“Large scale integration of offshore wind power through Wind Farm Clusters”

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Abstract

In 2030 wind energy should provide 25% of the EU electricity with an expected production of 935 TWh. Such a high share of wind generation requires reliable and secure grid integration levels. One of the current R&D challenges is to manage wind power (on and off-shore) as a conventional power source, contributing with the stability of the fundamental electric parameters, frequency and voltage.

This paper describes the power system requirements for high wind penetration as well as the concept of “Wind Farm Cluster”. It also focuses on the results of the German R&D project “*Integration großer Offshore-Windparks in elektrische Versorgungssysteme*” where control capabilities were tested including the new structure of “Wind Farm Cluster” developed by Fraunhofer IWES.

Index terms

Grid integration, active power control, reactive power control, voltage control, power factor, Wind Farm Cluster, ancillary services, grid codes, set points.

I. Introduction

Current and future large scale integration of wind energy demands that it should be manageable as a conventional power source, offering also ancillary services which nowadays are being provided by the conventional generation in a reliable and stable way.

As happened with other technologies, wind power was born when the level of sophistication of the technology was much lower than it is today representing a small share of the overall installed capacity and with a regulatory framework whose main goal is to maximize its utilization. Therefore, in the past, technical requirements for grid integration of wind energy were relatively low.

Currently TSOs are upgrading their grid codes due to the expected increase of wind energy into their grids as well as the availability of new developed technologies installed at wind turbine and wind farm level allowing higher levels of monitoring and controllability per each installed wind farm [5].

The structure of “Wind Farm Cluster” developed by Fraunhofer IWES will also play an important role in the future large scale integration of wind power.

This paper examines the power system requirements for high wind penetration, the “Wind Farm Cluster” structure as well as concrete R&D results from a German project oriented to the large scale integration of the off-shore wind power.

Fulfilling wind power plant capabilities implies that wind power has to be controlled and operated according to system requirements and has to support the grid during disturbances and faults. These capabilities are based on a proper active and reactive power control of wind farms as well as the supporting schemes during grid faults.

II. Power system requirements for high wind penetration

There is a need for further extended and integrated control and management of the wind power. Therefore the introduction of new control techniques, such as the Wind Farm Cluster Management System (see Section III), would allow grid operators to optimize the managing of wind power according to their power system requirements, which are described as following:

a. Active Power and Frequency Control Requirements

Increasing penetration of wind energy in power systems will require its participation in the power frequency control and balancing procedures which are already performed by conventional generation. The fulfilment of power and frequency control schemes in case of high wind penetration also implies the provision of primary, secondary and inertial energy (spinning reserve) from wind generators.

In some EU countries there are plans to implement in a new operative procedure strengthen requirements for the power and frequency control contribution from wind generators. This includes the participation in the power and frequency control schemes and in addition requirements for inertia provision by emulation from wind farms [5].

With an increasing wind penetration and bigger power ratings wind turbines and wind farms will have an important role to assure the frequency stability of the system. Therefore it will be expected in future grid codes requirements the obligation of wind generation to provide this ancillary service. This topic is an issue subject to regulation and discussion.

b. Reactive Power and Voltage Control Requirements

With an increasing wind power penetration, the voltage control and grid support has to be carried from wind farms. Therefore, some grid codes have already issued operational range for the voltage and power factor at the point of connection to which wind generation is obliged to cope with. An example of the power factor ($\cos\phi$) and voltage control requirements at the wind farm connection point are depicted in Figure 1.

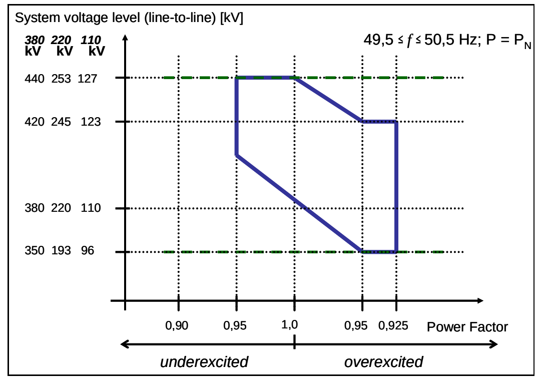

Figure 1 - Basic requirement for the reactive power supply for E.ON [4]

Furthermore, Figure 2 describes the requirements of several TSOs for the control of reactive power related to the available active power production from wind farms.

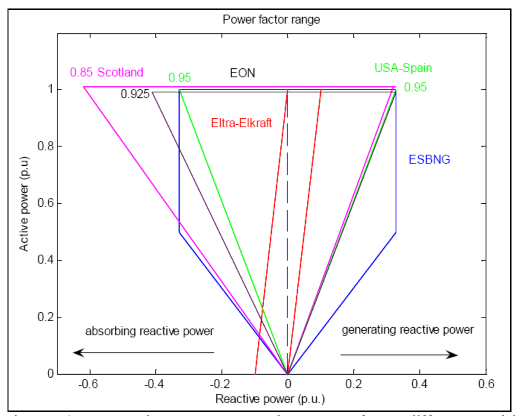

Figure 2 - Reactive power requirements from different grid codes related to the active provision [5]

c. Fault-Ride-Through-Capabilities

In some EU countries one of the most relevant problems in the recent years was the lack of adequacy of wind generators to withstand voltage dips and to remain connected to the grid supporting the system during faults. This situation could lead to lose great amounts of wind power generation in the event of any disturbance.

Nowadays wind farms are obliged to provide fault ride through capabilities (FRTC) in order to maintain the stability of the grid in cases of faults. Requirements are different in each country and are dependant on the voltage dip and the duration of the corresponding short circuit that the wind farm has to withstand. Most extreme requirements demand that wind power has to support the grid even during voltage dips of 0% (called Zero-Voltage-Ride-Through - ZRVT). In addition, the protections schemes have to be appropriate so that the wind turbines can offer the necessary short-circuit power to activate the protection mechanisms when it is necessary.

Fault-Ride-Through-Capability (FRTC) is one of the most demanding requirements for wind turbine manufacturers due to the heavy conditions that the wind turbine must withstand in case of voltage dips in the grid. Moreover, the larger the wind turbine is the bigger its influence on the transient stability of the grid in case of faults.

Many wind turbines from today are equipped with this option. Therefore, it can be concluded that current wind turbines are able to ride through a wide range of faults in the grid and this is not expected to change in the future. Future grid codes may issue regulations requirements for Zero-Voltage-Ride-Through for wind turbines.

d. Wind power forecasting

For the TSOs the previous paradigm of planning based on a small number of well known large power plants it is not applicable any more. Due to natural fluctuating characteristics of wind power, it is required an accurate and reliable forecast for the next hours to days ahead [1] [2]. This will lead to higher grid reliability and cost savings.

Nowadays the development of models for dynamical forecast uncertainty estimation for each time step has nearly the same priority as the wind power forecast itself (see Figure 3). This is due to the multiple applications concerning decision-making problems based on the stochastic nature of wind power prediction errors. Optimal scheduling of power generators and bidding strategies in the electricity markets requires information about a secured power feed-in. All these information can be deduced from wind power forecasts in combination with uncertainty intervals.

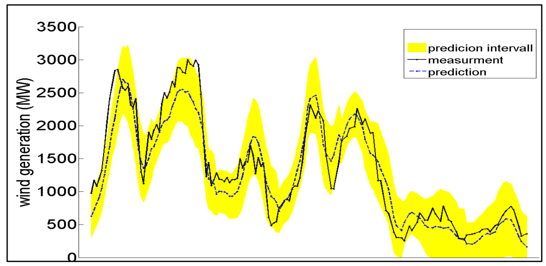

Figure 3 - Example of Forecast Interval Assessment – 90% Probability that all measurements will be within the prediction interval (yellow surface) [8]

III. Wind Farm Clusters

The Wind Farm Cluster concept was created and developed by Fraunhofer IWES as a natural evolution for wind energy management. In the past, Wind Turbines were grouped into Wind Farms, and nowadays Wind Farms are being grouped into Wind Farm Clusters [3] [6]. The aim of this structure is to allow the TSOs to manage wind energy as a conventional power source, avoiding some natural aspects of wind energy as the fluctuating nature of the wind, the distributed location of the wind farms and the existence of different generator technologies, among other issues.

A Wind Farm Cluster consists in is a logical aggregation of existing physical wind farms which are connected to the same grid node. The main goal of this structure is to allow the large scale management of wind energy and the operation of wind farms as conventional power plants.

For the proper administration of Wind Farm Clusters, the Wind Farm Cluster Management System (WCMS) was implemented. Advanced techniques and control strategies combined with high-tech wind energy forecast technologies were successfully developed. This platform allows wind farm clusters to provide grid operators with active and reactive power control, wind power reserve, congestion management, gradient control, voltage changes control and power factor control, among other issues, in order to fulfil the current and future requirements regarding operational flexibility and security issued by grid operators.

Figure 4 depicts the general structure of the wind farm clustering. Single wind turbine generators are aggregated under a wind farm.

These wind farms connected under the same grid node are logically grouped into a Wind Farm Cluster.

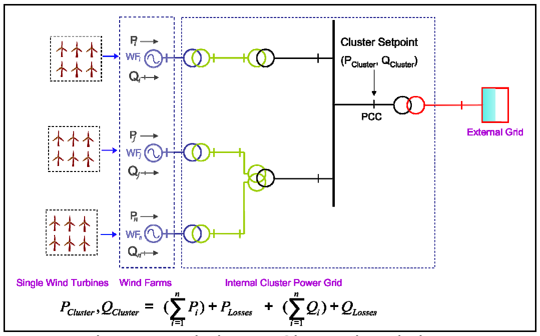

Figure 4 - Wind Farm Cluster description

The WCMS considers the existence of a hierarchical “two layers” structure: TSO and Dispatch Centres layer. As it is shown in Figure 5 the TSO receives monitoring information (P, Q, U) coming from the Dispatch Centres and at the same time the Dispatch Centres receive the control commands sent by the TSO to the wind farms.

The control command (set point) is being sent from the WCMS TSO to the WCMS Dispatch Centres. Once the set points are received by each Dispatch Centre, they have to forward each set point to the wind farms under their control. The distribution of these set points within the wind farms is performed by the WCMS Dispatch Centre.

Parallel to the command data flow (TSO-Dispatch Centres) there is a monitoring data flow (Dispatch Centres-TSO) which allows the WCMS TSO to identify the present state of the cluster and to run its own calculation tools. These monitored parameters allow the system to know the current situation of the generation at wind farm cluster level. Therefore, a permanent communication link between these levels (TSO-Dispatch Centres) has to be assured so the information can flow continuously.

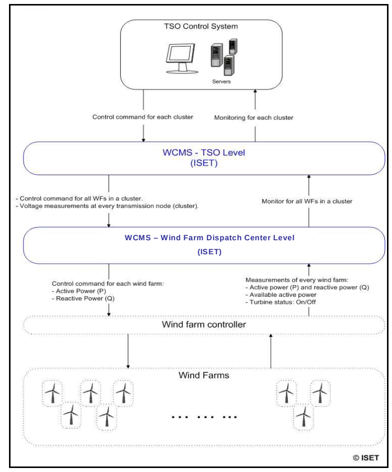

Figure 5 – WCMS structure

IV. Project “Integration großer Offshore-Windparks in elektrische Versorgungssysteme”

a. Project description

The overall aim of the project was to increase the energy economic value of wind power by improving the integration of large off-shore wind farms into the electrical power supply system. Control capabilities of a wind farm cluster were tested in order to address the potential future requirements of TSOs for on- and off-shore installations [7].

b. Tests scenarios

Considering that during the project there were no German R&D off-shore wind farms available as happens nowadays (see section V), it was selected an on-shore wind farm cluster with particular technical characteristics which have allowed the R&D results of the project to be analyzed also for the future off-shore requirements.

The selected cluster is composed by controllable wind farms, it is located in non meshed grid area with low influence in the cluster node from other wind farms installed nearby and has similar grid conditions as it would happen with an off-shore wind farm. It is connected to the transformer station “Bertikow” controlled by TSO Vattenfall Europe Transmission, as it is depicted in Figure 6. The geographic distribution of the involved wind farms is also shown in Figure 7.

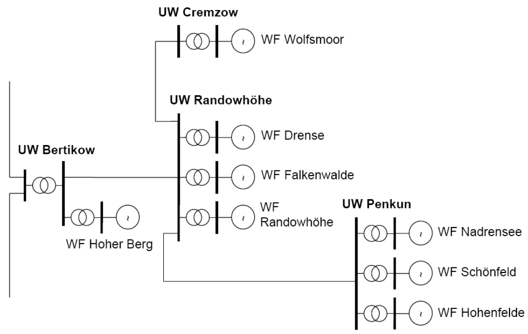

Figure 6 – Tested cluster

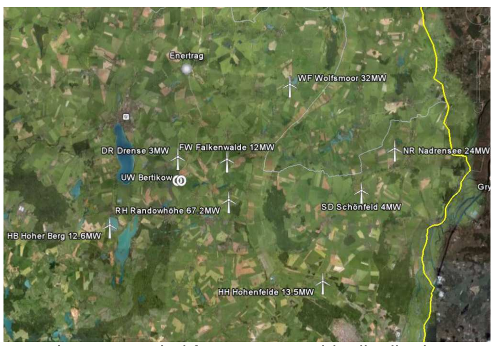

Figure 7 – Wind farms geographic distribution

c. Performed tests

R&D tests were performed in order to validate the capability of a wind farm cluster to contribute at cluster level with active and reactive power, and voltage control. Therefore a control command was sent through WCMS TSO to the WCMS Dispatch and finally distributed to each wind farm which belongs to the selected cluster (see Figure 6).

For each tests it was measured the reaction time at cluster and wind farm level, analyzing the capability of the whole cluster to be influenced by control commands sent to each wind farm.

Reactive power control

A reactive power control command was sent to the "Bertikow" cluster and forwarded to each wind farm which belongs to the analyzed cluster. The voltage behaviour during the set point can be observer in Figure 8 as well as the reactive power commands sent to each wind farm.

This test was relevant in order to analyze how a wind farm cluster could contribute with voltage stability through reactive power control both, capacitive and inductive.

In Figure 8 it can be appreciated how the reactive power set point has clearly influenced the voltage at cluster node level.

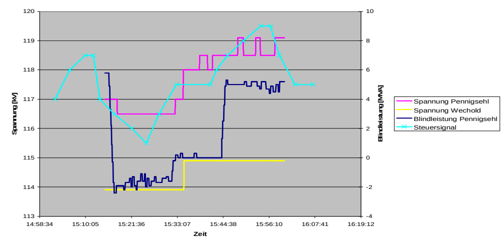

Figure 8 – Voltage control

Active power control

Active power control tests were performed analyzing how long it would take to a wind farm cluster to reach the desired value (control command sent by the TSO) and how accurately and stable this target is reached during the set point time frame, both at cluster and wind farm level.

Control commands with a reduction of 95, 80 and 60% of the available active power at the analyzed wind farm cluster were sent (see Figure 9). It can be also appreciated that even when the set point was reached, the active power measurements show that there was a certain degree of instability during the set point time frame. The differences between set point target and the reached operational point of the cluster are analyzed in Figure 10.

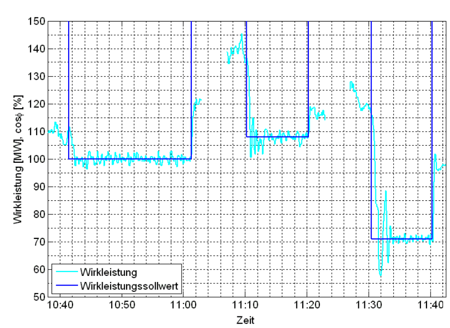

Figure 9 - Active power control wind farm cluster level

Figure 10 shows the deviation between the power production of "Bertikow" wind farm cluster and the given limitation command. More than 90% of the measured active power values do not deviate more than 1% of the power limitation set point. The biggest deviation is 3,5% from the given control command.

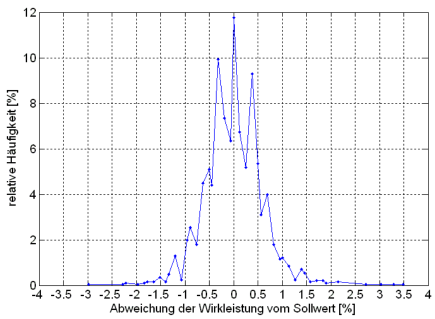

Figure 10 - Cluster deviation from set point

As it can be seen in Figure 11 during the first 200 seconds different power fluctuations were observed registering a clear relation between the requested power reserve volume and the duration of the power fluctuations. As bigger the test was, bigger was the oscillation detected.

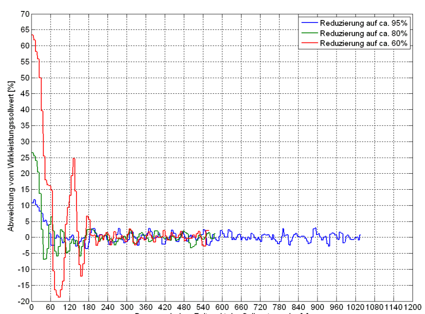

Figure 11 - Active power tests

Power factor control

Figure 12 depicts a reduction set point of the power factor from 1 to 0,99. This set point generates a reactive power output of -18,8 MVar approximately. It can be appreciated how reactive power reacts nearly 30 seconds after the set point was sent reaching in an stable way the level of -18,8 MVar during the 10 minutes set point time frame.

During this period it can also be appreciated 7 deviations of the set point from its original target. The first six were relatively smooth around the -18,8 MVar set point. The last deviation consisted in a power factor of 1,003. During this deviation the reactive power jumped to 10,44 MVar during 4 seconds approximately.

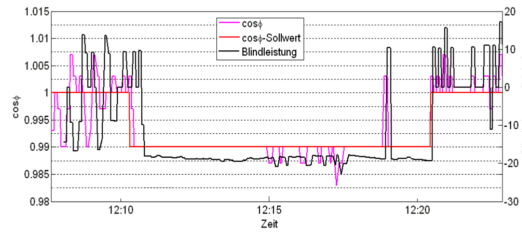

Figure 12 - Power factor reduction

Other power factor variations could also be observed in Figure 13. The longest power factor variation took place with a power factor of 0,94. During this fluctuation it could also be observed a new fluctuation of the power factor to 0,96 duration of 300 seconds. It can also be appreciated that as strong the power factor reduction was longer it took to reach the desired value.

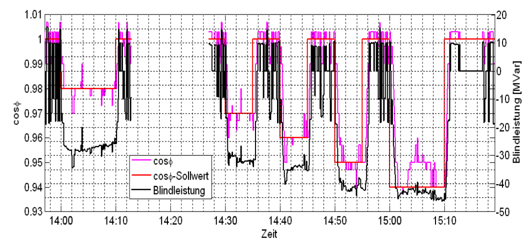

Figure 13 - Power factor reduction

V. Further R&D projects in the off-shore sector

As shows Figure 14, during the coming years wind energy development in Germany will continue growing. Therefore a large R&D project financed by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) is currently running: the RAVE initiative.

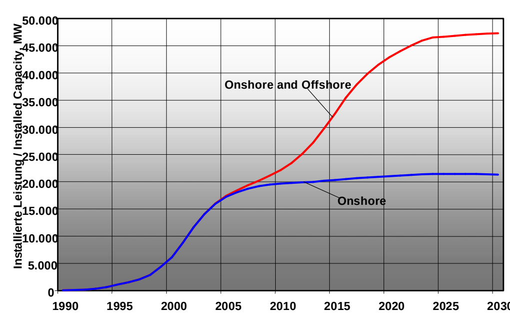

Figure 14 - Development of wind energy in Germany

The RAVE research initiative runs simultaneously with the construction and operation of the "alpha ventus" test site to obtain broad based experience and knowledge for future offshore wind farms.

„Alpha ventus“, the first German offshore wind farm testing and demonstration project, is initiating the utilisation of wind energy in the German North and Baltic Seas. The main focuses in the associated German research initiative, RAVE, are the reduction of costs, increased efficiency, advancing the availability of wind turbines, improving the technology for developing offshore wind energy, its ecologically responsible application as well as technologically optimising the turbines with regard to ecological impact. RAVE is sponsored by the Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) and is co-ordinated by Fraunhofer IWES. It joins the scientific activities of the plant manufacturers and a multitude of research institutions. In total the BMU has allocated 50 million Euro for the research and further development of wind energy utilisation at sea.

The research areas of Fraunhofer IWES will include the whole wind energy spectrum from materials development to grid optimization as well as energy systems technology for use of all forms of renewable energies. They are described as following:

- Engineering and operation of wind energy turbines and parks.
- Development of components: rotors, power trains and foundations.
- Fluid elasticity and dynamics
- Environmental analysis for wind and ocean energy technology.
- Control and system integration of decentralized energy converters and storages.
- Energy management and grid operation.
- Energy supply structures and systems analysis.

VI. Conclusions

This paper concentrated on the requirements and capabilities for large scale integration of wind power, focusing particularly in the coming off-shore wind power development which will dramatically increase the injected volumes of wind power into the EU’s grids.

A progressive displacement of conventional generation by wind energy is already taking place and will be even deeper during the coming years as soon as the new multi megawatt wind turbines start to be installed (7,5 MW units are already developed and 10 to 15 MW units are currently under concrete R&D). This situation leads to new technical requirements for wind generators in order to make wind energy controllable as the conventional generation is.

Clear definitions and agreements between manufacturers and grid operators will lead to clearer operational requirements for wind energy and in the future to harmonize grid code requirements which will be a step forward for the wind energy sector, saving costs and allowing larger amounts of renewable energies to be integrated into the grids world wide.

A new system tool for wind farm clusters control was presented. Through the Wind Farm Cluster Management System (WCMS), developed by Fraunhofer IWES, it is possible to operate wind farms as conventional power generators. WCMS was successfully tested in Germany, Portugal and Spain, showing that even with the current structures and available technologies wind power can achieve high controllability levels.

Forecasting algorithms and the impact of the uncertainty band of the forecasted wind power values are also essential for the secure and large integration of wind power and were integrated into WCMS too.

The analysis of the performed real tests in Germany described in this paper has shown that the deviation between the set point target and the real power production in 90% of the measurements was not more than 1%. The biggest deviation was 3,5% from the given control command. This shows high controllability levels of wind power during the execution period of the testings.

Finally it is remarkable that in some cases the needed technology for the improvement of wind power controllability levels is already being provided by the wind turbine manufacturers. This technology is available to be used as soon as the new grid codes and regulatory updates get in force.

Needed initiatives for larger scale integration of wind power can be described as following:

- New regulatory developments concreted into new technical requirement through new grid codes versions.
- Technical developments from manufacturers which provide wider capabilities to new machines enabling them to fulfil these new requirements and the possibility to adapt the old ones at a reasonable cost.
- A brand new architecture of Control Centres solely devoted to monitor and control wind power generation interconnected with TSOs facilities.
- Specific tools able to asses in real time the system security with high penetration of renewable generation to perform an operation within standard security margins as well as minimizing additional costs which in the past were afforded due to uncontrollable nature of wind power.

Thanks to the commitment of all involved sectors, wind energy is demonstrating once more that it is ready to face a new challenge in the renewables energies history. It is not only fulfilling the market demand with new modern multi mega-watt wind turbines (on and off-shore), it is also capable to face the challenge of progressively replace conventional generation bringing at the same time security to the system through its already demonstrated controllable characteristics.

This is it self a step forward in the direction of the 100% renewable energies scenario which was also presented by Fraunhofer IWES.

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Kurt Rohrig has being working at Fraunhofer IWES (former ISET) since 1991. Currently he is head of the R&D Division Energy Economy and Grid Operation. Mr. Rohrig has more than 10 years experience in wind power projects. He is the scientist-in-charge for projects handling the online monitoring and prediction of wind power for large supply areas – operated in co-operation with large power transmission utilities. Mr. Rohrig has contributed to numerous publications in the field of wind energy integration in the electrical energy supply and completed his PhD at the end of 2003.