Wind Power Plant Capabilities – Operate Wind Farms like Conventional Power Plants

K. Rohrig [1)], B. Lange [1)], A. Gesino [1)], M. Wolff [1)], R. Mackensen [1)], J. Dobschinski [1)], A. Wessel [1)], M. Braun [1)], C. Quintero [1)], J.-L.. Mata [2)], R. Pestana [3)]

Abstract-- Integration of wind energy demands that wind power should offer conventional power plant capabilities. However, in order to define them it must be first examined the status of the operational grid requirements for wind energy as well as the technological solutions developed by manufacturers. This paper examines the requirements for wind power capabilities in the grid in Germany, Spain and Portugal and introduces an innovative solution for the management of wind power: the Wind Farm Cluster Management System. In addition, an economical analysis of the ancillary services cost from wind energy is presented.

***Index Terms*--Wind power forecast, forecast uncertainty intervals, economical impact of auxiliary services provision, grid codes, grid integration, power-frequency control, reactive-voltage control, wind energy, wind farm cluster management system, wind power plant capabilities**

I. Introduction

In 2030, wind energy should provide 25% of the EU electricity. Such a high share of wind generation exerts important challenges for the reliable and secure integration of wind power in the grids. Therefore, there are increasing needs to operate wind generation as conventional power plants to ensure a reliable and secure integration of wind power. Wind power plant capabilities imply 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 upon the active and reactive power control of wind farms as well as the supporting schemes during grid faults such as Fault-Ride-Through capabilities.

This paper focuses on a summary of the power plant capabilities as well as the grid code requirements for wind energy. Furthermore, a new control solution such as the Wind Farm Cluster Management System which allows grid operators to manage wind energy according to their requirement is described. Finally, an economical assessment of the ancillary services provision from wind farms is presented in the final section of this paper.

In following, a brief overview of the present and expected wind power integration issues in Germany, Spain and Portugal is presented.

1.ISET e.V. , Königstor 59 – D-34119 Kassel – Germany (krohrig@iset.uni-kassel.de)

2.Red Eléctrica de España, Pº del Conde de los Gaitanes 177, 28109 Alcobendas Madrid – Spain (jlmata@ree.es)

3.Redes Energéticas Nacionais, SGPS, S.A., Avenida dos Estados Unidos da América 55, 1749-061 Lisboa – Portugal (rui.pestana@ren.pt)

Spain

Wind power in Spain has grown dramatically in the last years from 2.298 MW of installed capacity in 2000 to 15.400 MW at the end of 2008. In the future, the Renewable Energies Plan for Spain sets an objective of 20.000 MW by the year 2010 and in the medium term the network planning envisages the accommodation of 29.000 MW of installed capacity in the peninsular system by 2016 and 1.025 MW in Canary Islands. In the medium-long term the estimated wind power installed capacity needed to reach the EU objectives by 2020 is 35.000 MW.

With such installed capacity the operation of the Spanish System has to cope with very high levels of wind power penetration (Summarized in these figures: peak demand= 45450 MW, daily demand = 901870 MWh, max. wind power production = 10879 MW, max. daily wind power production = 213169 MWh; max % of instant. wind power in the system = 37%, with an average of 10% of the whole daily energy supported) by developing and using the proper mechanisms and tools.

As with other technologies, wind power in Spain 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 according to this status quo whose main goal is to maximize the exploitation of the primary resource in which the TSO has the responsibility of guaranteeing its operation in a safe manner. However, as wind power capacity increased rapidly some features of these generators which undermine the System security made certain difficulties obvious in maximizing its integration and making the operation more complex.

Portugal

The Kyoto Protocol and the related goals set by the European Union in the Directive 2001/77/CE for the promotion of electricity generated from renewable energy sources (RES), defining a target for Portugal of 39% of generation from RES in 2010, imposed a very important change in the development of the generation system and of the electrical transmission and distribution networks. This target was recently reviewed by the government and was settled in 45% for the same year.

The only possible way to accomplish the 39% (now 45%) objective by 2010 with current technologies was the creation of a component of wind power generation in the order of several thousand MW starting only from 120 MW of wind power in operation by the end of 2001.

However, the national objectives for the development of power generation from RES are not restricted to wind generation but include also a few new large hydro stations in the long term (1096 MW), as well as the increase of installed power in existing plants in the short / medium term (1330 MW), and the increase in small hydro, biomass, photovoltaic, among others. Two thirds of the new hydro power will be reversible, essential to allow the increase in wind power.

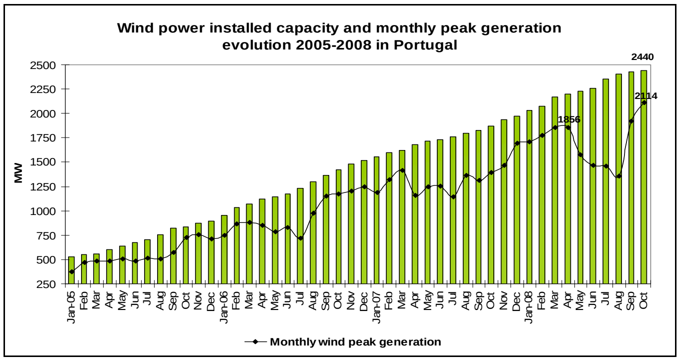

Fig. 1: Evolution of wind power in Portugal since 2005

Germany

In Germany there has been an increasing development of wind energy as depicted in Fig. 2. In 2007 more than 25 GW of wind energy and around 20.000 wind turbines are operating in Germany.

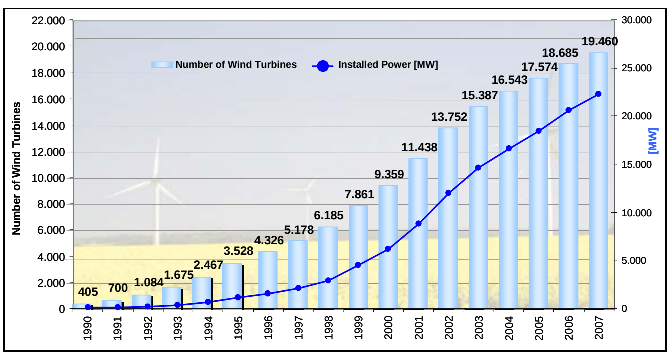

Fig. 2: Number of Wind Turbines and Installed Wind Power in Germany - Years 1990 – 2007 [1]

This development has been supported by the so called Renewable Energy Sources Act (EEG - July 2004) [2]. It was introduced in Germany with the purpose to facilitate a sustainable development of energy supply in the interest of managing global warming and protecting the environment and to achieve a substantial increase in the percentage contribution made by renewable energy sources to power supply in order at least to double the share of renewable energy sources in total energy consumption by the year 2010, in keeping with the objectives defined by the European Union and by the Federal Republic of Germany. This Act has been modified in 2009 [3], and some of the important changes are:

- The new law raises the feed in tariff for wind energy to a range of 9.2-15 EUR-cent/KWh.
- Transmission System Operators are not only responsible for the grid extension but for the optimization and reinforcement of the already existing grid
- An optional direct marketing of electricity generated from renewable energy units is possible

Until 2010, the share in electric-power generation (in Germany) from renewable energy sources shall rise to at least 12.5%, and by 2020, to at least 20% [4]. The following table provides the development (actual and targeted) of installed wind capacity in Germany.

Installed wind capacity in Germany, in GW					
Year	2003	2007	2010	2015	2020
Total	14,5	22,4	29,8	36,0	48,2

Table 1: Development of the installed wind capacity in Germany up to year 2020. [4]

II. Grid Planning and Operation with High Share of Wind Power

One of the main barriers to large-scale deployment of the wind energy technology is the limited capacity of the transmission grids. Spacious balancing will reduce large fluctuations of wind power by means of energy transmission over large distances. This requires an **efficient and sustainable extension and reinforcement** of the **grid infrastructure and interconnections** through strong planning and early identification of bottlenecks at European level. The integration of wind power is partially hampered by the lack of suitable dynamic models for use in transient stability programs in order to conduct the analysis of wind generation influence on power system operation. A future reliable and economic grid planning and operation requires an increased supervision, a better understanding and improved predictability of the power system state. Thus, there is a need of advanced monitoring, simulation and analysis tools combined with dynamic calculations of the interconnected European power system.

Future grid planning tools should be developed for the design of a sustainable, efficient grid structure, in particular for advancing of new offshore trans-national connections, eventually establishing an offshore super grid. These tools should also be able to assess grid connection of wind farms on land and offshore. Various options for grid connection should be considered and assessed to choice and determine the best connection technology e.g. HVAC, LCC HVDC or VCC HVDC. The reinforced and extended grid should facilitate the connection of offshore wind farms, trans-national exchange, leveling of demand and supply and improved efficiency of power system operation.

In addition to new transmission lines, a better and more reliable utilization of existing infrastructure is required. As wind generation has a low capacity factor, the existing rules and methodologies for determining transmission capacity may no longer be justified. The optimum solution may be to install transmission capacity which is less than the maximum wind capacity, and manage the infrequent overloads by advanced control of wind farms and wind farm clusters. In addition, regional overloads and fluctuations over short periods can be absorbed by an increased flexibility of loads and the utilization of new storage capacities, for example by electric vehicles.

In future, the complexity of the characteristics of electrical grids will rise with the increasing number of distributed and fluctuating energy producers. The usual mechanisms and processes are replaced by rules for fast changing and different grid states. This cannot be longer managed by traditional mechanisms and requires new tools like dynamic security assessment (DSA) and foresighted management under consideration of the static and transient grid behaviour of the neighboured control zones.

Trading, balancing, grid safety requirements increase the importance of wind power forecasting. Thus wind power forecast systems have to be integrated into the control room of the transmission system operator (TSO). Very high requirements of reliability and safety make this integration especially challenging. Apart from this, continuously updated wind power forecasts for the next 1 - 6 hours, directly linked to the grid operation tools will improve mains operation and assist grid operation.

In this context, wind power will be managed as an integral part of the European grid operation and implies an improved **TSO collaboration and coordination -** the interoperability of the control centres. A European wide Dynamic Security Assessment (DSA) based on extensive data sharing between controls zones will assist grid operators in grid operation.

III. Power System Requirements for High Wind Penetration

In this section, an overview of the power system requirements for high wind penetration in Spain, Portugal and Germany will be described. The wind farm capabilities dealing with these requirements are described in section IV of this paper.

A. General Requirements

- **Wind power integration issues in Spain (REE)**

In Spain, the most relevant problem in the recent years has been the lack of adequacy of wind generators to withstand voltage dips, i.e. to remain connected to the grid and support the System during faults. This situation could lead to lose great amounts of wind power generation in the event of any disturbance and in the case of Spain this problem is especially risky due to the limited interchange capacity with the rest of UCTE which constrains the available primary regulation.

Some others issues worth of mentioning are:

- The forecast errors, as a renewable source, in the different time scopes which demand more reserve capacity as well as more flexibility of the conventional generation units and take into consideration more uncertainty in the coverage at programming level.
- Voltage control in Transmission nodes neighbour on wind farms due to an obsolete regulation which does not take into account local system needs.
- Occasional overloads in evacuation lines for diverse reasons.

Such scenarios lead to some initiatives at all levels:

- New regulatory developments concreted into new technical requirement (Operational Procedures) for new machines and to promote the upgrading of the existing ones.
- 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 this generation (as well as all renewable generators and high efficiency facilities). On this side the first Control Centre at TSO level (CECRE) was commissioned at REE in 2006 as well as some other delegated Centres owned by utilities and manufacturers.
- Advanced and 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.

Fortunately and thanks to a huge effort from the whole sector the problem related to fault ride-through capability of wind farms is on the way to being solved (at this point 81, 3 % of machines are adequate) and the rest are also being addressed.

With regards to the wind power offshore, the Spanish shore is not the friendliest one for installing wind farms due to the proximity of the continental platform and so the restricted area of shallow waters. However according to the Grid Planning until 2016 is expected an offshore installed capacity of 734 MW by the end of this period.

Looking to the future, the sector is facing new challenges needed to succeed in the above mentioned goals. These challenges mainly arise from the progressive displacement of conventional generation by wind energy. This situation leads to new technical requirements for wind generators mainly oriented to balance the voltage level controllability, loss of inertia into the System, and guarantee the proper running of protection systems (from the grid and generation side) and also has an impact on the conventional generation which is set to become more flexible than it is today.

- **Wind power integration issues in Portugal (REN)**

For wind power grid integration in Portugal, two major issues had to be faced: reception capacity of the grid and technological adaptation of wind generators. The previous paradigm of transmission network (TN) planning based on a small number of well known large new power stations was no longer applicable because it was not possible any more to give individual connection solutions for each project coherent with all the others and to assure the future secure and adequate operation of the TN. So, the Transmission System Operator (TSO) started to define (and make it public) future reception capacities at the different areas/substations in the TN according to their development plans. This network investment plan has to respect and be coherent with the national global RES objectives.

Besides, a new Grid Code had to be developed, to ensure that wind generators to be connected to the grid will behave as much as possible as conventional power plants: they must stay connected to the grid during voltage dips (fault ride through capability), they must contribute with reactive current during short-circuits to minimize the propagation of voltage dips and contribute to the correct operation of protection systems and with different amounts of reactive power according to the day period.

Wind power will be, by far, the most important renewable component to grow in the years to come, with a present target of 6100 MW in 2014 and 7500 MW in 2019, probably approaching 5500 MW by the end of 2011. Taking as reference the forecasted peak demand in the system of 11400 MW in 2011, it can be said, in relative terms, that Portugal has one of the highest wind targets among the EU countries.

Assuming that the reception capacity and the adaptation of wind generators technology issues mentioned before are solved, the spinning reserve (frequency regulation) seems to be one of the most important questions to take care. According to the grid investment plan 2009 – 2014 (2019), in 2014 there may be periods in summer importing from Spain more than 3000 MW and with wind generation of about 4880 MW, with a peak demand of 11500 MW.

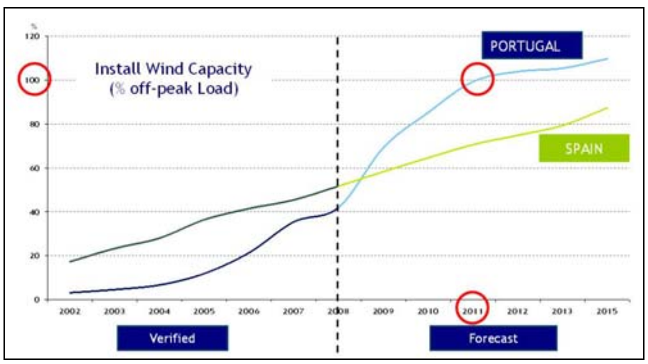

Fig. 3: Evolution of wind power in % off-peak load

Regarding the off-peak demand, the situation will become interesting by 2011, when the wind installed generation will meet the load. If we consider the Iberian Market context, the imports and wind will reach off-peak load sooner than 2011 in Portugal. These issues are intended to be addressed by means of the implementation of the Wind Farm Cluster Management System [5], [6]. [7].

- **Wind power integration issues in Germany**

The German Energy Agency (dena) commissioned the study “Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020” [4] or Dena Study I. The goal of this study was to enable fundamental and long term energy-economy planning, supported by as many stakeholders as possible. Results regarding future grid integration issues generated by future increase of wind energy penetration are in following summarized:

- For the further integration of renewable energy sources into the interconnected power system, an extension of the extra high voltage transmission network will be necessary. This will include a reinforcement of existing overhead lines, the construction of new extra high voltage lines, the implementation of quadrature-regulators to control power flows, and the implementation of units to provide reactive power.
- There is a need for the further extended and integrated control and management of the wind power feed-in in Germany. Therefore the introduction of control techniques, such as the Wind Farm Cluster Management System (see Section IV) would allow grid operators to optimize the managing of wind power in Germany according to their requirements.
- The adaptation of grid codes to the capabilities of wind turbine technologies represents an important step to increase the security of operating wind power. Therefore, specifications of new transmission and distribution codes should comply with the state of the art development of wind turbine manufacturers.
- In certain situations (strong wind and low load), [1] Germany sees a surplus in power generation on a few days a year. In such situations, huge power flows to neighboured countries can be observed. Further solutions, such as additional storage facilities, demand site management and reduced power output from wind energy converters are to be examined in the planned part II of the dena grid study.
- Only if the technical solutions (FRT Capabilities) are implemented on time, the forecasted wind power development up to 2015 can be realized without raising the mentioned “fault-run through” problem.
- The dena grid study shows, that the new grid codes and enhanced technical performance of wind turbines will improve system security by 2015 in the Northeast grid area and by 2010 in the Northwest grid area. In 2015 however, the situation in the Northwest grid area would worsen again, because major shut-downs of power plants are to be expected due to age or to the phasing-out of nuclear power stations. Without countermeasures in place, serious grid failures and resulting power station outages can be expected.

B. Balancing Requirements

In power systems with high wind energy penetration, balancing mechanisms are based on forecasting values of wind power and loads [8], [9]. In addition, power station outages, stochastic load variability and fluctuations of wind power injections represent the main factor of demand for controlling and balancing power. Therefore, wind power integration requires an accurate and reliable forecast from wind power for the next hours to days ahead. This will lead to a higher grid reliability and also enormous cost savings.

Today, the development of models for dynamical forecast uncertainty estimation (see Fig. 4).for each time step has nearly the same priority as the wind power forecast itself. This is due to the multiple applications concerning decision-making problems based on the stochastic nature of wind power prediction errors. Generally, the allocation of balancing power and reserve requirements depend on an accurate knowledge of the most probable to expect forecast errors. Furthermore, unit commitment for optimal scheduling of power generators and bidding strategies in the electricity markets (also with focus on direct-marketing) requires information about a secured power feed-in. All these information can be deduced from wind power forecasts in combination with uncertainty intervals.

It is evident that the predictor variables of the Numerical Weather Prediction (NWP) play the major role in wind power forecast purposes and also for uncertainty estimations [10], [11]. Currently, ensemble weather predictions [12] and probabilistic models [13] are mostly used due to their ability to forecast a whole probability density function (PDF) of the expected power. Out of this distribution the “best” point power forecast and the corresponding uncertainty estimations can be extracted [14], [15].

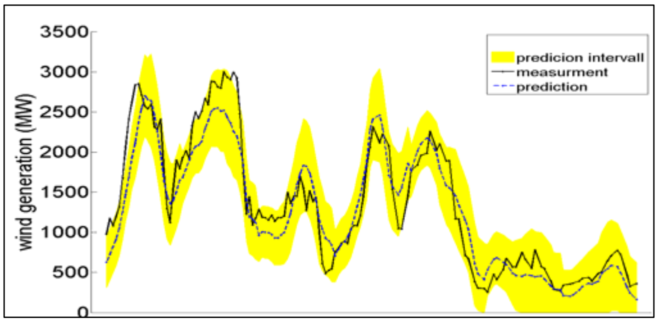

Fig. 4: Example of Forecast Interval Assessment – 90% Probability that all measurements will be within the prediction interval (yellow surface)

C. 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 traditional generation. The fulfillment 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 Spain, for instance, 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 energy converters. [16].

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 code requirements the obligation of wind generation to provide this ancillary services. This topic will be then an issue subject to regulation and discussion for the implementation in future grid code requirements.

D. Voltage and Reactive Power 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 whit it. An example of the power factor (cos ϕ) and voltage control requirements at the wind farm connection point is in Fig. 5 depicted

Furthermore, Fig. 6 depicts the requirements for the control of reactive power related to the available active power production from wind farms.

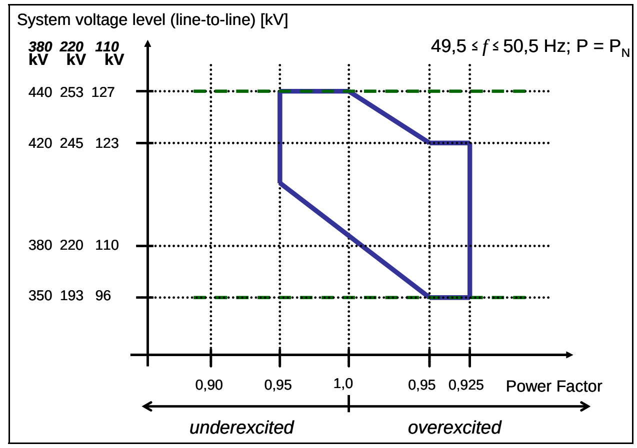

Fig. 5: Basic requirement for the reactive power supply for E.ON [17]

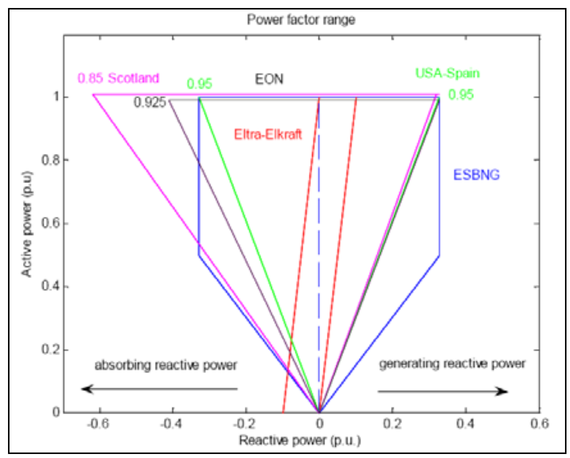

Fig. 6: Reactive power requirements from different grid codes related to the active provision [18]

E. Reactive Power Control Capability

Very large wind farms will have a relevant influence in the voltage stability of the grid. Today wind turbine technology has developed adaptive reactive power control in order to support the grid requirements for voltage stability.

Limits on the extension of the controllability of reactive power are imposed by the type of generation technology and costs. This type of control is usually performed at wind turbine level. However, reactive power compensation in wind farms can be also implemented by means of reactive power compensation devices such as: SVC, STATCOMS.

Implementation of this development has allowed the fulfilment of voltage stability required from grid codes. Furthermore, wind turbine manufacturers provide their wind farms with power quality filters in order to comply with regulations regarding voltage quality of the energy supply.

Therefore, future increases in the wind turbine ratings will surely adapt and include this already developed reactive control system in their generation units.

F. Fault-Ride-Through-Requirements

At the moment, wind farms or wind power plants are obliged to provide fault ride through capabilities (FRTC) in order to maintain the stability of the grid in cases of faults. Requirements are dependant on the voltage dip and the duration of the corresponding short circuit that the wind farm has to withstand. Most extreme requirement demand that wind power has to support the grid even during voltage dips of 0%. 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.

G. Fault-Ride-Through-Capabilities

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.

By means of FRT, wind turbines can remain connected and support the grid with reactive and active power during faults until a determined voltage dip. Some grid codes require grid support even with voltage dips down to 0% of the nominal voltage for different adjustable times for wind turbines. This is known as Zero-Voltage-Ride-Through (ZRVT) and many from today WT are equipped with this option. Therefore, it can be concluded wind turbines of today 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, but this is already fulfilled by present technology.

IV. Wind Farm Cluster Management System

A. Concept

A Wind Farm Cluster is a logical aggregation of existing physical wind farms which are connected to the same grid node. The main goal of the Wind farm Cluster Management System (WCMS) is to allow the large scale management of wind energy and the operation of wind farms as conventional power plants [19].

Fig. 7 depicts the general structure of the wind farm clustering. First, there are single wind turbine generators which are aggregated under a wind farm. The addition of different wind farms gives as a result a cluster which is being controlled by the WCMS.

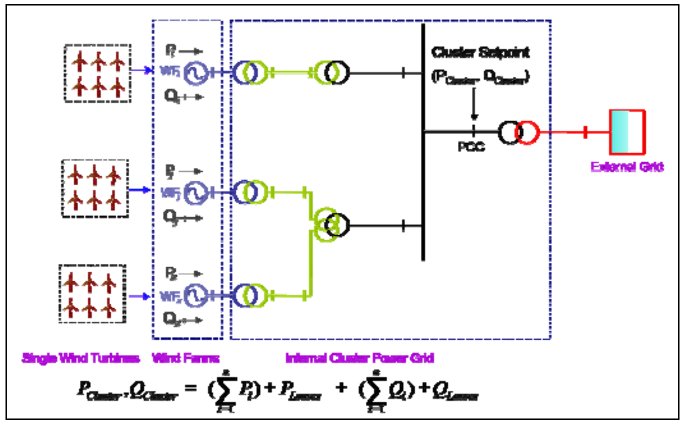

Fig. 7: Wind Farm Cluster Definition

B. System Description

The structure for the development of the WCMS depends on the system configuration where the WCMS is going to be installed. Fig. 8 depicts a basic system structure which consists of a transmission system operator (TSO) layer and wind farm dispatch centre layer.

The wind farm dispatch centre controls directly all wind farms aggregated under its control centre. This layer will receive wind power requirements (set points) from the TSO, and will report the wind power status to the TSO.

The command flow (set point flow) goes from the WCMS TSO to the WCMS Dispatch Centres. At TSO level, the power requirements for a given node are calculated by third parties TSO systems. Short-circuit level, maximum allowed power generation in the grid and grid transmission capacity, among others, are examples of grid security calculations which are usually performed at TSO level. All these calculations are then transformed to active and reactive power requirements (P and Q commands) for wind power generation. These requirements (set points) are sent from the TSO to the Dispatch Centres. Once the set points are received by each Dispatch Centre, they have to follow the received instructions, with their own controlled wind farms. The distribution of these set points within the wind farms has to be performed by the WCMS at Dispatch Centre level.

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

The implementation of such a control system, would lead to the introduction of new market rules and grid connection requirements for the operation and commercialization of wind energy in power grids.

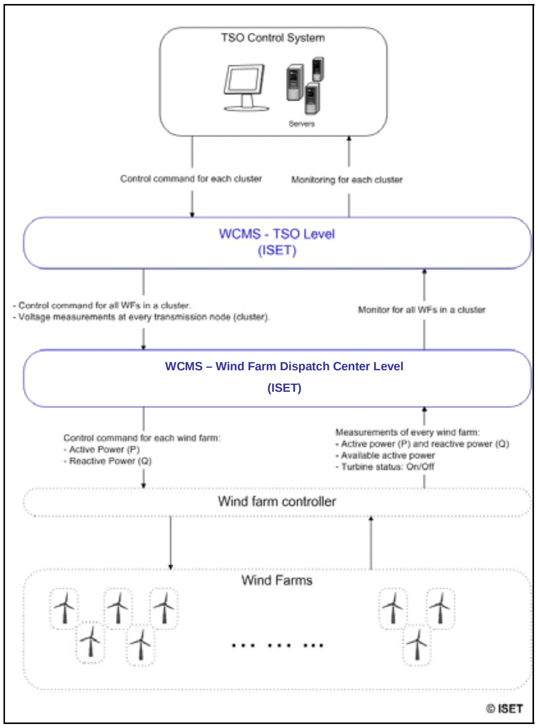

Fig. **8**: Command flow and monitoring structure for the WCMS

C. Assessment of the Uncertainty in Wind Power Forecasting

Wind power forecasting represent a relevant issue for the performance of control strategies for the wind farms aggregated under a cluster structure. This section deals with different assessments of the forecast uncertainties. It is importance lays in the capacity of the grid operator to asses the confidence interval in which a wind power forecast has been issued. This, for instance, serves to determine the reserve requirements, gradient controlling, reactive power provision which have to be deliver and performed according the here described WCMS control structure.

Modelling of prediction intervals

Six model approaches have been developed to estimate the forecast uncertainty of an existing wind power prediction system in terms of dynamic prediction intervals. A simple static approach serves as a benchmark.

Preface and static approach

The easiest solution to estimate the forecast uncertainty is the worst case expectation, i.e. the largest observed forecast error of the running system is applied to every forecast step as a constant uncertainty. Due to the fact that the size of the interval covers nearly the complete power range (see Fig. 9), green) it is suboptimal for uncertainty estimation. Intervals with smaller sizes provide relevant information, but one has to consider that generally smaller intervals lead to a smaller reliability and vice-versa.

The *reliability* is one of two quality criteria concerning prediction intervals. The reliability ranges from 0 to 100 % and provide the percentage of measurements inside the interval. In other words the reliability represents the probability that a single value is inside the interval. The other quality parameter is the *sharpness* that is expressed by the average interval size. A sharpness of 100 % would present an interval covering the complete power range.

The first problem concerning the generation of prediction intervals is to find the best trade-off between reliability and sharpness. It is evident that the average interval size increases rapidly for an increasing reliability higher ~90 %. The second problem is that the observed reliability can differ from the nominal reliability which has specified during model development. Hence the model must be calibrated and it must be guaranteed that the calibration does not change.

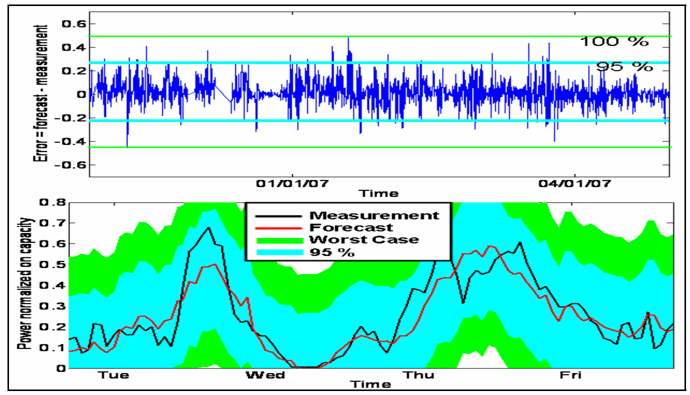

Fig. 9: Time series of observed forecast errors (top).

The lines demonstrate the deviations concerning the worst-case (green) uncertainty estimation and the 95 % - reliability (cyan). These constant quantiles were applied to the forecast (zoom in) in the lower plot in terms of prediction intervals.

The simple approach to generate smaller intervals is only based on already observed errors. As outlined in Fig. 9 the quantiles (cyan lines) have been derived in a way that 95 % (nominal reliability) of all measurements are located inside the interval and respectively 2.5 % above and 2.5 % beneath. As shown in the lower plot of Fig. 9 the resultant interval has a significant smaller size as the worst-case approach. Due to the simplicity in applying this approach it has been selected as benchmark for this work. The biggest disadvantage of this approach is that the width of the interval is constant in time, i.e. static. It is evident that such static intervals are suboptimal for uncertainty estimations with respect to decision-making problems.

Dynamic approach

The aim of this work is the development and evaluation of models for estimating the forecast uncertainty in terms of dynamic prediction intervals. All models presented in the next subsections are based on already observed forecast errors of an existing wind power forecast system. The models estimate the upper and lower deviation from the underlying power prediction in a way that the measurements are within the interval with a specified probability i.e. nominal reliability. To compute the final prediction interval each deviation has to be added/subtracted on/from the power forecast.

Adaptive model

The adaptive model is based on the regular updated error distribution with a higher weighting of the last g hourly forecasts errors (here g=48).

$$q_1(t_{fh}) = \frac{a_1 * q_1(t_1,\ldots,t_{fh\text{-}g\text{-}1}) + b_1 * q_1(t_{fh\text{-}g},\ldots,t_{fh\text{-}s})}{a_1 + b_1}$$
$$q_2(t_{fh}) = \frac{a_2 * q_2(t_1,\ldots,t_{fh\text{-}g\text{-}1}) + b_2 * q_2(t_{fh\text{-}g},\ldots,t_{fh\text{-}s})}{a_2 + b_2} \quad (1)$$

The parameters a_i and b_i (i=1, 2 and $a_i < b_i$) are the weighting factors, t_{fh} is the forecast time and s is the forecast horizon.

Simple classification

Using the simple classification method the model to generate prediction intervals was developed by investigating historical weather data and the simultaneous observed forecast errors. The determination of the respective forecast error rests on a simplified classification of the weather situation based on the wind speed ws_i and wind direction wd_i given by the NWP. Regarding this modelling method the error distribution and the consequent quantiles were computed depending on wind speed and wind direction:

$$q_1(t_{fh}) = q_1(ws_i, wd_i)$$
$$q_2(t_{fh}) = q_2(ws_i, wd_i) \quad (2)$$

It is worth to note that this modelling approach leads to discontinuities of the interval that have to be avoided. Smoothing techniques or fuzzy set logics [10] can be applied to handle this problem.

Artificial neural networks (ANN)

The ANN method that has been used to calculate a prediction interval of an individual wind farm requires the adaptation of two ANN and an investigation of historical time series of power forecasts. In the first step the respective time series of forecast errors is divided in one time series covering all positive errors and in a second with all negative errors. Moreover this error time series were scaled in way that the mean positive and negative errors are equal to the quantiles of the total error distribution corresponding to the specified reliability. Each of the both time series was used separately as output for the training of the two ANNs. As input for the ANN the same NWP parameters that have been used for the power prediction system, the predicted power itself and/or the recently observed forecast errors are potential predictor variables. The selection of the best input parameters concerning uncertainty estimation requires further investigation and can vary from wind farm to wind farm. In operation the resultant ANN output in form of the upper and lower uncertainty has to be combined with the power prediction to get the prediction interval.

Linear quantile and multi-linear regression

The regression models are developed to reflect a relation between the observed forecast errors and the selected input parameters, like NWP data and/or the predicted power and recent forecast errors.

Compared to linear regression models that approximate the conditional mean of the response variables, the quantile regression formalism relies on estimations of either the median or other quantiles of the response variables, which is an advantage for the development of prediction intervals based on various quantiles of the error distribution [13]. That is why the specification and implementation of the nominal reliability is comparable easy for all quantile regression models. In contrast the setup of the multi-linear model requires a splitting of the observed errors in positive and negative errors and an individual model training like done for the ANN model. Furthermore the positive and negative errors have to be scaled like done for the ANN training. In operation both regression models compute the upper and lower uncertainty

Ensemble average

The ensemble average has been calculated by averaging arithmetically the resultant upper and as well the lower uncertainties of the several models.

D. WCMS System conclusions

The cluster control of wind farms allows wind energy to better fulfil all TSO requirements and increases its grid integration capabilities. As a logical consequence more wind energy can be admitted into the grid.

Through the aggregation of wind farms by means of a cluster, the capacity to maintain the accuracy of a wind power feed-in schedule (forecast) is increased. Moreover, the forecast errors and its respective deviations can be balanced within the cluster.

For grid planning purposes, there are better possibilities for the management of grid contingencies such as transmission bottlenecks and provision of power reserve.

V. Economic Assessment on Providing Ancillary Services by Wind Turbines (WTs)

This section analyses economic aspects of the provision of ancillary services by WTs. Active and reactive power control (P and Q) are the two basic control capabilities that allow providing ancillary services such as balancing frequency (by P), voltage control (mainly by Q), and congestion management (by P and Q) [20]. Cost-Benefit-Analyses are performed for balancing services and reactive power supply.

A. Cost-Benefit-Analysis of Frequency Control Services by WTs

The majority of the presently installed WTs are actively pitch-controlled. This allows a control of the mechanical power and thereby the active power by changing blade angles. The active power control can be performed within seconds.

Costs of frequency control are constituted by costs of active power control. As reference for the benefits, balancing market prices in Germany are analysed.

B. Costs of Active Power Control

The costs of active power generation have a large range depending on the site's specific situation, e.g. given by the climatic conditions, policy situation and the technology applied. In Germany, the feed-in-tariff is a good reference for the costs because the tariff is regularly adjusted to a level that is expected to compensate the costs. Average costs of active power generation by WTs in Germany are approx. 9 c€/kWh [21]. From these total costs, only a marginal share is caused by generation-dependent variable operational costs.

Positive active power control requires reducing the actual possible active power generation first. Reducing active power causes opportunity costs of approx. 9 c€/kWh. For instance, a continuous reduction of power output of 1 MW in a wind farm over a period of 4 hours has costs of 1 MW * 4 h * 0.09 €/kWh = 360 € only for keeping the reserve. Differently, negative active power control reserve causes no opportunity costs as long as sufficient active power is generated.

C. Benefits from Participating on Balancing Markets in Germany

An analysis has been performed in [22] that compared prices on German balancing markets with the costs of active power control by renewable energy sources. The cost-benefit-analysis shows that the participation in primary and positive secondary frequency control services is not profitable for WTs at present. Prices on balancing markets are defined by conventional gas- and coal-fired power plants. Presently, they have lower generation costs than renewable energies but this gap may close when external costs are completely internalised. For the exemplary wind farm with positive active power control reserve costs of 360 € for 1 MW and 4 hours, the capacity revenues for primary control would have been 55-68 € and for positive secondary control 34-46 € in the years 2004-2006. It is obvious that the costs are not covered by these revenues.

Analysing the maximum possible capacity revenues of positive tertiary control in Germany of the year 2007 shows that the revenues were higher than the costs of 360 € during 47 periods of 4 hours (2.14 % of the time of the year). In these few hours an additional income of 11,427 € could have been generated that would have increased the total annual income of an exemplary wind farm with 20 MW installed capacity and full load hours of 3000 h/a by 0.2%.

Participation on negative secondary/tertiary frequency control markets in Germany can be interesting all the time because negative control reserve does not cause opportunity costs. Analysing the maximum possible capacity revenues of negative tertiary control in Germany of the year 2007 shows that additional income of 44,126 € could have been generated (0.8% of the total income) assuming that 1 MW is always available.

Not considered in these calculations are all additional costs such as for prequalification, hedging risks (e.g. of power and price forecasts) as well as transaction costs for market participation. These additional costs and unavailability reduce the benefits from frequency control services.

D. Cost-Benefit-Analysis of Reactive Power Supply by WTs

In principle all generators which are coupled to the network either with power electronic converters or with synchronous generators are capable of providing reactive power control [23]. Principal WT designs are

- directly-coupled induction generators (IGs) with capacitor banks;
- doubly-fed induction generators (DFIGs);
- directly-coupled synchronous generators (SGs); and
- inverter-coupled generators with a full power electronics converter (FCs) which couples IGs or SGs.

A detailed cost-benefit analysis of reactive power supply by WTs is given in [23]. Investment and operational costs of reactive power supply by WTs are analysed here and compared with the benefits from substituting conventional reactive power sources and network purchase prices.

E. Costs of Reactive Power Control

The costs of reactive power control can be distinguished in investment costs and operational costs.

<u>Investment Costs:</u>

In principle FCs, DFIGs and SGs can control reactive power without the need of additional investments. However, additional investment costs have to be considered if the converter's rated capacity is extended to guarantee a certain reactive power supply capacity even at maximum active power generation. Fig. **10** compares typical investment costs of conventional reactive power sources such as Static Var Compensators (SVCs), Static Compensators (STATCOMs), Synchronous Condensers and Static Capacitors (right side) with additional investment costs of WTs (left side). Different types of grid-coupling converters are considered for WTs that guarantee a certain capacity. A cost comparison directly shows that WTs can generally be cheaper at low guaranteed reactive power capacities.

<u>Operational Costs:</u>

Operational Costs of reactive power supply by WTs are mainly caused by additional losses in the grid-coupling converter. Fig. **11** gives an example of the operational costs of FC- or SG-coupled WTs with an efficiency of 98% and feed-in tariffs or power purchase costs of 9 c€/kWh. Compared to the operational costs of conventional reactive power sources, WTs can be cost competitive in general, especially at small additional loading levels. SVCs, STATCOMs and Synchronous Condensers have similar costs as the ones given with the blue curve (only Q) which are higher than those of WTs (Q and P). Only capacitor banks can be cheaper but the dynamic capabilities of FC-, DFIG- and SG-coupled WTs are much better.

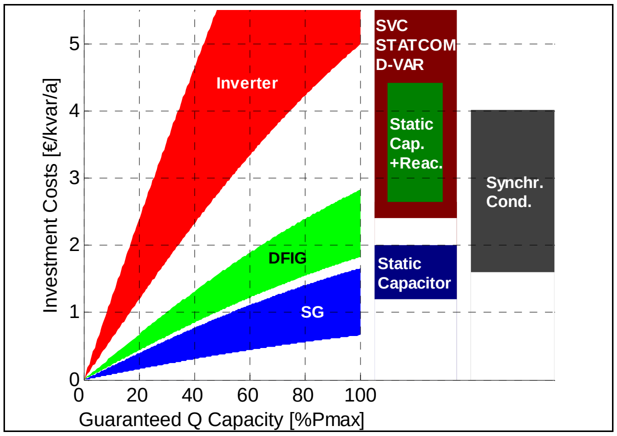

Fig. **10**: Investment costs for guaranteed reactive power supply capacity

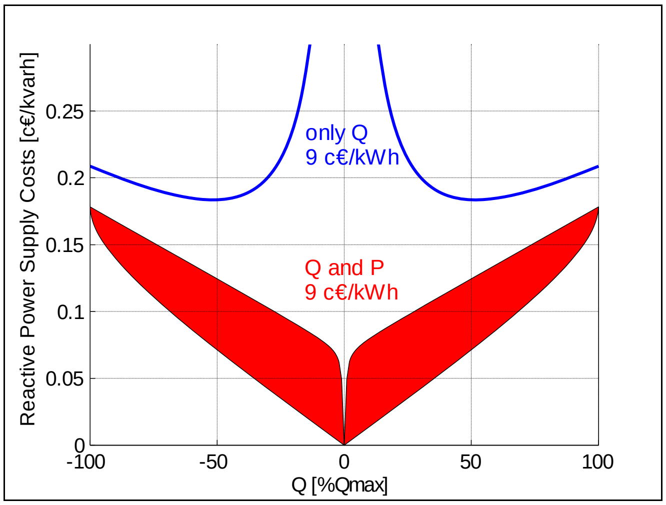

Fig. **11**: Operational cost (in c€/kVArh) of Q supply by FC- or SG-coupled WTs with an efficiency of 98% which only supply Q (blue) and which supply Q in addition to P (red)

F. Benefits from Supplying Reactive Power

Compared to the costs of conventional reactive power sources, WTs are evaluated to be cost competitive in general, especially when they increase their reactive power capacity modestly and share reactive power supply between each other so that small additional loading levels cause only little additional losses. This already leads to the conclusion that reactive power supply by WT is economically attractive for network operation.

Furthermore, the value of reactive power for network operators can be considered for comparison as well. German distribution network operators charge in average 1.1 c€/kvarh if the power factor is lower than 0.9 (in average) and in the high voltage network 1 c€/kvarh. National Grid in the United Kingdom spends approx. 0.2 c€/kvarh on the reactive power market of the transmission network [24]. The three transmission network organizations PJM, NYISO ad ISO-NE in the United States provide an annual payment in the range of 0.75-4.4 €/kvar/a [25]. The value for network operators seems to be higher than the costs for WTs as given in Fig. **10** and Fig. **11**.

The detailed benefits of reactive power supply for network operation are discussed in [23] with regard to voltage control, reduction of network losses and congestion management. The overall benefits of reactive power are often underestimated despite its importance for network stability. As stated in [26], "inadequate reactive power leading to voltage collapse has been a causal factor in major power outages worldwide".

VI. CONCLUSIONS

This paper concentrated on the capabilities and requirements for the fulfillment of the wind power plant capability concept. This concept is mainly based on the technological and operational fulfillment of the active-frequency power control, reactive-voltage control, fault-ride-through-capabilities. Clear definitions and agreements between manufacturers and grid operators will lead to clear operational requirement for wind energy and in the future to harmonized grid code requirements. An "International White Book on the Grid Integration of Static Converters" is prepared in the DERlab consortium. It is a long-term activity to achieve international harmonization on grid codes for static converters. [27]

The balancing power capabilities from wind energy exert an important role for the system planning due to the expected increase of wind energy in power grids. In this sense, the impact of the uncertainty band of the wind power forecasted values were assessed.

Furthermore, new system tools for the control of wind farms by the aggregation in cluster groups were presented. Through the Wind Farm Cluster Management System it is possible to operate wind farms as conventional power generators, i.e. to control wind energy according to the operational and security requirements of the grid operators.

An economical assessment of the impact of ancillary service provisions from wind turbines was presented. The main result is that participation in balancing services can be attractive as well as the supply of reactive power. Consequently, wind turbines can become active participants in network operation in future.

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