
	Re-synchronization	X	X	WF
	Active Power Limitation Control Mode	X	X	WT/WF
	Frequency Sensing	X	X	WT/WF
	Frequency Sensitivity Mode (or Droop Control)	X	X	WT/WF
	Reactive Power Control Scheme	X	X	WT/WF
Operational	Communication and Control Interface	X	X	WT/WF
	Communication and Control Interface with the SO	X	X	WF
	Power production forecast	X	X	WF
	Wind Power Plant Management System	X	X	WF

3 TECHNICAL CAPABILITIES FOR PROVIDING ANCILLARY SERVICES

This chapter presents the WT, WF, WPP and Clusters required technical capabilities to create the needed functionalities introduced in the Framework of Functionalities in Chapter 2. Those functionalities enable the provision of each single Ancillary Service. The definition of the most important parameters that describe each capability is presented. A distinction of capabilities is made for each of the two most common wind turbine (power conversion) technologies: Type 3 and 4.

3.1 Technical Capabilities regarding Frequency Support

3.1.1 Technical Capabilities related with the Active Power Control Mode

3.1.1.1 Technical Specifications

WPP shall implement active power control functions capable of controlling the active power output supply using SO orders containing setpoints, ramps and gradients (ENTSO-E, 2012), (Energinet.dk, 2010), (National Grid, 2010)). Those control capabilities are required to control the power output up to a certain limit if schedules are defined and to implement frequency control. WPP are also required to have active power constraint functions, to avoid overloading of the electricity network during congestions. See Figure 12, based on (Energinet.dk, 2010) requirements.

3.1.1.2 State-of-the-Art

Active power control capability is available in all modern WT (Type 3 and 4) (IEC, 2008), equipped with blade pitch control. This WT technology represents the majority of the wind power market in Europe.

There is a limited number of early designed fixed speed and limited variable speed WT in which active power control is not possible or it is very limited (up to 1-2% active power variation). These turbines are estimated to represent less than 20% the current installed capacity in Europe.

Modern WT are able to go from the lowest power level to full rated power in a maximum response time of 6-10 seconds, providing that wind resource is available. Consulted manufacturers have answered response times between 1-2 seconds to 4-6 seconds for up- and downward regulation [q3.1/3.5]. At WF level, active power control capability is generally available and very fast ramp rate control [q9.0] can be achieved (between 10-20 seconds adding the possible delay, settling and communication times).

3.1.1.3 Constraints and Limitations

At WT level, there are challenges for Delta Active Power Control related to the calculation of available power. These challenges come from the distortions on the measurements due to turbulence and the unequal distribution of the wind resource across the rotor. Reliability of measurements depends significantly on the site wind conditions.

At WF and WPP level, the unequal distribution of wind gusts and the complex behaviour of the WT wakes create and extra challenge to derive the available or possible active power to calculate the correct value for Active Power Delta Control Mode.

The response time of the entire WF may depend on how much active power was curtailed. If the active power has to be raised from 10% to 100% it may take up to 30 seconds according to one WF operator. This value seems to be too high considering the response time of the modern WT and the state of the art in communication technology. Nevertheless, this time might be necessary considering an already installed WF using older and outdated technology.

3.1.2 Technical Capabilities related with the Frequency Sensitivity Mode (or Droop Control) Functionality

3.1.2.1 Technical Specifications

According to (Sørensen, Hansen, Iov, Blaabjerg, & Donovan, 2005), the frequency control of conventional power plants typically uses droop control to maintain the balance between generation and demand.

Frequency Sensitive Mode is defined as the ratio of the steady-state change of power output (referred to Maximum Capacity) to the steady-state change in Frequency (referred to nominal Frequency) (see figure 16).

The TSO could define a Frequency Response Deadband that is used intentionally to make the Frequency Control unresponsive to small frequency changes and is basically adjustable. In contrast, the (in)sensitivity is the inherent feature of the control system defined as the minimum magnitude of the Frequency (input signal) which results in a change of output power (output signal).

One specific example of such a requirement is given in Figure 16 from the Spanish Grid Code (Gesino, 2011). This characteristic consists of a deadband as well as upper and lower power limits at high frequency deviations. The intermediate ranges are defined by a slope.

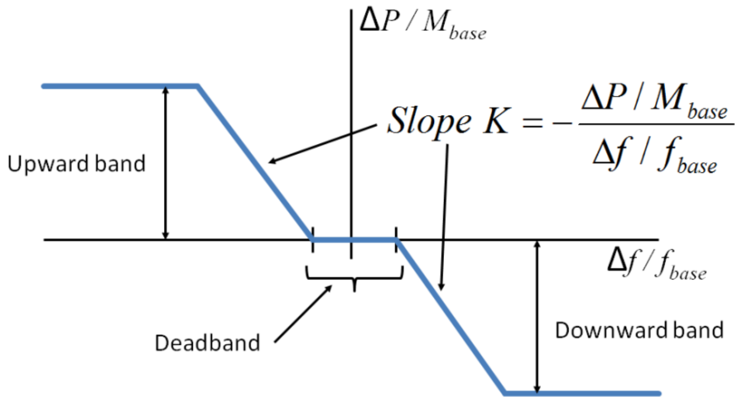


Figure 16: Active power control based on frequency variation (Spain)

3.1.2.2 State-of-the-Art

Modern WT are able to perform frequency droop control [q5.0] and switch between different settings or modes (under and over frequency operation mode) [q5.1].

The maximum initial delay to provide FSM at the WT level is less than 1 second according to the responses from the questionnaires [q5.3].

Similarly, WT are able to define a deadband for frequency control mode operation.

At WF level the capability is also available but there is an extra delay of the control response between 500 ms and 2 s. on top of the delay at WT level. This is due to the communication and/or processing time at the WFC.

3.1.2.3 Constraints and Limitations

One manufacturer have pointed out that the possibility of changing the Frequency Sensitivity Mode [q5.1] and to define a deadband = 0 [q5.4] is possible only in case of LFSM-O (Limited Frequency Sensitivity Mode for Over-frequency).

At WF level, in some cases, switching between FSM remotely is a procedure that can be done only by the manufacturer even though the capability is available in the WT. There might be cases that operators do not have direct access to enable themselves the functionality on the WFC.

3.1.3 Technical Capabilities related with the Frequency Sensing Method Functionality

3.1.3.1 Technical Specifications

Conventional Power Plant Control Systems measure the frequency based on the rotational speed of the generator itself (rotor) due to its coupling with the grid frequency. WT connected via power electronics have the rotational speed of the generator decoupled from the grid frequency. Hence, they rely on indirect methods for measuring grid frequency.

3.1.3.2 State-of-the-Art

WT are able to measure the grid frequency deriving its value from the measured grid voltage (Iov, Ciobotaru, & Blaabjerg, 2008). Well developed and available techniques exist for these purposes such as the Phase-Locked Loop (PLL) method (Gardner, 1979). In three-phase systems, the grid frequency information can easily be obtained utilising modal transformations (Timbus, Liserre, Teodorescu, Rodriguez, & Blaabjerg, 2006).

3.1.3.3 Constraints and Limitations

Since the PLL acts basically as a smoothing filter, it cannot be applied in case a very fast dynamic performance is required e.g. in short circuit situations. However, for frequency control purposes the PLL approach would be sufficient.

3.1.4 Technical Capabilities related with the Active Power Setpoint Processing Functionality

3.1.4.1 Technical Specifications

A setpoint is a target or reference value for any parameter typically used in control schemes. It is required for the power plant operator to send new target values to establish different operational modes and power output levels.

Grid codes define content and characteristics of the setpoints, as well as the expected behaviour of the power plant. For example, (Energinet.dk, 2010) stated, in case the active power setpoint is to be changed, such change must be commenced within two seconds and completed no later than 10 seconds after receipt of an order. The accuracy of the control performed and of the setpoint must not deviate by more than ±2% of the setpoint value or by ±0.5% of the rated power, depending on which yields the highest tolerance.

3.1.4.2 State-of-the-Art

The capabilities for establishing and following active power setpoints are available in modern wind turbines (IEC, 2008).

All wind turbine manufacturers provide with their products methods for processing active power setpoints [q3.0]. The accuracy of response is between ±2% and ±5% based on 1 minute average calculation [q3.8]

At the wind farm level, there is an additional settling time for setpoints generally below 2 seconds, but it could be up to 5-10 seconds [q6.0].

3.1.4.3 Constraints and Limitations

There are no technical constraints for delivering this capability at WT level. At WF level, the main challenge is dealing adequately with the communication delay between the WFC and the WT [q6.0].

At Cluster level the limitation is the unavailability of standard commercial solutions. Commercial solutions are available for connecting a large WF in blocks via several points of connection and operate these blocks as a WPP. However, these solutions are not suitable for clustering geographically dispersed WF connected via several POI to a grid as these grids also contains other elements like different kind of loads, compensation units, or transformers with tap changers. Thus more development in the future is required.

3.1.5 Technical Capabilities related with the Setpoint Priority Management Functionality

3.1.5.1 Technical Specifications

This capability is related with the functionalities of the SCADA system or the wind farm controller to manage direct links with different parties (wind farm owner, DSO, TSO, market, etc), recognize and manage setpoints and their priority.

Depending on the country and on the national TSO this functionality could nowadays either be required or not. For example, procedure PO 9.0 (REE, 2012) in Spain requires dedicated connections between the wind farm and the grid operator.

3.1.5.2 State-of-the-Art

There are control automation manufacturers offering solutions for remote setpoint prioritization by connecting the TSO and wind farms. Nevertheless, this capability is not available at WFC level for all manufacturers.

3.1.5.3 Constraints and Limitations

At wind farm level, capability of providing simultaneous connection to different parties and prioritization of set-points is not widely available.

At wind turbine level manufacturers provide capabilities for prioritisation of setpoints but not for set-points sent by TSO due to the lack of direct connection with the TSO.

In order to participate in the provision of ancillary services that are automatically activated, TSOs required a direct link to the power plant to activate or deactivate and/or to enable or disable a service. The power plant should be able to receive setpoints coming from the TSO. The priority of different setpoints provided from different parties (owner, TSO, DSO, etc.) should be analysed by the control system and, depending on the priority and on the situation, some setpoints might override the already existing and future setpoints that could come from another party. The utilization of such a prioritization depends on the grid code requirements and the service characteristics.

3.1.6 Technical Capabilities related with the Temporary Active Power Increase Functionality

3.1.6.1 Technical Specification

The initial frequency response of the system is dominated by the inertial response of the operating generators. The aim of this capability is to provide a temporary boost of active power on top of the possible active power output, affording a fast-acting response to changes in frequency, supporting any inherent inertial response of synchronous generators.

Only a few TSOs have so far specified requirements for wind turbines and wind farms, as Hydro Québec in Canada (Brisebois & Aubut, 2011), requiring response at WT level in less than 2 seconds. Others TSOs nominate this capability to minimize the ROCOF like (EirGrid and SONI, 2012), defining an activation time of less than 2 seconds and a delivery period of at least 15 seconds. The new ENTSO-E grid code (ENTSO-E, 2012) introduces this requirement, leaving the request of this service from generators and the final requirement specifications to the local TSO.

In a scenario with high penetration of renewables connected through non-synchronous generators, this capability shall be provided to avoid frequency instability and blackouts.

3.1.6.2 State-of-the-Art

Several wind turbine manufacturers can offer today inertia response capabilities according to (Enercon, 2010), (Wachtel, 2009), (GE, 2009), (Krueger, Geisler, & Schrader, 2012), amongst others).

Answers provided by WT manufacturers indicate that less than 50% of manufactures can provide inertial response [q4.0]. The settling time is a between 0.5 - 2 seconds [q4.1], providing at most between 5-10% additional power [q4.2] for a time span of between 5 to 10 seconds [q4.3]. Manufacturers have stated that it takes 10-30 seconds to restore the kinetic energy of the rotor of the WT and return back to possible active power production [q4.4]. During this time span WT are providing between 5-10% less active power [q4.5].

Some manufacturers have reported that it is feasible to increase temporarily the power output by 10% of the nominal power for up to 10 seconds. The settling time to deliver the extra power is of approx. 800ms. The overall average gradient to increase active output is 12.5% nominal active power per second.

This inertial response is possible either via a very fast control of the blades (pitch control) or the ability to extract the kinetic energy from the rotor. For the latter option, additional controls are necessary for the rotor to artificially emulate the effect of inertial response and to participate in the damping of frequency changes in a power system (Seman, 2011).

Using the stored kinetic energy from the rotor causes it to decelerate. At the same time the active power supplied to the grid is increased. After a time about 10 to 20 seconds the rotor has to be accelerated again, which lowers the output active power (Wachtel, 2009). See Figure 17 and Figure 18.

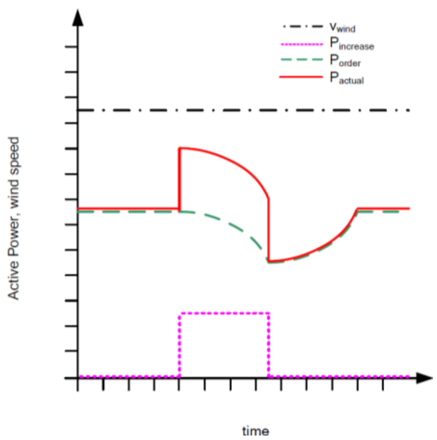


Figure 17: Power control including the rotational speed; P_{actual} depending on $P_{increase}$ and P_{order} at constant wind (Wachtel, 2009).

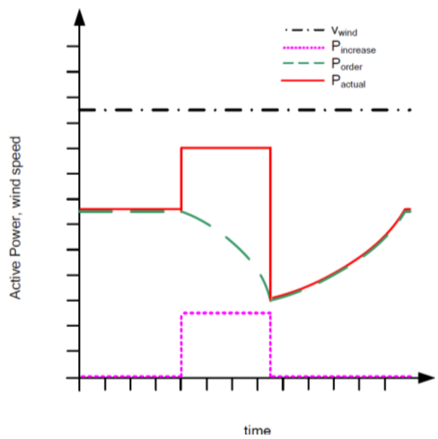


Figure 18: Power control excluding the rotational speed; $P_{increase}$ just depending on $P_{increase}$ at constant wind (Wachtel, 2009).

Generators and frequency converters can support wind turbines in provision of *synthetic inertia*[11] when properly dimensioned. However, according to power electronic manufacturers, full converter systems seem to be more flexible, providing up to 10% P_n at low wind speed (Seman, 2011). Considering converter current limits, a small overload in active power is always possible for Type 3 and Type 4 systems (Marinelli & Massucco, 2011).

[11] *Synthetic inertia* is the denomination given by (ENTSO-E, 2012)

The behaviour of the inertial response could be modified depending on the configuration parameters. The result on changing the parameterization is presented in Figure 19, avoiding the frequency decay going deeper and improving the response, and Figure 20, moderating the required recovery energy after providing the extra active power boost released during the inertial response.

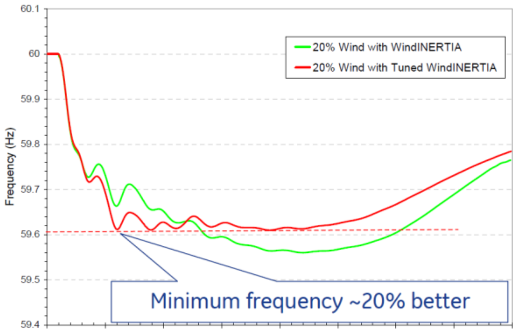


Figure 19: Improvements on performance by tuning the inertial response system (Miller, Clark, & Shao, 2011)

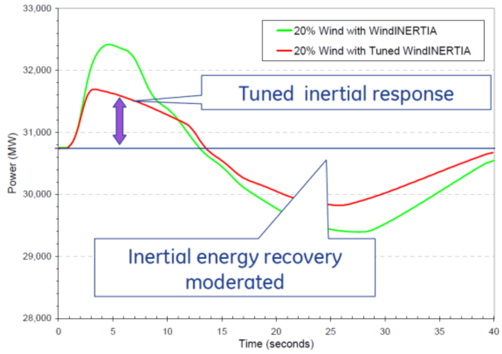


Figure 20: Inertial Response tuned to moderate the energy recocovery (Miller, Clark, & Shao, 2011)

Depending on the technology used and the wind conditions, the recovery times can vary as shown in Figure 21. By means of this graphic it is possible to estimate different recovery times and the associated reduction of power produced.

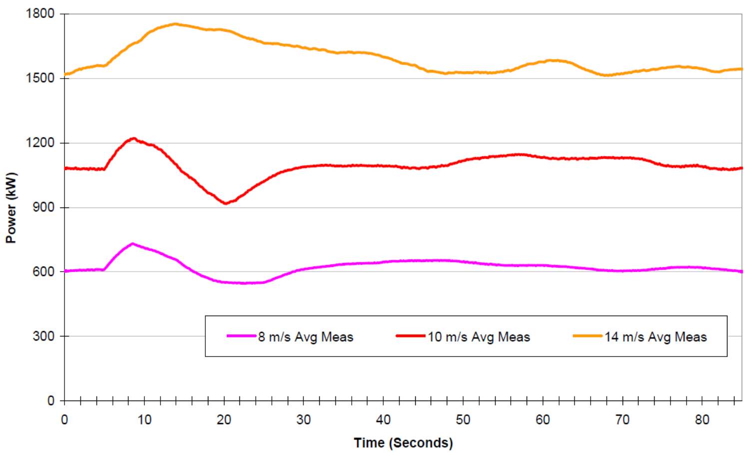


Figure 21: different tests performed with different wind conditions (19 tests at 8m/s, 19 tests at 10m/s and 52 tests at 14 m/s) when providing inertial response. The various recovery times and situations are clearly depicted (Miller N. , Wind Plant Functionality and Emerging Grid Codes, 2010)

Figure 22 shows the results of field tests performed by a manufacturer implementing inertial response. It shows the behaviour in the system comparing a reference case (losing 1GW synchronous generator trip compared with the tripping of 1GW wind with or without inertial response).

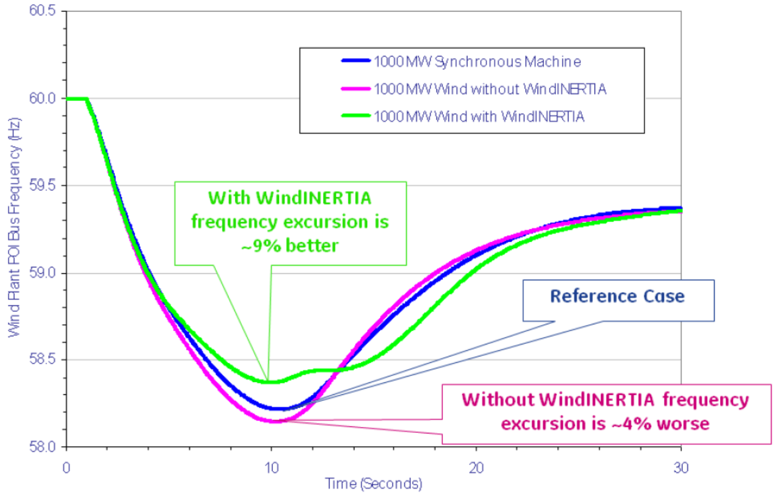


Figure 22: The chart illustrates the effect on system frequency drops in a large system. The ROCOF could be successfully reduced within system studies as well as field tests (Miller N. , Clark, Delmerico, & Cardinal, 2008).

Another approach is presented in (Christensen & Tarnowski, Inertia for Wind Power Plants, 2011) called Soft Fast Frequency Response (SFFR). The response time of SFFR is introducing a delay time which prevents the interaction with oscillations coming from inertia responses of synchronous generators, but is still able to support the grid frequency faster than FCR functionalities. Furthermore, early system studies and field tests pointed out that an inertial response identical to synchronous generators is neither possible nor necessary according to system needs (Miller, Clark, & Shao, 2011).

3.1.6.3 Constraints and Limitations

Inertial response using only pitch control requires the previous curtailment. However, at decent wind conditions the additional active power can be maintained for a longer time. The response time in those cases are proportional to those provided for active power regulation using pitch system and reduced power operation.

The power converter, the electric generator, and the mechanical components of the WT must be designed to withstand the overloading condition created once the energy is extracted from the aero dynamical components.

As already depicted, the inertial response capability implemented by generator control is limited by the minimal rotor speed. Therefore, it can only be kept up to 10-20 seconds. It influences the technical capabilities of the droop control within its dedicated time frame. A combination of pitching control and the extracting kinetic energy from the rotor could improve this behaviour (Erlich & Wilch, 2010). For bigger wind farms a spreading of the ending time of the FFR could reduce this effect (Morren, de Haan, Kling, & Ferreira, 2006).

Another limitation according to the literature could be the (low) speed of SCADA control systems (Seman, 2011).

At wind farm level, common methods and definitions of frequency grid measurements, deviations and rate of change are missing (Quitmann, 2012). Furthermore, the requirements regarding inertia itself are not well defined. In addition, the benefit of this functionality regarding power system frequency stability is not fully proven.

3.1.7 Technical Capabilities related with the Ability to Calculate Actual Active Power Production Functionality

3.1.7.1 Technical Specifications

This functionality is related with the ability of instantaneously calculating the possible active power output when a WPP is curtailed. It must not be confused with the short-term calculation based in forecast, which is reviewed in Chapter 4, and allows calculating the available power in the near future, in terms of minutes or hours.

The functionality is directly related with the capability of a WPP to implement Active Power Delta Control, as described in (Energinet.dk, 2010).

The accuracy of the achieved power output established by a setpoint must not deviate by more than ±2% of the setpoint value or by ±0.5% of the rated power, depending on which yields the highest tolerance (Energinet.dk, 2010).

3.1.7.2 State-of-the-Art

Close to 30% of the questionnaire respondents confirmed Active Power Delta Control capability with an accuracy between +2% and +10% [q7.1]. The estimates of possible power output are performed by the wind turbine controller using data from an anemometer located in the nacelle.

3.1.7.3 Constraints and Limitations

An anemometer at the nacelle is influenced by the turbulence caused by the rotor and its measurements are not representative of the available resource that could be captured by rotor.

The accuracy of the "delta" or percentage reduced compared with the available power is too much dependent on the wind conditions (high speed winds, turbulence), the operation point (low active power output, high power output) and the reduced power (the delta) in comparison with the available power.

3.1.8 Technical Capabilities related with the Power Production Forecast Functionality

A complete technical and economical assessment of the impact of the forecast is provided in Chapter 4 ("Impact of wind power variability and predictability on the provision of ancillary services").

3.1.9 Technical Capabilities related with the Communication and Control Interface and Communication and Control Interface with the System Operator Functionalities

3.1.9.1 Technical Specifications

In case of power plants prequalified to provide ancillary services, grid codes require having a dedicated link between the grid operator and the power plant. Depending on the specific Ancillary Service, the countries and the TSOs some procedures shall be performed automatically, semi automatically or even manually through verbal coordination (TSO providing instructions to operators by telephone). A description about the activation type could be found in D2.1.

In order to operate in the same way, WPP shall have the capability to send setpoints for the majority of the ancillary services (FRR, RR, RM, SSVC), to activate or deactivate an automatically provided ancillary service (FCR, FFR, FCRI) and to sense constantly the status of the WPP.

In Spain the TSO requires a link to the power plant to send setpoints, but this is not the case throughout Europe. During the Stakeholders Workshop organized on April, 6th 2013 with manufacturers and TSOs the consensus was that in the future TSOs should have a direct link not only to activate an AS, but to enable or disable it, too.

3.1.9.2 State-of-the-Art

All WPP have the capability to implement this communication based on an international standard IEC 61400-25, which provides uniform information exchange for monitoring and control of wind power plants.

The communication and control interface comprises the WT communication interface, the internal network of a WF and the WFC communication interface, enabling the WPP operator connection and the grid operator connection with the WPP.

For supporting fast services at wind farm level, like FRCI, manufacturers are implementing new technology capable of providing reaction time <1 millisecond (Kordtomeikel, 2012).

3.1.9.3 Constraints and Limitations

At wind farm level the internal and external connection availability and transmission speed and networks latency are determinant to provide ancillary services.

3.1.10 Technical Capabilities related with the Wind Power Plant Management System Functionality

3.1.10.1 Technical Specifications

Control system able to create dispatchable services expanding the WFC capabilities, incorporating signals from e.g. forecasts or the ability to coordinate services with others WF/WPP. This control could be fully automatic, implemented into a WFC or a third party system; partially automatic or even manual, implemented in a dispatch centre.

3.1.10.2 State-of-the-Art

Several control approaches exist in literature to control and dispatch aggregations of WPP, mainly represented by the Virtual Power Plant (VPP) (Fenix Project, 2009) and Wind Farm Cluster Management Systems (WCMS) (Rohrig, et al., 2009), (Gesino, 2011).

This functionality is mostly implemented by third party companies providing solutions of interoperating with the wind farm SCADAs.

Only big operators implement nowadays this ability through their own control and dispatch centres.

Only one respondent has answered affirmatively to the question if they clustered the wind farms [q18.0].

3.1.10.3 Constraints and Limitations

The required intelligence at wind farm controller to create a dispatchable wind power plant is currently not fully available, including e.g. forecasting integrated capabilities. This functionality should be implemented at a higher level of aggregation such as cluster level [i1.2].

This functionality mainly relies on the development of enhanced capabilities on WFC or a dispatch centre to coordinate the behaviour of one or more wind farms or wind power plants.

3.2 Technical Capabilities regarding Voltage Support

In order to evaluate the technical capabilities of wind power plants regarding voltage and reactive power support, the differences between different generators concepts should be presented. The first one, related with the different available technologies (Type 3 and 4). The other, according to different control levels: wind turbine, wind farm control and cluster levels are defined. Furthermore the type of grid connection (AC or DC) has to be taken into account.

3.2.1 Technical Capabilities related with the Reactive Power Setpoint Processing Functionality

3.2.1.1 Technical Specification

This capability is needed to be able to receive set points for the selected control mode including the change of the mode.

(ENTSO-E, 2012) requires voltage setpoint capabilities covering at least 0.95 to 1.05 pu in steps no greater than 0.01 pu with a slope with a range of at least 2 to 7% in steps no greater than 0.5% and achieving 90% of the change in Reactive Power output within the range of 1 - 5 seconds and settle at the value defined by the operating Slope within a time in the range of 5 - 60 seconds, with a steady-state reactive tolerance no greater than 5 % of the maximum Reactive Power.

3.2.1.2 State-of-the-Art

This capability is present in almost all wind turbines. Only one manufacturer had answered that it is not possible to provide this functionality with its wind turbines during normal operation [q10.0]. Manufacturers and developers have been consulted about the possibility to set a reactive power reference value at wind farm level during normal operation: 87% have responded affirmatively [q13.0].

Regarding the settling time of the reactive power setpoints, answers received from the questionnaire are inconclusive [q10.2]: only one value was depicted and it is between 150 and 300 ms and some manufacturers have expressed they don't have a performance measurement of setpoints. The rise and settling times of pure reactive power commitment are not a critical issue, since the control on turbine level can be adjusted to achieve the new set point from several minutes down to one second. However, since the complete signal chain has to be taken into account, it takes about 100 ms to 200 ms after the new set point has arrived to the wind farm controller until the new set point is reached. While for VSC-HVDC converter stations the steady-state voltage control is not a critical issue, their dynamic performance is as good as that of the WT control of the Type 4 systems. The rise times following step changes in the reference value are shorter than one second, according to (Du & Agneholm, 2007) and (Bjorklund, Srivastava, & Quaintance, 2006).

3.2.1.3 Constraints and Limitations

If the farm or turbine is performing a steady-state voltage control, the dynamic is affected by the given Impedance of the connected grid [q13.2] The grid influences highly the possible response time, so no general answer of settling times can be given for that option, but again, timing issues in this case are not seen as a critical topic for wind turbines [q10.5].

The change of the control mode itself during operation is possible but this functionality could introduce some stability risks that have to be treated [q13.3].

3.2.2 Technical Capabilities related with Reactive Power Provision Functionality

3.2.2.1 Technical Specifications

Reactive Power can be supplied up to certain value. The range is normally defined by PQ diagrams. Using converters with self-commutated switching device, independent supply of active in reactive power is possible.

3.2.2.2 State-of-the-Art

Regarding Type 4 systems no fundamental hardware restrictions are present regarding reactive power limits at low or no active power feed-in. This results in possible STATCOM (Static synchronous Compensator) functionalities of Type 4 wind turbines, as it is introduced in (Beekmann, Marques, Quitmann, & Wachtel, 2009). Using bigger dimensioned converters extends reactive power capabilities are possible. Both possibilities are compared in Figure 23.

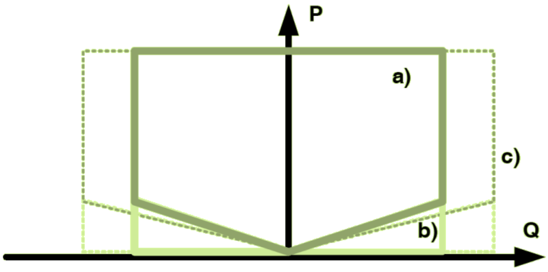


Figure 23: capability of a commercial FSCG wind turbine, a) default capability b) with optional STATCOM functionality c) with optional extended reactive power capability (Beekmann, Marques, Quitmann, & Wachtel, 2009).

STATCOM functionalities at low or no active power supply are also possible with Type 3 systems up to a value of about 20% of wind turbine rated power when the turbine is switched off. By extending the converter capabilities, a reactive power supply of full rated power is also possible. (Miller & Marken, Facts on grid friendly wind plants, 2010).

One approach for developing the PQ diagram of Type 3 systems can be found in (Engelhardt, Erlich, Feltes, Kretschmann, & Shewarega, 2011) with respect to certain physical aspects. The limitations regarding VSC-HVDC systems can be found in (Chaudhary, Teodorescu, & Rodriguez, 2008)

At wind farm level, the grid connection can affect the reactive power capability to the POI. One example is given in Figure 24, where the interconnection causes a strong distortion of the PQ curve due to reactive power consumption of the cable and transformers (Stock, Faiella, Löwer, Rohrig, Hofmann, & Knorr, 2012).

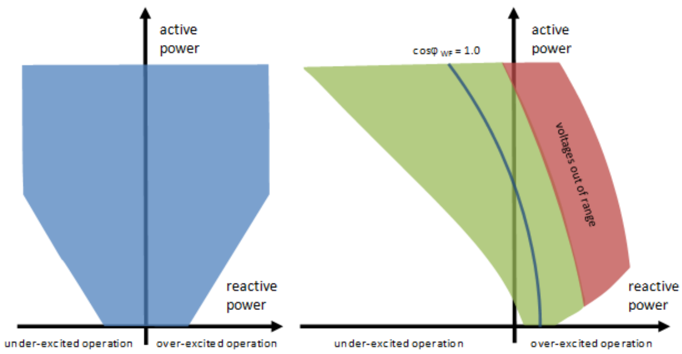


Figure 24: Distortion of the PQ characteristic at the point of grid connection (Stock, Faiella, Löwer, Rohrig, Hofmann, & Knorr, 2012).

Figure 25 and Figure 26 are showing the opinion of manufacturers and developers on the most suitable equipment of the power to achieve this functionality and both groups believe that wind turbines can do it effectively. Depending on the capacitance and reactance of the grid, wind turbines can act as FACTS device, which is still quite unknown to many system operators in Europe [q13.4].

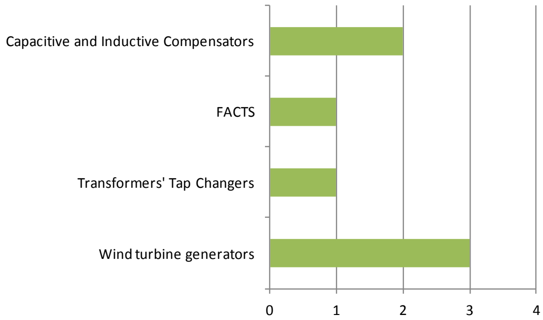


Figure 25: More suitable methods to provide and control Reactive Power at WF level (manufacturers' vision) [q13.4]

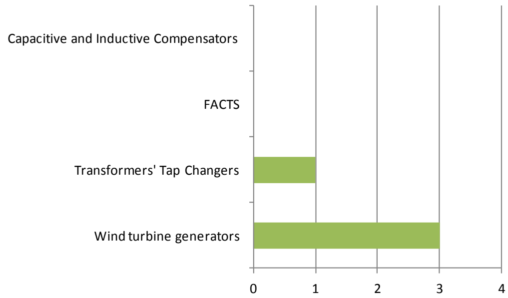


Figure 26: More suitable methods to provide and control Reactive Power at WF level (developers' vision) [q13.4]

3.2.2.3 Constraints and Limitations

No limitations.

3.2.3 Technical Capabilities related to the Reactive Power Control Scheme Functionality

3.2.3.1 Technical Specification

In order to keep the voltage at the POI within a tolerance band, the adjustment of reactive power with the grid has to be controlled by a specified mode.

All reviewed grid codes have requirements regarding provision of reactive power within defined boundaries. In (ENTSO-E, 2012) a particularly large range of reactive power is requested. For supporting and solving voltage issues WPPs have to be able to provide a reactive power.

There are three different modes to control the transfer of reactive power to the POI: fixed power factor, reactive power commitment and steady-state voltage control by Q(U) characteristic (Erlich, Fortmann, Engelhardt, & Kretschmann, 2009). The term Steady-State Voltage Control (also used in (National Grid Electricity Transmission plc, 2013)), which is adopted from WP2, is used to address the difference in time scale of this functionality to the possibilities coming with the FRCI functionality reacting on transient voltage deviations.

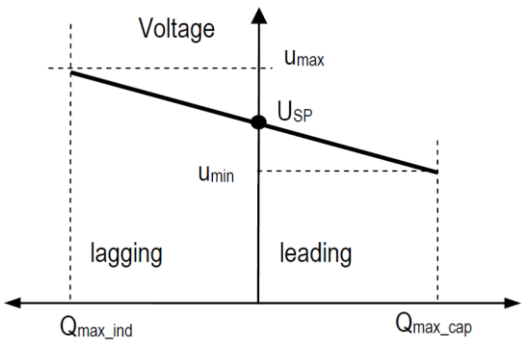


Figure 27: steady-state voltage control scheme by Q(U) characteristic.

One manufacturer stated that DSO forbids the connected wind turbines to run voltage control mode. For some distribution grids this lead to higher voltages because of the active power production; this has to be taken into account by the developers by oversizing the cabling [i2.1].

In (Bhattacharya & Ullah, 2009) and (Ullah, Bhattacharya, & Thiringer, 2007) the physical limitations of Type 4 systems are specified (PQ diagram) according to voltage and current ratings of the converter.

3.2.3.2 State-of-the-Art

Figure 28 and Figure 29 are showing the possible control schemes at turbine WPP level from manufacturer and developer/operator side. So far, developers do not use the possibility of steady-state voltage control via Q(U) characteristic. Adjusting the power factor as a function of active power is also possible.

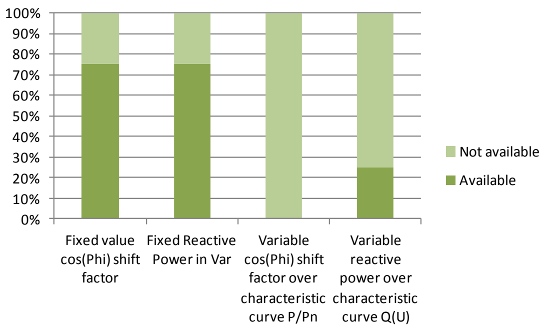


Figure 28: Reactive Power control schemes available at WIND TURBINE level (manufacturers) [q10.1]

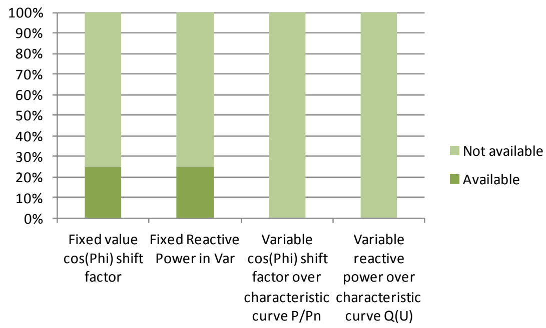


Figure 29: Reactive Power control scheme available at WIND TURBINE level (developers & operators) [q10.1]

If a VSC-HVDC interconnection is used, the reactive power transfer can also be organized by either one the three already mentioned methods and the reactive power capabilities are determined by the converter station at the POI.

Based on the manufacturer contribution:

- The control mode depends predominantly on the markets (e.g. in Scotland all wind farms have to do Q(U)-control, but in Germany 2/3 are still using fixed cos(phi) mode).
- Most grid codes don't define properly what the system operator wants to have in terms of reactive power.
- Rough estimation: for 1/3 of the sold active power capacity, the reactive power capability is not used at all.

No consensus among manufacturers has been provided on the possibility of the wind turbines to provide reactive power at low wind conditions (at no active power provision level) [q11.0]. Only about 50% of the manufacturers have responded affirmatively.

The availability of the technical capability was evaluated very different by the manufacturers: the spectrum differs from to be a quite mature technology, which is already requested by TSOs, to the fact, that wind turbines do not participate in voltage control at all [i2.1-6].

In a wind farm, the steady-state voltage control takes place on wind farm controller level that spreads the demand onto the turbines (Beekmann, Marques, Quitmann, & Wachtel, 2009), (Erlich, Fortmann, Engelhardt, & Kretschmann, 2009), (Fortmann, Wilch, Koch, & Erlich, 2008). Therefore, optimization techniques for the reactive power setpoint allocation from farm to turbine level are already proposed taking into account additional FACTS devices as well as transformers equipped with on-load tap changers (Cai, Erlich, & Fortmann, 2012). This leads to coordinated steady-state voltage control functionalities. The adapted communication infrastructure is a pre-condition for any reactive power supply on farm level (Beekmann, Marques, Quitmann, & Wachtel, 2009). Furthermore, the fast reactive current injection is left on turbine level to guarantee a good dynamic performance. Asked the manufacturers about the possibility of providing coordinated voltage control, one of them answered that the capability is already available. It is mentioned the experience from

France (Lefebvre, Fragnier, Boussion, Mallet, & Bulot, 2000) and the fact that there is no other European market. The capability depends very much on the definition, which is the case for the mentioned example. In Figure 32 and Figure 33 the results of the questionnaire regarding coordinated voltage control functionality are shown.

In a wind farm cluster, the combination of the different control options, different technologies and an intelligent setpoint allocation can lead to coordinated steady-state voltage control, which was successfully performed within field tests (Arlaban, et al.), (Arlaban, et al., 2012). The allocation procedure is able to reflect power system demands (Meegahapola, Abbott, Morrow, Littler, & Flynn, 2011) and the cluster control can be implemented in the TSO or DSO management system (Lin, Wang, Zhu, Li, Liu, & Xu, Investigation of active power coordination control strategy of wind farm cluster using hierarchical principle, 2012), (Rohrig & Lange, Improvement of the Power System Reliability by Prediction of Wind Power Generation, 24-28 June 2007). Since a hierarchical control structure is assumed that allows the control of smaller time scales with decreasing control level, the cluster control would not affect FRCI functions in operation. However a parameter setting of this function could be possible according to system needs.

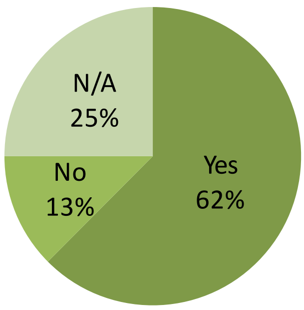


Figure 30: Coordinated Voltage Control strategy on the connected grid at WIND FARM level [q15.0]

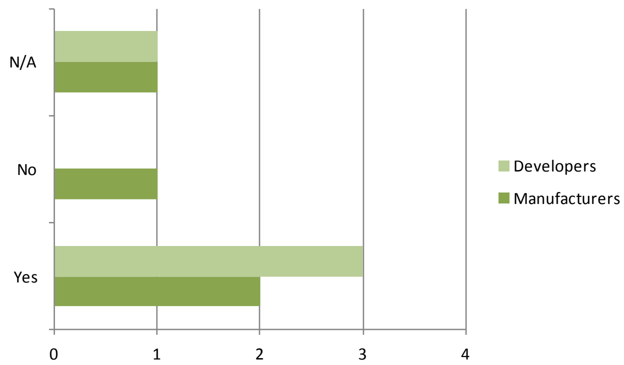


Figure 31: Coordinated Voltage Control strategy on the connected grid at WIND FARM level (divided by manufacturers and developers) [q15.0]

3.2.3.3 Constraints and Limitations

Synchronous generators in conventional power plants can be equipped with a power system stabilizer (PSS). The PSS is able to calculate an additional signal for the set point of the excitation control system to damp power system oscillation. Therefore, one expected challenge could be the integration of damping controllers into the voltage control concepts of wind turbines, farms or clusters (Jose Luis Domınguez-Garcıa, 2012) (Alivirdizadeh, Tousi, Ghahramani, Khazaie, & Rajebi, 2011).

One manufacturer mentioned that starting up from 110 kV voltage level a simple power factor control is a waste of investment [i2.3]. Of course, the achieved supply by any control scheme is constrained by the physical limitations that can be found in section 3.2.2.

3.2.4 Technical Capabilities related with the Fast Positive Sequence Reactive Current Injection Functionality

3.2.4.1 Technical Specification

In case of a fault within the grid a voltage dip will occur. In order to prevent the expansion of the voltage sag affecting larger areas of the power system, wind turbines are requested to feed in reactive current to support the voltage of the power system.

(ENTSO-E, 2012) requires the provision of at least 2/3 of the additional reactive current within a time period which shall not be less than 10 milliseconds. The new version of the German grid code for high voltage grid connections still on draft version (VDE, 2013) is stipulating rise time shorter than 30 ms and settling time shorter than 60.

3.2.4.2 State-of-the-Art

Since Type 4 wind turbines are fully decoupled from the grid, the dynamic performance is determined by the power electronic switching devices only. Therefore, they can react very fast on voltage dips even - with STATCOM functionality - at zero active power (Fischer & Schellschmidt, 2011). Since during a fault the delivered active power is reduced, the rotating energy from the rotor has to be dissipated. To meet state of the art grid codes requirement and remain full controllability during the fault the DC chopper is considered, but it is not treated as additional investment anymore.

In contrast Type 3 wind turbines need dedicated control due to the direct grid connection of the stator. However, with modern control techniques and DC chopper Type 3 wind turbines can meet German grid code requirements regarding fast reactive current injection (Feltes, Engelhardt, Kretschmann, Fortmann, & Erlich, 2010). The magnitude of the reactive current can be raised up 1.1 p.u. related to the rated converter current.

As shown in Figure 32, all manufacturers have answered that their wind turbines are able to provide FRCI. Furthermore, only one developer has responded that this feature is not available in the wind turbine that they operate. In Figure 33 the vision of the manufacturers and developers with regard to the recommended speed to deliver 100% of reactive current during a fault is shown [q12.3]. All manufacturers think that the right settling time is located between 30-60 ms (two of them) and 75-150 ms (the other two). However, some manufacturers state that there cannot be a clear answer, since the required behaviour depends on the grid the wind farm or turbine is injecting to. Different grids (depending on the short circuit ratio and the impedance) require different responses [q12.3].

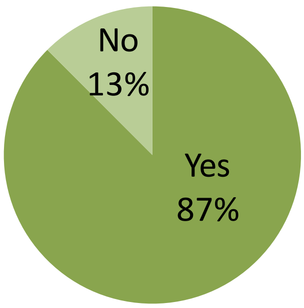


Figure 32: Possibility to inject Reactive Current during faults at WIND FARM level [q12.0]

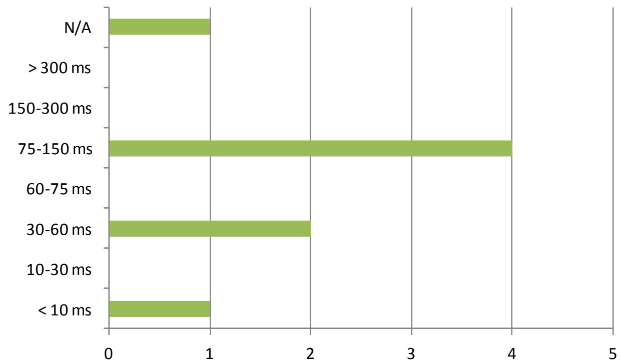


Figure 33: Manufacturers and developers recommended settling time of the Reactive Current [q12.3]

Regarding post-fault reactive current support [q14.0], only one manufacturer has responded that such a support is not possible. However, within developers a consensus exist that this feature is not integrated.

Some questions were performed regarding a dead time in Fast Positive Sequence Reactive Current response by presence of a voltage drop, which is defined in many grid codes. Most of the companies replied that it is not possible to change this dead band during operation dynamically [q12.5]. One manufacturer stated that modifying dynamically the real time parameters of the converter control can cause stability problems [q12.7]. However, another manufacturer was referring to remove the dead band if the trigger conditions for starting FRT are defined clear enough from TSO/DSO side. If this is ensured, then also a remove of the reactive current dead band could not be a problem. If the existence (or non-existence) of such a dead band leads to control or stability problems in the power system has to be decided by the power system operator [q12.7].

Moreover, there is a gap between manufacturers and developers in assessing the effort that is needed to realize such feature. This is implied by Figure 34 to Figure 36.

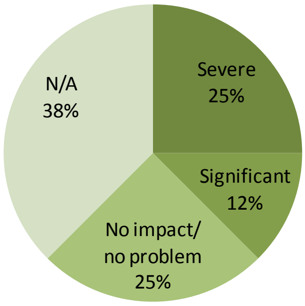


Figure 34: Qualification of the possible control problem to define a Reactive Current deadband = 0 [q12.6]

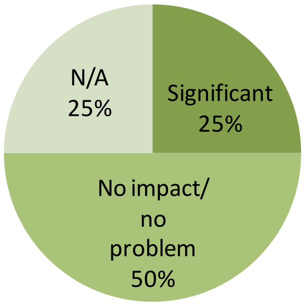


Figure 35: Qualification of the possible control problem to define a Reactive Current deadband = 0 (Vision of the manufacturers) [q12.6]

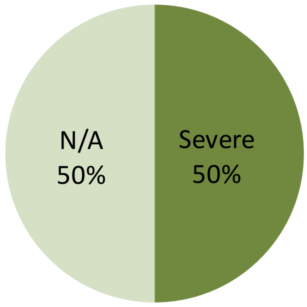


Figure 36:Qualification of the possible control problem to define a Reactive Current deadband = 0 (Vision of the developers) [q12.6]

If the wind turbines are connected via a VSC-HVDC transmission system, the fast positive sequence reactive current provision is a topic for the converter station at the connection point to the grid. In order to limit the raising voltage of the DC link, the converter on the farm side can be used. This requires a communication link between both stations. The converter on the farm side is then in charge to lower the output active power of the turbines. This can be done either by controlling electrical quantities of the farm interconnection grid or by another communication link to the turbines. However, with VSC-HVDC it is also possible to fulfil grid codes requirements regarding fast reactive current injection (Feltes, Wrede, Koch, & Erlich, 2009).

3.2.4.3 Constraints and Limitations

Certainly, the lower limit of the rise times that can be achieved is always constrained by the delay time that is required to detect the voltage dip. This time strongly depends on the detection method that is used in the control. Since voltage dips are defined as deviations within the positive sequence, additional signal filtering might be necessary depending on the voltage measurement signal, which can contain high frequency and negative sequence components. This slows down the dynamic performance of the fast positive sequence reactive current response.

- EWEA position wants to introduce the detection time of the voltage drop into the definition of the rise time (EWEA & EPIA, 2013).
- Grid codes do not define the detection procedure
- New German grid code (VDE, 2013) defines the rise times from the physical phenomenon of the voltage drop on, so the rise time does already include the detection time, while the used method is not stipulated

A future implementation of this functionality could provide a voltage control feature in transient time domain also in normal operation and not only during faults (also without dead band). A technical proposal can be found in (Erlich, Fortmann, Engelhardt, & Kretschmann, 2009).

3.2.5 Technical Capabilities related with the Active Current Reduction Capability Functionality

3.2.5.1 Technical Specification

This feature comes directly with the current limits of the converter. When running into current limitation, the active current component is of higher priority while the reactive current component is reduced during normal operation. However, in fault situations the reactive current component is shifted to the higher priority

3.2.5.2 State-of-the-Art

Active current has to be limited in a fast way while the reactive current is raised up. The assignment of the priorities as well as the reduction of the treated current components in different situations has to be fast enough to meet dynamic requirements. This implies demands to the electronic control unit and their processing capacity, which can be fulfilled with state of the art signal processors.

3.2.5.3 Constraints and Limitations

This aspect is growing more importance when taking into account negative sequence control or additional active filtering capabilities, since those components also have to be treated separately within the priority allocation (Feltes, Advanced Fault Ride-Through Control of DFIG based Wind Turbines including Grid Connection via VSC-HVDC, 2012).

3.2.6 Technical Capabilities related with the Fast Negative Sequence Current Provision Capability Functionality

3.2.6.1 Technical specification

Asymmetrical system faults or unbalanced grid operations lead to a negative sequence voltage component. While conventional synchronous generators are able to reduce this voltage component by conducting negative sequence currents, wind turbines with converter grid coupling do not affect negative sequence voltages by implication. Hence additional functionalities have to be built into the conversion system and control to enable giving a negative sequence response.

For high voltage level, a new Grid Code version still on draft applying for Germany (VDE, 2013) is stipulating this functionality with dynamic parameters that are the same as for Fast Positive Sequence Reactive Current Provision.

3.2.6.2 State-of-the-Art

Various wind turbine manufacturers are able to provide this capability that could be implemented as a possible ancillary service in the future.

3.2.6.3 Constraints and Limitations

In order to reduce the negative sequence voltage component, an additional negative sequence control functionality of wind turbines could be taken into account. The full decoupling from the grid via converter of Type 4 concepts allows the compliance with the requirement without great effort and a full suppression of negative sequence voltages is possible (Ng, Ran, & Bumby, 2008). Type 3 systems need again dedicated control concepts at least for the machine-side converter, since the control of negative sequences on stator side need frequencies in the rotor circuit that are different from positive sequence control and therefore have different transfer properties between rotor and stator of the asynchronous machine.

Another issue is the presence of an oscillatory torque component within the air-gap resulting from the interaction of positive and negative sequence current components. However, in (Engelhardt, Kretschmann, Fortmann, Shewarega, Erlich, & Feltes, 2011) a concept is proposed which allows negative sequence control with DFIG systems. A fundamental functionality of the described capability is a decomposition procedure to distinguish between positive and negative sequence voltage measurement signals. Furthermore, the wind turbine have to handle both components separately within the control scheme and the prioritization feature of active and reactive current in positive sequence have to be expanded for negative sequences as well (Feltes, Advanced Fault Ride-Through Control of DFIG based Wind Turbines including Grid Connection via VSC-HVDC, 2012).

If the wind turbines are coupled to the grid via VSC-HVDC the negative sequence control has to be done via the converter station at grid connection. The demands on the control are nearly the same as for FSCG or the line-side converter of DFIG systems (Song & Nam, 1999)

3.2.7 Technical Capabilities related with the Communication interfaces Functionality

See "Technical Capabilities related with the Communication interfaces Functionality" in the section regarding the technical capabilities for Frequency Support.

3.3 Technical Capabilities regarding System Restoration Support

Any analysis regarding the technical capabilities of WPP to deliver system restoration support should start from the stochastic, hence not controllable or fully predictable nature of the prime mover. In a critical situation of such a system blackout, the reliability of supply, in terms of capability to deliver the service, is of massive importance. The reliable participation of WT in the restoration process, at least as the main suppliers of the service, is a subject that needs much further investigation.

An approach could be that WT are not the first line of restoration, but they could contribute at later stages of the process, when there are already other generators online. It has to be stated that grid codes do not stipulate requirements regarding system restoration. In addition, the state of the art can only be defined according to the on-going research projects in this area. Assuming that there is sufficient wind to start up the WT, there are additional physical limitations described below.

3.3.1 Technical Capabilities related with the Ability to Energize the Grid Functionality

3.3.1.1 Technical Specification

Wind turbines synchronize themselves onto the voltage of the power system. If no voltage information is present, the classical control approach cannot be applied. However, modern wind turbines connected via self-commutated semi-conductor switches (Type 3 or 4) are in principle able to generate their own symmetrical three-phase voltage system by working as voltage source, if the DC link is charged.

3.3.1.2 Constraints and Limitations

This functionality requires a major change in the control concept of state of the art wind turbines. Therefore, the effort has to be estimated as very high.

3.3.2 Technical Capabilities related with the Ability to start the auxiliary equipment of the plant Functionality

3.3.2.1 Technical Specification

If a full black start has to be performed, wind turbines need to start up their auxiliary systems e.g. electronic devices for control and need to have the possibility to move their blades into the wind without external power supply.

3.3.2.2 Constraints and Limitations

For wind turbines a certain amount of backup energy may be necessary. This energy has to be provided by storage, or an additional supplier may be necessary that is independent of wind conditions (Diesel generator) to ensure the reliability of supply at any time.

3.3.3 Technical Capabilities related with the Frequency Control Capabilities for Cell Operation Functionality

3.3.3.1 Technical Specification

Black start as well as islanding operation within a cell requires the possibility to balance the loads and the generation. This can be done via an extended frequency control capability.

3.3.3.2 Constraints and Limitations

Due to the fact that loads and generators will connect or disconnect within the re-commissioning process, the wind turbine or farm has to withstand disturbances without losing synchronism.

If a cluster control level is established, coordination with other (conventional) power plants is possible to speed up re-commissioning. (Lin & Wang, Investigation of the strategy of wind farm power regulation considering system frequency regulation demand, 2011)

3.3.4 Technical Capabilities related with the Voltage Control Capabilities for Cell Operation Functionality

3.3.4.1 Technical Specification

During supplied isolated operation and stable operation in an islanded network also a voltage control has to be applied.

3.3.4.2 Constraints and Limitations

Within the process of energizing and connecting loads/turbines, wind power plants have to withstand voltage disturbances that can exceed by far normal operation tolerance. Moreover, the larger voltage deviations may require additional reactive power capabilities.

3.3.5 Technical Capabilities related with the Re-synchronization Functionality

3.3.5.1 Technical Specification

Since islanding operation is not the aspired condition, synchronization with other cells or with the built-up power system has to be possible. This requires a function on wind farm level to sense the voltage system in to different system areas and send commands to the turbine which is in charge of the voltage system within the cell.

3.3.5.2 Constraints and Limitations

An iterative process has to be in operation that is able to achieve the switching conditions of equal voltage magnitude, equal frequency and equal phase angle at the point of coupling. During the whole process an interface to the system operator has to be maintained to interrupt and change the procedure at any time to guarantee a restoration (Aktarujjaman, Kashem, Negnevitsky, & Ledwich, 2006).

3.4 TSO/DSO Level Issues

This part of the chapter condenses the most important issues to keep into account on a further analysis of the presented functionalities in the context of the TSO and DSO levels.

3.4.1 Frequency control

3.4.1.1 Setpoint Priority Management:

In the future would be interesting to provide different access and priority levels for the operator/ owner of a WPP, the corresponding TSO (in charge of activating most of the ancillary services) and the DSO (to be able to activate some other services, like local voltage control based on reactive power provision).

A clear definition of the potential control level (owner, TSO, DSO, etc.) and their priorities shall be clearly defined in order to participate in the provision of Ancillary Services.

3.4.1.2 Temporary Active Power Increase:

Frequency deviations are more important and thus monitored and reacted at TSO level rather than DSO level. The frequent activation of this capability to provide FFR and its impact on the distribution system could be taken into account to avoid instabilities (Christensen & Tarnowski, Inertia for Wind Power Plants, 2011) at both levels, but especially at DSO.

3.4.1.3 Calculate Actual Active Power Production:

In general, there are no differences apply to both levels. A different impact could appear in function of the wind farm sizes connected to a TSO grid compared with the size of those connected to a DSO; and related with the size, the impact of the accuracy considering the electrical system could be different.

3.4.1.4 Power Production Forecast:

Actually, TSO acquire forecasts from different provider to calculate the available wind power. In the near future, TSO would require from the wind farm operators not only the power output schedules, but also the forecast schedule. This requirement could be included in the Ancillary Service Grid Code draft.

3.4.1.5 Wind Power Plant Management System:

Dispatching clusters or aggregation of wind farms imply certain degree of coordination, TSO and DSO level (Rohrig, et al., 2009).

3.4.2 Voltage control

3.4.2.1 Reactive Power Setpoint Processing:

The important differences between TSO and DSO are the related short circuit ration as well as the impedance which affects the dynamic behaviour as stated above.

3.4.2.2 Reactive Power Control Scheme:

The differences in DSO and TSO demands are mainly associated with the dedicated voltage level, since at medium voltage level the voltage variations are much higher than on high voltage level. This results in additional thermal stress at converters and other electrical equipment at under-voltage conditions, because the reactive current has to be raised, if the reactive power demand remains constant.

While TSO are already requesting the voltage control functionality, DSO is reluctant to do so, which can be related to commercial issues as well [i2.3]. At the moment DSO transforming the voltage that is controlled by the TSO only, but if more generation will be located on the DSO level, they should control the voltage themselves [i2.2].

3.4.2.3 Fast Reactive Current Injection:

TSO/DSO shall define the trigger conditions for FRT conditions. Furthermore, Type 4 devices (both, wind and solar) do not have one defined response to voltage dips. The trigger conditions as well as the response in defined by software only. The only limit for the technology is the speed and accuracy of the internal control. Several replies to voltage dips can be offered. While DSOs prefer mainly NO current injection at all faults, TSOs would like to have a fast reactive current injection. [q12.11]

There is also the possibility of additional reactive current feed-in after the fault clearance. Therefore DSO and TSO should define what triggers the fault and furthermore what triggers the post-fault condition. In addition the reactive current demand also should be defined, which can be different at TSO and DSO level. However, this infeed after fault clearance will lead to higher voltages at the wind turbine terminals which has to be taken into account in the wind turbine investment costs [q14.5].

4 IMPACT OF WIND POWER VARIABILITY AND PREDICTABILITY ON THE PROVISION OF ANCILLARY SERVICES

4.1 Methodology

The approach to the analysis of the variability and predictability is described graphically in Figure 37.

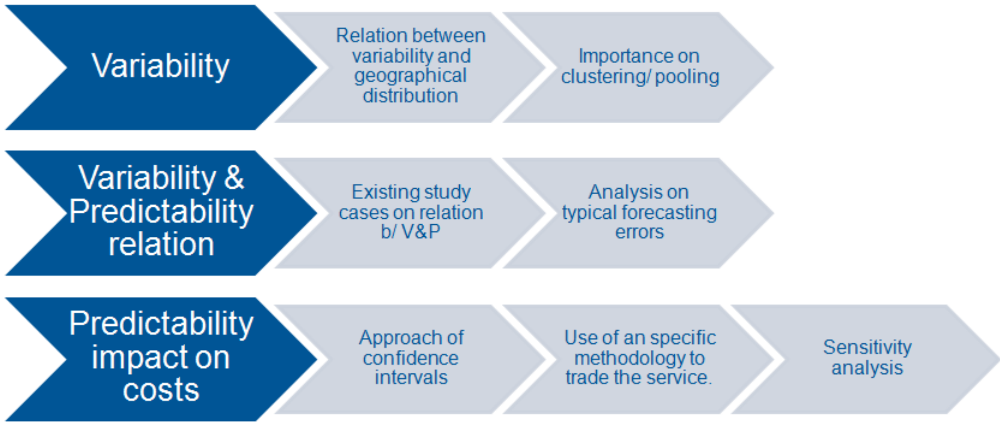


Figure 37: variability and predictability analysis approach.

The first step is to analyze the variability phenomena and how it is related with the geographical distribution and dispersion of wind power plants, arriving to the idea of mitigating and reducing the variability by clustering or aggregating the power plants resulting in smoothing of the total power output.

Then, the relationship between variability and predictability is established by mentioning several case studies presented for different portfolio sizes. Afterwards, the typical forecasting error is analysed for different time horizons and the relation between the forecast error and energy losses is established.

Finally, a methodology to create confidence intervals is presented along with the possible methodologies to trade the energy proposed by the literature. The sensitivity analysis is based on the confidence intervals, the gate closure times and forecast horizons.

4.2 Wind variability

Due to stochastic nature of the wind speed, the power generated by wind power plants is characterized by its variability. This characteristic of wind power introduces uncertainty that has to be dealt with in the day-to-day operation of the power system. To some extent, this uncertainty is dealt with through forecasting, leading to the issue of wind power predictability. The impact of variability and predictability goes beyond operational issues in terms of balancing production and demand, affecting the capability of wind power to deliver ancillary services.

Wind power generation variability is not random, as it is mainly caused by large scale weather phenomena like pressure gradients in the atmosphere. Pressure gradients are correlated over long distances since they depend on high- or low-pressure areas or temperature difference prevalent in specific conditions (e.g., land-sea breeze) (Holttinen et al, January 2013).

Variability can be very high for a single wind turbine of wind power plant, but it shows significant smoothing effects when looking at larger areas. An example of this is given in Figure 38. Those are duration curves of the hourly production level over a year plotted in a descendent order.

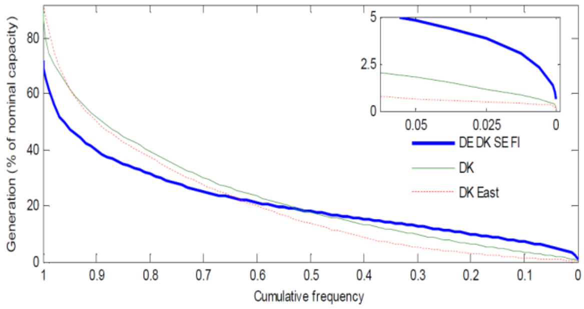


Figure 38: aggregating wind generation over larger geographic areas decreases the number of hours of zero output and reduces the maximum power as relative to installed capacity. Cumulative frequency (i.e., duration curve) of wind power generation in areas with different size: Eastern Denmark; Denmark; and a combined area of Germany, Denmark, Sweden, and Finland (assuming an equal amount of wind power in Denmark, Sweden, and Finland while Germany has as much as the other countries put together). The inset displays the tail of the distribution more closely. Reproduced from (Holtinnen et al, 2013)

Furthermore, variability depends also on the time scale. In general, wind power production will exhibit higher variability for longer time horizons. For power system operation, the time horizon of interest ranges from 15 minutes to several hours. An example of how variability increases with time is shown in Figure 39.

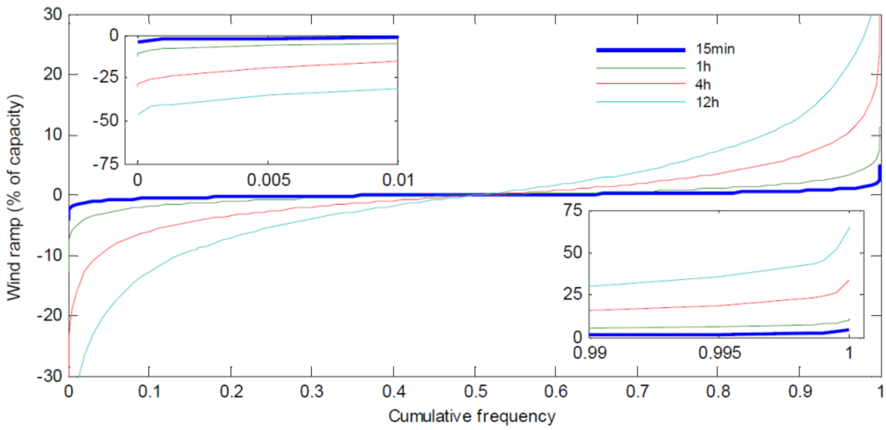


Figure 39: smoothing effect reduces variability more at shorter time scales, as seen from cumulative frequency of ramps of different time scales in Germany for 2010–2011. Reproduced from (Hotinnen et al, 2013)

Variability is probably the most important factor that limits the ability of wind power plants to participate actively in delivering in ancillary services. The uncertainty introduced by variability is directly seen in the predictability of wind power generation, at different time scales.

As consequence, this uncertainty induced by the high variability is the main limiting factor in wind power delivering ancillary services, especially frequency support. Forecasting systems are getting better and better, meaning that the overall shape of wind generation is usually predicted most of the times, but there still are significant errors regarding the level and timing of wind generation. This means that the confidence level in wind power ability of delivering power reserves when needed is still below that of conventional generation".

4.2.1 Wind farm cluster control strategies

Besides the definition provided in this project of Wind Farm Clusters for sake of clarity, there is not a generally accepted definition of wind farm clusters. One definition of cluster – given in (Gesino, 2011) – is considering all the wind farms connected to the same transformer station. This means that the geographical spreading of a wind farms cluster, with this definition, is not significant. One could imagine another level of wind power clustering, possibly as “cluster of clusters”, which would then increase the geographical spreading and maximize the advantage of smoothening. According to (Rohrig, et al., 2005) some control strategies that could be implemented using wind farm clusters are: limitation of power output, energy control, and minimization of ramp rates, among others.

In the literature, the main reasons to clustering are:

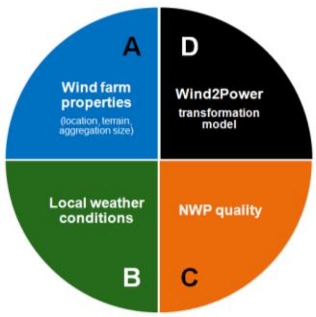
- Variability approach: pooling of several wind farms into clusters to overcome fluctuating behaviour of wind, combined with a prediction technology (Rohrig & Lange, Improvement of the Power System Reliability by Prediction of Wind Power Generation, 24-28 June 2007), (Gesino, 2011).
- Hierarchical principle: levelised control perform at turbine control level, wind farm control level and wind cluster control level (Lin, Wang, Zhu, Li, Liu, & Xu, Investigation of active power coordination control strategy of wind farm cluster using hierarchical principle, 21-24 May 2012).
- Cluster control integrated in TSO/DSO control centre/energy management system level (Rohrig & Lange, Improvement of the Power System Reliability by Prediction of Wind Power Generation, 24-28 June 2007), (Gesino, 2011), (Lin, Wang, Zhu, Li, Liu, & Xu, Investigation of active power coordination control strategy of wind farm cluster using hierarchical principle, 21-24 May 2012).
- Geographical and time scale domain management: cluster is related with hours, wind farm with minutes and wind turbines related with seconds (Lin, Zhu, Wang, Li, Liu, & Xu, 21-24 May 2012).

The pooling or aggregation of group of clusters is also possible. In the development of the present document the concept cluster is mainly used as the aggregation of different wind farms connected to the same POC, but on this chapter the concept is expanded to logical aggregation at the level of all connected wind farms into a control area or even all wind farms in a country (e.g. Germany).

4.3 Variability and predictability relationship

The main factors that influence the forecast quality are, according to (Dobschinski & Lange, 2012):

Forecast Quality = fct(A,B,C,D)



where the parameters A to D denote:

A : wind farm properties (like location, terrain, aggregation size, etc);
B : local weather conditions;
C : Numerical Weather Prediction (NWP) quality;
D: transformation model to transduce wind into power.

In (Dobschinski & Lange, 2012), a comprehensive study of the correlation between the variability (wind power fluctuations) and predictability (forecast quality) for a single wind farm (Figure 40) and for clusters of wind farms (Figure 41). The results show that in both cases, the correlation between the Mean Absolute Gradients (MAG) of the measured 1h-power time series, defined as the absolute difference between the power in each time step, and the Root Mean Square Error (RMSE), normalized with the installed capacity, is very good.

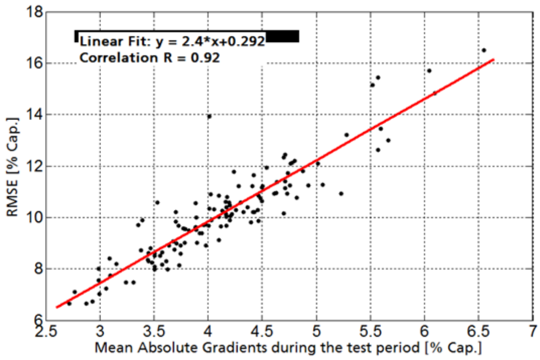


Figure 40: correlation between RSME and MAG (Dobschinski & Lange, 2012).

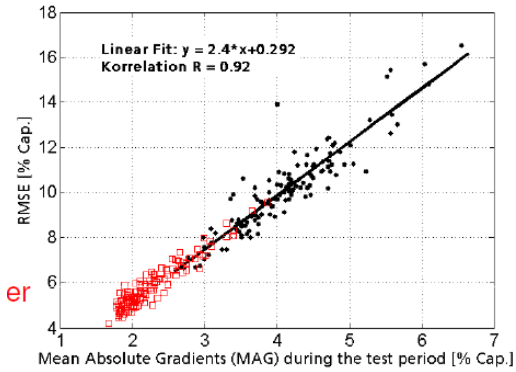


Figure 41: the correlation between RMSE and Meand Absolute Gradients (MAG), proving an excellent correlation of 0.92 (Dobschinski & Lange, 2012).

Therefore, minimizing the wind power variability will result in better predictability. The analysis showed that wind power fluctuations are influencing the quality of the power forecast more than the NWP grid resolution.

The main outcomes are:

- Linear dependency between the RMSE of wind farm/portfolio power forecasts and the mean absolute 1h-gradients of the power time series.
- Minimizing the power fluctuations of the wind farm portfolio leads to a better forecast quality.

4.4 Methodology for delivering AS from wind considering predictability

The participation of the wind power in the frequency support i.e. FRR is not possible today, mainly due to the unregulated creation of bids in the market and for the wind power disadvantageous method for calculation of the delivered power reserve. This is done by comparing the real power production with the scheduled one, with the difference having to match the power reserve. This implies that wind power production will have to follow a scheduled production pattern, usually established on a day-ahead basis.

Recent studies (Gesino, 2011) and (Jansen, Speckmann, & al, Impact of Control reserve Provision of Wind Farms on Regulating Power Costs and Balancing Energy Prices, 2012) have proposed new methods for proof of power reserve provision.

The first proposes an 8-hour procedure where economic variables are considered as well as the stability of the offered reserve is being monitored and evaluated according to TSO requirements, at wind farm level. The main idea of the procedure is that power reserves are tendered every hour, 8 hours before the “Power Reserve Activation Time”. During this period, the tenders are posted, economically evaluated and finally their availability and stability is validated. The validation process has as objective to evaluate the relation between “offered power” and “available power” during the last 4 hours before the power activation takes place. The “offer stability” validation process considers an offer to be unstable when the offered power volume is bigger than the one reported by a pre-defined lower interval from the wind power forecast for a given wind farm. Several metrics proposed for this methodology can be found in (Gesino, 2011). The main idea of the proposed methodology is that wind power cannot be forecasted accurately enough on a day-ahead basis, introducing a shorter – 4 hours – forecasting horizon. One potential disadvantage of the methodology is that it is defined at wind farm level, where the predictability is lower. At the same time, his methodology defines a technical possibility without analyzing into details the economical aspects.

Another approach is presented in (Jansen & Speckmann, Wind turbine participation on Control Reserve Markets, 2013). It uses the concept of available active power, which is defined as the amount of energy that the wind power plant would have produced if it wasn't down-regulated. The estimation of the available active power is an on-going activity in several research projects, i.e. *PossPOW: Possible Power of Offshore Wind power plants* (Giebel, Sørensen, Poulsen, & Runge Kristiansen, 2013) and *Regelenergie durch Windkraftanlagen*, plus a working group established by National Grid (National Grid, 2012). In this approach, having a reliable method for calculating the available active power (AAP) is crucial. A comparison of several different methods for calculating the AAP is given in (Schneider, Siefert, & Speckmann, 2013), together with their performance. Considering that the method has a reliability level that is accepted by the TSO, the need of down-regulation and thus spilled energy is alleviated. The wind power output is lowered with the tendered amount when the dispatch is called by the TSO. This will then be the difference between the available active power and the actual infeed, as shown in Figure 42.

This methodology minimizes the spilled energy due to down-regulation, but it still involves the need of being able to forecast wind power production. In order to be able to meet a security level of 99.994, comparable to the security levels of current market participants, probabilistic forecasts are used. By decreasing the lead time (see also (Gesino, 2011)) to a favourably one hour or less, the probabilistic forecast -at high security levels- is close to the original non-probabilistic forecast.

Despite the important role of forecast systems in planning and operation, the majority of the consulted companies are nowadays not implementing forecasts in their daily operation, as shown in Figure 43.

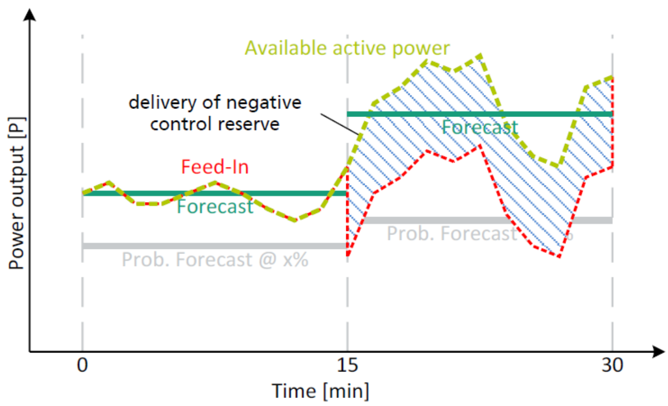


Figure 42: Proof of control reserve under the available active power mechanism, reproduced from (Jansen, 2013)

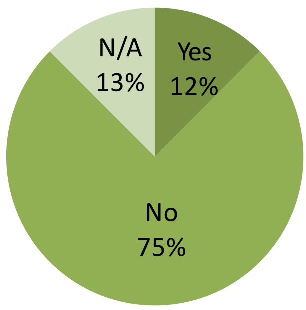


Figure 43: use of forecast systems for the operation of your WIND FARMS [q16.0]

Nevertheless, according to the answers received, not a single manufacturer or developer is incorporating forecasted data into the wind farm controller [q9.1].

Only one company has answered positively to the question [q16.1] referring to the use of probabilistic forecast at wind farm level and to [q16.2], stating that a statistical model is used. At the same time, only one manufacturer mentioned that they would take into account forecasting uncertainty when planning the operation of a wind farm [q16.3].

4.5 Predictability impact on losses

The costs of providing FRR (secondary and tertiary reserve) is analysed in (Jansen, Speckmann, & al, Impact of Control reserve Provision of Wind Farms on Regulating Power Costs and Balancing Energy Prices, 2012) and (Jansen & Speckmann, Wind turbine participation on Control Reserve Markets, 2013).

There are different approaches for creating probabilistic forecasts and defining the confidence interval. One method uses a kernel density estimator. The outcome of such a probabilistic forecast is shown in Figure 44 for a wind power portfolio of app. 30 GW and in Figure 45 for a portfolio of 1 GW.

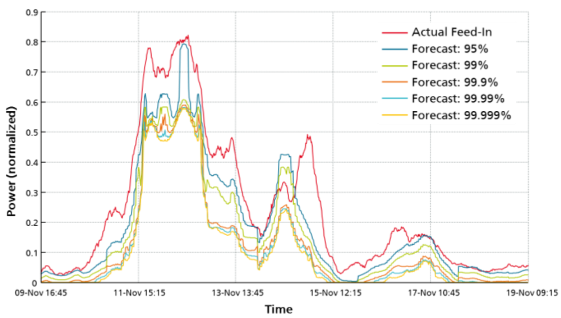


Figure 44: Probabilistic forecasts at different reliability levels as well as the actual feed-in of the entire German wind farm portfolio (~30 GW) (Jansen, 2013)

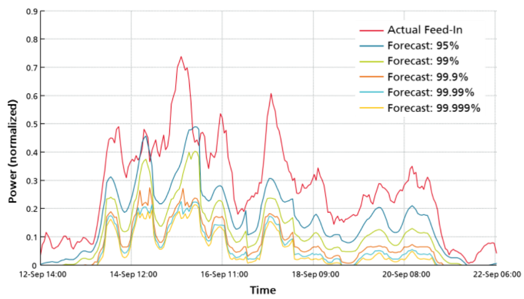


Figure 45: Probabilistic forecasts at different reliability levels as well as the actual feed-in of a pool of wind farms with an installed capacity of 1 GW (Jansen, 2013)

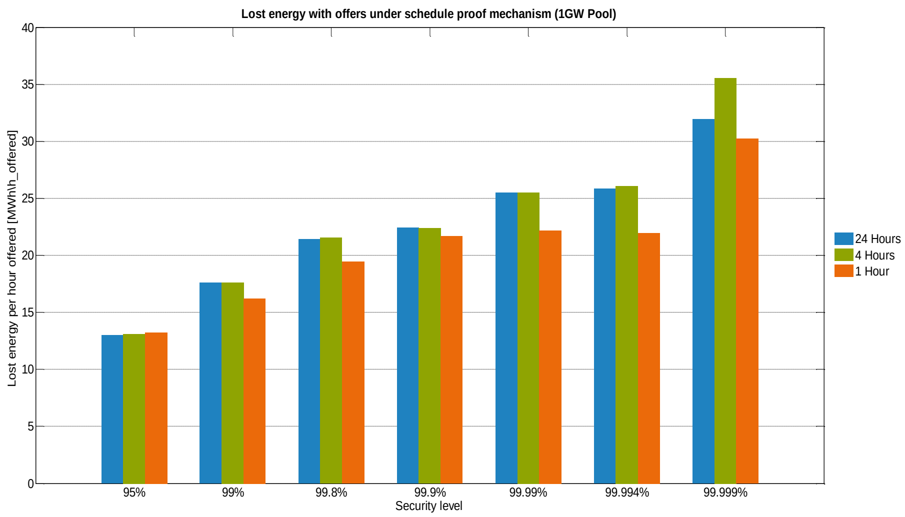


Figure 46: Aggregation level: regional level into 1 control area (1 GW). Confidence interval vs. lost energy per hour offered.

The average energy losses per hour offered are shown in Figure 49 for a wind power portfolio of 1 GW and in Figure 46 for a portfolio of 30 GW. The results show that, when using the balance proof method for the 1GW pool of wind farms in the second half of 2010. e.g. with a reliability of 99.994% the curtailment on average is 22MW (≙2.2%). Reducing the confidence interval, results in a significant reduction of the energy losses, down to 12-13 MW depending on the product length. That means, around 1.25% of the offer.

In Figure 47 the average energy losses per hour offered due to curtailment induced by the balance proof method for the German pool of wind farms in the second half of 2010. e.g. with a reliability of 99.994% the curtailment on average is 1GW (≙3.3%).

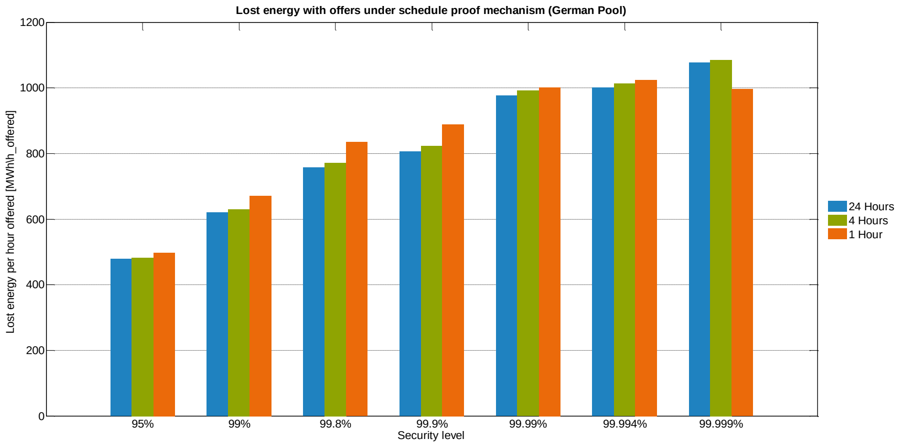


Figure 47: Aggregation level: country (Germany) level (30 GW). Confidence interval vs. lost energy per hour offered (Jansen, 2013)

For the 30 GW pooling, relaxing the confidence interval until 95% represents energy losses by curtailment of around 500 MW (≙1.65%).

4.6 Considerations about forecast impact on services

The last section of this chapter presents specific comments regarding the impact of the predictability on each ancillary service.

4.6.1 FCR - Frequency Containment Reserve

Based on the wind power production in 2009, wind power would have been able to deliver primary reserve – 800MW – with a 99% confidence interval for more than 40% of the time (3656 hours), as showed in Table 5 (Gesino, 2011). This analysis indicates the potential of wind power to provide primary control if the proper conditions are created.

Primary power reserve (800 MW)	
Reliability	Potential power reserve provision during 2009
100%	19.58%
99%	41.74%
95%	57.00%
90%	66.22%

Table 5: Potential primary power reserve provision with wind power in Germany (Gesino, 2011).

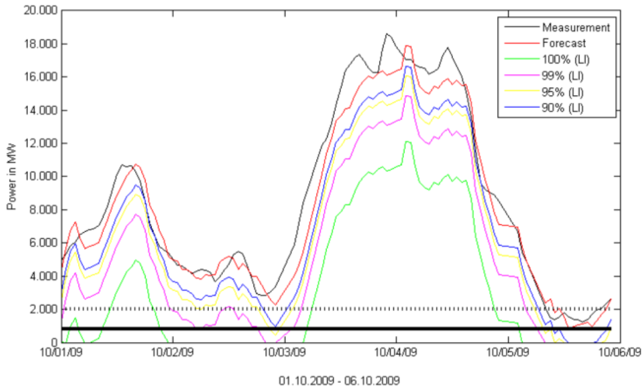


Figure 48: lower interval (LI) calculation for wind power forecast in Germany, 10/01/2009 - 10/06/2009 (Gesino, 2011).

4.6.2 FRR - Frequency Restoration Reserve

In 2009 according to (Gesino, 2011) could have been possible to provide with wind power and a 99% confidence secondary reserve during 2,580 hours (29.46%), as showed in Table 6.

Table 6: Potential secondary power reserve provision with wind power in Germany (Gesino, 2011).

Secondary power reserve (2,000 MW)	
Reliability	Potential power reserve provision during 2009
100%	13.95%
99%	29.46%
95%	41.97%
90%	47.98%

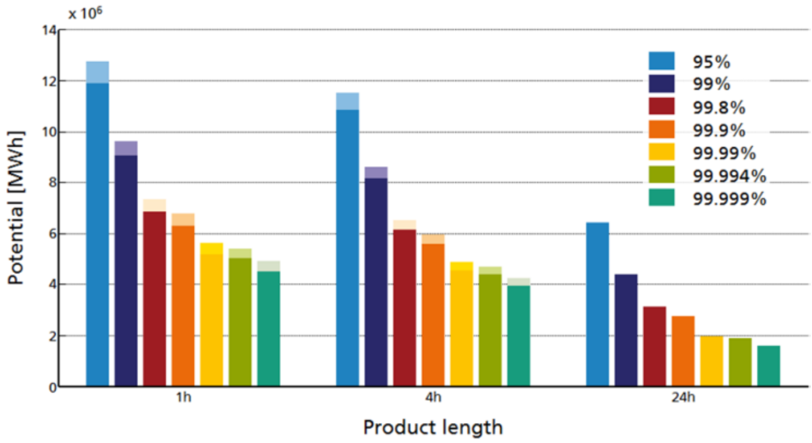


Figure 49: offerable control reserve (lighter colours: theoretical potential; darker colours: potential with restrictions from the tendered amounts) (Jansen, 2013)

The available amount of control reserve from wind farms Figure 49 depends on the product length and security level, according to (Jansen & Speckmann, Wind turbine participation on Control Reserve Markets, 2013). The theoretical potential for the second half of 2010 at a security level of 99.994 %

and a product length of one hour is 5.4 TWh. This potential is the offer multiplied with the product length. With a product length of four hours the potential would be 4.7 TWh and with a product length of 24 hours the potential would be 1.9 GWh. The potential at the same security level with the restrictions would be 5.0 TWh (1 hour), 4.4 TWh (4 hours) and 1.9 GWh (24 hours).

The product length in the tertiary control reserve market is 4 hours. Under this condition the cost saving potential of the new proof mechanism at a security level of 95 % is 31.8 % higher than under the balance control mechanism. At a security level of 99.999 % the cost saving potential is 53.4 % higher than under the balance control mechanism, as shown in Figure 50.

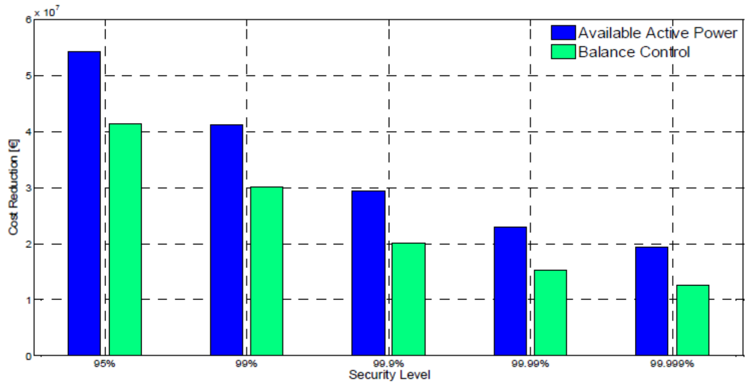


Figure 50: Difference between Balance Control and Available Active Power with a product length of four hours (Jansen, 2013)

4.6.3 RM - Ramping Margin

Available active power according to the definition of the service should be calculated in the same way as FCR and FRR for the corresponding time horizon.

4.6.4 FFR - Fast Frequency Reserve

Forecasting does not play a significant role in the provision of FFR, as the time scale of interest is very short.

4.6.5 SSVC - Steady-State Voltage Control

The overall goals of a Wind Cluster Monitoring System (WCMS), introduced by (Lange, 2010), are to ensure voltage and frequency stability, to avoid congestion, to optimize grid operation (minimization of losses and fluctuations) as well as to supply wind power according an externally specified schedule. In order to reach these goals several calculations have to be performed taking detailed information like power forecast, reactive power capabilities (PQ-curves) of single generators like wind turbines or wind farms and the current grid topology into account. Due to the utilization of forecast data, information about the state of the grid (voltages, component utilization factors) is not only available for the actual moment but also for the near future.

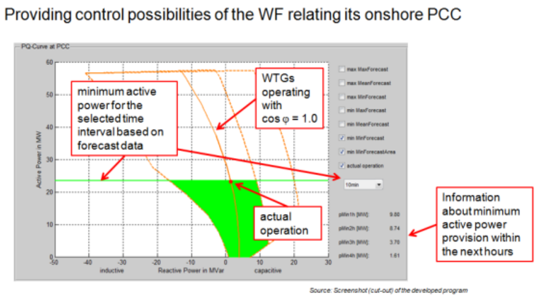


Figure 51: Calculation of available reactive power based on forecasts and PQ diagram.

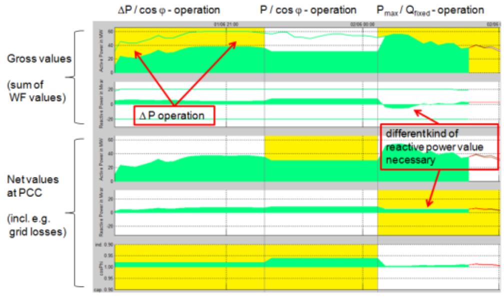


Figure 52: calculation of available reactive power based on forecast (time line show)

Thus, it can be easily estimated if there will be a grid problem within the next time slots, forecast data is available, based on the actual settings for the power feed-in of the wind farm cluster and remedial action can be performed easily before the problem occurs.

A previous version of the WCMS has been implemented, validated and tested in Portugal and Spain. Here, 250 MW of wind energy were monitored, controlled and forecasted in Portugal and Spain. Also real time tests were carried out. Set points from WCMS to the Wind Farm Clusters were sent and wind farms were controlled as it was expected. The actual version has been developed and used within the project RAVE-Research at alpha ventus. This project was sponsored by the Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) following a resolution by the German Federal Parliament.

4.6.6 FRCI - Fast Reactive Current Injection

Forecasting does not play a significant role in the provision of FRCI, as the time scale of interest is very short.

4.7 Conclusion

The impact of wind power variability on the provision of ancillary services can be significant, especially if one looks at individual wind farms. In order to overcome this, it is necessary to use the smoothening effect that geographical spreading has on the wind power production. Moreover, it is shown that there is an almost linear relation between variability and predictability or forecast quality. The latter means that the uncertainty level – crucial in delivering frequency support services – can be reduced by geographical spreading. A further reduction of the uncertainty can be achieved by using probabilistic forecast, being able to reach confidence intervals that are similar to the conventional power plants. Therefore, the use of probabilistic forecasts -together with pre-qualification methods adapted to the characteristics of wind power- are issues that need to receive more attention in the future.

5 COSTS FOR PROVIDING ANCILLARY SERVICES

5.1 Methodology

The main objective of the analysis was to assess the cost for wind power plants to deliver the ancillary services as defined in previous chapters. While the functionalities defined in Chapter 2 are critical for the ability of the wind power plants to deliver ancillary services and for the range that this is possible, the cost estimate went further trying to give a more holistic image. The cost structure used is the one defined in WP2, divided into:

- capability of delivering the service, investments costs (CAPEX),
- cost of being ready to deliver the service (in most cases related to energy that could have been produced and sold),
- costs incurred when the service is actually delivered (variable OPEX).

Various levels of aggregation were used, starting from wind turbine level and going through WF, WPP and Cluster level.

In general, the costs were calculated using a combination of literature review, answers from the questionnaires and inputs from the interviews.

Table 7: cost categories considered in REserviceS project.

Ability / capability	Readiness / holding / availability	Utilisation / response
• investment cost related to providing the capability	• cost for capacity reserved, opportunity cost loosing energy that cannot be sold • link to other markets	• actual provision of the service, like energy as used with fuel cost • increased maintenance costs (wear and tear)

Graphically, the methodology is illustrated in Table 1. Starting from the service, the costs were estimated, for each category, using literature review, industry enquire and interviews.

5.2 Frequency support

In order to be able to deliver FCR, wind power plants will have to operate down-regulated. From a technical point of view, wind power plants are able to provide this feature. While this capability is required in several grid codes, there is not much literature presenting research done for quantifying the impact, if any, on the wind turbine loads. Very recently, in (Jeong, 2013) there is a comparison between different control strategies for primary frequency control, with some focus on the wind turbine loads. While it is not expected to have a dramatic impact on wind turbine lifetime, the regime and frequency of utilization could result in larger stress, especially for the blades and the rotor.

Implementing this capability, where not present, is estimated to not exceed a level of 5% of the cost of the wind turbines electrical system, as resulted from the industry enquiry. To put a value, the numbers available in the IRENA cost analysis report were used (IRENA, 2012). There, the electrical system is evaluated to represent around 13% of the total wind turbine costs, hence implementing the capability required for delivering FCR, is estimated to be 5% of 13% of the wind turbine cost.

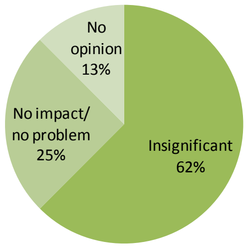


Figure 53: characterization of the industry regarding the impact at WT level of the down-/up -regulation on the WT's life time when this capability is used [q3.2/ q3.6]

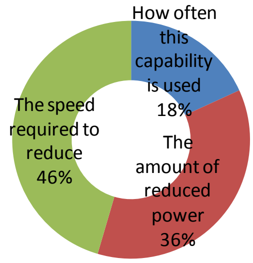


Figure 54: most important factor that contribute to this impact on the life time for both, down-/up-regulation [q3.3/ q3.7]

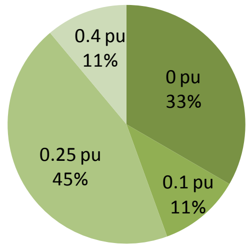


Figure 55: LOWEST power level (or minimum regulating level, in pu) for which Active Power regulation under full wind conditions can be performed [q3.4]

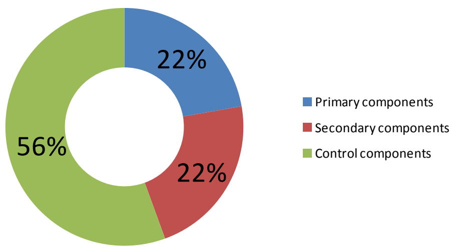


Figure 56: What would be incorporated/ enhanced in order to be able to perform Active Power setpoint control? [q3.9]

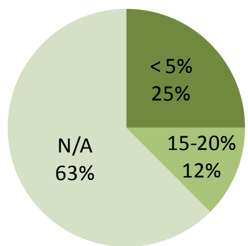


Figure 57: Estimation of ADDITIONAL INVESTMENT cost to enable frequency droop control [q5.6]

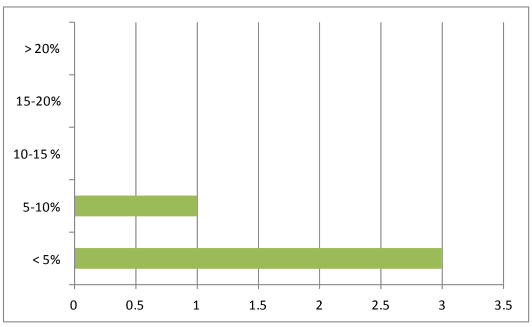


Figure 58: Additional investment cost for enabling/ improving Delta Active Power (ΔP) Control strategy [q7.4] (as fraction of the electrical part cost)

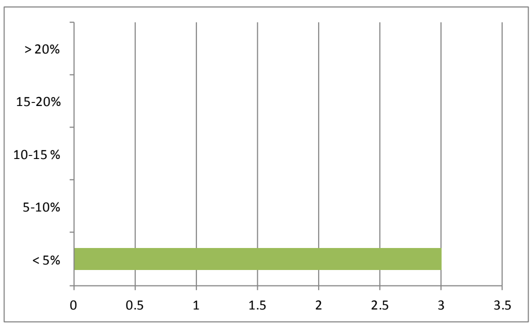


Figure 59: Additional operational cost for enabling/ improving Delta Active Power (ΔP) Control strategy [q7.5] (as fraction of the electrical part cost)

When considering the wind farm level, the extra costs are associated with the added (or enhanced) communication equipment between the wind farm controller and the wind turbines, the communication between the TSO/DSO and the wind farm controller and additional hardware for faster sensing of the frequency deviations. Similarly to the wind turbine level, the cost is calculated as fraction of the total wind farm electrical part cost. The methodology is similar for the cluster level, where only the communication equipment between the cluster and the wind farms is considered. Depending on the use of those values, they should be read as cumulative.

If a power plant is participating in the FCR market – as this is implemented today - it means that it will operate down-regulated. By that it is understood that the energy produced and sold by the wind power plant is reduced by a certain level. Assessing the energy that could have been produced if not down-regulated is not a trivial exercise. The issue has received relatively low attention in the literature, with a limited number of references.

A study about the costs of curtailing wind for frequency regulation is presented in (Rose & Apt, 2010). The study is based on simulations of 100 MW wind farm. Based on the simulation results, the lost energy is claimed to be in the range of 20-50% of the offered up-regulation capacity. This level is decreasing as the capacity increases. The study is considering perfect forecast, therefore neglecting the extra down-regulation that will most likely be needed in order to compensate the forecast error. In our estimations, we considered a forecast horizon of 4 hours for an hourly service delivery. The typical forecast error for this horizon, for a single wind farm, is in the range of 8-10% (Giebel, Pinson, & Martí, The State-Of-The-Art in Short-Term Prediction of Wind Power - A Literature Overview, 2nd Edition, 2011).

Under those assumptions, for every MW of frequency reserve offered by a wind farm, the lost energy amounts to approximately 1.2-1.3 MWh. If we consider a provision mechanism as the one presented in Chapter 4, then the lost energy could be reduced to below 5%, i.e. 1.05 MWh for each MW offered. Therefore, the costs related to the lost energy will depend a lot on what is the considered methodology for acquiring and delivery of the service. In the case of down-regulation, there is no lost energy and therefore no lost energy cost. The cost associated with the actual delivery of the system will mainly have to do to increase O&M costs due to extra utilization of the pitching mechanism, for example. It is not trivial to estimate those costs, since they will massively depend on the frequency of the actual service delivery. For the case studies, this cost has been estimated as an increase in the range of 1% of the typical O&M wind farm costs.

Table 8: Cost associated with FCR

	FCR		
	Ability/Capa New k€/MW	Availability/Re Lost energy MWh	Utilisation/Pr Variable €/MWh
Wind			
Wind turbine	7	N/A	N/A
Wind farm	6	Upward = 1.05 - 1.3 MWh/MW Downward = 0	Upward = 0.16 €/MWh Downward = 1 MWh/MW
Wind Cluster	1	Upward = 1.02 - 1.2 MWh/MW Downward = 0	Upward = 0.16 €/MWh Downward = 1 MWh/MW

The costs associated with delivering FRR and RR are related to the ones estimated for delivering FCR. Enabling the capability cost is very similar. In fact, the assumption made is that if the wind power plant is enabled for delivering FCR, then it does not require any additional investment. The same assumptions are also made with respect to the availability and utilization costs.

Table 9: Costs associated with FRR and RR

	FRR			RR		
	Ability/Capa New k€/MW	Availability/Re Lost energy MWh	Utilisation/Pr Variable €/MWh	Ability/Ca New k€/MW	Availability/ Lost energy MWh	Utilisation/P Variable €/MWh
Wind						
Wind turbine	Included in FCR	N/A	N/A	Included in FCR	N/A	N/A
Wind farm	Included in FCR	Upward = 1.05 - 1.3 MWh/MW Downward = 0	Upward = 0.16 €/MWh Downward = 1 MWh/MW	Included in FCR	Upward = 1.05 - 1.3 MWh/MW Downward =	Upward = 0.16 €/MWh Downward = 1 MWh/MW
Wind Cluster	Included in FCR	Upward = 1.02 - 1.2 MWh/MW Downward = 0	Upward = 0.16 €/MWh Downward = 1 MWh/MW	Included in FCR	Upward = 1.02 - 1.2 MWh/MW Downward = 0	Upward = 0.16 €/MWh Downward = 1 MWh/MW

The cost assumptions for FFR have not been taken from literature but, from the questionnaire replies and the interviews. The implementation of a FFR control response in wind turbines is more a matter of control software rather than additional hardware. For that, in the cost estimation made it was assumed that the technical capability is included in the FCR.

Table 10: Costs associated with FRR and RM

	FFR			RM		
	Ability/Capa New k€/MW	Availability/Re Lost energy €/MWh	Utilisation/Pr Variable €/MWh	Ability/Ca New k€/MW	Availability/ Lost energy €/MWh	Utilisation/P Variable €/MWh
Wind						
Wind turbine	Insignificant	Insignificant	N/A	Included in	N/A	N/A
Wind farm	2	Insignificant	0.16	Included in FCR	1.3 MWh/MW	0.16
Wind Cluster	1	Insignificant	0.16	Included in FCR	1.2 MWh/MW	0.16

5.3 Voltage support

The cost of providing various levels of voltage support will depend on the type of wind turbine employed. As mentioned in Chapter 2, the size (margin in the dimensioning) of the power electronics will define the capability of the wind turbine to provide reactive power at all levels of active power production. In the cost estimation, it was assumed that the preferred technical solution for being able to deliver reactive power all the way down to zero active power was to use a STATCOM at the point of common coupling of the wind power plant. The cost estimates for enabling the capability, as they result from the questionnaires, are shown in Figure 60 and Figure 61. Under this assumption, the investment costs will mainly depend on the sizing of the STATCOM. The STATCOM dimensioning is assuming full delivery of the reactive power at zero active power (including the internal wind farm reactive power losses) – for Type 3 wind turbines – or compensates the losses inside the wind farm – in the case of Type 4 wind turbines. The internal wind farm losses are assumed to be generic, in the order of 5%. Since the STATCOM is the one providing the service, the ability and delivery costs are zero.

The costs related to the provision of fast reactive current during grid faults depend on the wind turbine type and the, presented in Chapter 2, and on the dynamic specifications. The cost estimations made were based on the assumption that the rise time is minimum 60ms and the settling time is 100ms. Then, if there is no STATCOM installed at wind power plant level, the investment costs for Type 3 wind turbines are mainly related to the need of an extra hardware component, namely a DC chopper, plus enhanced sensors for fault detection. For Type 4 wind turbines, only the costs related to the enhanced sensors are considered. The cost estimations resulted from the industry enquire are shown in Figure 60 to Figure 65.

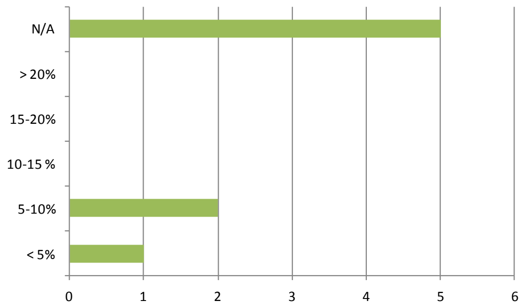


Figure 60: Estimated ADDITIONAL INVESTMENT cost to enable Reactive Power setpoint (reference) control possible at WIND TURBINE level during normal operation [q10.4]

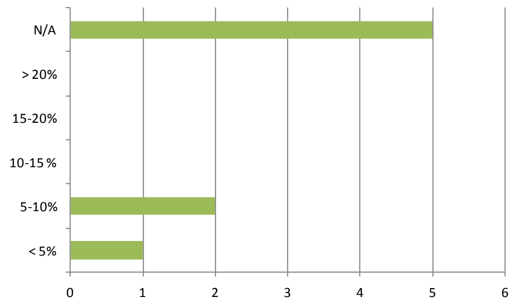


Figure 61: Estimation of ADDITIONAL INVESTMENT cost to enable delivering Reactive Power in case of no wind and during normal operation [q11.2]

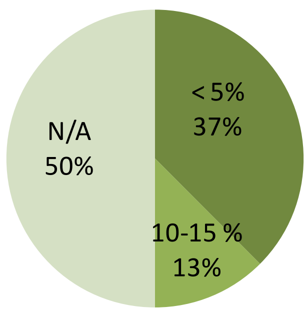


Figure 62: Estimated ADDITIONAL INVESTMENT cost to enable Reactive Power post-fault injection(time limited) at WIND FARM level [q14.3]

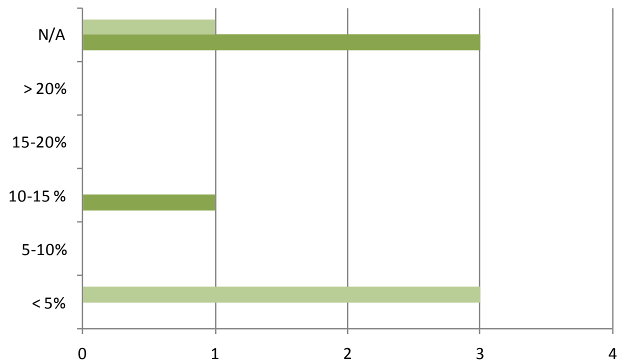


Figure 63: Estimated ADDITIONAL INVESTMENT cost to enable Reactive Power post-fault injection(time limited) at WIND FARM level (divided in manufacturers and developers) [q14.3]

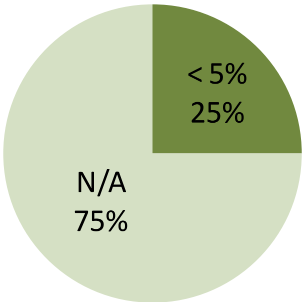


Figure 64: Estimated ADDITIONAL OPERATIONAL cost to enable Reactive Power post-fault injection(time limited) at WIND FARM level [q14.4]

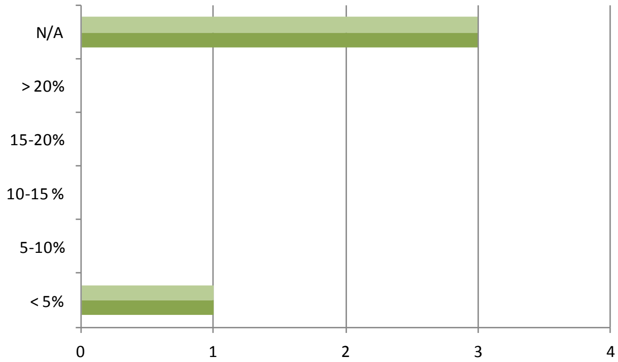


Figure 65: Estimated ADDITIONAL OPERATIONAL cost to enable Reactive Power post-fault injection(time limited) at WIND FARM level (divided in manufacturers and developers) [q14.4]

Table 11: Costs associated with voltage services

		SSVC			FRCI		
	Technology	Ability/Capa New k€/MW	Availability/Re Lost energy €/MWh	Utilisation/Pr Variable €/MWh	Ability/Cap New k€/MW	Availability/ Lost energy €/MWh	Utilisation/ Variable €/MWh
Wind							
Wind turbine	Type III	N/A	Insignificant	Insignificant	6 (if not STATCOM)	Insignificant	Insignificant
	Type IV	N/A	Insignificant	Insignificant	2 (if not STATCOM)	Insignificant	Insignificant
Wind farm	Type III	50	Insignificant	Insignificant	3 (if not STATCOM)	Insignificant	Insignificant
	Type IV	16	Insignificant	Insignificant	3 (if not STATCOM)	Insignificant	Insignificant
Wind Cluster	Type III	0.05	Insignificant	Insignificant	N/A	Insignificant	Insignificant
	Type IV	0.05	Insignificant	0	N/A	Insignificant	0

5.4 System restoration

The use of wind power in the power system restoration process is a relatively new subject. There is a lack of literature available on this subject, albeit the issue is being investigated in some high profile EU FP7 projects like iTESLA (www.itesla-project.eu). In the project, two PhD studies are dedicated to investigating the role that renewable generation could play in the defence and restoration of power systems with significant penetration of renewable generation.

At this stage, the estimation of the costs for wind power to take active part in the power system restoration process has not been possible.

6 TECHNICAL CHALLENGES AND GAP ANALYSIS

In general, the analysis confirms that wind power has adequate control capabilities that make it suitable to participate actively in ancillary services markets. However, there are steps that need to be taken in order to further improve the reliability of delivery and to ensure economically feasible ways of providing ancillary services. This chapter evaluates the technical challenges that are faced or will be faced in the future, when the system needs for AS from wind is substantially increased due to high penetration of non-synchronous generation (or replacement of synchronous generation) and tries to map the necessary steps in order to get there. The analysis of this chapter builds on responses from major OEM's in a targeted interviews (see annex).

6.1 Technical Challenges

6.1.1 Frequency support

The overview of what is needed for frequency support, in terms of technical capabilities, and what is the status in the industry today is given in Table 12. This is similar with Table 2 presented in Chapter 2, but now the functionalities are graded according to their availability today.

Table 12: Gap analysis table for Frequency Support functionalities.

Type of functionality	Functionality name	Ancillary Service					Implemen-tation level
		FCR	FRR	RR	FFR	RM	
Technical	Active Power Control	X	X	X		X	WT/WF
	Active Power Delta Control Mode	+	+	+			WT/WF
	Active Power Limitation Control Mode	+	+	+		X	WT/WF
	Active Power Gradient Control Mode	+	+	+		+	WT/WF
	Frequency Sensing	X	X		X		WT/WF
	Frequency Sensitivity Mode (or Droop Control)	+	+				WT/WF
	Active Power Setpoint Processing	X	X	X	X	X	WT/WF
	Setpoint Priority Management	-	-	-	-	-	WF
	Temporary Active Power Increase				-		WT
Operational	Ability to Calculate Actual Active Power Production	+	+				WT
	Power production forecast		+	+		+	WF
	Communication and Control Interface	X	X	X	X	X	WT/WF
	Communication and Control Interface with the SO	X	X	X	X	X	WF
	Wind Power Plant Management System	+	+	+		+	WF

Legend:

X	Functionality required and today generally available
+	Functionality required but not always available or optionally available
-	Functionality rarely available/ not implemented but implementable/ programmable
O	Functionality required and NOT available
WT	Functionality considered at Wind Turbine level
WF	Functionality considered at Wind Farm (controller) level

It can be concluded that modern wind turbines and wind power plants have good active power control capabilities. Specific control modes, like Active Power Delta Control Mode, are not provided by all manufacturers today, but this is more due to absence of a clear specification/obligation for operation of this control mode, than caused by technical limitations.

Where not present, the costs for implementing the capabilities are not significant, being estimated to up to 5% of the electrical system in wind turbines. Similar investment levels are estimated for enhancing those capabilities, as shown in Figure 57 - Figure 59.

From an operational point of view, forecasting wind power production is a crucial aspect in the provision of frequency support. Wind turbine manufacturers today do not provide the capability of including wind power production forecast directly into the control systems of the wind power plants. Providing this capability is not a big challenge, but it is not clear how this can be used in practice. The practice today is that wind power forecasting systems are acquired and used by wind power plants operators. Where not available, the costs are limited.

6.1.1.1 FCR

The challenges are not the control methods, but are more related to the potential impact on the wind turbine life time when steady state and dynamic operating regimes (like fast ramping) are employed on sustained (daily) basis. One solution is to take these load situations into account in the wind turbine design load spectrum, with all the economic impacts that this implies.

A new approach in the definition of frequency would be beneficial. The definition of frequency based on the intrinsic behaviour of synchronous generators and their rotational speed is not directly applicable to non-synchronous generators that have their frequency decoupled from the grid frequency, due to the power electronics interface. Therefore, another approach for frequency sensing, should be developed e.g. sensing the voltage variations and then clearly define e.g. detection delay, sampling cycles, etc. This aspect is even more important in the case of FFR.

6.1.1.2 FRR

The main challenge regarding provision of frequency restoration reserve lies in the accuracy of forecasting and the reliability of estimating the possible active power. Current wind turbine technologies are capable to provide this service.

6.1.1.3 RR

Similar to the FRR, no specific wind turbine technology challenges.

6.1.1.4 FFR

Wind power plants are technologically able to provide extremely fast ramping, i.e. in the range of 0.1 pu/sec, but there is a lack of knowledge how this would affect the life time of the wind turbines. Clear specification regarding the signals used for activating the control (df/dt) needs to be in place. It might require faster and more reliable communication between wind power plant controller and wind turbines. In general, wind power plants have the minimum technological capabilities needed to deliver this service. An important aspect here is the fact that there is not a clear formulation of the desired control response from the TSO, or even an in-depth analysis of the impact that such a response – temporary instantaneous boost in the active power, followed by a sag in the delivered power – will have on the power system. The technical solutions for providing FFR are still under development and there is a need of moving towards a more general solution that could be, for example standardized.

The technology is mature enough to provide accurate measurements. The manufacturers have pointed out in the questionnaire, interviews and on the REServiceS Workshop organized on Feb, 6th in Vienna that for manufacturers of non-synchronous generators, based on inverters, the traditional frequency definition depicted on modern grid codes is not enough to clearly define how to behave when facing frequency changes, due to the fact wind turbines measure frequency based on voltage measurements.

6.1.1.5 RM

From a technology point of view, wind power plants are perfectly capable of delivering this service. Forecast accuracy is the main challenge in providing an accurate and reliable response.

6.1.2 Voltage support

Modern wind turbines and wind power plants have important voltage support capabilities. The extent of those capabilities depends mainly on the type of conversion system used in the wind turbine.

The current situation, in terms of required functionalities and availability of the technical capabilities related with them, per voltage support service, is given in Table 13.

Table 13: Gap analysis table for Voltage Support functionalities.

Type of functionality	Functionality name	Ancillary Service SSVC	Ancillary Service FRCI	Implementation level
Technical	Reactive Power Setpoint Processing	X		WT/WF
	Reactive Power Control Scheme	X		WT/WF
	Reactive Power Control	X		WT/WF
	Voltage Control	X		WT/WF
	Power Factor Control	X		WT/WF
	Reactive Power Provision	+		WT/WF
	Fast Possitive Sequence Reactive Current Injection Capability		+	WT
	Fast Active Current Reduction Capability		+	WT
	Fast Negative Sequence Current Provision		-	WT
Operational	Communication and Control Interface	X	X	WT/WF
	Communication and Control Interface with the SO	X	X	WF

References:

X Functionality required and today generally available

+ Functionality required but not always available or optionally available

- Functionality rarely available/ not implemented but implementable/ programmable

O Functionality required and NOT available

WT Functionality considered at Wind Turbine level

WF Functionality considered at Wind Farm (controller) level

Similarly to the frequency support, wind power plants are capable of delivering both steady state and dynamic voltage control. Challenges arise depending on the wind turbine conversion technology and the requirements imposed.

6.1.2.1 SSCV

There are no major technical challenges in delivering voltage control in normal operation. There are limits imposed by the technology, but those can be compensated either by oversizing the converters or/and installing additional equipment like STATCOM devices. The main economic challenges here are related to the range of the P/Q capability. If this is extended down to zero active power or enlarged Q ranges, then this would imply extra costs. Nevertheless, it is technically possible. The industry replies regarding the costs involved are given in Figure 61 and Figure 62.

A particular economic challenge is the provision of reactive power at MV level where larger fluctuations in voltage can occur, leading to a higher need of oversizing electrical components.

6.1.2.2 FRCI

Wind turbines of Type 3 and Type 4 can in principle be designed to provide a controlled fast reactive current response. The issue is mainly a proper definition of what is needed: lack of quantification of the need for the fast reactive current in-feed, as well as about the impacts on power system stability of various in-feed strategies (i.e. more research needed).

Another significant issue is how to properly measure the voltage including the changes of the voltage inside the wind farm. a well established solution does not exist yet that would properly take into account technical possibilities and power system needs.

6.1.3 System restoration

6.1.3.1 Black start and Islanding

Providing black start capabilities from wind power plants is a subject that has not been sufficiently investigated yet in the wind industry. Most of the technical capabilities – as identified in the framework of functionalities – required are technically feasible in modern wind turbines and wind power plants. Nevertheless, the critical issue of availability of wind (thus power) and reliability of delivery are things that can raise significant challenges. It is not straightforward how ensuring the availability of the service can be done today.

The power electronics interface of modern wind turbine provides some degrees of freedom for islanding operation. Type 3 wind turbines have a limited technical capability of operating in islanding mode, due to the size of the converter. Nevertheless, wind turbines today are not designed for islanding operation, thus requiring major changes in their control systems, at the minimum.

Table 14: Gap analysis table for System Restoration Support functionalities

Type of functionality	Functionality name	Ancillary Service BS	I	Implementation level
Technical	Ability to Energize the Grid	+		WT
	Ability to start the auxiliary equipment of the plant	-		WT/WF
	Frequency Control Capabilities for Cell Operation	X	X	WF
	Voltage Control Capabilities for Cell Operation	+	+	WT/WF
	Re-synchronization	O	O	WF
	Active Power Limitation Control Mode	X	X	WT/WF
	Frequency Sensing	X	X	WT/WF
	Frequency Sensitivity Mode (or Droop Control)	+	+	WT/WF
	Reactive Power Control Scheme	X	X	WT/WF
Operational	Communication and Control Interface	X	X	WT/WF
	Communication and Control Interface with the SO	X	X	WF
	Power production forecast	+	+	WF
	Wind Power Plant Management System	+	+	WF

References:

X	Functionality required and today generally available
+	Functionality required but not always available or optionally available
-	Functionality rarely available/ not implemented but implementable/ programmable
O	Functionality required and NOT available
WT	Functionality considered at Wind Turbine level
WF	Functionality considered at Wind Farm (controller) level

6.2 Gap Analysis

From a technical point of view, wind power plants are technically capable of delivering both frequency and voltage support. There are a few critical technical aspects that need to be overcome in order to be able to deliver AS, depending on the AS. In addition performances need to be improved and developing into the direction of the service oriented operation.

Those steps are divided into technological and operational.

6.2.1 Technological aspects

Wind power technology today in general is able to cope with the required characteristics for AS delivery. For the frequency support services, the necessary improvements in capabilities for enabling adequate service provision in the future seem to be more directed towards communication and control, so the time constraints for delivering the fast services, i.e. FCR and FFR are met, rather than wind turbine components. There are not yet conclusive answers as to the optimum way nature of FFR response that wind power plants can deliver – a temporary and instantaneous boost in power, followed by a sag in the delivered power – could lead to a response that has no adverse impacts on is adverse to the power system operation. Therefore, it is very important what the requirement is. Of course, there are limitations regarding the extent to which those services can be delivered, but in principle there are no significant technological barriers. The "tear & wear" implications of AS delivery are an issue that needs to be further investigated, as not enough knowledge or experience exists today. It does not seem to be a critical issue though. For the voltage support services, the Type 3 wind turbine has limitations arising from the technology used, namely the sizing of the power electronics used. Nevertheless, the hardware components needed to enhance their capability are readily available today, making it again more an issue of control and communication.

For the FCRI, the main issue is the performance required. Nevertheless, it is debatable how fast this rise time should be and, if chosen in reasonable limits, i.e. 60ms rise time for FRCI, then wind power plant technology is able of delivering the service.

For system restoration services, the technology today seems to be able to deliver some of the required characteristics; with differences based on the technology Nevertheless the subject has not received enough attention so far, so it is challenging to draw hard conclusions.

6.2.2 Requirements

Special attention needs to be accorded to the technical requirements, expressed mainly in grid codes, since they are influencing the way the technology evolves. Furthermore, the requirements are directly affecting the operation of the power system.

Responses to the enquiry showed a perceived lack of clear specifications of the requirements, doubled by a feeling that sometimes the required responses could have adverse reaction on the operation of the power system.

This is the case specifically for FFR, where an instantaneous boost of the power delivered by wind power plants is followed by a sag in the power supply. This behaviour might end up in having an impact on the power system stability, as it may lead to double-dips in the frequency.

For the voltage support level, the required performances should be carefully assessed, as they might end up in answering a power system need that does not actually exist. Especially regarding the FRCI, the industry expressed the concern that a very fast response from wind power plants could lead to instability in the system. Finally, the need of clear and precise specifications of the technical requirements is a critical aspect in tuning wind power plants dynamic responses.

6.2.3 Operational

The main barrier in the actual delivery of AS today is the way that those services are acquired. The methodologies of pre-qualification are highly disadvantageous for wind power plants. With today's practice, based on schedules, wind power would have to operate significantly down-regulated, such that it would cover for the uncertainty induced by the forecasting systems. It is considered an absolute requirement that both the proof of concept and time horizon for service activation and delivery should be changed. The changes should take into account the stochastic nature of the wind speed. Furthermore, the methods for estimating the available power need to be improved in order to create a sufficient level of confidence in the capability of actually delivering the offered reserve.

7 DISCUSSION

The identified necessary capabilities for delivering the ancillary services as set out in WP2 in principal are present in modern wind power technology. Where this is valid in the present situation where non-synchronous generation represents a relatively low fraction of power generation, this task of REServiceS has explored the issues arising with higher levels of non-synchronous penetration.

In reviewing literature and interviews with major industry players only few critical technology issues were discovered. Besides the limitations induced by the stochastic nature of the wind speed, most of the functionalities necessary for delivering the considered AS are either already existing in wind power plants today, or possible to implement, but not used today. From a technical point of view, most of the necessary enhancements are related to communication – which needs to be fast and reliable – and controllers, that need to be developed and/or tuned for delivering the required performances. Regarding reactive power support, where technological limitations were found, they could be overcome using hardware that is available today.

The lack of clear specifications and definitions of requirements coming from TSO is an important obstacle in enhancing wind power plants technical capabilities in the direction of providing AS. In the industry interviews several of the replies regarding the technical capabilities expressed the view that some of them are not available in the wind power plants today simply because there are no clear specifications regarding those requirements. On the other hand, some of the requirements proposed today seem to be excessive and unjustified. It is important that the requirements are defined through an interaction between the TSO's and the industry. Detailed and clear specifications are of crucial importance when designing control strategies and tuning controllers for dynamic performances.

Therefore, one can say that the main discussion should about the economics of delivering AS, rather than the technical capabilities. In most cases, the requirements for delivering specific services are met. If not, in most cases the technical solutions are there, but they are not used today because it does not make sense from an economic point of view. Probably the most stringent need is the development of clear procedures and methodologies for AS acquiring and delivery that take into account the stochastic nature of wind power production. The methodology used today for the proof of delivery or pre-qualification for the frequency support services are a big obstacle in the participation, in an economically competitive mode, of wind power in the AS markets. Maintaining this approach will lead to wind power not being economically attractive to deliver frequency support services (FCR especially, but also FRR and RR) due to the need of curtailed operation over large time horizons. This could be overcome by adopting new methodologies and procedures for pre-qualification and delivery of frequency support AS.

Forecasting of wind power production is a key element in increasing the utilization of wind power in the AS markets. Significant improvements have brought the overall performances of the forecasting systems to very good levels, but the issue of how to use the forecasting information in the daily operation remains. The use of deterministic forecast is limiting, since the level and phase errors that it inherently includes can be significant. Advances in probabilistic forecasting, where future production is given in confidence intervals indicate that this is, most likely, the way forward. In addition, pooling wind power production – and forecasting – will diminish the variability of the produced power and lower the uncertainty.

The changes in how forecasts are delivered imply that also the way the markets operate should change. It is very hard to see significant contribution from renewable generation in the AS markets, if the current setup prevails. Forecasting horizon and mechanisms for bidding with confidence intervals are areas that need much more attention in the future.

7.1 Summary of Technical Challenges

The present summary is based on the interviews of selected manufacturers and developers held in the frame of WP3, Task 3.2.2 of the project.

For the summary tables on frequency and voltage, have been introduced a column "mitigation/ needed solutions". The information presented there is partly based on responses and partly on the analysis of the provided information.

Only the costs related to capability have been considered, distinguishing between costs that can be directly allocated to the plant, and efforts (i.e. implying costs) that need to be made to arrive at the necessary solutions, mainly R&D efforts.

The estimations Low, Medium, High (L/M/H) mean:

- Low, less than 5%;
- Medium, between 5 and 10%;
- High, above 10%.

Table 15: SUMMARY TABLE - FREQUENCY CONTROL

	Technical challenges	Mitigation / needed solutions	Cost implications	
			Plant	R&D
FCR	Enhanced mechanical loading	Structural design adaptations Add ST storage devices	L M/H	n.a. n.a.
	High resolution of frequency measurement	Improved measurement accuracy	L	R&D
	Unclear TSO requirements for Delta ΔP	Improved TSO requirements	n.a.	n.a.
FRR and RR	Forecast accuracy	Improved forecasting methods (real time data / more models)	n.a.	R&D
	Estimation of available power	Pooling of WPP / portfolio management	n.a.	n.a.
	Increased loading at low and high power	Siting Improve estimation methods for available power Control and design adaptations	n.a. L / M	R&D n.a.
FFR	Fast and reliable communication	Development /adoption of improved communication methods	L	n.a.
	Uncertainty of impact on design loading	Improvement of grid code requirements to enable load cases definition	n.a.	R&D
	Enhanced 'electrical' loading Interaction with power system	Oversizing of electrical equipment	H	n.a.
	Reliable detection of df/dt	System studies	n.a.	R&D
	Mechanical loads at high ramp rates	Improved measurement method	L/M	n.a.

	Technical challenges	Mitigation / needed solutions	Cost implications	
			Plant	R&D
		Design loads and structural design adaptations	M/H	n.a.
RM	Forecast accuracy	Improved forecast methods	n.a.	R&D

Table 16: SUMMARY TABLE - VOLTAGE CONTROL

	Technical challenges	Mitigation / needed solutions	Cost implications	
			Plant	R&D
SSVC	Enhanced electrical loading, higher currents higher losses	Oversizing of electrical equipment, especially at MV level	H	n.a.
	Enhanced mechanical loading at idling level when providing high Q for prolonged time	Use external devices (reactors, synchronous condensers, STATCOMS)	M/H	n.a.
	Lacking requirements for negative sequence current provision	Redesign (structural, mechanical) of wind turbine	H	n.a.
		System studies - Improvement of grid code requirements – development of WT control methods	H	R&D
FRCI	Very fast controlled response (Short rise times)	Sub-cycle rise times require complete new design	M	n.a.
		Improve sensing and control	H	R&D
	Recognize fault type for unbalanced faults	Develop tuning methods for controllers	M	R&D
	Provision of adequate response	Improve simulation methods and models	M	R&D
		Improve grid code specifications	n.a.	R&D
	Lacking specification of number of FRT occurrences		n.a.	R&D

Table 17: MOST CHALLENGING ISSUES (Compiled mainly from answers to questions 1.1 and 2.1)

	Manufacturers	Developers
Frequency control	MECHANICAL / STRUCTURAL DESIGN Mechanical impact of FFR (very fast ramp rates) Fatigue impact on WT beyond certain number of FFR Lack of design feedback on operation beyond certified ranges Influence of rotor speed variations on WT dynamics Redesign / recertification is time consuming DESIGN OF CONTROL AND ELECTRICAL SUBSYSTEM Design of control systems and reliable communications between WF controller and all WTs Higher rating of auxiliary electrical/electronic systems Limitations of WT control and actuation systems CONTROL METHODS AND STRATEGIES Accurate estimation of available power (WT and WPP) df/dt: Accurate measuring and producing reference signal Dealing with uncertainty of forecast GENERAL Providing the solutions in a cost effective way	PLANNING Limited availability of the FFR functionality from manufacturers Availability of very large wind turbines providing fast ramping OPERATION WTs operating outside design (certified) range Communication with TSO / obtaining right setpoints from TSO Achieve frequency control in a cost effective way WIND FARM CONTROL Develop WF controller strategies, with varying conditions at the individual WTs. Implementing forecasts
Voltage	DESIGN OF CONTROL AND ELECTRICAL SUBSYSTEM Design limitations of the converter Design of auxiliary equipment for over and under-voltages CONTROL METHODS AND STRATEGIEs Voltage stability, avoiding hunting phenomena and oscillations Correct plant FRCI response with respect to grid fault clearance, for example also avoiding over-voltages Parallel operation of plants in voltage control mode Symmetric voltage support, provision of negative currents GENERAL Provide the solutions in a cost effective way	PLANNING Availability of wind turbines in the market with capability to provide SSVC /PQ without external additional equipment Complexity of FCRI according TSO specs with actual technology WIND FARM CONTROL Combined control of WTs and external solutions Uncertainty about control behaviour of WT outside+/-5% of U rated GENERAL Achieve enhanced PQ in a cost effective way

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9 ANNEXES

This section is located on a separated file. The content of the Annexes are:

9.1 Industry Questionnaire

9.2 Industry interview

9.3 Grid code parameters for defining technical capabilities