Grid integration of wind power

Alejandro J. Gesino

Power reserve provision with wind farms

Fraunhofer IWES

kassel university press

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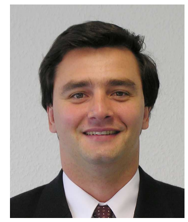


The present study is the result of my work as Research Engineer at Fraunhofer IWES in the area “Energy Meteorology and Wind Power Management” at the “R&D Division Energy Economy and Grid Operation”.

Since May 2007 I have been working with large scale grid integration of wind power involved into several R&D projects in Germany, Portugal, Denmark, Spain and Mexico. These projects were supported by the “European Commission” and by the “German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety”.

In many “*wind energy developed*” countries power production is increasingly based on wind power, therefore all production units, including wind farms, have to contribute to the system security through the provision of ancillary services. The trend goes towards more decentralized structures and an increase in complexity due to a higher number of market participants. This requires innovative technical solutions to be implemented.

Based on the available technologies during the eighties and nineties wind energy was defined as a non-controllable energy source fully dependent on unstable weather conditions. This concept was a strong barrier for its development.

In order to address the coming grid integration challenges, a new research area is currently forming on the border between electrical power engineering, industrial automatization, control engineering, energy economy, communications technologies, software engineering and intelligent systems.

New technologies are already developed at wind turbine and wind farm level and, in many cases, are already installed in the field. Making use of them, innovative procedures should be developed considering wind energy also as a source to contribute to the system security, allowing its expansion while at the same time keeping the current security levels of the power system.

This PhD addresses one of the fundamental ancillary services researching about a secure and flexible methodology for power reserve provision with wind farms.

Kassel, 22 November 2010

Alejandro J. Gesino

I. Abstract (English)

One of the most important challenges nowadays and in the future, is to accept the large scale integration of high volumes of wind power in coordination with other energy sources while keeping the grid stability and the security of supply. Because of the diversification of the European energy matrix and the introduction of several renewable energy sources, grid stability has become one of the main issues to be considered.

In the past, wind energy was considered a non controllable energy source fully dependent on unstable weather conditions. Therefore, it was not requested for wind power plants to contribute to the system security, through the provision of ancillary services. Nowadays, due to the increasing penetration of wind energy into the European grids, several grid codes have started to include new technical requirements for wind farms with regard to their control capabilities.

After providing a literature review of the main European grid codes with regard to wind power controllability, this PhD focuses on the development of a secure, flexible and reliable methodology for power reserve provision with wind farms. During this research and based on technical and scientific information included in the different chapters, wind energy has been considered as a controllable energy source fully capable to contribute with the system security through ancillary services provision.

Based on the current needs and security standards summarized in the literature review of those highly developed European grid codes, a new model for power reserve provision with wind power is developed. This methodology, algorithms and variables are tested based on real scenarios from five German wind farm clusters.

Finally, once the methodology for power reserve provision with wind power has been tested, real control capabilities from already installed wind farms in Germany and Portugal are analyzed. Their capabilities of following control commands as well as an error deviation analysis are also presented.

I. Abstract (Deutsch)

Eine der heute und zukünftig wichtigsten Herausforderungen ist die Akzeptanz der großflächigen Integration von viel Windenergie in Koordination mit anderen Energieträgern bei gleichzeitiger Gewährleistung der Netzstabilität und Versorgungssicherheit. Aufgrund der Vielfalt der europäischen Energiematrix und der Neueinführung einiger erneuerbare Energiequellen, ist die Netzstabilität zu einem der wichtigsten Punkte geworden, die mit in Betracht gezogen werden müssen.

In der Vergangenheit wurde Windenergie als eine Energiequelle betrachtet, die man nicht kontrollieren konnte, da sie komplett von der instabilen Wetterlage abhängig war. Deshalb wurde bisher von Windenergieanlagen kein Beitrag für die Systemsicherheit mit Hilfe der Bereitstellung von Systemdienstleistungen gefordert. Aufgrund der zunehmenden Einspeisung von Windenergie in die europäischen Netze haben einige several grid codes damit begonnen neue technische Anforderungen für Windparks hinsichtlich ihrer Kontrollmöglichkeiten mit aufzunehmen.

Nach einer Bewertung der aktuellen Literatur bezüglich der wichtigsten europäischen Netzbestimmungen im Hinblick auf die Regelbarkeit der Windenergie, konzentriert sich diese Doktorarbeit auf die Fragestellung wie Windenergie Regelleistung auf einem stabilen und verlässlichen Weg anbieten kann. In dieser Arbeit und basierend auf den technischen und wissenschaftlichen Informationen, die in den verschiedenen Kapiteln vorkommen, wird die Windenergie als regelbare Energiequelle angesehen, die vollkommen dazu in der Lage ist durch das Anbieten von Systemdienstleistungen zur Systemsicherheit beizutragen.

Basierend auf den heutigen Bedürfnissen und Sicherheitsstandards, die in der Literaturbewertung der hoch entwickelten europäischen Netzbestimmungen zusammengefasst wurden, wurde ein neues Modell für die Bereitstellung von Regelleistung mit Windenergie entwickelt. Diese Methodik, Algorithmen und Variablen beruhen auf realen nicht simulierten Szenarien von fünf deutschen Windparkclustern.

Abschließend, nachdem die Methodik für die Bereitstellung von Regelleistung mit Windenergie getestet wurde, werden reale Steuerungseinsatzmöglichkeiten von bereits installierten Windparks in Deutschland und Portugal analysiert. Ebenfalls dargestellt werden ihre Fähigkeiten Steuerungskommandos zu befolgen, sowie eine Fehlerabweichungsanalyse.

II. Executive summary (English)

Since the last years wind energy is not only increasing its install capacity, it is also starting to replace conventional generation in some countries. Figure A describes by each energy source in Europe in 2009 the new installed and de-commissioned capacity. It can be observed that nuclear and coal power have de-commissioned more than they have installed, and at the same time wind power has installed more MWs than any other energy source, confirming a trend which started in 2008 and continues in 2009 and 2010.

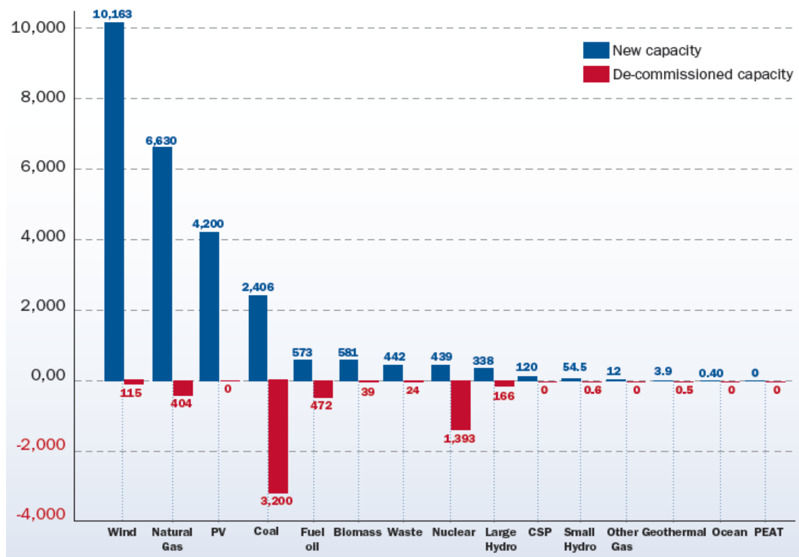


Figure A – New installed capacity and de-commissioned capacity in Europe during 2009 in MW (EWEA)

As a consequence from the situation described in Figure A, wind power penetration is reaching levels of 50, 60 or 70% during certain periods of the day in some European countries. In the near future this will also happen for longer periods, complete days, weeks or even months.

Historically, conventional generation was responsible for the power system security as it was considered a stable and controllable energy source. At the same time wind power was considered a non controllable energy source fully dependent on unstable weather conditions. Therefore it was not requested for wind power plants to participate in the ancillary services markets as they were rather more treated from the system security point of view as “negative loads”.

Within the last years, several grid codes started to request higher controllability levels to wind farms. Ancillary services which were exclusively requested to conventional generation are currently also being successfully provided by wind power.

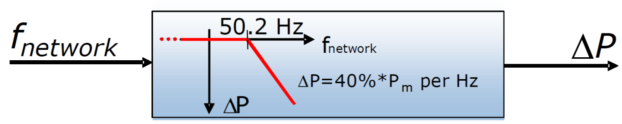
Wind energy differs from conventional generation since the production is not driven by the demand for electricity, but by meteorological conditions. This increases the complexity to match consumption and production. Whenever there is an imbalance in a power system, the frequency will start deviating from its nominal value. This activates the power reserves which should be available and ready to be deployed into the power system. Currently, balance is restored only by conventional generation. However, as the share of wind power in the production increases, its participation in the ancillary services market is becoming more necessary.

The aim of this PhD is to analyze how wind farms are able to contribute with power reserve, both positive and negative, in a stable and reliable way. Therefore the following topics have been addressed:

- Literature review I: Current grid connection requirements in Europe with regard to active power.
- Literature review II: Power reserve and frequency control, the problem analysis.
- Methodology development: Power reserve provision with wind farms. Algorithm, variables and data flow are described.
- Methodology validation I: simulation of the model implementation with two positive power reserve offers based on real time series from five German wind farm clusters.
- Methodology validation II: implementation of the developed model with the time series from wind power production in Germany during 2009.
- Real test field analysis I: positive power reserve tests in Germany with real wind farms.
- Real test field analysis II: positive power reserve tests in Portugal with real wind farms.

After making a distinction between "*system services*" and "*ancillary services*", the new technical requirements which started to be included into the different grid codes are described. The analysis is focused to active power control requirements, grouped as following: controllability and control range, ramping and limitation, control modes, reduction due to over frequency and reduction for protection schemes and frequency control. The analyzed countries are Germany, Denmark, Spain, Great Britain and the "Nordel" control zone.

Focusing particularly on the German Transmission Code from 2007, the identification of possible risks or disturbances in the transmission network is analyzed. Finally, the requirements upon generating units using renewable energy sources in Germany are addressed (see Figure B). This topic is particularly relevant with regard to the subject of this PhD because it includes wind energy and states that "*Generating units using renewable energy sources must be controllable in terms of active power output according to the requirements of the TSOs with a view to counteracting a risk to or disturbance of the system balance pursuant to Article 13, paragraph 2 EnWG. It must then be possible to reduce the power output under any operating condition and from any working point to a maximum power value (target value) defined by the network operator.*" This statement is particularly relevant as far as it refers to wind energy as a controllable power source.



$$\Delta P = 20\, P_m \frac{50.2\,Hz - f_{network}}{50\,Hz} \quad \text{at } 50.2\text{ Hz} < f_{network} < 51.5\text{ Hz}$$

P_m instantaneously available power

ΔP power reduction

$f_{network}$ network frequency

within the range of	$47.5\text{ Hz} < f_{network} \leq 50.2\text{ Hz}$	no limitation
at	$f_{network} \leq 47.5\text{ Hz}$ and $f_{network} \geq 51.5\text{ Hz}$	disconnection from the grid

Figure B – Active power reduction of wind power plants in the case of over-frequency (Germany)

Considering the ENTSO-E[1] recommendations, technical requirements for primary and secondary frequency control are described. Finally, frequency control is addressed as well as the control actions which currently are performed in different successive steps, each with different characteristics and qualities and all depending on each other.

Based on the input information provided by the literature review, a methodology for power reserve provision with wind farms is developed taking into consideration that traditional schemes regarding ancillary services are not directly transferable to wind power. The

[1] European Network of Transmission System Operators for Electricity

main challenge is also to overcome its natural characteristics through a process which provides the proper structure and the needed data flow.

Figure C describes the proposed concept for power reserve provision with wind farms, based on the interaction between the TSO and the Wind Farm Operator.

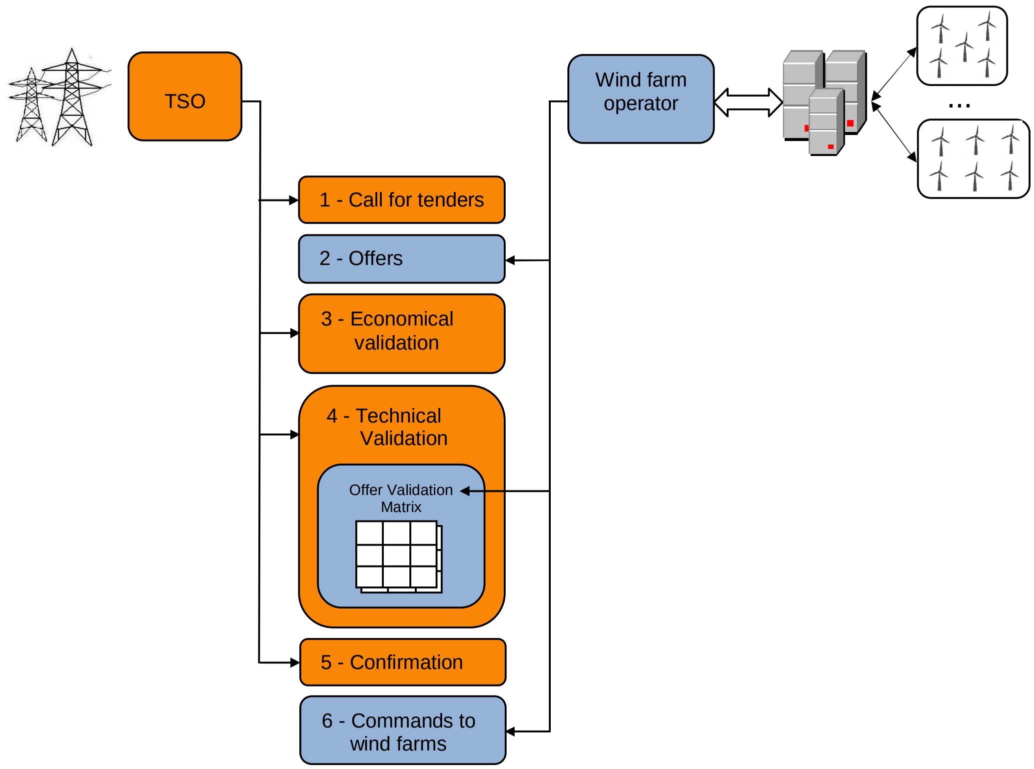


Figure C – Schema of the proposed methodology

The behaviour of the developed methodology is analyzed as well as the effectiveness of the complete model with regard to its control capability and the possibility of wind power to provide power reserve in a stable and secure way.

The proposed methodology is validated based on two positive power reserve offers. The aim of these simulations is to observe the behaviour of the offer validation factors as well as their control capabilities. One of the developed structures is the “Offer Validation Matrix” and it is considered the data exchange structure between the TSO and the wind farm operator. During both simulations, this matrix was loaded in an hourly basis with the available information based on the real wind power production time series from the main simulation scenario. The first control is based on the “Hour Stability Factor”. The aim of this factor is to evaluate the stability of each offer every hour during the last 4 hours before the PRAT (Power Reserve Activation Time). Just before the PRAT the “Offer Stability

Factor" indicates how stable each offer is and as a consequence if the offer could be activated or not.

The first simulation is based on a positive power reserve offer of 195 MW from 5 wind farm clusters. During the simulation, the power reserve offers were below the lower interval of the wind power forecast from each wind farm cluster. Therefore, their stability was proved and the power reserves were activated.

The second simulation is based on a positive power reserve offer of 265 MW from 5 wind farm clusters. In this case, some of the offers were above the lower interval of the wind power forecasts. As a consequence the methodology has detected that these offers were unstable and therefore they should not be activated.

Finally, the developed methodology is also applied to the German wind power production time series from 2009. Confidence intervals of 90, 95, 99 and 100% have been calculated. Based on the available information (see Figure D as an example) it is calculated for each confidence interval, which percentage of the year primary and secondary power reserve could have been provided by wind power using the proposed methodology described in Figure C.

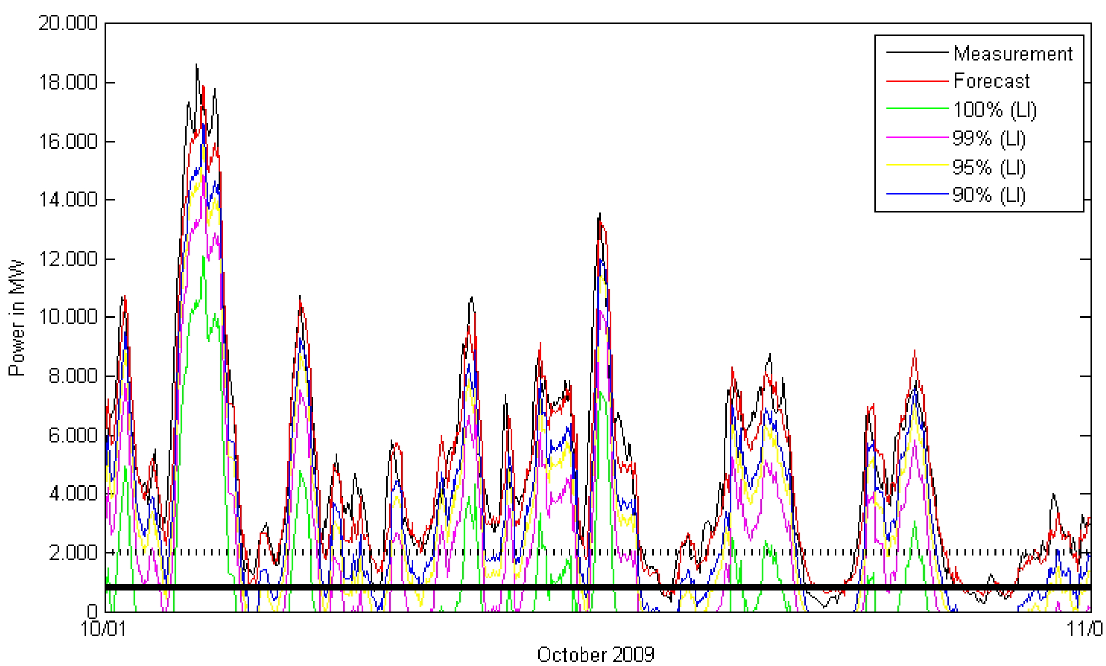


Figure D – Lower Interval calculation for wind power forecast in Germany, October 2009

After validating the proposed methodology, the already developed and implemented technologies at wind farm level are addressed. Concrete tests of real wind farms located in Germany and Portugal are presented. The aim is to demonstrate that the needed technology for wind power being able to provide power reserve is already available and in some cases also installed in the field. R&D results of two projects are described as well as the test scenarios and their grids are also illustrated. The analyzed results are oriented to active power control at wind farm and wind farm cluster level, focusing on the main subject of this PhD.

Finally, conclusions and recommendations for further research are stated.

Methodologies currently applied to conventional generation can not be directly applied to wind energy. Therefore, a new methodology has been proposed and validated during this PhD in order to allow wind energy to provide power reserve while keeping the security standards requested by the TSOs.

Based on the results presented during this PhD, it can be said that wind farms are controllable and able to provide power reserve in a stable, reliable and flexible way.

III. Executive summary (Deutsch)

In den vergangenen Jahren wurde mit dem Ausbau der Windenergie nicht nur die installierte Leistung erhöht, sie verdrängt in einigen Ländern sogar bereits die konventionelle Energieerzeugung. Abbildung A stellt diese Situation für alle Energiequellen in Europa im Jahr 2009 dar. Man erkennt, dass mehr Kohle- und Kernkraftwerke stillgelegt und zurückgebaut wurden als im Vergleichszeitraum neue in Betrieb genommen wurden. Gleichzeitig wurde im Sektor Windenergie eine größere Gesamtkapazität neu installiert als für alle anderen Energiequellen. Hierdurch wird die Entwicklung bestätigt, die 2008 begann und sich 2009 und 2010 fortsetzte.

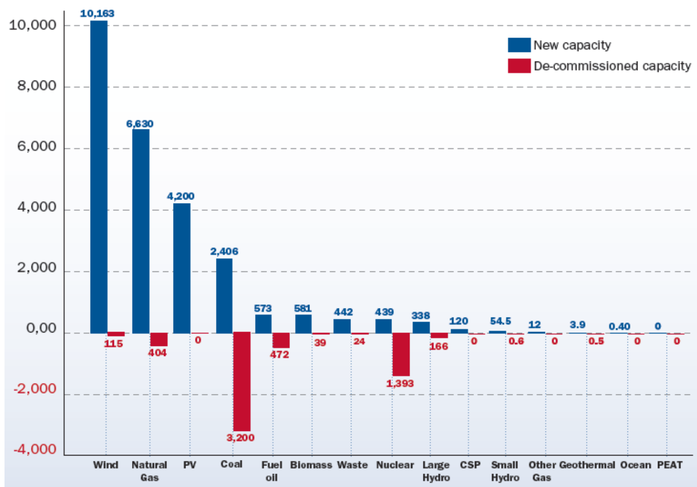


Abbildung A: Neu installierte und rückgebaute Kraftwerkskapazitäten in Europa in MW (Quelle: EWEA)

Als Folge der in Abbildung A dargestellten Entwicklung, erreicht der Beitrag der Windenergie an der Elektrizitätsversorgung in einigen europäischen Ländern während bestimmter Tageszeiten Höhen von 50 bis 70 Prozent. In naher Zukunft wird sich diese Situation auch für längere Zeiträume, also für Tage, Wochen oder gar Monate ergeben.

Historisch betrachtet, war die konventionelle Energieerzeugung für die Sicherheit und Stabilität des Netzes zuständig, da sie als stabile und zur Regelung als die prädestinierte Energiequelle angesehen wurde. Gleichzeitig wurde die Windenergie als eine nicht beeinflussbare Energiequelle eingeschätzt, die vollständig von externen Wetterbedingungen abhängig ist. Aus diesen Gründen wurden Windkraftanlagen für die Bereitstellung von Systemdienstleistungen nicht in Betracht gezogen, sondern systemtechnisch als “negative” Lasten betrachtet.

Seit einiger Zeit werden aufgrund der verschiedenen Netzanschlussbedingungen deutlich höhere Anforderungen an die Regelbarkeit von Windparks gestellt. Systemdienstleistungen, die bisher exklusiv durch konventionelle Kraftwerke bereitgestellt wurden, werden mittlerweile erfolgreich durch Windkraftanlagen erbracht.

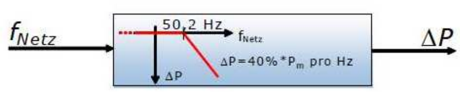
Windenergie unterscheidet sich von der konventionellen Energie derart, dass ihre Erzeugung nicht durch die Nachfrage gesteuert ist, sondern von den meteorologischen Bedingungen abhängt. Diese Tatsache erhöht die Komplexität, Erzeugung und Verbrauch aufeinander abzustimmen. Jede Differenz zwischen diesen führt in einem Energieversorgungssystem zu Abweichungen der Nennfrequenz des Systems. Hierdurch werden Leistungsreserven aktiviert, die jederzeit zur Netzstützung einsatzbereit sein müssen. Dieser Ausgleich wird momentan durch konventionelle Kraftwerke erbracht. Mit zunehmendem Anteil der Windenergie an der Stromerzeugung wird auch eine Beteiligung am Regelenergiemarkt erforderlich.

Das Ziel der vorliegenden Dissertation ist es, zu untersuchen, inwiefern Windparks sich dafür eignen, sowohl positive als auch negative Leistungsreserven dauerhaft und zuverlässig bereit zu stellen. Hierfür wurden die folgenden Schwerpunkte gesetzt:

- Literaturüberblick 1: Derzeitige Netzanschlussbestimmungen in Europa in Bezug auf Wirkleistungseinspeisung.
- Literaturüberblick 2: Problemanalyse zu Leistungsreserve und Frequenzregelung.
- Methodenentwicklung: Bereitstellung von Leistungsreserven durch Windparks. Darstellung von Algorithmen, Variablen und Datenfluss.
- Methodenvalidierung 1: Modellsimulation, Implementierung mittels zwei positiver Leistungsreserveangebote auf Grundlage von Echtzeitdaten von fünf Windpark-Clustern in Deutschland.
- Methodenvalidierung 2: Modellimplementierung mit Zeitreihen der Windleistungserzeugung in Deutschland 2009.
- Feldversuch 1: Tests zur positiven Leistungsreserve mit realen Windparks in Deutschland.
- Feldversuch 2: Tests zur positiven Leistungsreserve mit realen Windparks in Portugal.

Zunächst werden die Unterschiede zwischen „Systemdienstleistungen“ und „Nebenleistungen“ erläutert. Anschließend erfolgt eine Darstellung der aktuellen technischen Anforderungen für verschiedene Netzanschlussbedingungen. Es werden schwerpunktmäßig die folgenden Anforderungen zur Wirkleistungsregelung analysiert: Regelbarkeit und Regelbereich, Anstiegsdynamik und Grenzen, Betriebsarten, Leistungsreduktion wegen Überfrequenz, Netzsicherungsverfahren und Frequenzregelung. Hierzu werden die Anschlussbedingungen in Deutschland, Dänemark, Spanien, Großbritannien sowie in der „Nordel"-Regelzone analysiert.

Unter besonderer Berücksichtigung der Vorschriften der Übertragungsnetzbetreiber in Deutschland von 2007, werden mögliche Risiken oder Beeinträchtigungen identifiziert und analysiert. Schließlich werden die Anforderungen an regenerative Erzeugungseinheiten erörtert (vgl. Abb. B). Diese geänderten Vorgaben sind für die vorliegende Dissertation besonders relevant, weil sie die Windenergie explizit als eine regelbare Energiequelle definieren. Darin heißt es: „Erzeugungseinheiten mit regenerativen Energiequellen müssen in der Wirkleistungsabgabe nach Vorgabe der ÜNB steuerbar sein, um gemäß § 13 Abs. 2 EnWG einer Gefährdung oder Störung des Systemgleichgewichtes entgegenzuwirken. Dabei muss die Leistungsabgabe bei jedem Betriebszustand und aus jedem Betriebspunkt auf einen vom Netzbetreiber vorgegebenen maximalen Leistungswert (Sollwert) reduziert werden können".



$$\Delta P = 20\,P_m \frac{50{,}2\,Hz - f_{Netz}}{50\,Hz} \quad \text{bei } 50{,}2\text{ Hz} < f_{Netz} < 51{,}5\text{ Hz}$$

P_m Momentane verfügbare Leistung

ΔP Leistungsreduktion

f_{Netz} Netzfrequenz

Im Bereich $47{,}5\text{ Hz} < f_{Netz} \leq 50{,}2\text{ Hz}$ keine Einschränkung

Bei $f_{Netz} \leq 47{,}5\text{ Hz}$ und $f_{Netz} \geq 51{,}5\text{ Hz}$ Trennung vom Netz

Abbildung B: Wirkleistungsreduktion bei Überfrequenz bei Erzeugungsanlagen mit regenerativen Energiequellen

Unter Berücksichtigung der ENTSO-E[2] Empfehlungen werden die technischen Anforderungen zur Primär- und Sekundärregelung beschrieben. Abschließend werden sowohl die Frequenzregelung als auch die Regelmaßnahmen erörtert, die zurzeit in aufeinanderfolgenden Schritten angewendet werden und die alle über unterschiedliche Eigenschaften und Qualitäten verfügen und voneinander abhängig sind.

[2] European Network of Transmission System Operators for Electricity

Auf Grundlage der Erkenntnisse der Literaturrecherche wurde eine Methode zur Bereitstellung von Reserveleistung mit Windkraftanlagen entwickelt. Hierbei wurde berücksichtigt, dass die herkömmlichen Verfahren im Bezug auf Netzdienstleistungen nicht direkt auf die Windenergie übertragen werden können. Die größte Herausforderung hierbei besteht darin, die charakteristischen Eigenschaften der Energiequelle Wind durch Bereitstellen adäquater Strukturen und Datenflüsse, zu überwinden.

Abbildung C zeigt das vorgeschlagene Konzept zur Bereitstellung von Reserveleistung mit Windparks. Die Grundlage hierfür besteht in der Kommunikation und Interaktion zwischen dem Betreiber des Übertragungsnetzes und Windparkbetreiber.

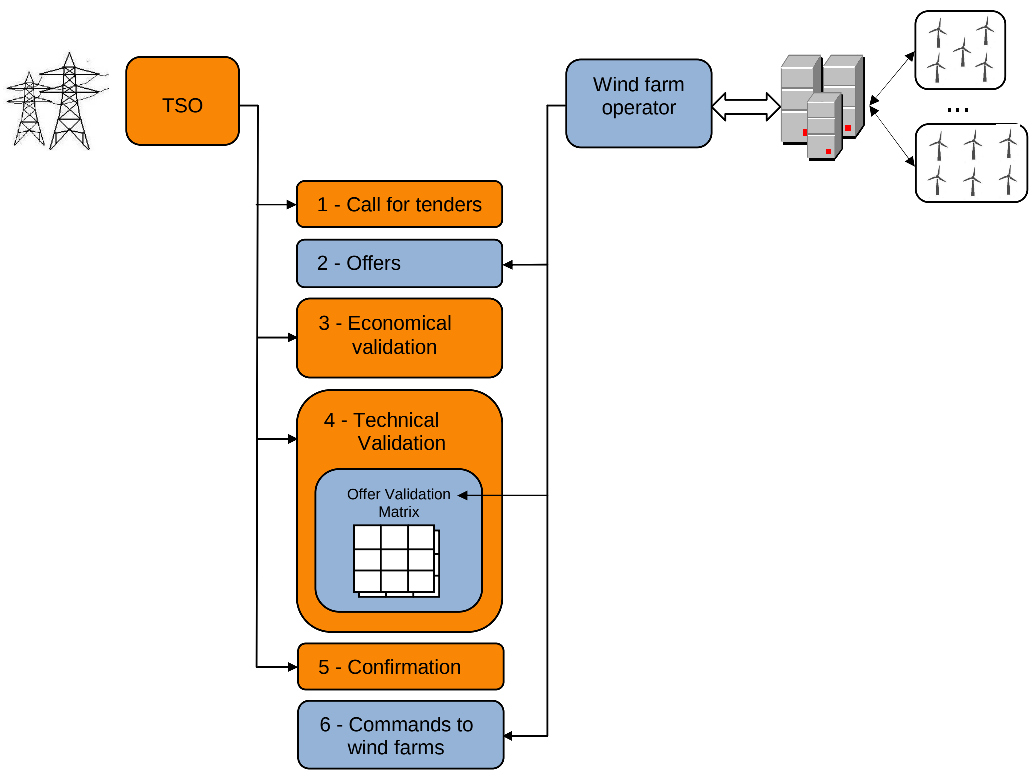


Abbildung C: Konzept zur vorgeschlagenen Methode

Die hier entwickelte Methode wird sowohl auf ihre dynamischen Eigenschaften als auch auf die Effektivität des vollständigen Modells im Hinblick auf Regelfähigkeit und der grundsätzlichen Möglichkeit, Regelleistung mit Windenergie sicher und zuverlässig bereit zu stellen, analysiert.

Hierzu wird das Verfahren durch zwei Simulationsrechnungen mit positivem Regelleistungsangebot validiert. Das Ziel dieser Simulationen ist, die Charakteristik der „Angebotsvalidierungsfaktoren“ sowie deren Regeleigenschaften zu beobachten. Hierzu wird als Kriterium der „Angebotsvalidierungsfaktor“ respektive die

„Angebotsvalidierungsmatrix" als rechnerische Kenngrößen zur Beurteilung der Gültigkeit eines Angebots für Regelleistung neu eingeführt. Die „Angebotsvalidierungsmatrix" stellt somit die Struktur des Datenaustauschs zwischen Übertragungsnetzbetreiber und Windparkbetreiber dar.
In beiden Simulationsläufen wurde diese Matrix mit den auf Stundenbasis verfügbaren Informationen aus den realen Windleistungszeitreihen des Hauptsimulationsszenarios geladen. Die erste Kontrolle beruht auf dem Faktor „Stunden Stabilität". Das Ziel ist, mit diesem Faktor die stündliche Stabilität jedes einzelnen Angebots während der zurückliegenden letzten vier Stunden vor der erforderlichen Aktivierungszeit zur Regelleistungsbereitstellung (PRAT oder Power Reserve Activation Time) auszuwerten. Unmittelbar vor der PRAT zeigt der „Angebotsstabilitätsfaktor" (Offer Stability Factor) die Stabilität jedes einzelnen Angebots. Hieraus ergibt sich, ob das jeweilige Angebot aktiviert werden kann oder nicht.

Die erste Simulation basiert auf der Bereitstellung einer positiven Regelleistung von 195 MW aus fünf Windpark-Clustern. Während der Simulation liegen die Angebote für Leistungsreserven unter dem unteren Intervall der Windleistungsvorhersage jedes einzelnen Wind-Clusters.
In der zweiten Berechnung wird ein positives Regelleistungsangebot über 265 MW aus fünf Windpark-Clustern simuliert. Das Ergebnis ist in diesem Fall, dass einige der Angebote über dem Wert des unteren Konfidenzintervalls liegen. Durch das hier vorgestellte Verfahren wird gezeigt, dass es sich um instabile Angebote handelt, die daher auch nicht zur Aktivierung freigegeben werden.

Schließlich wird das entwickelte Verfahren auf die Zeitreihe der deutschen Windstromproduktion aus dem Jahr 2009 angewendet. Es werden Konfidenzintervalle von 90, 95, 99 und 100 Prozent berechnet. Auf Grundlage der verfügbaren Informationen wird für jedes Konfidenzintervall berechnet, welche jährlichen Anteile an Primär- und Sekundärleistungsreserve mittels Windenergie und der vorgeschlagenen Methode theoretisch hätten bereitgestellt werden können (vgl. Abbildung D).

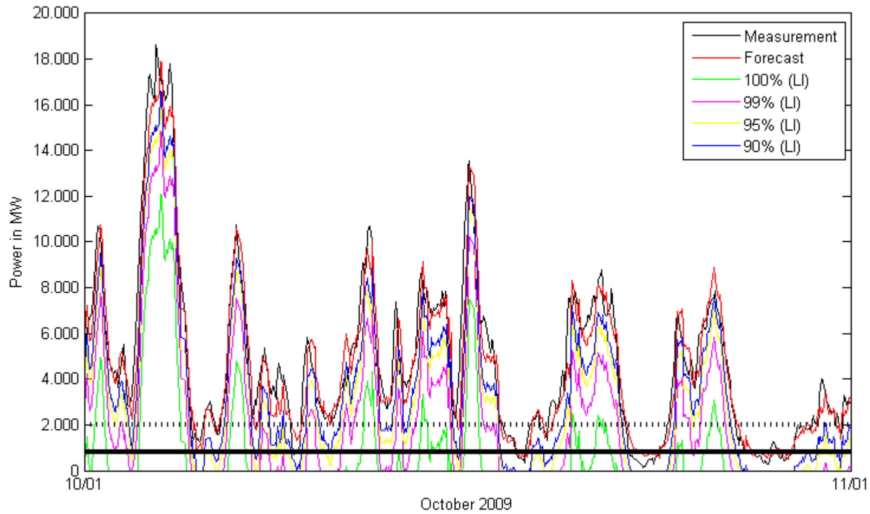


Abbildung D: Untere Intervall-Berechnung der Windleistungsvorhersage für Deutschland, Oktober 2009.

Nach der Validierung der vorgeschlagenen Methode werden die entwickelten und implementierten Technologien auf Windparkebene thematisiert. Hierzu werden Testergebnisse aus realen Windparks in Deutschland und Portugal vorgestellt. Ziel ist es, zu belegen, dass die benötigte Technologie, Regelleistung mit Windenergie bereit zu stellen, bereits verfügbar und teilweise bereits vor Ort installiert ist. Die Ergebnisse aus zwei F&E-Vorhaben, die Testszenarien sowie die jeweiligen Netzstrukturen werden vorgestellt. Die ausgewerteten Ergebnisse beziehen sich auf die Regelung von Wirkleistung auf der Ebene von Windparks und Wind-Clustern. Sie sind das Kernstück dieser Dissertation.

Abschließend werden Schlussfolgerungen und Empfehlungen für weitere Forschungsarbeiten genannt.

Verfahren, die gegenwärtig im Bereich der konventionellen Erzeugung eingesetzt werden, lassen sich nicht unmittelbar auf die Windenergie übertragen. Aus diesem Grund wird eine neue Methode im Rahmen dieser Dissertation vorgeschlagen und verifiziert. Damit soll die Windenergie befähigt werden, Regelleistung bereit zu stellen, während die Einhaltung von Sicherheitsstandards im Verantwortungsbereich der Übertragungsnetzbetreiber verbleibt.

An Hand der Ergebnisse, die in dieser Dissertation vorgestellt werden, wird gezeigt, dass Windparks steuerbar und in der Lage sind, stabil zuverlässige Regelleistung bereit zu stellen.

1. Introduction

During this chapter, the development of wind energy is analyzed as well as the motivation, objectives, focus and thesis outline of this PhD.

The main topic of this research is extremely linked with the evolution of wind energy and its future perspectives. The possibility for wind energy of starting to provide ancillary services which currently are being provided by conventional generation, would lead to higher penetration levels of wind power into the grids, avoiding technical current existing barriers for its large scale integration.

1.1 Development of wind energy

The evolution of wind energy and its promotion mechanisms are described as well as the future European targets and perspectives.

1.1.1 Evolution of wind energy

The use of wind as a source of power became part of history several thousand years ago. The human race made use of the available natural resources on earth (water, wind and solar power) since its first steps of development.

During the twentieth century, after the oil crisis and its global consequences, renewable energies were considered as one of the best answers to the energy dependent problem, assuming that new “oil crisis” would appear, that fossil fuels would be extinguished and that a sustainable human development should be based on renewable and non polluting energy sources. Wind energy was one of the most popular energy sources, being considered the real option for the future world energy matrix, and being expected to contribute with large amounts of energy to the electrical supply systems.

As a consequence of this decision, several developed countries started to promote wind energy as an important part of their energy matrixes. Governments, R&D institutions and the private sector started, or increased, their R&D activities in this field. After the publication of the first results of R&D activities and the introduction of successful regulatory models for the promotion of wind energy, wind turbines started emerging into the landscape of the world’s windy areas. At the same time wind energy was facing a new challenge to its development, with still a long way to go, technologies to be improved, new materials to be used and several other studies to be performed, but also with a clear concept about clean evolution and a strong political and technical commitment of those countries which were pioneers in this sector [65].

Wind turbines technology has developed at an extraordinary rate over the last 20 years. Stall regulated machines have given way to pitch regulated ones, and plain induction wind turbines have evolved into sophisticated variable speed Double Fed Induction Generators (DFIG) and Permanent Magnet Generators (PMG) equipped with Full Converter (FC) systems. These developments have dramatically improved functionality and related controllability, benefiting the wind farm owner and the Distribution System Operator as well as the Transmission System Operator.

With the challenge already met, stand alone R&D wind turbines started giving their place to commercially significant wind farms. Since then, the number of wind farms has been increasing constantly, as well as the installed capacity of wind power from countries like Germany, Denmark and Spain, among others. At the very beginning of wind power development, the ratio between the countries installed capacity and the wind power penetration was very low. Therefore wind power was not expected to contribute to grid security as expected from conventional generation units.

Nowadays there is a very high penetration of wind power into the European grids, and even higher volumes are expected for the coming years according to the new European targets for 2010, 2020 and 2030 [1]. This development of wind power can also be confirmed based on a higher capacity factors as technology evolves and the trend moves towards offshore technologies where wind farms will become large offshore power plants, using multi-megawatt wind turbines technologies with a higher installed capacity per wind farm [65].

1.1.2 Promotion mechanisms and benefits of wind energy

During this topic, the existing promotion mechanisms for the development of wind energy and its benefits are described and summarized. The further evolution of these mechanisms, applied to the ancillary services market, is extremely relevant as far as wind energy is being considered a power source capable enough to provide those ancillary services which were historically provided by the conventional generation. This situation will lead to the need of new promotion mechanisms, in order to allow wind energy to participate in those new ancillary services markets which would be created.

Promotion mechanisms for wind energy

As it is described in the book “Wind energy - The facts” [65] published by EWEA (European Wind Energy Association), when grouping the different types of support mechanisms available for renewable energy sources, a fundamental distinction can be made between direct and indirect policy instruments. Direct policy measures aim to stimulate the installation of renewable energy technologies immediately, whereas indirect instruments focus on improving long-term framework conditions. Besides regulatory instruments, voluntary approaches for the promotion of renewable energy technologies also exist mainly based on the willingness of consumers to pay premium rates for green electricity. Further important classification criteria are whether policy instruments address price or quantity, and whether they support investments or generation.

	Direct		**Indirect**
Regulatory	Price driven	Quantity driven	
Investment focused	▪ Investment incentives. ▪ Tax credits. ▪ Low interest/Soft loans.	▪ Tendering system for investment grant.	▪ Environmental taxes. ▪ Simplification of authorization procedures.
Generation based	▪ Feed-in tariffs (Fixed). ▪ Fixed premium system.	▪ Tendering system for long-term contracts. ▪ Tradable Green Certificate system.	▪ Connection charges, balancing costs.
Voluntary			
Investment focused	▪ Shareholder programs. ▪ Contribution programs.		▪ Connection charges, balancing costs.
Generation based	▪ Green tariffs.		

Table 1 – Types of renewable energies support mechanisms - EWEA [65]

The regulatory strategies are also addressed in the EWEA's book "Wind energy - The Facts" [65], and are summarized as following:

Regulatory price-driven strategies

Renewable energy generators receive financial support in terms of a subsidy per kW of capacity installed, or a payment per kWh produced and sold. The major strategies are:

1. **Investment-focused strategies:** financial support is given by investment subsidies, soft loans or tax credits (usually per unit of generating capacity).
2. **Generation-based strategies:** financial support is a fixed regulated feed-in tariff (FIT) or a fixed premium (in addition to the electricity price) that a governmental institution, utility or supplier is legally obligated to pay for renewable electricity from eligible generators.

Regulatory quantity-driven strategies

The desired level of renewable energy generation or market penetration – a quota or a Renewable Portfolio Standard – is defined by governments. The most important points are [65]:

1. **Tendering or bidding systems**: calls for tender are launched for defined amounts of capacity. Competition between bidders results in contract winners that receive a guaranteed tariff for a specified period of time.
2. **Tradable certificate systems**: these systems are better known in Europe as Tradable Green Certificate (TGC) systems and in the US and Japan as renewable portfolio standards (RPS). In such systems, the generators (producers), wholesalers, distribution companies or retailers (depending on who is involved in the electricity supply chain) are obliged to supply or purchase a certain percentage of electricity from renewable energy. At the date of settlement, they have to submit the required number of certificates to demonstrate compliance. Those involved may obtain certificates:

    a) From their own renewable electricity generation.
    b) By purchasing renewable electricity and associated certificates from another generator.

c) By purchasing certificates without purchasing the actual power from a generator or broker, that is to say purchasing certificates that have been traded independently of the power itself.

Voluntary approaches

This type of strategy is mainly based on the willingness of consumers to pay premium rates for renewable energy, due to concerns over global warming, for example. There are two main categories:

1. **Investment focused**: the most important are shareholder programs, donation projects and ethical input.
2. **Generation based**: green electricity tariffs, with and without labelling.

Indirect strategies

Aside from strategies which directly address the promotion of one (or more) specific renewable electricity technologies, there are other strategies that may have an indirect impact on the dissemination of renewable energies. The most important are:

1. Eco taxes on electricity produced with non-renewable sources.
2. Taxes/permits on CO_2 emissions.
3. The removal of subsidies previously given to fossil and nuclear generation.

There are two options for promoting renewable electricity via energy or environmental taxes [65]:

1. Exemption from taxes (such as energy and sulphur taxes).
2. If there is no exemption for RES, taxes can be (partially or wholly) refunded.

Both measures make renewable energies more competitive in the market and are applicable for both established and new plants.

Indirect strategies also include the institutional promotion of the deployment of renewable energy plants, such as site planning and easy connection to the grid, and the operational conditions of feeding electricity into the system. Firstly, sitting and planning requirements can reduce the potential opposition to renewable energy plants if they address issues of concern, such as noise and visual or environmental impacts. Laws can be used, for example, to set aside specific locations for development and/or omit areas that are particularly open to environmental damage or injury to birds.

Secondly, complementary measures also concern the standardization of economic and technical connection conditions. Interconnection requirements are often unnecessarily onerous and inconsistent and can lead to high transaction costs for project developers, particularly if they need to hire technical and legal experts. Safety requirements are essential, particularly in the case of interconnection in weak parts of the grid. However, unclear criteria on interconnections can potentially lead to higher prices for access to the grid and use of transmission lines, or even unreasonable rejections of transmission access. Therefore, it is recommended that authorities clarify the safety requirements and the rules on the burden of additional expenses.

Figure 1 and Figure 2 show the successful evolution of the electricity generation from renewable energies in Germany since the implementation of the "Renewable Energy Sources Act" in 2000. Since then the total install capacity from renewable energy sources has more than tripled.

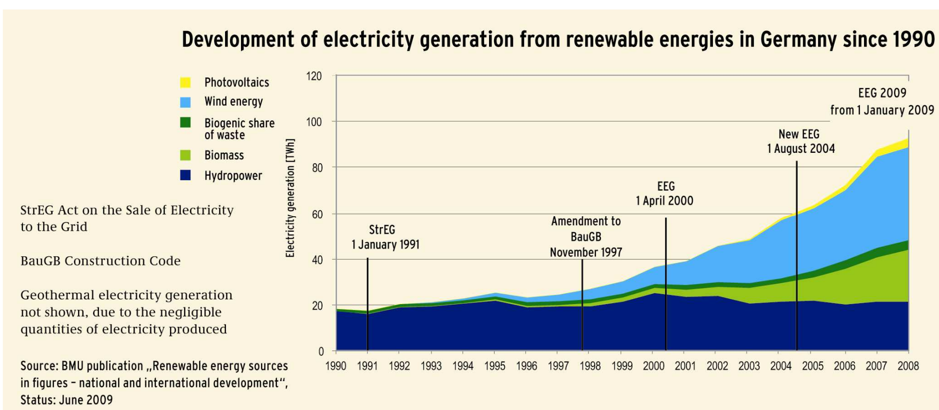


Figure 1 – Development of electricity generation from renewable energies in Germany

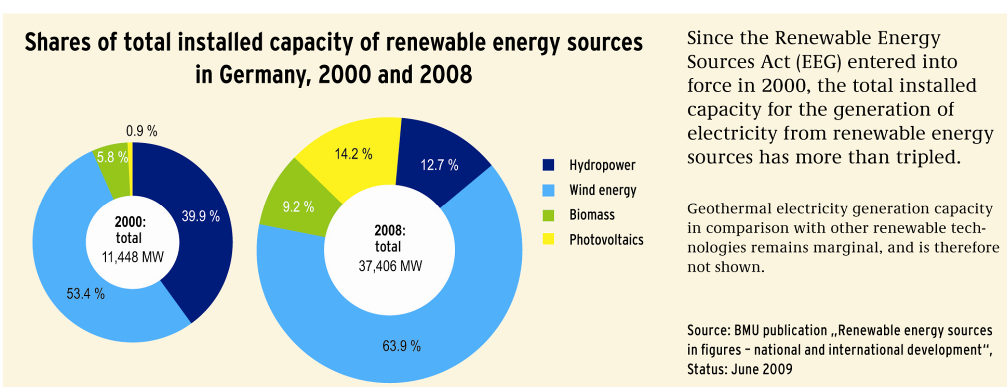


Figure 2 – Shares of total installed capacity of renewable energy source in Germany

Benefits of wind energy

There is no need to choose between protecting the environment and growing economy. Both are compatible if renewable energies are considered.

The “Energy supply security” report [66], published by the GWEC (Global Wind Energy Council), addresses the “security of supply” as one of the main benefits of wind energy. This report is summarized as following:

Security of supply

Depending on the efficiency measures implemented, by 2030 world energy needs are predicated to be between 30 and 60% higher than current levels. The IEA (International Energy Agency) estimates that around 4.500 GW of new energy capacity needs to be installed before 2030, requiring investments of more than US$ 13 trillion.
This sharp increase in world energy demand will require significant investment in new power generating capacity and grid infrastructure, especially emerging economies such as India and China.

Industrialized countries face a different but parallel situation. While demand is increasing, the days of overcapacity in electricity production are coming to an end. Many older power plants will soon reach the end of their working lives. The IEA predicts that by 2030, over 1.600 GW of power generation capacity will need to be built in the OECD countries alone, including the replacement of retiring plants.

Just as energy demand continues to increase, supplies of the main fossil fuels used in power generation are becoming more expensive and more difficult to extract. One result is that some of the major economies of the world are increasingly relying on imported fuel at unpredictable cost, sometimes from regions of the world where conflict and political instability threaten the security of that supply.

In contrast to the uncertainties surrounding supplies of conventional fuels, and volatile prices, wind energy is a massive indigenous power source which is permanently available in virtually every country in the world. There are no fuel costs, no geo-political risk and no supply dependence on imported fuels from politically unstable regions.

Wind power also has the advantage that it can be deployed faster than other energy supply technologies. Even large offshore wind farms, which require a greater level of infrastructure and grid network connection, can be installed from start to finish in less than two years. This compares with the much longer timescale for conventional power stations such as nuclear reactors.

Several economic considerations related with wind power were published by the GWEC in the report “Wind energy makes sound economic sense” [67]. The main conclusions of this report are summarized as following:

Economic considerations

- **No fuel price risk:** in contrast to the uncertainties surrounding supplies of conventional fuels, and volatile prices, wind energy is a massive indigenous power source which is permanently available in virtually every country in the world.
- **The cost of wind energy:** wind power is already competitive with new-built conventional technologies and in some cases much cheaper. Although nothing can compete with existing, embedded conventional generation plant that has already been paid off (and was mostly constructed with significant state subsidies: governments still subsidize conventional technologies), wind power is commercially attractive, especially when taking into account the price of carbon, which is a factor in a growing number of markets.
- **Investment and jobs:** already in 2008, over €36.5 billion were invested in wind energy worldwide, and the sector is now employing well over 400,000 workers. The annual value of global investment in wind energy would reach €149.4 billion by 2020 and account for over 2.2 million jobs.

  Especially at times of economic uncertainty and high unemployment rates, any technology which demands a substantial level of both skilled and unskilled labour is of considerable economic importance, and likely to feature strongly in any political decision-making over different energy options.
- **Regional economical development:** regional economic development is also a key factor in economic considerations surrounding wind energy. The wind power industry is revitalising regional economies, providing quality jobs and expanding tax bases in rural regions struggling to keep their economies moving ahead in the face of the global flight to the cities.
- **No geo-political risks:** there are no fuel costs, no geo-political risk and no supply dependence on imported fuels from politically unstable regions. Every kilowatt/hour

generated by wind power has the potential to displace fossil fuel imports, improving both security of supply and the national balance of payments.

- **Speed of deployment:** wind power also has the advantage that it can be deployed faster than other energy supply technologies. Building a conventional power plant can take 10 or 12 years or more, and it is not producing power until it is fully completed. Wind power deployment is measured in months, and a half completed wind farm is just a smaller power plant, starting to generate power and income as soon as the first turbine is connected to the grid. Even large offshore wind farms, which require a greater level of infrastructure and grid network connection, can be installed from start to finish in less than two years.
- **Emissions:** Wind energy emits neither climate change inducing carbon dioxide nor the other air pollutants, and as a result has none of the high external costs related with conventional energy sources. Within three to six months of operation, a wind turbine has offset all emissions caused by its construction, to run carbon free for the remainder of its 20 year life. In an increasingly carbon-constrained world, wind power is risk-free insurance against the long term downside of carbon intense investments.

Finally with regard to the environmental benefits of wind energy, the GWEC has published the report "Wind energy and the environment" [68] which is summarized as following:

Environmental concerns

Wind power is a clean, emissions-free power generation technology. Like all renewable sources it is based on capturing the energy from natural forces and has none of the polluting effects associated with 'conventional' fuels.

- **Climate change:** wind energy produces no carbon dioxide - the main greenhouse gas contributing to climate change – during its operation, and minimal quantities during the manufacture of its equipment and construction of wind farms. By contrast, fossil fuels such as coal, gas and oil are major emitters of carbon dioxide. Wind energy is a key solution in the fight against climate change, and it is well on track to saving 10 billion tons of CO_2 by 2020.
- **Air pollution:** wind power also has a positive effect on the quality of the air we breathe. The combustion of fossil fuels also produces the gases sulphur dioxide and nitrogen oxide, both serious sources of pollution. These gases are the main components of the 'acid rain' effect - killing forests, polluting water courses and corroding the stone facades of buildings; not to mention the human health effects.

- **Water:** Another consideration of wind energy deployment concerns water. In an increasingly water-stressed world, wind power uses virtually none of this most precious of commodities in its operation. Most conventional technologies, from mining and extraction to fuel processing and plant cooling measure their water use in the millions of liters per day.
- **Environmental impacts:** wind energy is arguably the cleanest electricity generation technology, but, like any other industry, does have environmental impacts. The construction and operation of wind farms, often in rural areas, raises issues of visual impact, noise and the potential effects on local ecology and wildlife. Most of these issues are addressed during consultation with local authorities.

  The wind industry takes its responsibility to reduce the impacts of wind energy on the environment very seriously, and, since the early days of this relatively young industry, significant improvements have been made with regards to the development of wind farms and the design of turbines.
- **Visual impact:** wind turbines are highly visible elements in the landscape. They need to be in order to catch the prevailing wind and work effectively. How people perceive them varies, but many see wind farms as elegant and graceful symbols of a better, less polluted future.
- **Noise:** compared to other types of industrial plants, wind farms are extremely quiet. Even though turbines are commonly located in rural areas, where background noise is lower, the roar of the wind often masks any sound their operation might make. Measured in a range of 35 to 45 decibels at a distance of 350 metres from the turbines, their sound is similar to the background noise found in a typical home.

Offshore wind farms: as on land, offshore wind developers have to ensure that their turbines and transmission infrastructure do not interfere with marine life and ecosystems. National regulations ensure that project developers assess in both qualitative and quantitative terms the expected environmental impacts on the marine environment. These procedures ensure that projects comply with international and EU law as well as conventions and regulations covering habitat and wildlife conservation. Within the structure of an environmental impact assessment, an initial baseline study is conducted. Subsequent monitoring is necessary to record any changes within the marine environment which may have been caused by human activity. The monitoring phase may go on for several years, and evaluations and conclusions are updated annually to assess changes over time.

1.1.3 Wind energy world wide

Again the year 2009 brought new records for wind energy utilisation around the world. In spite of the global economic crisis, investment in new wind turbines exceeded by far all previous years.

The wind capacity worldwide reached 159.213 MW, after 120.903 MW in 2008, 93.930 MW in 2007, 74.123 MW in 2006, and 59.012 MW in 2005 (see Figure 3). It can be seen that the installed wind capacity is more than doubling every third year.

Figure 3 – World total install capacity – WWEA [72]

The market for new wind turbines showed a 42,1 % increase and reached an overall size of 38.312 MW, after 26.969 MW in 2008, 19.808 MW in 2007 and 15.111 MW in the year 2006 (see Figure 4). Ten years ago, the market for new wind turbines had only a size of 4 GW, only one tenth of the size of 2009.

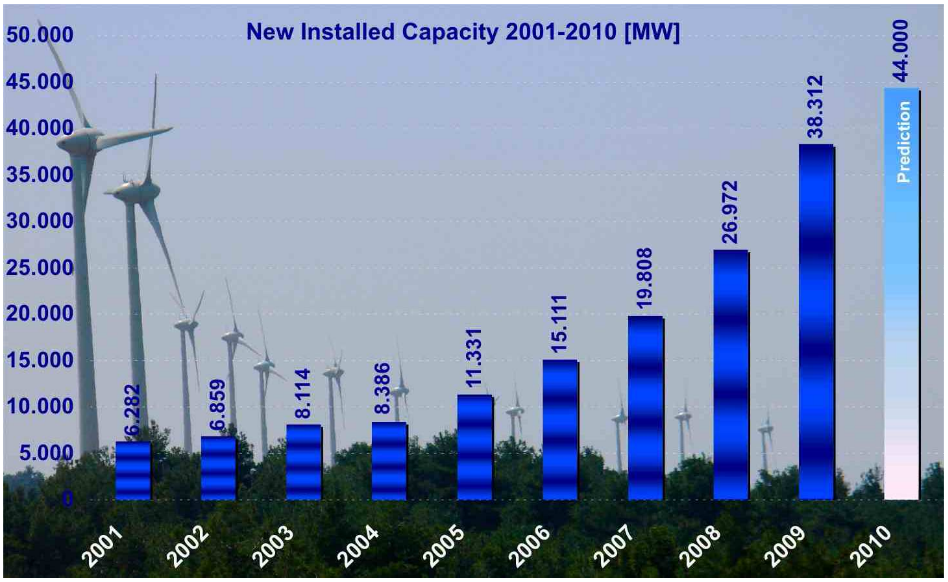


Figure 4 – New installed capacity 2001 – 2010 – WWEA [72]

1.1.4 Wind energy in Europe

During 2009, 10.526 MW of wind power was installed across Europe, 10.163 MW of that being in the European Union countries (see Figure 5). This represents a market growth in the EU of 23% compared to 2008 installations. Of the 10.163 MW installed in the European Union, 9.581 MW were installed onshore, and 582 MW offshore. In 2009 the onshore wind power market grew 21% compared to the previous year, and the offshore wind power market grew 56% compared to the previous year [63].

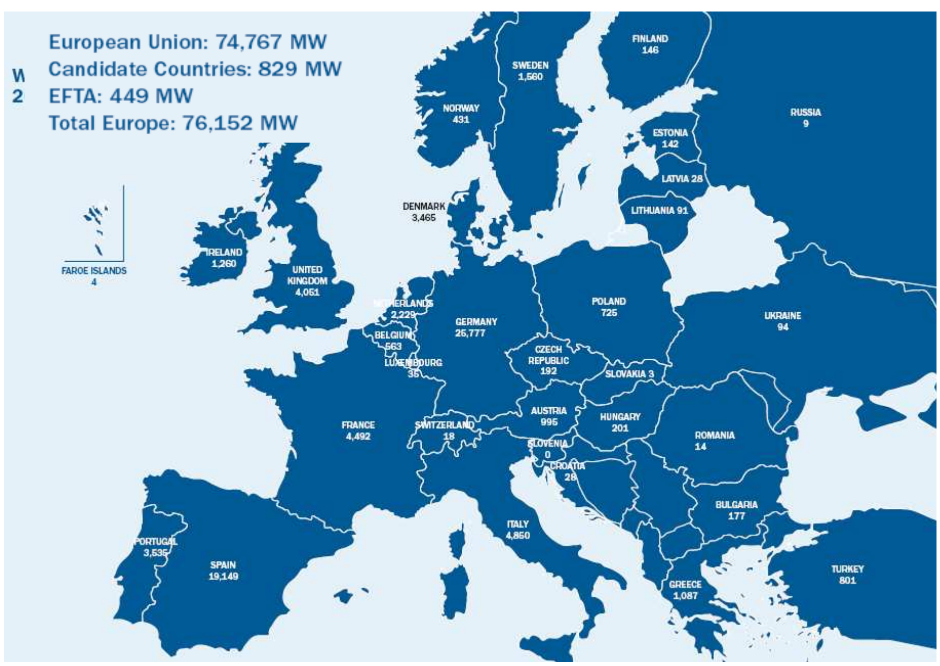


Figure 5 – Wind power installed in Europe by the end of 2009 (cumulative) [63]

In terms of annual installations Spain was the largest market in 2009, installing 2.459 MW, compared to Germany's 1.917 MW. Italy, France and the United Kingdom battled for third, fourth and fifth place respectively, with Italy installing 1.114 MW, and France 1088 MW and the UK 1.077 MW [63]. Europe's 2009 installations are characterised by a continuing strong development in the mature markets of Spain and Germany, together with countries such as Italy, France, and the United Kingdom. Portugal (673 MW), Sweden (512 MW), Denmark (334 MW), and Ireland (233 MW) also performed strongly.

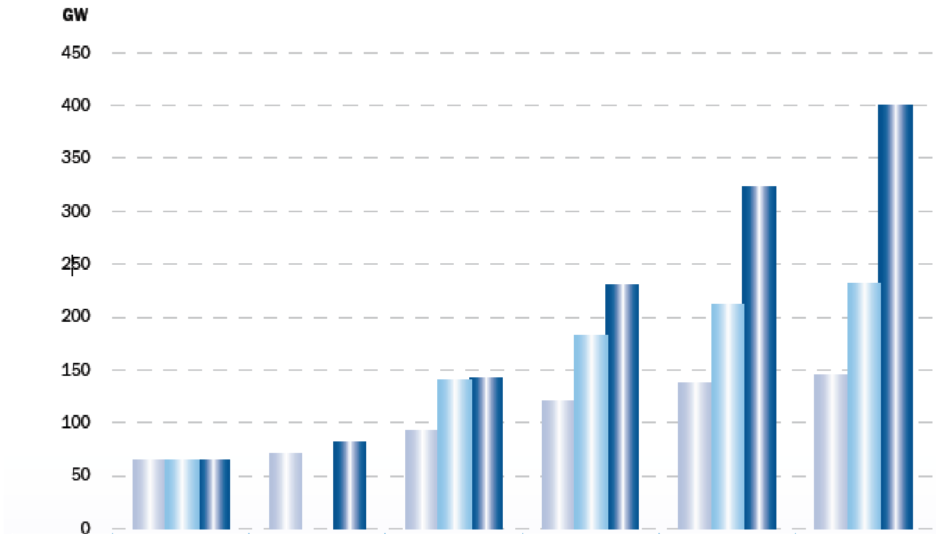
One of the main factors which should also be analyzed is the relation between wind generated electricity and the national electricity demand of each country. This relation is described in the "Annual Report 2008" [74] from the IEA (International Energy Agency).

National Statistics of the IEA Wind Member Countries for 2008					
Country	**Total installed wind capacity (MW)**	**Annual net increase in capacity (MW)**	**Wind generated electricity (GWh/yr)**	**National electricity demand (TWh/yr)**	**% of national electricity demand from wind[3]**
Australia	1.306	482	3.462	267	1,3%
Austria	995	14	2.050	70,7	2,9%
Canada	2.369	523	5.800	575	1%
Denmark	3.163	39	6.975	36,2	19,3%
Germany	23.902	1.665	40.400	615,1	6,5%
Ireland	1.002	207.7	2.298	26,2	8,8%
Italy	3.736	1.010	6.637	337,6	1,9%
Netherlands	2.214	490	4.259	119,3	3,6%
Portugal	2.819	694	5.737	50,6	11,3%
Spain	16.740	1.609	31.100	266,5	11,7%
United Kingdom	3.331	912	5.274	406	1,3%
United States	25.369	8.558	71.000	3.736,8	1,9%

Table 2 – National Statistics of the IEA Wind Member Countries for 2008

Considering the perspectives for 2020 and 2030, described in Figure 6, the trend shows that wind energy will continue growing and also will start to replace conventional generation. At the same time, wind farms are starting being requested to provide those ancillary services which historically were provided by conventional generators.

[3] % of national electricity demand from wind = (wind generated capacity/national electricity demand)/100



	2008	2010	2015	2020	2025	2030
EC 2008	64.9	71.3	92.2	120.4	137.2	145.9
IEA 2008	64.9	N/A	140	183	211	232
EWEA 2009	64.9	82.6	142.9	230	323.5	400

Source: EC, IEA and EWEA

Figure 6 – Wind baseline scenarios for the EU-27 (2008-2030)

1.1.5 Wind power is replacing conventional generation

In 2009, for the second year running, in the EU more wind power was installed than any other electricity generating technology. 25.963 MW of new capacity was installed in total, of which 10.163 MW (39%) was wind and 6.630 MW was gas (26%). Solar PV - came in third at 4.200 MW1 (16%). In addition 2.406 MW (9%) of new coal was installed, 581 MW (2,2%) of biomass, 573 MW (2,2%) of fuel oil, 442 MW (1,7%) of waste, 439 MW (1,7%) of nuclear, 338 MW (1,3%) of large hydro, 120 MW (0,46%) of concentrated solar power, 55 MW (0,2%) of small hydro, 12 MW (0,04%) of other gas, 3,9 MW (0,01%) of geothermal, and 405 kW3 of ocean power [63].

During the same year, the nuclear and coal power sectors decommissioned more MW than they installed: nuclear power sector decommissioned 1.393 MW, and the coal power sector decommissioned 3.200 MW, the continuation of an ongoing trend.

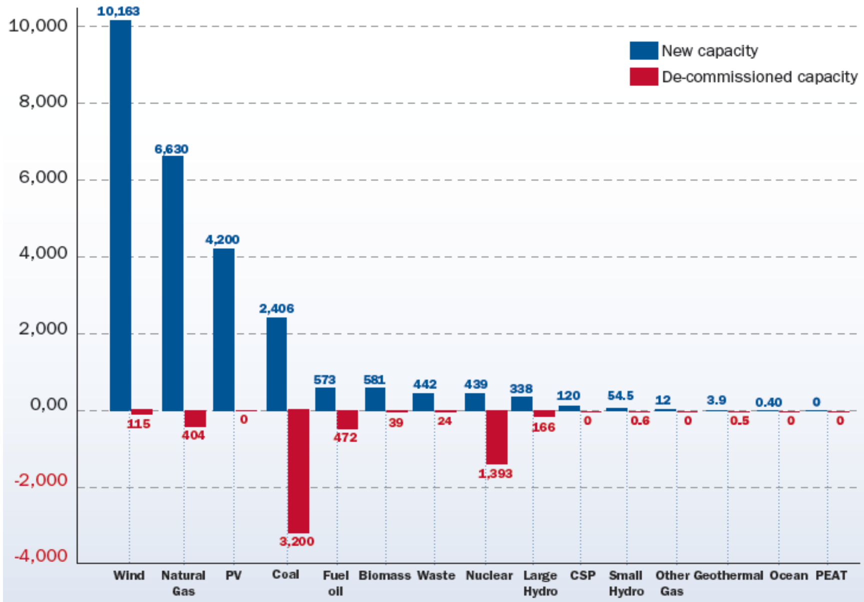


Figure 7 – Installed capacity and de-commissioned capacity in Europe (2009) [63]

Since 2008, each year renewable electricity generating technologies have accounted for more than 50% of new power installations – mostly wind power, but also solar PV, hydro power and biomass. This trend has increased from just 14% of new installations in 1995 to 61% in 2009.

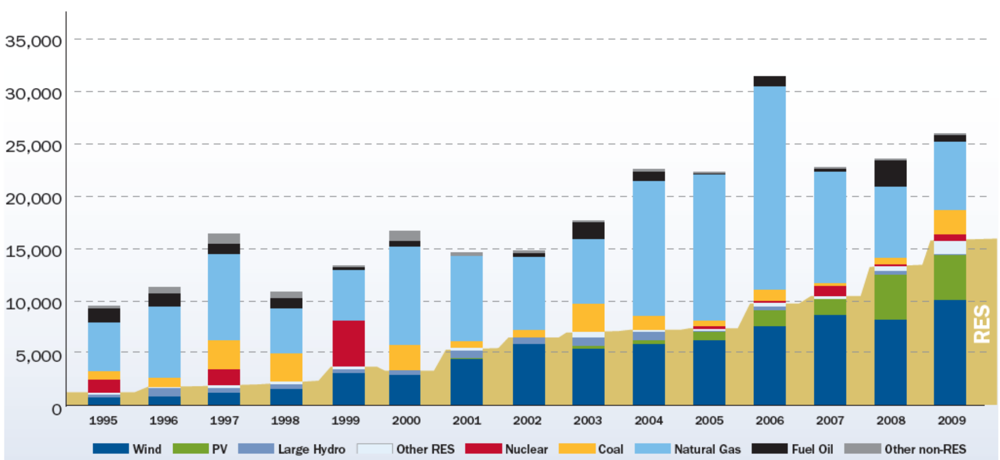


Figure 8 – New installed capacity per year in MW in Europe – Source: EWEA [63]

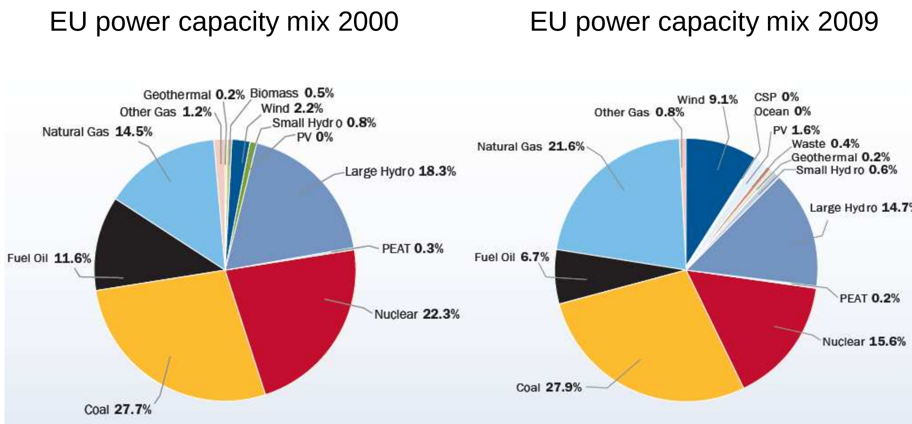


Figure 9 – European power capacity mix 2000 - 2009 – Source: EWEA [63]

1.2 Motivation, objectives, problem statement and focus

1.2.1 Motivation of this PhD

Since the last three years wind energy is not only constantly increasing its install capacity, it is also starting to replace conventional generation in some countries. This leads to situations were wind power is reaching penetration levels of 50, 60 or even 70% during a certain periods of the day. This is already happening in Portugal and described in Figure 10, where two examples of wind power penetration as described and Figure 11. In the near future this will also happen for longer periods, complete days, weeks or even months.

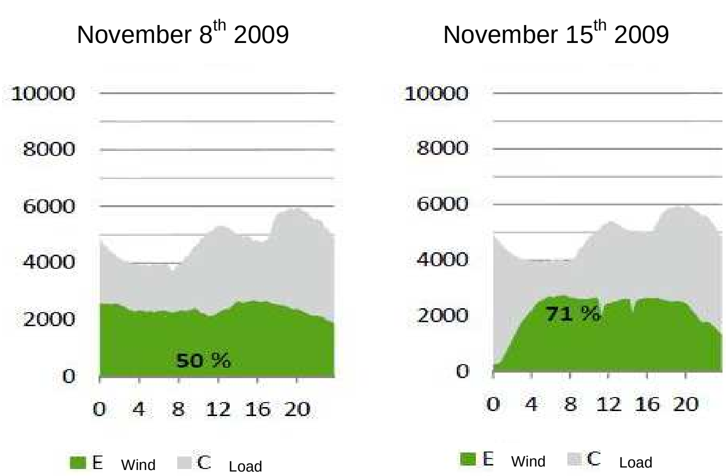


Figure 10 – Wind power penetration in Portugal (Source: REN)

Figure 11 describes a particular situation during May 2nd 2009 in Portugal where renewable energies have supported the whole country between 4 and 8 o'clock in the morning. It can be observed in green the power produced by the "Special Regime Production"[4] units (mainly wind energy).

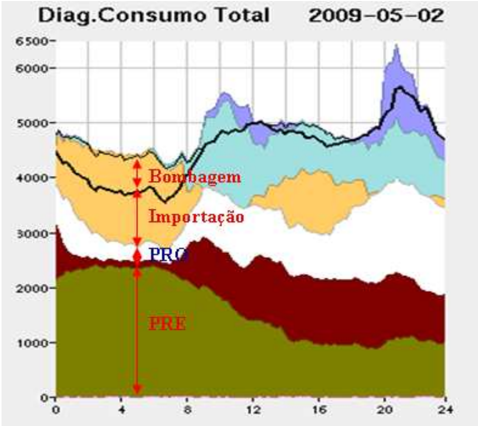


Figure 11 – Renewable energies penetration in Portugal during May 2nd 2009 (REN)[5]

One of the most important challenges is to accept the integration of higher volumes of wind power into the European grids in coordination with other energy sources (see Figure 11) and still keep the grid stability. Because of the diversification of the European energy matrix and the introduction of several renewable energy sources, grid security has become one of the main issues to be considered. Therefore, as long as wind power is expected to play a major role into the European energy matrix, it must have the functionality required by power plants: reliable, predictable, dispatchable and controllable. In other words: *wind power shall be manageable as a conventional power plant system*.

In recent years wind energy has been considered a non dispatchable source and therefore mostly connected to the grid without any option for active communication and interaction with the grid operator or the electricity markets. However new developments and real tests, described during this research, have shown that wind energy is manageable as a conventional power source.

The extensively growing shares of wind power combined with its manageable characteristics allows wind energy to participate supporting system security by providing ancillary services, which currently are being provided by the conventional generation.

[4] This information is published with the kind permision of REN.
[5] PRE: Special Regime Production (Produção em Regime Especial) - Source: REN
PRO: Ordinary Regime Production (Produção em Regime Ordinário) - Source: REN

Without the participation of the wind power in the provision of ancillary services in the coming years the reliability, quality of supply and stability of the power system cannot be kept in the today's quality. New technical and regulatory conditions for involving wind energy into the provision of quality supply are required.

The today applied regulations shall be qualified in two directions:

- Involvement of wind energy into the energy market mechanisms
- Bringing more flexibility on the power reserve market

1.2.2 Objectives

The aim of this PhD is to develop a methodology for wind power to be able to provide positive and negative power reserve.

Through an analysis of the ancillary services which currently are being requested at wind farm level in the most advanced wind power countries in the world, and considering the structure of wind farm clusters [2] developed at Fraunhofer IWES as the natural evolution for wind power management, a concept for primary and secondary power reserve provision with wind power is developed and tested in both, simulation and real test fields scenarios.

Over-frequency and under-frequency events are considered as well as frequency response procedures with wind farms are developed taking into consideration the needed quick response. It is also analyzed which control strategy could best provide the needed power reserve according to the frequency event which could occur.

In case an under-frequency event happens, positive power reserve should be injected into the grid contributing to the system stabilization. In order for the wind farms to be able to do so, they should be targeted during normal operation time with a certain value of active power to be reduced and known as an available power reserve by the system operator.

How to dynamically fulfil the TSOs needs concerning the volumes of primary and secondary power reserve, keeping the current security standards, adding the needed flexibility and minimizing costs and power looses, are also discussed in this PhD.

Once an upper-frequency event occurs, negative power reserve should be activated according to the frequency variation. The related control strategies for this event are also analyzed in this PhD. How to contribute to balance a system with wind power after an upper-frequency event, minimizing losses and fulfilling the needed time response requirements, are addressed through the development of control strategies. The influence of available wind power forecasts and their uncertainties [3] [28] [73] is also considered.

Finally, through real test fields it is analyzed the current existing capability of wind farms to contribute with power reserve provision as happens nowadays with conventional generation.

1.2.3 Problem statement

Wind energy differs from conventional generation since the production is not driven by the demand for electricity, but by meteorological conditions. This increases complexity to match consumption and production. To continuously balance supply and demand, ancillary services are defined. Whenever there is imbalance in a power system, the frequency will start deviating from its nominal value. This activates both primary and secondary control. These control mechanisms stabilise frequency variations and restore the frequency to its nominal value. Currently, distributed generators do not participate in primary control, nor in secondary control. Balance is restored only by conventional generators. However, as the share of wind power increases, its participation in power reserve provision will become necessary [50].

The main issue which is being analyzed during this PhD is how wind power could provide this kind of ancillary service in a secure, flexible and reliable way.

1.2.4 Focus and approach

The focus of this PhD is on the possibility of wind power to provide power reserve, while considering technical, market/economic and environmental aspects. The technical research is oriented to active power control capabilities from wind farm clusters being able to be operated as conventional power plants. As a guide line for power systems and technical requirements, the ENTSO-E recommendations are applied.

The approach of this research follows the previous discussion in Section 1.2.3. The first step is the literature review regarding current existing grid code requirements for wind power into the EU, in particular with regard to active power control. It is also analyzed the present procedures and technical characteristics of primary and secondary power control, currently applied to conventional generation.

Once clarified the background and technical requirements, the second step is to develop an innovative methodology for power reserve provision with wind power which considers its natural characteristics, the available current wind power forecasting structures and their uncertainties, and at the same time the security restrictions of TSOs while a market oriented approach has been implemented.

The third step involves the implementation of the developed methodology considering real data. The behaviour of the developed algorithms and control structures is tested, in two different environment simulations of positive power reserve provision.

For the fourth step current technical capabilities of wind farms were analyzed and validated in real test fields in Germany and Portugal. These results are analyzed considering the needed requirements for wind power being able to provide power reserve.

1.3 Thesis outline

The structure of this thesis reflects the research objectives, focus and approach formulated above. Every chapter starts with an introduction, describing the most relevant topics to be addressed and ends with a summary stating the main contributions and concrete findings. An overview of the structure if this PhD is described in Figure 12:

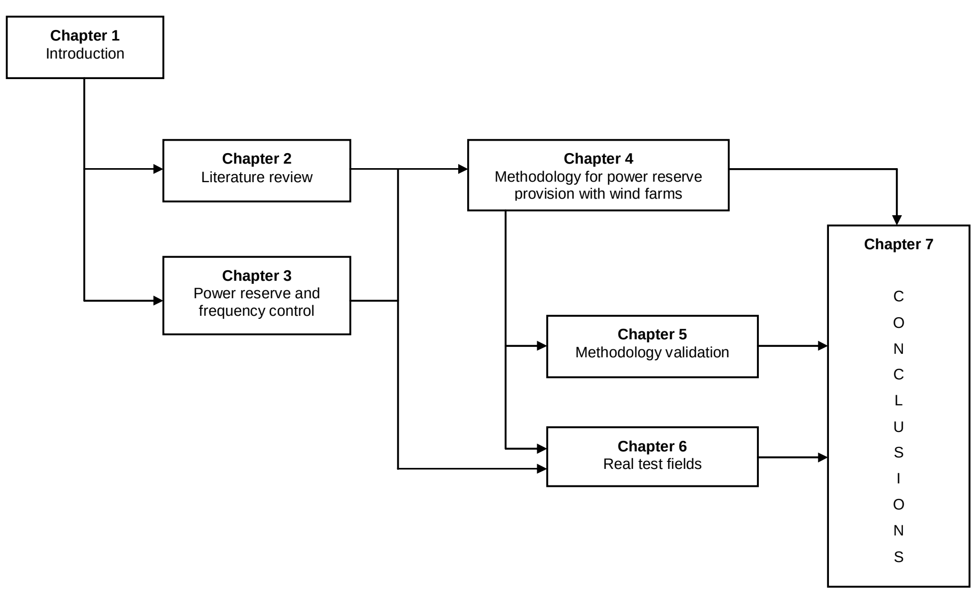


Figure 12 – Chapter overview and PhD structure

In Chapter 2, the current grid codes requirements for active power control with wind energy are discussed. Countries like Germany, Denmark, Great Britain and Spain are summarized and their requirements for controllability and control range, ramping and limitation, control modes, reduction due to over frequency and protection schemes are compared, providing a compact and summarized *state of the art* analysis. This chapter is particularly relevant considering that in the past wind energy was referenced as an uncontrollable energy source, fully dependent on unstable and unpredictable weather conditions. Nowadays, based on its current and future penetration it is start being considered as a controllable source, with different characteristics than the conventional power generation, but fully capable to contribute with the system security through ancillary services provision.

In Chapter 3, the technical characteristics and definitions from primary and secondary frequency control are addressed[6] comparing the control parameters from different power systems. At the same time the “frequency control” problem and the different control actions are analyzed.

In Chapter 4, based on the input information provided in Chapter 2 and Chapter 3 (see Figure 12), a new model for power reserve provision with wind power has been developed.

In Chapter 5, the methodology developed in Chapter 4 is being validated through two simulation scenarios. The developed structures and algorithms are being tested and their behaviour evaluated with real time series from 5 wind farm clusters in Germany.

In Chapter 6, the control capabilities of real wind farms in Germany and Portugal are being evaluated. Tests scenarios as well as their grid description are presented. Finally, concrete results with regard to active power control with wind farm clusters are presented as well as their accuracy and control commands deviation analysis.

In Chapter 7, the conclusions of this PhD are presented and recommendations for further research are made.

[6] Based on the ENTSO-E recommendations.

2. Literature review of grid code requirements for wind energy

2.1 Introduction

The increasing contribution of wind energy into the European grids requires advanced solutions to keep the existing power quality level and safety of supply. During this chapter it is analyzed the existing literature with regard to grid codes for wind farms, in particular those referencing active power control, ramping and limitation, and frequency control with wind power. It is also described the current initiatives with regard to the harmonization of the European grid codes [69] in order to establish a grid code template with common definitions, parameters, units and figures, as well as a common structure.

Before going further it is important to make a distinction between *system services* and *ancillary services*. System services are those provided by the system operator to all users of the network which are indispensable for the proper functioning of the system, while ancillary services are those supplied by some of the users of the network to the system operator. To provide the needed system services, the system operator usually buys ancillary services from generators and consumers [39]. As part of the provision of system services, the TSO shall pay adequate remuneration for the delivery of the necessary ancillary services to the bidders/providers in accordance with contractual agreements.

2.2 Current grid connection requirements in Europe with regard to active power

In the past wind power was referenced as a non controllable energy source, fully dependent on unstable and unpredictable weather conditions. Based on these two definitions, high controllability levels were not required by TSOs to any wind farm as far as they were considered as non controllable power sources. In some cases only emergency remote control procedures were required in order for the TSOs to be able to shut down any wind farm in their control zone within a given time period.

During the last years this concept has radically changed due to the higher penetration levels of wind power as well as the new available technologies developed and implemented by the wind turbine manufacturers.

As a consequence some technical requirements started to be included into several grid codes with regard wind farms controllability considering active and reactive power control.

Particularly with regard to active power control the current requirements in Europe are described as following: controllability and control range (Table 3), ramping and limitation (Table 4), control modes (Table 5), reduction due to over frequency and reduction for protection schemes (Table 6) and frequency control (Table 7) [70].

	Germany	Denmark	Nordel	Spain
Active power --- Controllability and control range	Wind energy plants must be controllable in terms of active power output according to the requirements of the TSO (see Figure 13). It must then be possible to reduce the power output under any operating condition and from any working point to a maximum power value (target value) defined by the TSO. This target value is given by the TSO at the grid connection point and corresponds to a %age value related to the network connection capacity.	It shall be possible to limit the production of a wind farm to a random set-point value in the range of 20…100 % of rated power. The deviation between a set-point value and a metered 5-minute mean in the connection point shall not exceed ± 5 % of the rated power of the wind farm.	It must be possible to control the active power production from the wind plant. An adjustable upper limit to the active power production from the wind plant shall be available whenever the wind plant is in operation. The upper limit shall control that the active power production, measured as a 10 minute average value, does not exceed a specified level and the limit shall be adjustable by remote signals. It must be possible to set the limit to any value with an accuracy of ±5%, in the range from 20% to 100% of the wind plant rated power.	The wind farm will permit to set the reference active power for all the feasible active power range until the maximum active power available, according to the primary energy resource. This can be required by the System Operator.
	Great Britain			
	The Active Power output of Wind Energy plants must be controllable. This is a prerequisite if they wish to participate in the wholesale electricity market but equally important if they are not party to such requirements and embedded in			

	a Network Operators System. The standard deviation of load error at steady state load over a 30 minute period must not exceed 2.5% of a Power Park Module's Registered Capacity. A Power Park Module must be capable of operating over a range between Registered Capacity and the Designed Minimum Operating Level. A Power Park Module Owner (ie a Generator) submits these values, together with other dynamic parameters to the System Operator in advance of real time. Submission of such data is a requirement of the Grid Code.	

Table 3 – Controllability and control range

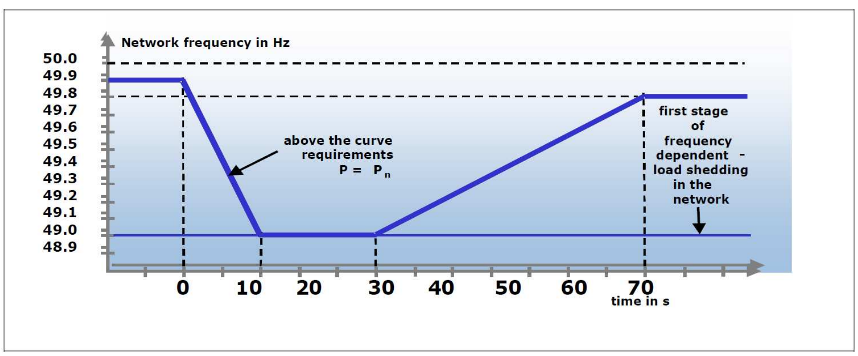


Figure 13 – Requirements upon the output from generating units feed into the network with dynamic short-time range

	Denmark	Nordel	Spain	Great Britain
Active power --- Ramping and limitation	It shall be possible to set the regulation speed at upward and downward regulation in the interval 10…100 % of rated power per minute.	Ramping control of active power production must be possible. It must be possible to limit the ramping speed of active power production from the wind turbine in upwards direction (increased production due to increased wind speed or due to changed maximum power output limit) to 10% of rated power per minute. There is no requirement to down ramping due to fast wind speed decays, but it must be possible to limit the down ramping speed to 10% of rated power per minute, when the maximum power output limit is reduced by a control action.	The wind farm will have the capability of limiting the ramp up or ramp down production values (not related with the reduction of primary energy resource). Those limits will be set by the SO. The wind farm will have the capability of sending the SO measures corresponding to the difference between the active power available (according to the available primary energy resource) and the active power set point received from the System Operator.	The Ramp rates apply to all forms of generation irrespective of type with limits as below: * Up to 300MW – No Limit * 300 MW – 1000MW: 50 MW/min * Greater than 1000MW: 40 MW/min Fast Down Regulation: Under Emergency Instructions there may be instances where it is necessary for the System Operator to deload or instruct a Power Park Module to shut down.

Table 4 – Ramping and limitation

	Denmark	Great Britain
Active power --- Control modes	For each wind farm a joint function is to ensure remote control of the farm's total active power production. The function is called "farm controller" and is to ensure that regulating orders to the wind farm's total production are met in the connection point. The farm controller shall enable ordering of the various	In the wholesale Electricity market Active Power must be regulated on a BM Unit (Balancing Market Unit) basis. In the onshore environment it is usual for one directly connected Power Park Module to equate to one BM Unit, although there are rules which permit for non standard BM Unit configurations. For embedded Connections, it is

	types of regulation as total orders which can be given both locally and via remote control. Each wind farm shall cover the following regulation functions for active power performed by the farm controller: -Absolute production constraint -Delta production constraint -Balance regulation -Stop regulation -Power gradient constrainer -System protection -Frequency control The precise regulation functionality and possible setting ranges for regulation parameters shall be arranged and be approved by the TSO before a wind farm is connected to the network. The operator of the wind farm shall be responsible for ensuring that power control, is done statically and dynamically stable for the farm as a whole. To ensure that the various and constraint functions do not interfere with each other in an	generally the case that the Power Station (which comprises of one or more Power Park Modules) is 100MW or above. For embedded power stations which are sub100MW, the generator has the option of selecting to be a BM Unit and part of the wholesale Electricity Market. In Great Britain, Generators are subject to self despatch and National Grid as System Operator will adjust each BM to balance generation and demand. In the Offshore environment, provisions apply at a threshold of 10MW. In view of this lower threshold, the Grid Code is much more flexible in the ability of a Generator to aggregate Power Park Strings into Power Park Modules and Power Park Modules into BM Units.

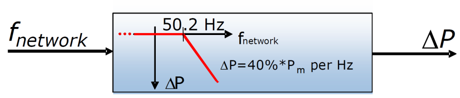
	unintended way, the following priority ranking shall be observed: -System protection -Frequency control -Stop regulation -Balance regulation -Power gradient constraint -Absolute production constraint -Delta production constraint. The active power control functions shall be agreed in with the system operator.	

Table 5 – Control modes

	Germany	Nordel	Spain	Great Britain
Active Power --- Reduction due to over frequency and reduction for protection schemes	The reduction of the power output to the signalized value must take place with at least 10 % of the network connection capacity per minute without disconnection of the plant from the network. All wind energy plants must reduce, while in operation, at a frequency of more than 50.20 Hz the instantaneous active power with a gradient of 40 % of the generator's instantaneously available capacity per Hertz within 10 seconds (Figure 14). If the	It must be possible to regulate the active power from the wind turbine down from 100% to 20% of rated power in less than 5 seconds. This functionality is required for system protection schemes. Some system protection schemes implemented for stability purposes require the active power to be restored within short time after down regulation. For that reason disconnection of a number of wind turbines within a wind plant cannot be used to fulfil this requirement.	The wind farm is required to increase/decrease the active power as a function of the rise/decrease of the frequency, according to Figure 15. Besides, depending also on the bus bar voltage, the disconnection time settings allowed are defined in Figure 16. The wind farms low frequency protections must be in coordination with the load shedding scheme of the Spanish power System. Therefore wind farms will only disconnect in case of grid	All Plant (irrespective of type) must automatically de-load at a minimum rate of 2% of output for each 0.1Hz increase in System Frequency above 50.4 Hz (ie a minimum droop of 10%). Generators are responsible for protecting their plant from damage should frequency excursions outside the range 52Hz occur. Should excursions occur it is up to Generators to decide whether to disconnect the Generating Plant for reasons of safety of Plant

	frequency returns to a value of f ≤ 50.05 Hz, the active power output may be increased again as long as the actual frequency does not exceed 50.20 Hz. This control is realized in a decentralized manner (at each individual generator). The neutral zone must be below 10 mHz. If required, the TSO may determine different values for the over-frequency and active power gradients.		frequency drops below 48 Hz during, as a minimum, 3 s. Over frequency protections are allowed to disconnect the wind farm sequentially if frequency raises over 51 Hz	and personnel.

Table 6 – Reduction due to over frequency and reduction for protection schemes



$$\Delta P = 20\,P_m \frac{50.2\,Hz - f_{network}}{50\,Hz} \quad \text{at } 50.2\text{ Hz} < f_{network} < 51.5\text{ Hz}$$

P_m instantaneously available power

ΔP power reduction

$f_{network}$ network frequency

within the range of 47.5 Hz < $f_{network} \leq$ 50.2 Hz no limitation

at $f_{network} \leq$ 47.5 Hz and $f_{network} \geq$ 51.5 Hz disconnection from the grid

Figure 14 – Active power reduction of wind farms in the case of over-frequency

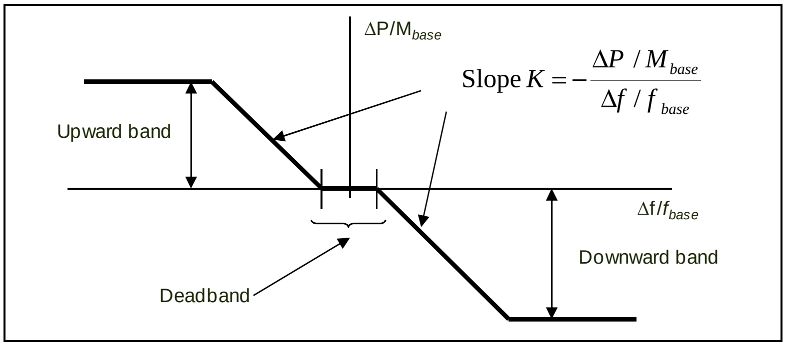


Figure 15 – Active power control based on frequency variation (Spain)

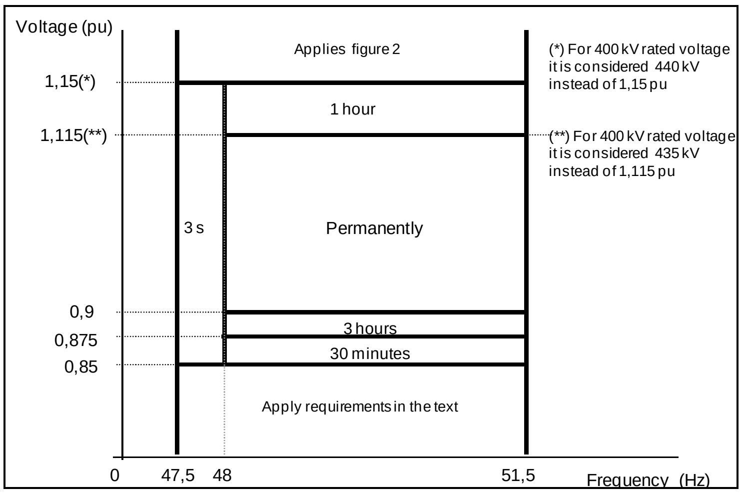


Figure 16 – Disconnection time settings (Spain)

	Germany	Nordel	Spain	Great Britain
Active Power --- Frequency control	Generating units using renewable energy sources may be exempted from the requirement to be capable of operation under primary control.	Automatic control of the wind turbine active production as a function of the system frequency must be possible. The control function must be proportional to frequency deviations and must be provided with a dead-band. The detailed settings will be provided by the TSO.	The wind farm is required to increase/decrease the active power as a function of the rise/decrease of the frequency, according to Figure 15. The slope of the Pf control, K, must be adjustable. The power response will be adjustable, in terms of speed, until a 10% of the rated apparent power per second. This speed might be lower in case of agreement with SO. The wind farm must maintain the ΔP required by the Pf	All Generating Plant including Power Park Modules are required to have a frequency response capability. This requires Power Park Modules to provide 10% Primary Response (ie 10% of Power Park Module Registered Capacity to be provided in 10 seconds and sustainable for 30 seconds), 10% Secondary Response (ie 10% of Registered Capacity to be provided in 30

			control at least during 15 min. The wind farm will be able to adjust the deadband between ±10 mHz and ±200 mHz. If the voltage drops below 0.85pu, the Pf control can be disabled temporarily. SO may require different upwards/downwards reserves and the plant must inform the SO about the available reserves in each moment. The wind farm will modify its production according to the available wind resource in order to assure upward reserve. The wind farm is exempted from providing upwards reserve in case its production is below 20%. In case the wind farm cannot supply this control, it can be supplied by other power plant "outsourced" by the wind farm under mutual agreement.	seconds and sustainable for a further 30 minutes) and 10% High Frequency Response (ie 10% of Registered Capacity to be provided within 10 seconds indefinitely or until instructed by the System Operator). See Figure 17 below.

Table 7 – Frequency control

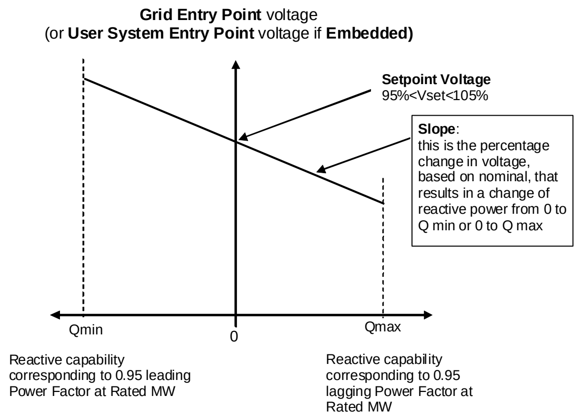


Figure 17 – Onshore Wind Farm Module (Great Britain)

2.3 Identification of possible risks in the transmission network in Germany

In Germany, the use of electricity networks is based in the regime of *regulated grid access*. The current Transmission Code 2007 [38] considers the new conditions in terms of energy policy resulted from the refinement of the Transmission Code 2003 which was formulated on the basis of *negotiated grid access*.

Operators of transmission networks are required to maintain a secure, reliable and efficient electricity network. Therefore, the technical rules laid down in the Transmission Code are based on a disturbance-free operation of the transmission grid and on the control of disturbances, granting at the same time access to the grid in a non discriminative manner. The TSOs ensure the complete acceptance of electricity from renewables-based plants into their networks and a Germany-wide distribution in accordance with the Renewables Energy Sources Act (EEG).

In order to be able to identify possible risks or disturbances in the transmission network and request appropriate adjustments the TSO needs to obtain information from distribution networks and from producers/end-use customers directly connected.

2.3.1 Identification of risks the day before

The identification of risks is based on data for the following day(s) and on calculations carried out in accordance with Table 8 [38]:

	Information	Update interval	Responsible party
Generating plants according to the EEG	▪ Installed capacity of all generating plants. ▪ Available capacity of generating plants with online data recording. ▪ Wind forecast and resulting forecast of electricity feed-in from wind energy plants (forecasted generation management included)	▪ Annually ▪ Annually ▪ Daily	▪ DSO ▪ Power Plant Operator ▪ TSO

Table 8 – Data and calculations enabling risks to be identified

2.3.2 Identification of risks or disturbances on the same day

It is based on the supervision of data and the implementation of calculations according to Table 9 [38]:

	Information	Responsible party
Renewables based generating plants according to the EEG.	▪ Updated wind forecast and the resulting forecast of electricity feed-in from wind energy plants. ▪ Current extrapolations on electricity feed-in from wind energy plants based on timely recorded feed-in from renewables- based reference plants within the control area. ▪ Online data feed-in into the transmission grid and distribution networks, i.e. power values from renewables-based plants with injection management or remote-control existing at their point of connection.	▪ TSO ▪ TSO ▪ Power Plant Operator

Table 9 – Data and calculations enabling risks to be identified the same day

2.4 Requirements upon generating units using renewable energy sources

In the case of wind energy plants, the installed capacity of an entire wind farm is to be considered as nominal capacity. Generating units using renewable energy sources must be controllable in terms of active power output according to the requirements of the TSOs with a view to counteracting a risk or disturbance of the system balance. It must then be possible to reduce the power output under any operating condition and from any working point to a maximum power value (target value) defined by the network operator. This target value is given by the network operator at the grid connection node and corresponds to a percentage value related to the network connection capacity. The reduction of the power output to the signalized value must take place with at least 10% of the network connection capacity per minute without disconnection of the plant from the network.

All renewables-based generating units must reduce, while in operation, at a frequency of more than 50,2 Hz the instantaneous active power with a gradient of 40% of the generator's instantaneously capacity per Hertz (see Figure 14).

Generating units using renewable energy sources may be exempted from the requirement to be capable of operation under primary control.

In accordance with the capabilities of conventional generating units to interfere in the event of sudden power imbalances by means of network sectionalizing and islanding, and in order to contribute to network restoration, renewables-based generating facilities shall utilize control concepts which correspond to the latest stat of the art [38]. Deliveries of the TSO to the suppliers according to the EEG are implemented in the form of schedule-based deliveries through the existing balancing groups.

2.5 Summary chapter 2

During the last two decades wind power was considered a non controllable energy source fully dependent on unstable weather conditions. In this chapter current grid codes from Germany, Denmark, Spain and Great Britain were analyzed and their technical requirements for active power control with wind farms categorized described and compared.

The next chapter addresses the technical requirements from primary and secondary frequency control comparing the control parameters from different power systems. Finally, the frequency control problem and their control actions are analyzed.

3. Power reserve and frequency control

3.1 Introduction

Frequency deviations should remain within certain limits to avoid blackouts or damaged equipment. To ensure this, ancillary services for balance management have been introduced. In the ENTSO-E interconnection, these ancillary services consist of primary, secondary, tertiary, time control and scheduling and accounting.

Primary Control

Primary control is performed decentralised. Each participating generator has a proportional controller which increases the power output of a generator if the frequency is below the nominal value. Vice versa, the power output will be decreased if frequency is above the nominal value. Primary control acts fast (within 30 seconds), stops the frequency deviation and holds the frequency at a commonly called quasisteady-state frequency deviation. Participation in primary control can be either obliged or stimulated with economic incentives [4].

Secondary Control

After primary control stabilises the frequency, secondary control restores the frequency from its quasi-steady-state frequency deviation to its nominal value. Therefore secondary control is based on a proportional integral controller activated per control zone. Secondary control is slower (within 900 seconds) than primary control and in liberalised markets based on a market for control power [4].

Primary, secondary and tertiary control are activated subsequently. This sequence is displayed in Figure 18.

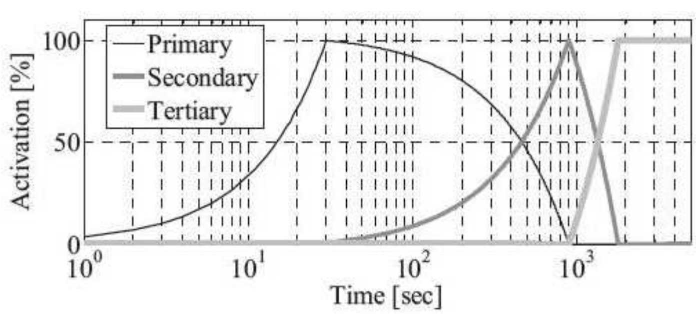


Figure 18 – Subsequent deployment of primary, secondary and tertiary reserve

It can be concluded that each type of control power has a specific deployment time, capacity and increase rate. The specifications for primary and secondary control are stated in Table 10. Next to these technical specifications, each type of control power has a price for being available and a price for the actual deployment [51].

	Primary	Secondary
Deployment time	30 seconds	15 minutes
ENTSO-E capacity	3000 MW	5700 MW[7]
Ramping rate	200%/min	7%/min
Activation duration	< 15 min	Not specified

Table 10 – Characteristics of primary and secondary reserve capacity

3.2 Frequency control: problem analysis

As a result of high penetration levels of wind power into the European grids, and also expecting that these levels will be even higher in the coming years due to the European Union targets regarding renewable energies [1], wind power is being requested by TSOs to meet the same grid stability and grid codes requirements as conventional power plants, including balancing procedures and frequency regulation facilities.

In any electrical system, active power has to be generated at the same time as it is consumed, keeping a constant equilibrium between consumed and generated power in order to keep the system stability. Frequency falls when demand is greater than generation and rises when generation is greater than demand. In order to manage frequency effectively, system operators utilize a range of balancing services that operate over different time horizons.

System frequency deviations are caused by unexpected unbalances between generation and demand, and are of particular concern in systems where the ratio of potential variation caused by fluctuating wind in relation to the total amount of generated energy is high. These deviations could activate a significant share of primary power reserves. A further increase of these phenomena, for example due to high wind power penetration into the grids, could create frequency deviations large enough to activate the complete available primary power reserves reducing the security margins for frequency control and putting into question the adequacy of primary reserves to limit frequency variations, and secondary reserves to restore frequency variations. Up to now an adequate frequency

[7] 5700 MW is the sum of all control zones individual available secondary control capacity. The individual capacities are based on maximum load values of the ENTSO-E.

control[8] depends on conventional generation resources made available by generation companies to TSOs for this specific porpoise [5].

To cover sudden unplanned disturbances that may occur in the system, TSOs procure sufficient dynamically available operating power reserve in order to secure the system with the largest acceptable losses of generation and demand. Still based on conventional generation, needed volumes of primary, secondary and tertiary power reserve have been typified and calculated by TSOs since many years ago in a reliable way.

The network power frequency characteristic describes the real dependency between system frequency and power imbalance with a linear approximation. In order to ensure that the principle of joint action is observed, the network power frequency characteristic of the various control areas is taken to remain as constant as possible. The set point frequency defines the target value of the system frequency for the system operation. Outside periods for the correction of synchronous time, the nominal frequency value in the synchronous area is 50 Hz [17].

As is shown in Figure 19, in case of a loss of generation causing a frequency drop each control area will maintain its interconnections with adjoining control areas, provided that the secure operation of its own system is not jeopardized.

[8] Control actions are performed in different successive steps, each with different characteristics and qualities and all depending on each other:
Primary control: starts within seconds as a joint action of all undertakings involved.
Secondary control: replaces primary control after minutes and is put into action by the responsible undertakings/TSO only.
Tertiary control: frees secondary control by re-scheduling generation and is put into action by the responsible undertakings/TSOs.

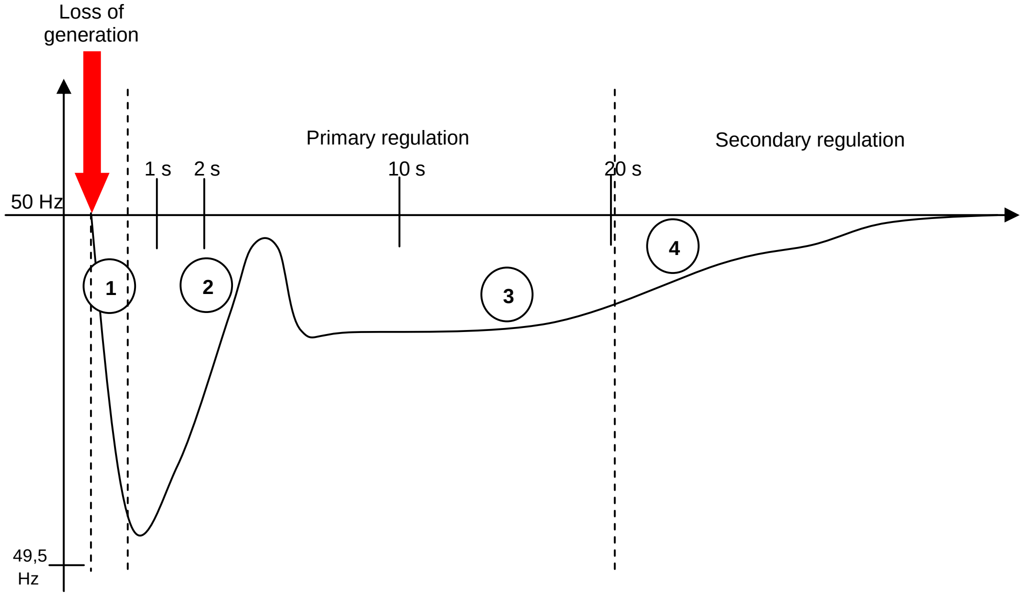


Figure 19 – Schematic view of an under-frequency event due to a generation loss.

1- Power provided by the inertial reserve of the system by the frequency reduction.
2- Generation increase and frequency recovery by the primary regulation.
3- Frequency stabilization by primary regulation.
4- Generation increase and definitive frequency recovery due to secondary regulation.

This deviation in the system frequency will cause the primary controllers of all generators subject to primary control to respond within a few seconds. The controllers alter the power delivered by the generators until a balance between power output and consumption is re-established. As soon as the balance is re-established, the system frequency stabilizes and remains at a quasi-steady-state value, but differs from the frequency set-point because of the droop of the generators which provide proportional type of action. Consequently, power cross-border exchanges in the interconnected system will differ from values agreed between companies. Secondary control will take over the remaining frequency and power deviation after 15 to 30 seconds. The function of secondary control is to restore power cross-border exchanges to their (programmed) set-point values and to restore the system frequency to its set-point value at the same time [12].

3.3 Power equilibrium and system frequency control

The physical properties of the electricity mean that it is essential to keep the frequency[9] of the European system within a range from 49,99 Hz to 50,01 Hz. ENTSO-E[10] is the body responsible for the co-ordination of the development of the European interconnected system, known as synchronous area[11] and also for defining how the various system operators belonging to the European interconnected system are able to achieve the needed frequency control. It demands that each of the interconnected European countries maintains a frequency level within the already mentioned range. If frequency deviates substantially from 50 Hz, a significant proportion of grid users will be no longer be able to inject electricity into or take electricity from the system, which would cause grid instability, which may degenerate into a blackout.

Since power grids are subject to both injections and off takes of energy, it is inevitable that there will be imbalances between generation and consumption. Such imbalances have an impact on the frequency level, making ongoing frequency control necessary to avoid the grid becoming unstable. Any major variation in the frequency level can very quickly spiral out of control [11], as the size of the variation has a direct effect on how fast the grid becomes unstable.

The generation of power units connected to the ENTSO-E network needs to be controlled and monitored for secure and high-quality operation of the synchronous areas. The generation control, the technical reserves and the corresponding performance measurements are essential to allow TSOs to perform daily operational business. Control actions which are described into the ENTSO-E's "Operation Handbook" [17], are performed in different successive steps, each with different characteristics and qualities, and all depending on each other:

[9] System frequency is the electric frequency of the system that can be measured in all network areas of the synchronous area under the assumption of a coherent value for the system in the time frame of seconds (with minor differences between different measurement locations only). The set point frequency for the synchronous area is 50 Hz [18].

[10] European Network of Transmission System Operators for Electricity (www.entsoe.eu)

[11] A synchronous area is an area covered by interconnected systems whose control areas are synchronously interconnected with control areas of members of the association. Within a synchronous area the system frequency is common on a steady state. A certain number of synchronous areas may exist in parallel on a temporal or permanent basis. A synchronous area is a set of synchronously interconnected systems that has no synchronous interconnections to any other interconnected systems [18].

- Primary control: starts within seconds as a joint action of all undertakings involved.
- Secondary control: replaces primary control after minutes and is put into action by the responsible TSOs only.
- Tertiary control: frees secondary control by re-scheduling generation and is put into action by the responsible TSOs.
- Time control: corrects global time deviations of the synchronous time in the long term as a joint action of all TSOs.

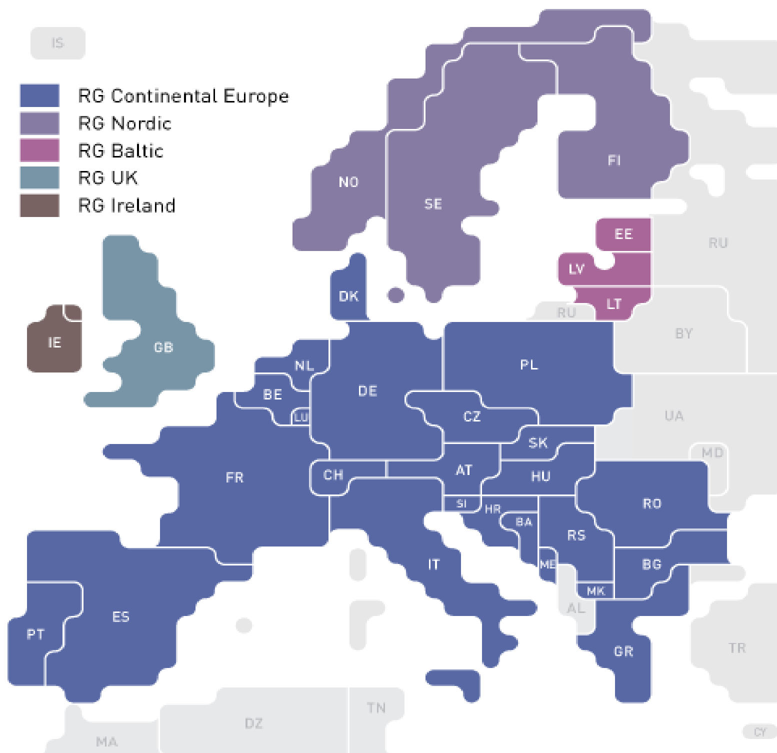


Figure 20 – ENTSO-E network

Regional group	Participating countries
Continental Europe	Austria, Belgium, Bosnia-Herzegovina, Bulgaria, Czech Republic, Croatia, Denmark (West), France, FYROM, Germany, Greece, Hungary, Italy, Luxemburg, Montenegro, Nederland, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain and Switzerland.
Nordic	Denmark (East), Finland, Norway and Sweden
Baltic	Estonia, Latvia, Lithuania
UK	Great Britain
Ireland	Ireland, Great Britain

Table 11 – ENTSO-E Participant countries by regional group

The maximum instantaneous deviation between generation and demand in the synchronous area (by the sudden loss of generation capacity, load shedding/loss of load or interruption of power exchanges) to be handled by primary control starting from undisturbed operation depends on the size of the area and on the size of the largest generation unit or generation capacity connected to a single bus bar located in that area.

There are three types of operating conditions considered [17]:

- Normal condition: $\Delta f \leq 50$ mHz
- Impaired condition: 50 mHz < $\Delta f \leq 150$ mHz
- Severely impaired condition: $\Delta f > 150$ mHz

In the impaired condition there are no major risks, provided that control facilities in the affected areas are ready to deployment. During the severely impaired conditions there are significant risks of the malfunction of the interconnected network. The accuracy of frequency measurements will depend upon the objective associated with the process in which frequency is to be use as a parameter. In the case of load shedding, accuracy of 50 –100 mHz will generally suffice for relay trip thresholds. The synchronous time is defined by Equation 1:

$$t = \frac{1}{f_0} \int f(t)dt \quad \text{Where } f_0 = 50 \text{ Hz.}$$

Equation 1 – Synchronous time definition

Finally, as it is also stated into the ENTSO-E's "Operation Handbook" [17], the discrepancy between synchronous time and universal co-ordinated time must not exceed ± 30 seconds. The Launfenbourg control centre in Switzerland is responsible for the calculation of synchronous time and the organization of its correction. Correction involves the setting of the set point frequency (i.e. 50 Hz) for secondary control in each area at 49.99 Hz or 50.01 Hz, depending upon the direction of correction, for periods of one day. Frequency thresholds must be defined for load shedding. It is recommended that members of ENTSO-E should initiate the first stage of automatic load shedding in response to a frequency threshold no lower than 49 Hz. The quality of frequency will be regarded as satisfactory over a one month period where the standard deviation for 90% and 99% of measurement intervals is less than 40 mHz and 60 mHz respectively for the whole month considered. The number of days operation at a set point frequency of 49.99 or 50.01 Hz does not exceed eight days per month respectively.

3.4 Primary control reserve

The primary control reserve is the positive-negative part of the primary control range measured from the working point prior to the disturbance up to the maximum primary control power. The concept of the primary control reserve applies to each generator, each control area and the entire synchronous area.

In general it must be physically distributed as evenly as possible between the different regions in the synchronous area. The total primary control reserve (in MW) required for the operation of the synchronous area is of the same size as the reference incident for that area. In total and as minimum, the full primary control reserve for each area must be available continuously without interruption, not depending on the unit commitment in detail [18].

3.4.1 Characteristics

As it is described in the ENTSO-E “Operation handbook” [17], primary control is based on the principle of joint action to ensure system reliability and interconnected operation. This includes an overall distribution of reserves and control actions, as determined and decided by the ENTSO-E. Each control area must contribute to the primary control reserve as required. The respective shares are defined by multiplying the calculated reserve for the entire synchronous area and the contribution coefficients of the various control areas. The sum of all shares must amount to the total primary control reserves. The contribution coefficients must be determined and published annually for each control area, binding for the corresponding TSO for one calendar year. They are based on the share of the energy generated within one year in relation to the entire synchronous area. The sum of all contributions coefficients must amount to 1.

The primary control power must be delivered until the power deviation is completely offset by the secondary control reserve of the control area in which the power deviation has occurred (the minimum duration for the capability of delivery for primary control is 15 minutes). The time for starting the action of primary control is a few seconds starting from the incident. The deployment time for 50 % or less of the total primary control reserve is at most 15 seconds and from 50 % to 100 % the maximum deployment time rises linearly to 30 seconds (see Figure 21).

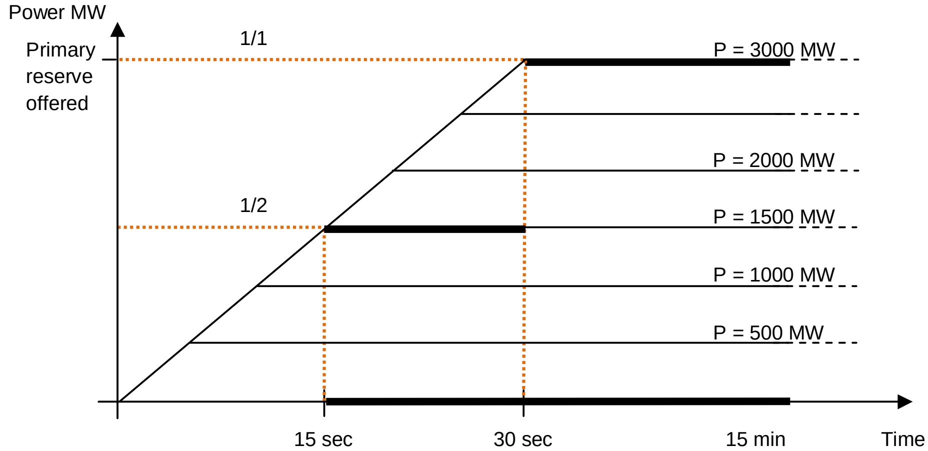


Figure 21 – Deployment times of Primary Control Reserve (Source: ENTSO-E)

Providing primary reserve is a measure required by ENTSO-E for implemented primary frequency control. ENTSO-E determines the overall volume of the European primary reserve and how the volume is distributed amongst the system operators. Within a specified time measured in seconds, the primary reserve is activated automatically by the facilities of the grid users which are providing this service.

The primary reserve's function is to avoid inadmissible frequency deviations. For this purpose, disturbances of the load balance especially due to breakdowns of big power units must be compensated within several seconds.

The contribution of a generator to the correction of a disturbance on the network depends mainly upon the droop of the generator and the primary control reserve of the generator concerned. The following Figure 22 shows a diagram of variations in the generating output of two generators "a" and "b" of different droop under equilibrium conditions, but with identical primary control reserves.

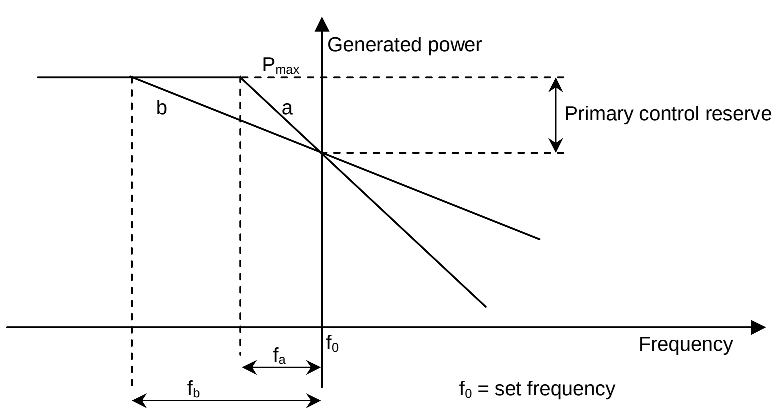


Figure 22 – Diagram of variations in the generating output of two generators

In case of a minor disturbance (frequency offset < Δf_b), the contribution of generator "a" (which has a controller with a smaller droop) to the correction of the disturbance will be greater than that of generator "b", which has the controller with the greater droop. The frequency offset (Δf_a) at which the primary control reserve of generator will be exhausted (i.e. where the power generating output reaches its maximum value P_{max}) will be smaller than that of generator "b" (Δf_b), even where both generators have identical primary control reserves.

In case of a major disturbance (frequency offset > Δf_b), the contributions of both generators to primary control under quasi-steady-state conditions will be equal [12].

3.4.2 Parameters for primary control

Currently the maximum instantaneous deviation ΔP between generation and demand to be corrected by primary control is 3000 MW. The quasi-steady-state frequency deviation must not exceed 100 mHz and instantaneous frequency must not fall below 49.2 Hz in response to a shortfall in generation capacity equal to or less than 3000 MW [19] [22].

Each control area contributes to primary control in accordance with its respective contribution coefficient described in Equation 2:

$$C_i = \frac{E_i}{E_u}$$

Equation 2 – Contribution coefficient from control areas

With:

- C_i: contribution coefficient.
- E_i: is the annual electricity generation of area "i".
- E_u: is the total sum of annual electricity generation in all control areas comprised within the zone of synchronous operation.

The primary control main characteristics are[12]:

- Provided in a way of solidarity by all synchronously connected TSOs inside the ENTSO-E area.
- To be activated within 30 seconds.
- Time period per single incident 0 < t < 15 minutes.

[12] Considering Germany as the country reference [24].

In case of a steady-state frequency deviation, a generator participating in the primary control will change its power output according to the droop S_G defined below [24]:

$$S_g = -\frac{\Delta f \,/\, f_n}{\Delta P_G \,/\, P_n}$$

Equation 3 – Change of power output from a generator participating in primary control

With:

- ΔP_G being the steady-state change in generation.
- P_n being the nominal output power.
- Δf being the steady-state frequency deviation.
- f_n being the nominal frequency.

The resulting control scheme is described in Figure 23 considering that the power system being represented has inertia. The primary frequency control consists in a proportional action on primary control power of generating units, in addition to the supplied scheduled and secondary power control. The performance of primary frequency control is linked with a set of parameters like: the deployment time, the droop of generators, the frequency deviation for which the entire reserve is used or the insensitivity of controllers [24]. The primary frequency control parameters for different power systems which are included Table 12 are the following:

- Full availability.
- Deployment end.
- Frequency characteristic requirement.
- Droop of generators.
- Accuracy of the frequency measurement.
- Controller intensity.
- Full deployment for or before a deviation.

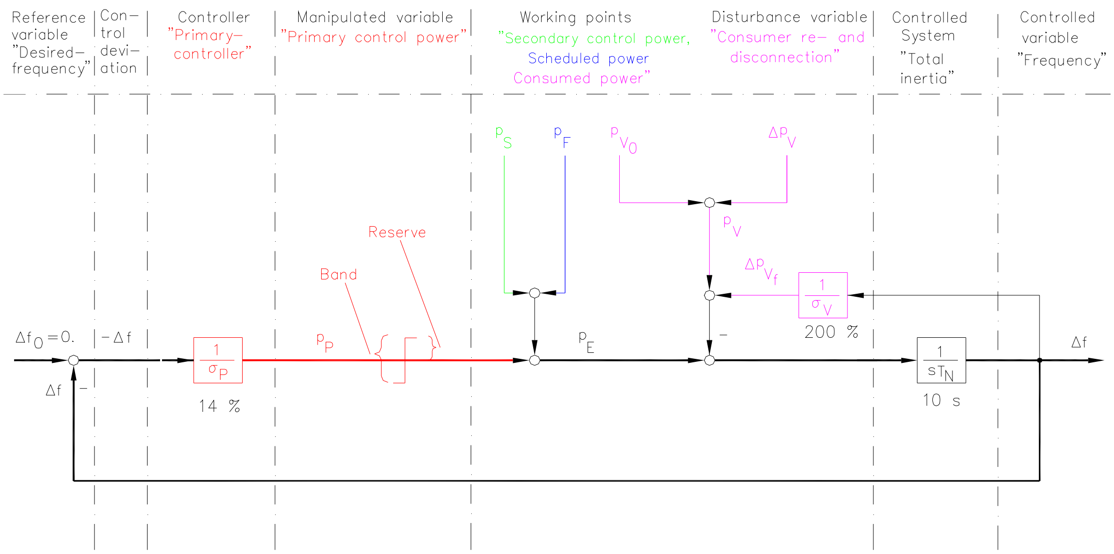


Figure 23 – Primary frequency control scheme [24]

	NERC[13]	ENTSO-E	DE	FR	ES	NL	BE	GB
Full availability	No rec.	≤ 30 s	≤ 30 s	≤ 30 s	≤ 30 s	≤ 30 s	≤ 30 s	Pri.: ≤ 10 s Sec.: ≤ 30 s Hi.: ≤ 10 s
Deployment end	No rec.	≥ 15 min	≥ 15 min	≥ 15 min	≥ 15 min	≥ 15 min	≥ 15 min	Pri.: ≤ 30 s Sec.: ≤ 30 min Hi.: as long as required
Frequency characteristic requirement	10% of the balancing authority's estimated yearly peak demand/Hz	20,570 MW/Hz	≈ 4,200 MW/Hz	≈ 4,200 MW/Hz	≈ 1,800 MW/Hz	≈ 740 MW/Hz	≈ 600 MW/Hz	Variable ≈ 2,000 MW/Hz
Droop of generators	5% in 2004; no rec. anymore	No rec.	No rec.	3-6%	≤7,5	5 – 60 MW: 10% > 60 MW: 4-20%	No rec.	3-5%
Is an adjustable droop compulsory?	No rec.	No rec.	Yes	Yes	No rec.	5 – 60 MW: No rec. > 60 MW: Yes	No	Yes
Accuracy of the frequency measurement	No rec.	Within ± 10 mHz	Within ± 10 mHz	No rec.	No rec.	No rec.	Within ± 10 mHz	No rec.
Controller intensity	T: ±36 mHz in 2004; no rec. anymore. NI: No rec. I: No rec.	T: ±10 mHz. NI: No rec. I: Should be compensated within the zone.	T: ±10 mHz NI: No rec. I: ± 10 mHz	T: ±10 mHz. NI: No rec. I: Should be compensated within the zone.	T: ±10 mHz NI: No rec. I: ± 10 mHz	5 – 60 MW: T: ±150 mHz; NI: no rec.; I: No rec.; > 60 MW: T: ±10 mHz;, NI: ±10 mHz, I: ±0 mHz	T: 10 ±mHz NI: ±10 mHz I: no rec.	T: ±15 mHz NI: No rec. I: No rec.
Full deployment for or before a deviation of:	No rec.	± 200 mHz	± 200 mHz	± 200 mHz	± 200 mHz	5-60 MW: 30% for ± 150-200 mHz >60 MW: 70% for ± 50-100 mHz	± 200 mHz	Pri.: -800 mHz Sec.: -500 mHz Hi.: +500 mHz

No rec.: no recommendation – Pri., Sec. or Hi.: primary, secondary or high frequency response; I: international; NI: non international; T: total

Table 12 – Technical comparison of primary frequency control parameters [26]

13 NERC: North American Electric Reliability Corporation

The contracts for primary control power are awarded by taking cost aspects (demand rates of the bids) and the following conditions into consideration [20]:

- The generating units intended for providing the primary control power have the performance characteristics stated in the pre-qualification.
- The demand for primary control power put out to tender will be satisfied over the entire contract period.
- Aspects of system reliability have been taken into account by the locations of generation.
- Bid structures have been considered.

3.5 Secondary control reserve

Since all control areas contribute to the control process in the interconnected system, with associated changes in the balance of generation and consumption, an imbalance between power generation and consumption in any of them will cause power interchanges between individual control areas to deviate from the agreed / scheduled values (power interchange deviations). The function of secondary control (also known as load-frequency control or frequency power-control) is to keep or to restore the power balance in each control area and, consequently, to keep or to restore the system frequency to its set-point value of 50 Hz and the power interchanges with adjacent control areas to their programmed scheduled values, thus ensuring that the full reserve of primary control power activated will be made available again. In addition, secondary control may not impair the action of the primary control. These actions of secondary control will take place simultaneously and continually, both in response to minor deviations and in response to a major discrepancy between production and consumption (associated e.g. with the tripping of a generating unit or network disconnection).

All control areas provide mutual support by the supply of primary control power during the primary control process, only the control area affected by a power unbalance is required to undertake secondary control action for the correction. Consequently, only the controller of the control area, in which the imbalance between generation and consumption has occurred, will activate the corresponding secondary control power within its control area / block. parameters for the secondary controllers of all control areas need to be set such that, ideally, only the controller in the zone affected by the disturbance concerned will respond and initiate the deployment of the requisite secondary control power. within a given control area, the demand should be covered at all times by electricity produced in that area, together with electricity imports (under purchase contracts and/or electricity production from jointly operated plants outside the zone concerned). In order to maintain this balance, generation capacity for use as secondary control reserve must be available to cover power plant outages and any disturbances affecting production, consumption and transmission. Secondary control is applied to selected generator sets in the power plants comprising the control loop. Secondary control operates for periods of several minutes, and is therefore timely dissociated from primary control [12].

When consumption exceeds production on a continuous basis, immediate action must be taken to restore the balance between the two (by the use of standby supplies).

3.5.1 Characteristics

Thanks to the primary frequency action, the frequency stabilizes at a value different from its target value. Therefore, the secondary control must not only to restore frequency but also bring interchanges back to their target value. This action is performed by a controller for the whole control areas or for control blocks within this area.

This control is required to minimize the Area Control Error (ACE) which represents the area's unbalance and its contribution to primary frequency control (see Equation 4).

$$ACE = P_{meas} - P_{prog} + K_{ri}\left(f_{meas} - f_0\right)$$

Equation 4 – Area Control Error (ACE)[14]

With:

- P_{meas} being the measured value of the total power exchanged by the zone with other zones (positive in case of export).
- P_{prog} being the scheduled value of the total power exchanged by the zone with other zones.
- K_{ri} being the K-factor of the control area in MW/Hz.
- f_{meas} being the measured frequency.
- f_0 being the nominal frequency.

The action of secondary frequency control is commonly based on proportional-integral controllers so as to bring ACE to zero, as described in Figure 24. The controlled system takes into consideration the supplied primary control power.

[14] Written according to the ENTSO-E standards (with K_{ri} positive)

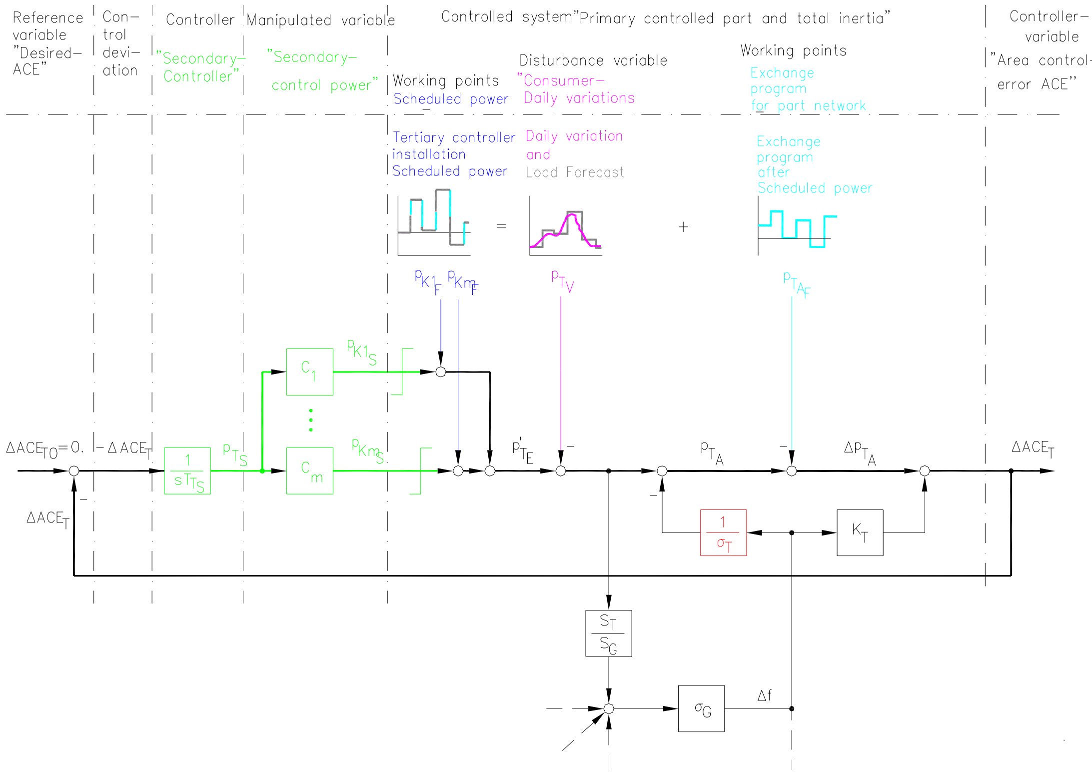


Figure 24 – Secondary frequency control scheme [24]

Each power system has its own set of parameters, as reported in Table 13. Secondary frequency control leads to the end of the primary frequency control.

	NERC[15]	ENTSO-E	DE	FR	ES	NL	BE
Deployment start	No rec.	≤ 30 s	Immediate or ≤ 5 min	≤ 30 s	No rec.	30 s-1 min	≤ 10 s
Full availability	No rec.	≤ 15 min	≤ 5 min	≤ 430 s or ≤ 97 s	≤ 300-500 s	≤ 15 min	≤ 10 min
Deployment end	No rec.	As long as required	As long as required	As long as required	≥ 15 min	≤ 15 min and as agreed	As long as required
Control organization	No rec.	No rec.	Pluralistic	Centralised	Hierarchical	Pluralistic	Centralised
Frequency measurements	ε ≤ 1 mHz T ≤ 6 s	1.0 ≤ ε ≤ 1.5 mHz T = No. rec.	1.0 ≤ ε ≤ 1.5 mHz T = 1 s	ε ≤ 1.0 mHz T = 1 s	ε = Unknown T = 2 s	ε ≤ 1.0 mHz T = 4 s	ε ≤ 1.0 mHz T: variable
Exchanges measurement	ε ≤ 1.3% T ≤ 6 s	ε ≤ 1.5% T ≤ 5 s	ε ≤ 1.5% T ≤ 1 s	ε ≤ 1.5% T ≤ 10 s	ε: Unknown T = 4 s	ε ≤ 0.5 % T = 4 s	ε ≤ 0.5 % T = variable
Controller cycle time	≤ 6 s	1 – 5 s	1 – 2 s	5 s	4 s	4 s	5 s
Controller type	No rec.	I or PI	PI	I	P or PI, depending on the regulation zone	PI, with additional heuristics	PI
Proportional term	No rec.	0-0.5	Unknown	0	Unknown	0.5	0-0.5
Integral term	No rec.	50-200 s	Unknown	115-180 s	100 s	100-160 s	50-200 s
K-factor for measuring the ACE	The frequency characteristic	110% of the frequency characteristic	Unknown	Unknown	Unknown	900 MW/Hz	≈660 MW/Hz

No rec.: no recommendations; ε: accuracy; T: cycle;
P, I or PI: proportional, integral and proportional-integral controller
Table 13 – Secondary frequency control features in different systems [26]

15 NERC: North American Electric Reliability Corporation

3.5.2 Parameters for secondary control

- To maintain the scheduled power exchange programme between the areas concerned and all other adjoining interconnected zones [19].
- To take over from the primary control reserve deployed by all members to offset an imbalance between generation and demand.
- To restore the synchronous system frequency to its reference value.
- Direct and automatic activation by the affected TSO.
- To be activated within 5 minutes.
- Time period per single incident: 30 s < t < 15 min.

Secondary control must begin within 30 seconds of the disturbance concerned. When the schedule exchange between control areas and adjoining areas is modified, the set point value of the interchange will be adjusted on the linear basis. If the loss of the largest generating unit supplying the area concerned is not covered by the secondary reserve of that area, provision must be made for an additional reserve which will offset the loss of capacity within the requisite time.

Each TSO is responsible for the maintenance of secondary control in its own control area. By means of a mathematical approach, the German TSOs determine the necessary volume of secondary control for their control areas in such a way that the defined residual risk probability of a power surplus or deficit that cannot be balanced is not exceeded [17]. In control areas of different sizes, load variations of varying magnitude must be corrected within approximately 15 minutes. To this end, the following minimum value (see Equation 5) for the secondary control reserve related to load variations is recommended for a control area:

$$R = \sqrt{a \cdot L_{\max} + b^2} - b$$

Equation 5 – Minimum value for secondary control reserve

With:

- R = the recommendation for secondary control reserve in MW.
- Lmax = the maximum anticipated load in MW for the control area.
- The parameters a and b are established with the following values by the ENTSO-E:

  a = 10 MW and b = 150 MW.

Contracts for secondary control power reserve are awarded separately according to whether the control direction is positive or negative. In addition to the costs (demand and kilowatt-hour rates), the following conditions are considered when deciding for a bid [20]:

- The generating units intended for providing the secondary control power have the performance characteristics stated in the pre-qualification.
- Adherence to the control power to be kept available while considering the total control speed required in each hour in the positive and negative directions.
- The daily control energy to be used and forecast will be met in both positive and negative directions.
- Bid structures have been considered.

3.6 Summary chapter 3

This chapter provides the present technical characteristics and definitions from primary and secondary power control, based on the ENTSO-E recommendations. The control parameters from different power systems are also compared while the problem analysis of frequency control is described.

The next chapter presents the developed methodology for power reserve provision with wind farms, considering as a framework the information and conclusions from chapter 2 and chapter 3.

4. Power reserve provision with wind farms

4.1 Introduction

Considering the relation between system frequency and power equilibrium, the technical characteristics of primary and secondary power reserve and the fact that traditional schemes regarding ancillary services are not directly transferable to wind power, a new concept is developed during this PhD addressing how wind power could provide power reserve, both positive and negative, in a stable and reliable way.

The main challenge is to overcome the natural fluctuating characteristic of wind power through a process which provides the structure and the needed data flow allowing wind energy to contribute with both, positive and negative power reserve, within a reliable framework regarding power availability and stability, as happens nowadays with conventional generation.

For wind power to provide power reserve, it would be required for all involved wind farms the same controllability level and connectivity than the conventional power generation. Therefore "Appendix III: Pre-qualification rules for wind farms" describes the requirements that wind farms should have to fulfil in order to be controllable and reliable enough to provide this kind of ancillary services. Considering that in some cases the needed technical requirements are already installed at wind farm level, several R&D tests have been carried out in real test fields in Germany and Portugal in order to demonstrate that currently wind power is controllable enough to provide positive and negative power reserve. These real tests and their scientific results are analyzed in Chapter 6 [29] as well as the technical capabilities of the involved wind farms [29] [36].

During this chapter existing barriers, available technologies and design parameters have been considered for the development of a methodology in order to allow wind power to provide primary and secondary power reserve in a secure, flexible and stable way.

In the algorithm from the proposed methodology it is included the use of wind power forecast and the lower boundary of its confidence interval, among other variables. A few definitions are provided in order to avoid possible misunderstandings with regard to the application of these concepts during this chapter.

For an effective management of the wind power input into the electricity supply systems, wind power forecasts are essential. They are either based on statistical forecasting methods using actual online power data or on the use of the outcome of numerical weather predictions. These methods are being studied and successfully developed since 1990, approximately.

The confidence interval estimates the error between the produced and predicted wind power. The lower level of the confidence interval is the one which is considered for wind power, as far as it will be available with the higher probability. Confidence intervals provide an estimation of the error linked to wind power predictions. Typically confidence intervals are calculated from about 90, 95 and 99%, also estimations with regard to the 100% accuracy are usually performed.

The use of the lower confidence interval from a given wind power forecast is requested by the proposed methodology. This allows, with a given degree of certainty, to know when and for how long how many MWs would be available to provide positive or negative power reserve.

4.2 Objectives of the developed methodology

The integration of large shares of fluctuating generation into the existing energy transmission and distribution systems requires a new strategy for the operational management of wind farms which should be equivalent (but not equal) to the strategies followed by the conventional generation power management. Some basic facts should be considered before addressing the objectives of the developed methodology and algorithm. The considered facts are described as following:

1. Considering the technologies available nowadays, wind power has the capability to be forecasted with a 98% level of accuracy in a time frame of 8 hours ahead [33] [73].
2. The “lower interval” from each forecast has to be considered as the reference forecasted power.
3. Wind farms should be prequalified in order to be able to provide ancillary services as happens nowadays with conventional generators.
4. Due to the needed time response, an automatic algorithm is needed to monitor and control the different steps until the power reserve is provided by the selected

wind farms. This algorithm may consider the interaction between the TSO, the wind farm operator and the wind farms SCADA system.

Finally, the objectives of the developed methodology are described as following:

1. Increase the power quality at low costs of those electrical systems which may have a strong penetration of wind power.
2. Allow a control of the grid in a more flexible and intelligent way, keeping the current security levels of the system requested by the TSOs.
3. Provide a secure and stable environment for all market participants to allow complex interactions between independent actors.
4. Promote the aggregation of wind farms into wind farm clusters [2] [4] in order to support the coordination between TSOs, dispatch centres, wind power producers and energy markets.
5. Promote the "multi layer control structure"[16] as the next step for large scale integration of wind power in order to allow wind farm clusters to be monitored and controlled in real time according to the TSO needs.
6. Provide a communication structure to coordinate the bidirectional data flow and to participate in the dynamics of the power market.
7. Encourage the needed changes in the current procedures in order to allow wind power to be integrated in a flexible and secure way into the ancillary services market.

4.3 Control system main concept definition

As the concept of "control system" is going to be strongly referred during the methodology development, a few definitions of commonly used terms regarding "control systems" will help to avoid misunderstandings as well as locating the proposed solution within already well known schemas.

The terms for three general types of control - centralized, distributed and decentralized – are frequently used in an ambiguous way. They are distinguished by the flow of information between the location of data acquisition, the location of decision making and the location where an action is performed [56].

[16] TSO, RTO and DSO

In a fully centralised control system, data acquisition, decision making and the enhancement of decisions are concentrated in a single location (see Figure 25). In a centralised controller, data from all parts of the controlled system needs to be sent to the central unit for processing.

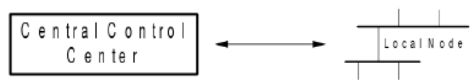


Figure 25 – Centralized control

A distributed control system refers to a collection of independent devices that appears to its users to be a single system [57]. It could be defined a distributed controller as centralized control with a decentralized execution stage. The difference is in the flow of information. In a distributed controller, data may be processed and e.g. reduced locally, supervised or remote-controlled by a central control unit (see Figure 26). This structure could be comparable with the structure existing between TSOs and dispatch centres where the information flows in a bidirectional way: TSO - Dispatch Centre - TSO. This is the implementation of a distributed control system where main information is supervised by the TSO and at the same time, the dispatch centres have a local independency with regard to the monitoring and management from their wind farms.

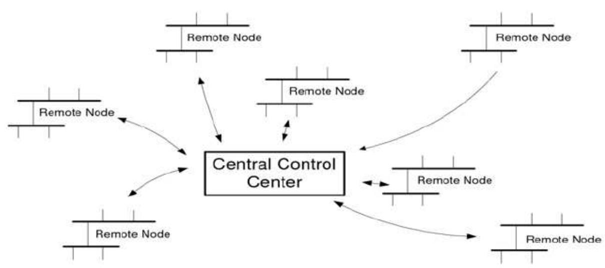


Figure 26 – Distributed control

In a decentralized controller, a problem is split into smaller ones that are solved locally, using local data. Then, information is shared between local distributed control centres to solve the larger problem (see Figure 27) [58]. This structure is similar than the structure existing at ENTSO-E level. Each TSO could be considered as “Decentralized Control Centre” with its own structure and control rules. At the same time each TSO has communication with its neighbour and exchange information. ENTSO-E coordinates this structure and receives some relevant information from the TSOs.

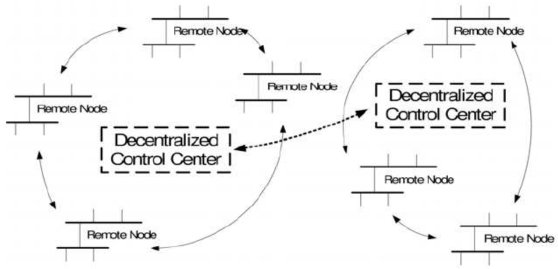


Figure 27 – Decentralized control

4.4 Methodology for providing power reserve with wind power

The developed methodology makes use of the advantages of the already described centralized and decentralized control systems, providing a two layers architecture (TSOs and dispatch centres) as well as giving the dispatch centres their own autonomy based on their own monitored and calculated data. It is also decreases the complexity of the control and decision making process with regard to the power reserve provision considering that a large volume of wind farms is expected to be able to participate in the power reserve provision markets.

This process is based on an 8 hours procedure where economical variables are considered as well as the stability of the offered power reserve, at wind farm level, is being monitored and evaluated according to the TSOs requirements. A schematic description is depicted in Figure 28.

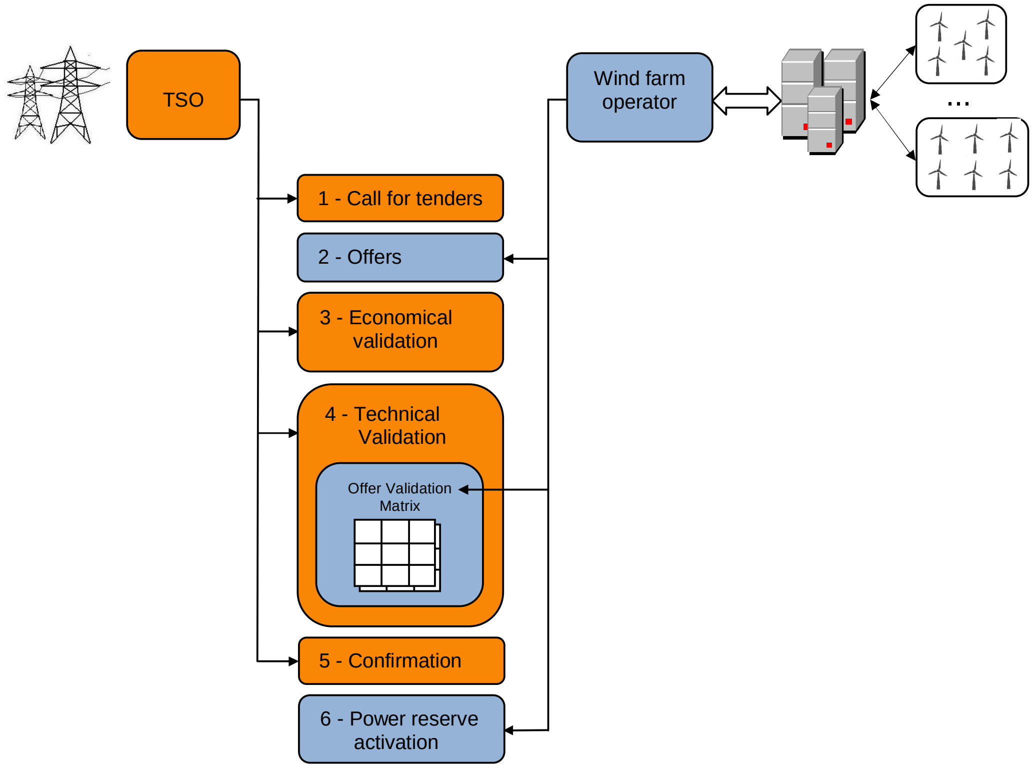


Figure 28 – Schema of the proposed methodology

Call for tenders: the needed power reserve volumes are published by the TSO one month in advance as it is described in Figure 29.

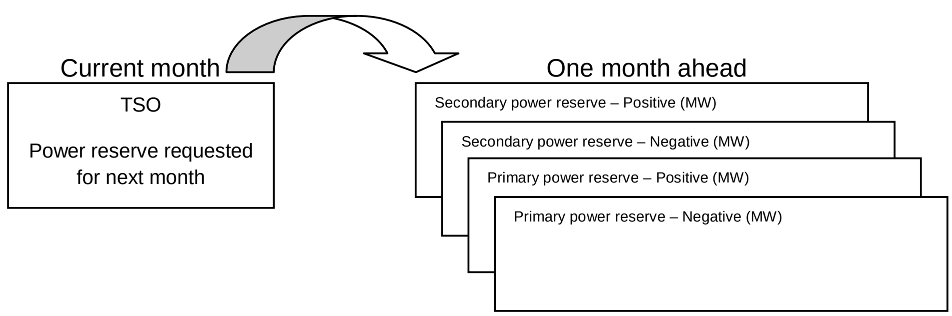


Figure 29 – Month ahead power reserve request

Tendering process: based on the requested power reserve volumes by the TSO, a “tendering process” would be opened every hour, 8 hours before the “Power Reserve Activation Time” (PRAT), as it is depicted in Figure 30. During these 8 hours tenders are posted, economically evaluated and finally their availability and stability is validated.

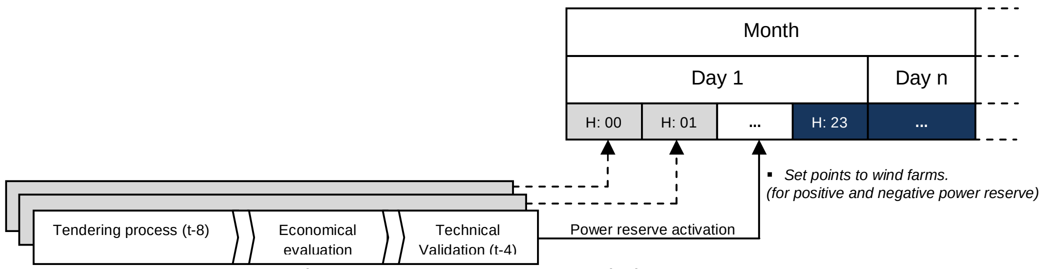


Figure 30 – Reserve power tendering process

As it is described in Figure 31 the “tendering process” takes place during the first four hours after the call for tenders is opened. During this period power reserve offers should be posted by each power producer based on prequalified wind farms.

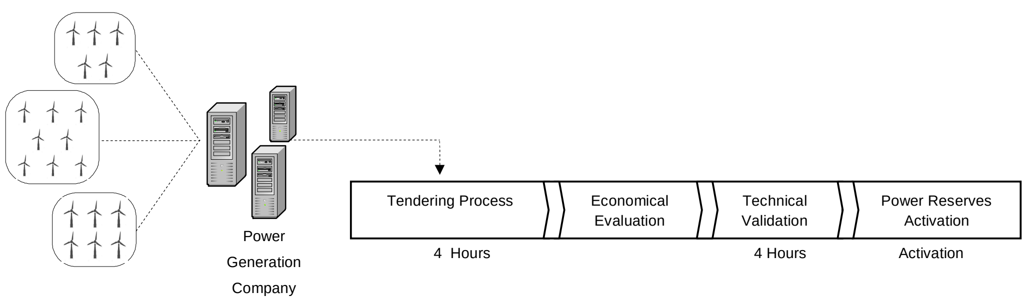


Figure 31 – Tender process

Economical evaluation: once the tendering process is closed, an economical evaluation of each offer is performed. This is a market oriented process where the economical variables of each offer are being considered allowing the TSOs to optimize and reduce costs concerning power reserve provision. Those successfully evaluated economical offers are going to be technically verified during the last four hours before the power reserve activation takes place.

Validation process: the objective is to evaluate the relation between “offered power” and “available power” during the last four hours before the power reserve activation takes place. This “offer stability” validation process considers an offer to be unstable when the offered power volume is bigger than the one reported by the Lower Interval (LI) from the wind power forecast for a given wind farm.

The “Validation Process” is performed through the “Offer Validation Matrix”, described in Table 14. Every hour the required updated information should be loaded by the wind farm operator or the dispatch centre. In order to evaluate the offer stability, two factors were developed during this PhD (“Hour Stability Factor” and “Offer Stability Factor”) considering as input data for them the information available in the “Offer Validation Matrix”. Based on these two factors all offers are monitored in an hourly basis as well as in a global concern regarding the whole offer and the power availability at the activation time.

Offer Validation Matrix						
Company	Wind farm	t-4	t-3	t-2	t-1	osf
Name	Offer type Install capacity Offered power Price (€)	f(P) LI (f(P)) --- hsf(t-4)	f(P) LI (f(P)) --- hsf(t-3)	f(P) LI (f(P)) --- hsf(t-2)	f(P) LI (f(P)) --- hsf(t-1)	

Table 14 – Offer validation matrix with a time frame horizon of four hours

f(P):	Forecasted active power for offered time frame
LI (f(P)):	Forecasted Lower Interval (LI) for offered time frame
hsf:	Hour Stability Factor
osf	Offer Stability Factor

Additionally to the already described schema, a weight factor was attached to each one of the four hours before the PRAT (see Table 15). The aim of this factor is to give a degree of relevance to each hour considering that potential fluctuations may occur during these hours and depending on when they occur, they could be more or less relevant with regard to the stability of the offer. This weight factor combined with the “hour stability factor” is being referred in Equation 7 by the “offer stability factor” calculation, which evaluates each offer as a whole based on the hourly evaluation described in Equation 6.

Time frame	t-4	t-3	t-2	t-1
Weigh factor (w)	0,25	0,50	0,75	1

Table 15 – Weigh factor

The two developed factors are explained as following:

- **H**our **S**tability **F**actor (hsf): evaluates the offer stability by each of the four hours previous to the power reserve activation. This factor indicates by each hour how stable the offer was keeping as a reference the offer time frame. It is based on the forecasted active power and on its Lower Interval (LI). As it is described in Equation 6 the "hsf" could have two possible values: 0 or 1, meaning with 0 that for a given hour the offer was not stable enough and with 1 that the offer was sufficient stable.

  The needed conditions for the "hsf" to report an offer to be stable are included into Equation 6 and described as following:

  1. For a given hour the Lower Interval from a wind power forecast should be lower than the forecasted power (as it always should be under normal conditions).
  2. The Lower Interval should be above 20% of the offered power reserve

$$\overbrace{f(P) - LI(f(P)) > 0}^{1} \wedge \overbrace{LI(f(P)) - 20\%(offer) > offer}^{2} \quad hsf = 1$$
$$\text{else} \quad hsf = 0$$

Equation 6 – Calculation of the "hsf"

- **O**ffer **S**tability **F**actor (osf): evaluates the complete offer based on the "hsf" results of each hour previous to the power reserve activation time and the hours weigh factor. As it is described in Equation 7, each offer would be evaluated at wind farm level considering its stability during the past four hours.

$$osf = hsf(t-4) * w(t-4) + hsf(t-3) * w(t-3) +$$
$$hsf(t-2) * w(t-2) + hsf(t-1) * w(t-1)$$

Equation 7 – Calculation of the "offer stability factor"

With regard to the result of Equation 7, an offer is considered stable enough if its final value is bigger than "2", representing that at least during the last 3 hours before the activation time of the offered power reserve from a given wind farm, the offer was always available.

4.5 Summary chapter 4

The developed methodology for providing power reserve with wind farms is described in this chapter. The aim of this methodology is to overcome the natural fluctuating characteristics of wind power and to increase the power quality at low costs allowing large volumes of wind power to be integrated into the grids in a secure way.

The methodology steps are addressed as well as the implementation of the “Offer Validation Matrix”, the “Hour Stability Factor” and the “Offer Stability Factor”.

The next chapter presents a validation of the described methodology based on real time series from 5 wind farm clusters.

5. Methodology validation for power reserve provision with wind farms

5.1 Introduction

In order to validate the methodology described in Chapter 4, two simulations of power reserve provision with wind power were carried out based on real wind farm clusters. More than 650 MW of install capacity were considered for the simulations development and the implementation of the developed methodology.

The behaviour of the power reserve stability validations during the different steps of the process was also analyzed as well as the effectiveness of the complete model with regard to its control capability and the possibility of wind power to provide power reserve in a stable and secure way.

Finally, it was studied the concrete capability of wind power to provide primary and secondary power reserve during one year. The analysis was performed based on the German wind power production time series from 2009 [62].

5.2 Description of the scenario for the methodology validation

The scenario considered during the simulations is based on five wind farm clusters (see Table 16) and its time frame can be described as following:

- Timeframe: between January 9th 21:00 and January 10th 04:00 (year 2007).
- The PRAT takes place between 04:00 and 05:00 on January 10th.
- After the economical evaluation, the technical validation process takes place between 00:00 and 04:00 from January 10th.

Wind farm cluster (WFC)	Install capacity (MW)
A	262,3
B	72,6
C	229,8
D	62
E	51,45
Total	**678,15**

Table 16 – Wind farm clusters for methodology validation

The considered time series from each wind farm cluster are described in Figure 32, Figure 33, Figure 34, Figure 35 and Figure 36. In each figure it is presented real power production, eight hours ahead forecast (indicated with red dots) and its Lower Interval (indicated with green dots).

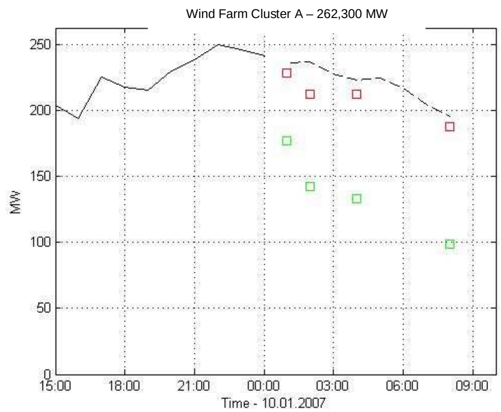


Figure 32 – Wind farm cluster “A”

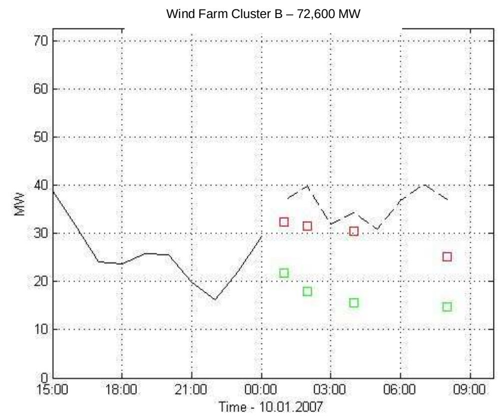


Figure 33 – Wind farm cluster “B”

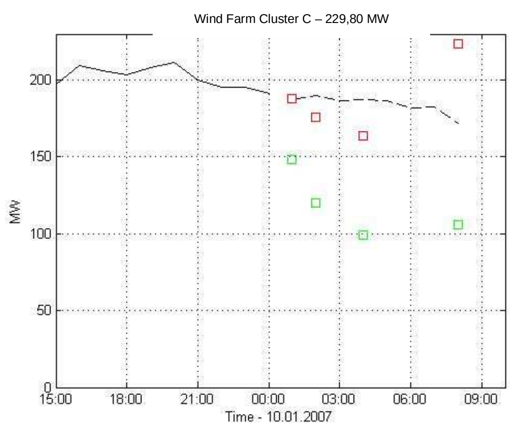


Figure 34 – Wind farm cluster “C”

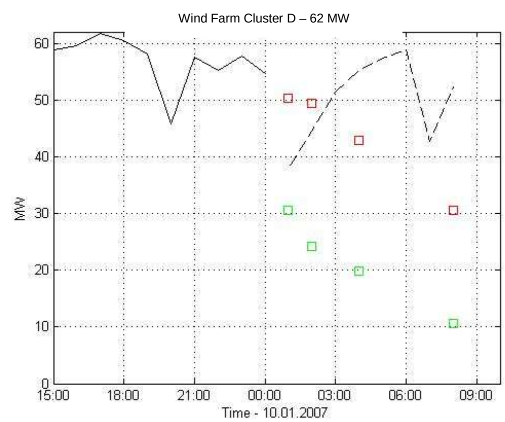


Figure 35 – Wind farm cluster “D”

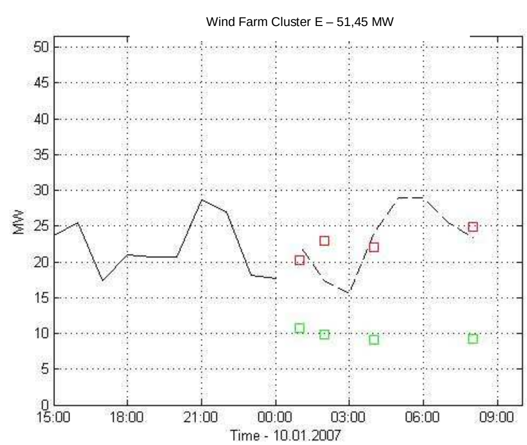


Figure 36 – Wind farm cluster “E”

References:

- Wind power forecast
- Lower Interval
- --- Produced active power
- — Produced active power

5.3 Simulation scenario based on 195 MW of positive power reserve

As it is described in Table 17, this simulation consists on a positive power reserve offer of 195 MW. Each offer is represented in Figure 37, Figure 38, Figure 39, Figure 40 and Figure 41.

Wind farm cluster (WFC)	Offered positive power reserve (MW)
A	100
B	10
C	70
D	10
E	5
Total	195

Table 17 – Positive power reserve offer during simulation 1

The “Offer Validation Matrix” was loaded during the simulation with real time series from the already described scenario. Each simulated offer was validated in an hourly basis by the “Hour Stability Factor” (see Equation 6). Just before the PRAT each offer as a whole was also evaluated at the end of the technical validation based on the “Offer Stability Factor” (see Equation 7).

As it is described in Table 18, during each one of the four hours before the PRAT, every wind farm has submitted its wind power forecast and lower interval to the “Offer Validation Matrix”. At the end of each hour, the “Hour Stability Factor” was calculated (see Table 19). This factor represents with “1” a stable offer and with “0” an unstable offer. As it can be seeing, during this first simulation all offers were below their lower intervals during the four hours before the PRAT. That means that the offered power reserve by each wind farm has been always guarantied.

Finally, in order to validate each offer as a whole, the “Offer Stability Factor” was calculated just before the PRAT (see Table 20). The “Offer Stability Factor” calculation considers the “Hour Weight Factor” and the “Hour Stability Factor” from each one of the four hours before the PRAT. According to the current values calculated during this study, it is considered as “acceptable” an unstable situation during the hour t-4 before the PRAT. Other potential unstable situations which may occur between the hour t-3 and t-1 before the PRAT would be considered unacceptable.

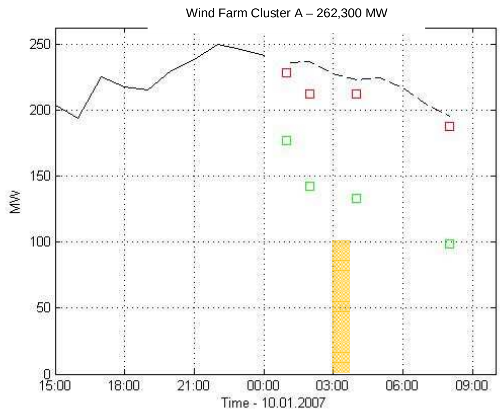


Figure 37 – Power reserve offer from WFC “A” (S1)

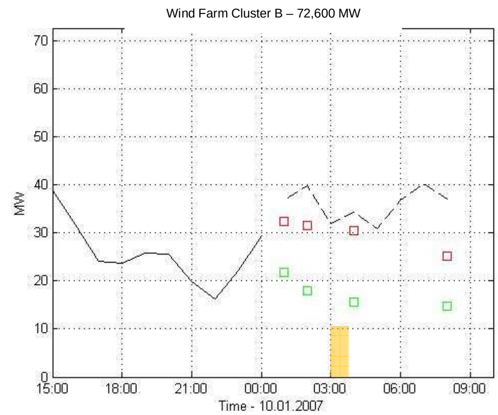


Figure 38 – Power reserve offer from WFC “B” (S1)

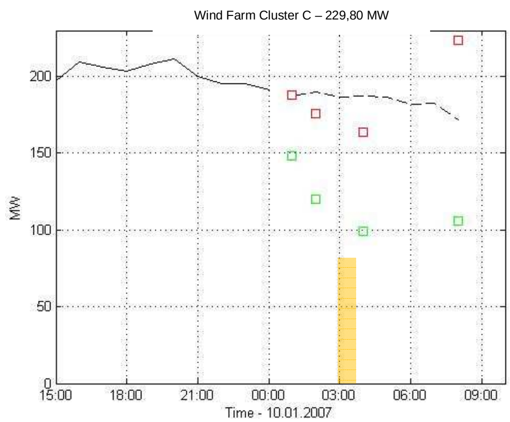


Figure 39 – Power reserve offer from WFC “C” (S1)

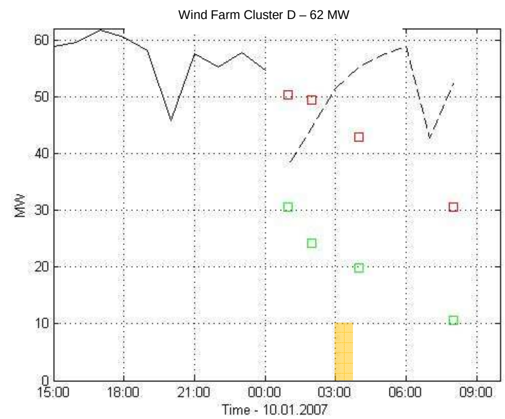


Figure 40 – Power reserve offer from WFC “D” (S1)

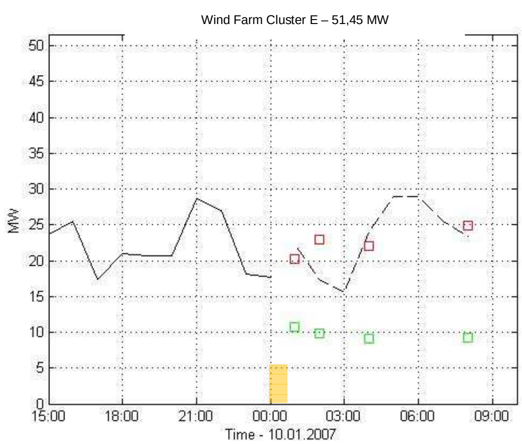


Figure 41 – Power reserve offer from WFC “E” (S1)

References:

- □ Wind power forecast
- □ Lower Interval
- --- Produced active power
- — Produced active power
- Offer

Offer Validation Matrix Power reserve activation: 10.01.2007 04:00 - 05:00					
Company	Wind farm cluster	t-4 (00:00 – 00:59)	t-3 (01:00 – 01:59)	t-2 (02:00 – 02:59)	t-1 (03:00 – 03:59)
---	WF Cluster "A" Primary reserve Positive Volume (MW): 100	f(P): **230 MW** LI (f(P)): **180 MW** --- hsf(t-4) = 1	f(P): **220 MW** LI (f(P)): **145 MW** --- hsf(t-3) = 1	f(P): **220 MW** LI (f(P)): **142 MW** --- hsf(t-2) = 1	f(P): **218 MW** LI (f(P)): **140 MW** --- hsf(t-1) = 1
---	WF Cluster "B" Primary reserve Positive Volume (MW): 10	f(P): **33 MW** LI (f(P)): **22 MW** --- hsf(t-4) = 1	f(P): **31 MW** LI (f(P)): **18 MW** --- hsf(t-3) = 1	f(P): **30 MW** LI (f(P)): **17 MW** --- hsf(t-2) = 1	f(P): **30 MW** LI (f(P)): **16 MW** --- hsf(t-1) = 1
---	WF Cluster "C" Primary reserve Positive Volume (MW): 70	f(P): **185 MW** LI (f(P)): **150 MW** --- hsf(t-4) = 1	f(P): **175 MW** LI (f(P)): **120 MW** --- hsf(t-3) = 1	f(P): **170 MW** LI (f(P)): **110 MW** --- hsf(t-2) = 1	f(P): **165 MW** LI (f(P)): **100 MW** --- hsf(t-1) = 1
---	WF Cluster "D" Primary reserve Positive Volume (MW): 10	f(P): **50 MW** LI (f(P)): **30 MW** --- hsf(t-4) = 1	f(P): **49 MW** LI (f(P)): **23 MW** --- hsf(t-3) = 1	f(P): **47 MW** LI (f(P)): **21 MW** --- hsf(t-2) = 1	f(P): **42 MW** LI (f(P)): **20 MW** --- hsf(t-1) = 1
---	WF Cluster "E" Primary reserve Positive Volume (MW): 5	f(P): **20 MW** LI (f(P)): **11 MW** --- hsf(t-4) = 1	f(P): **23 MW** LI (f(P)): **10 MW** --- hsf(t-3) = 1	f(P): **22 MW** LI (f(P)): **9 MW** --- hsf(t-2) = 1	f(P): **22 MW** LI (f(P)): **9 MW** --- hsf(t-1) = 1

Table 18 – Offer Validation Matrix after simulation 1

Table 19 describes how the "Hour Stability Factor" of each offer was calculated based on the available information at the "Offer Validation Matrix" (see Table 18). During this simulation the technical validation has shown that all offers were stable enough. The equation of the "Hour Stability Factor" (see Chapter 4, Equation 6), is the following:

$$f(P) - LI(f(P)) > 0 \wedge LI(f(P)) - 20\%(offer) > offer \quad hsf = 1$$
$$\text{else} \quad hsf = 0$$

	t-4	**t-3**	**t-2**	**t-1**
WFC A	230 - 180 > 0 **ok** 180 - 20 > 100 **ok**	220 - 145 > 0 **ok** 145 - 20 > 100 **ok**	220 - 142 > 0 **ok** 142 - 20 > 100 **ok**	218 - 140 > 0 **ok** 140 - 20 > 100 **ok**
WFC B	33 - 22 > 0 **ok** 22 - 2 > 10 **ok**	31 - 18 > 0 **ok** 18 - 2 > 10 **ok**	30 - 17 > 0 **ok** 17 - 2 > 10 **ok**	30 - 16 > 0 **ok** 16 - 2 > 10 **ok**
WFC C	185 - 150 > 0 **ok** 150 - 14 > 70 **ok**	175 - 120 > 0 **ok** 120 - 14 > 70 **ok**	170 - 110 > 0 **ok** 110 - 14 > 70 **ok**	165 - 100 > 0 **ok** 100 - 14 > 70 **ok**
WFC D	50 - 30 > 0 **ok** 30 - 2 > 10 **ok**	49 - 23 > 0 **ok** 23 - 2 > 10 **ok**	47 - 21 > 0 **ok** 21 - 2 > 10 **ok**	42 - 20 > 0 **ok** 20 - 2 > 10 **ok**
WFC E	20 - 11 > 0 **ok** 11 - 1 > 5 **ok**	23 - 10 > 0 **ok** 10 - 1 > 5 **ok**	22 - 9 > 0 **ok** 9 - 1 > 5 **ok**	22 - 9 > 0 **ok** 9 - 1 > 5 **ok**

Table 19 – "Hour stability factor" validation process during simulation scenario 1

Finally, once the technical validation process was finished, the “Offer Stability Factor” was evaluated considering the “Hour Stability Factor” as well as the “Weigh factor” of each hour. As Table 20 describes, all offers would have been activated on time and the 195 MW of positive power reserve would have been successfully provided.

	Offer Stability Factor	Value	Action
WFC A	1*0,25 + 1 * 0,50 + 1 * 0,75 + 1 * 1	2,5	Power reserve activated
WFC B	1*0,25 + 1 * 0,50 + 1 * 0,75 + 1 * 1	2,5	Power reserve activated
WFC C	1*0,25 + 1 * 0,50 + 1 * 0,75 + 1 * 1	2,5	Power reserve activated
WFC D	1*0,25 + 1 * 0,50 + 1 * 0,75 + 1 * 1	2,5	Power reserve activated
WFC E	1*0,25 + 1 * 0,50 + 1 * 0,75 + 1 * 1	2,5	Power reserve activated

Table 20 – Offer stability factor calculation after simulation 1

5.4 Simulation scenario based on 265 MW of positive power reserve

As it is described in Table 21, this simulation is based on a positive power reserve offer of 265 MW. Each offer is represented in Figure 42, Figure 43, Figure 44, Figure 45 and Figure 46.

Wind farm cluster (WFC)	Offered power (MW)
A	150
B	20
C	70
D	20
E	5
Total	265

Table 21 – Simulation scenario 2

The “Offer Validation Matrix” was loaded during the simulation with the available information from the already described scenario. Each simulated offer was validated in an hourly basis by the “Hour Stability Factor” (see Equation 6). Just before the PRAT, each offer as a whole was also evaluated at the end of the technical validation based on the “Offer Stability Factor” (see Equation 7).

As it can be seeing in Figure 42, Figure 43 and Figure 45, during this simulation the power reserve offers from wind farm cluster A, B and D were above of the Lower Interval from their wind power forecasts.

It can be observed in Table 23 how the “Hour Stability Factor” calculation indicates that those power reserve offers coming from wind farm cluster A, B and D are considered unstable. This evaluation can also be observed in the “hsf” value from the “Offer Validation Matrix” (see Table 22).

Finally Table 24 describes the “Offer Stability Factor” calculation. As it was described in Chapter 4, this factor is highly dependant on the “Hour Stability Factor” calculation, therefore considering the previous results of this evaluation, the unstable offers were rejected.

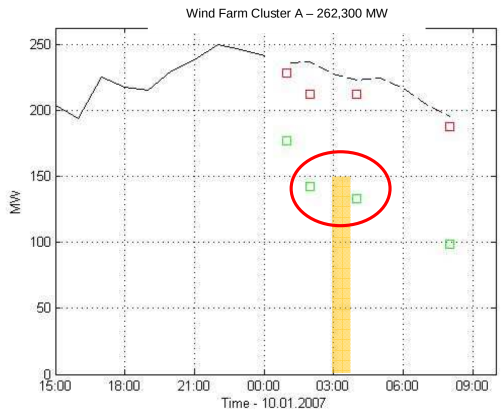


Figure 42 – Power reserve offer from WFC “A” (S2)

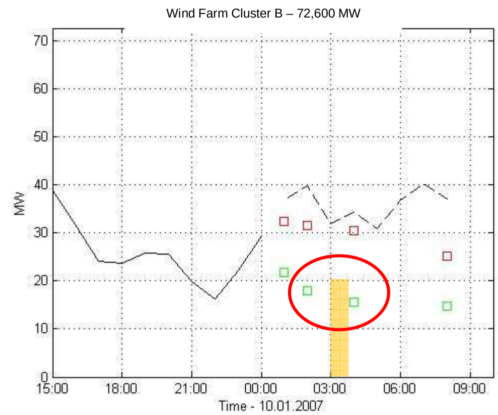


Figure 43 – Power reserve offer from WFC “B” (S2)

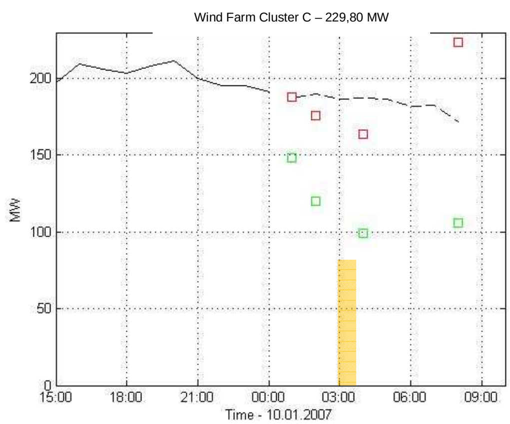


Figure 44 – Power reserve offer from WFC “C” (S2)

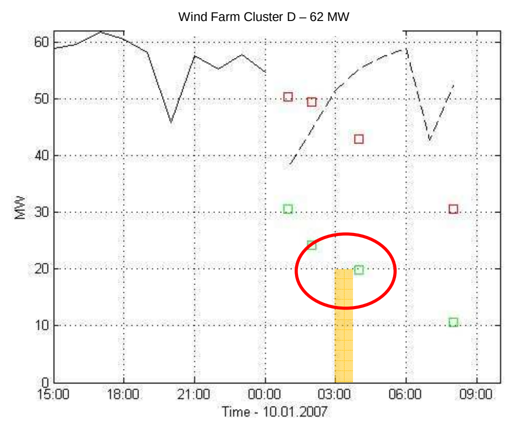


Figure 45 – Power reserve offer from WFC “D” (S2)

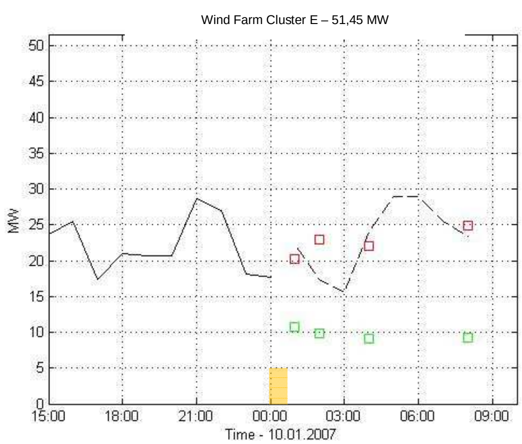


Figure 46 – Power reserve offer from WFC “E” (S2)

References:

- □ Wind power forecast
- □ Lower Interval
- --- Produced active power
- — Produced active power
- ▮ Offer

Offer Validation Matrix Power reserve time frame: 10.01.2007 04:00 - 05:00					
Company	Wind farm cluster	t-4 (00:00 – 00:59)	t-3 (01:00 – 01:59)	t-2 (02:00 – 02:59)	t-1 (03:00 – 03:59)
---	WF Cluster "A" Primary reserve Positive Volume (MW): 100	f(P): **230 MW** LI (f(P)): **180 MW** --- hsf(t-4) = 0	f(P): **220 MW** LI (f(P)): **145 MW** --- hsf(t-3) = 0	f(P): **220 MW** LI (f(P)): **142 MW** --- hsf(t-2) = 0	f(P): **218 MW** LI (f(P)): **140 MW** --- hsf(t-1) = 0
---	WF Cluster "B" Primary reserve Positive Volume (MW): 10	f(P): **33 MW** LI (f(P)): **22 MW** --- hsf(t-4) = 0	f(P): **31 MW** LI (f(P)): **18 MW** --- hsf(t-3) = 0	f(P): **30 MW** LI (f(P)): **17 MW** --- hsf(t-2) = 0	f(P): **30 MW** LI (f(P)): **16 MW** --- hsf(t-1) = 0
---	WF Cluster "C" Primary reserve Positive Volume (MW): 70	f(P): **185 MW** LI (f(P)): **150 MW** --- hsf(t-4) = 1	f(P): **175 MW** LI (f(P)): **120 MW** --- hsf(t-3) = 1	f(P): **170 MW** LI (f(P)): **110 MW** --- hsf(t-2) = 1	f(P): **165 MW** LI (f(P)): **100 MW** --- hsf(t-1) = 1
---	WF Cluster "D" Primary reserve Positive Volume (MW): 10	f(P): **50 MW** LI (f(P)): **30 MW** --- hsf(t-4) = 1	f(P): **49 MW** LI (f(P)): **23 MW** --- hsf(t-3) = 0	f(P): **47 MW** LI (f(P)): **21 MW** --- hsf(t-2) = 0	f(P): **42 MW** LI (f(P)): **20 MW** --- hsf(t-1) = 0
---	WF Cluster "E" Primary reserve Positive Volume (MW): 5	f(P): **20 MW** LI (f(P)): **11 MW** --- hsf(t-4) = 1	f(P): **23 MW** LI (f(P)): **10 MW** --- hsf(t-3) = 1	f(P): **22 MW** LI (f(P)): **9 MW** --- hsf(t-2) = 1	f(P): **22 MW** LI (f(P)): **9 MW** --- hsf(t-1) = 1

Table 22 – Offer Validation Matrix after simulation 2

During this simulation some of the power reserve offers were detected as unstable through the technical validation process as it can be seen in Table 23. From the operational point of view, in some cases, it would have been an error to post those offers which would not be possible to be validated. Offers from wind farm clusters A, B and D have been detected as unstable during different moments of the simulation.

	t-4	t-3	t-2	t-1
WFC A	230 - 180 > 0 **ok** 180 - 30 > 150 **x**	220 - 145 > 0 **ok** 145 - 30 > 150 **x**	220 - 142 > 0 **ok** 142 - 30 > 150 **x**	218 - 140 > 0 **ok** 140 - 30 > 150 **x**
WFC B	33 - 22 > 0 **ok** 22 - 4 > 20 **x**	31 - 18 > 0 **ok** 18 - 4 > 20 **x**	30 - 17 > 0 **ok** 17 - 4 > 20 **x**	30 - 16 > 0 **ok** 16 - 4 > 20 **x**
WFC C	185 - 150 > 0 **ok** 150 - 14 > 70 **ok**	175 - 120 > 0 **ok** 120 - 14 > 70 **ok**	170 - 110 > 0 **ok** 110 - 14 > 70 **ok**	165 - 100 > 0 **ok** 100 - 14 > 70 **ok**
WFC D	50 - 30 > 0 **ok** 30 - 4 > 20 **ok**	49 - 23 > 0 **ok** 23 - 4 > 20 **x**	47 - 21 > 0 **ok** 21 - 4 > 20 **x**	42 - 20 > 0 **ok** 20 - 4 > 20 **x**
WFC E	20 - 11 > 0 **ok** 11 - 1 > 5 **ok**	23 - 10 > 0 **ok** 10 - 1 > 5 **ok**	22 - 9 > 0 **ok** 9 - 1 > 5 **ok**	22 - 9 > 0 **ok** 9 - 1 > 5 **ok**

Table 23 – Validation process based on Equation 6 after simulation 2

Finally, as it is indicated in Table 24, after the “Offer Stability Factor” calculation, three power reserve offers would have been rejected by the technical validation procedure. During this particular simulation, unstable situations were detected during different hours, therefore those unstable offers would not have been activated.

	Offer Stability Factor	Value	Action
WFC A	0*0,25 + 0*0,50 + 0*0,75 + 0*1	0	Power reserve offer rejected
WFC B	0*0,25 + 0*0,50 + 0*0,75 + 0*1	0	Power reserve offer rejected
WFC C	1*0,25 + 1*0,50 + 1*0,75 + 1*1	2,5	Power reserve activated
WFC D	1*0,25 + 0*0,50 + 0*0,75 + 0*1	0,25	Power reserve offer rejected
WFC E	1*0,25 + 1*0,50 + 1*0,75 + 1*1	2,5	Power reserve activated

Table 24 – Offer stability factor calculation for simulation scenario 2

5.5 Potential power reserve provision with wind power in Germany during 2009

During Chapter 4, the developed methodology and structures were described. In topics 0 and 5.4 from this chapter, the methodology was implemented through two positive power reserve simulations. The data flow and control structures from the developed algorithm were tested and validated.

A larger evaluation has been carried out applying the developed methodology to the German wind power production time series from 2009. The aim of this analysis is to calculate for which percentage of the year primary and secondary power reserve could have been provided by wind power, considering the developed methodology in Chapter 4. In Table 25, Table 26 and Table 27 the results are presented.

The considered time series from 2009 are described in Figure 47. A better description of the available information can be observed in Figure 48, where October 2009 is represented.

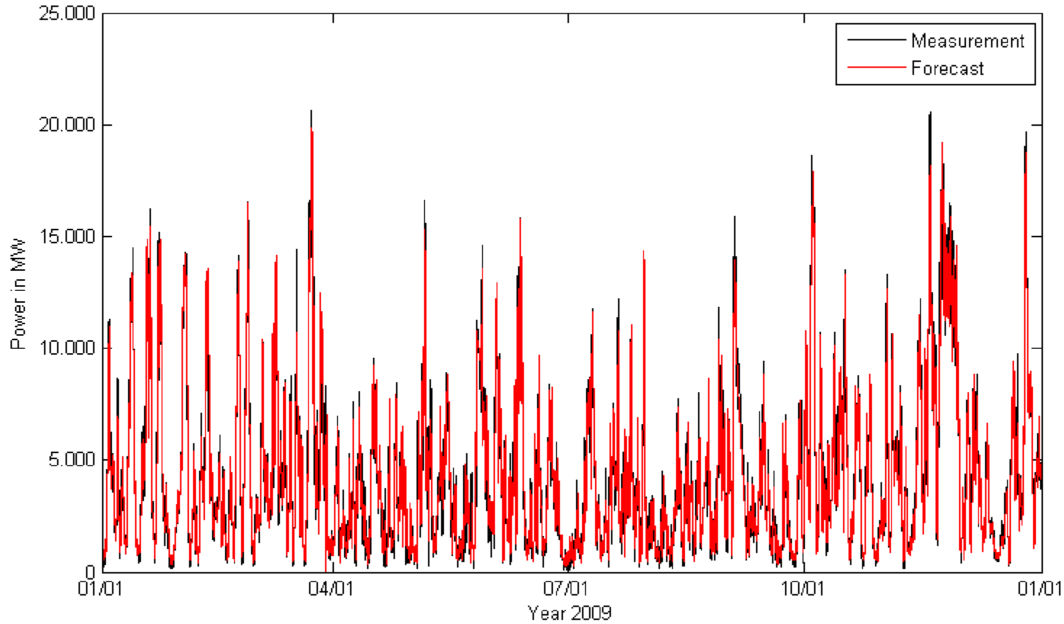


Figure 47 – Wind power production and forecast in Germany, 2009

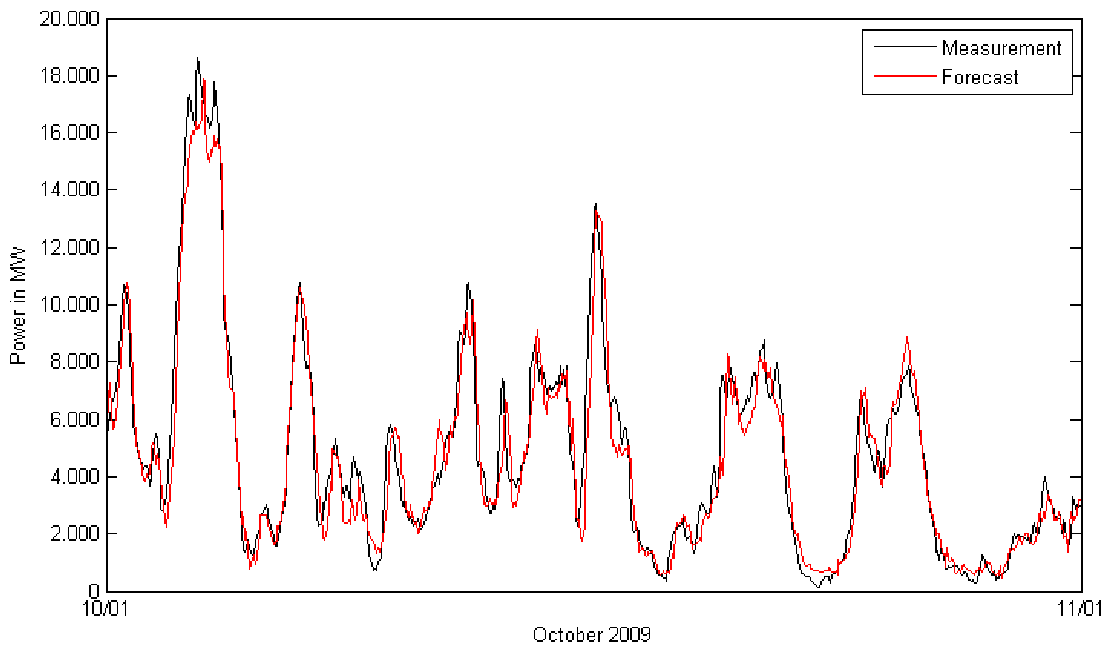


Figure 48 – Wind power production and forecast in Germany, October 2009

Based on the information represented in Figure 47 and deeply described in Figure 48, Lower Intervals (LIs) from the wind power forecast were calculated considering different reliability factors (see Figure 49 and Figure 50). The reliability factors used for the lower intervals calculation are 90%, 95%, 99% and 100%.

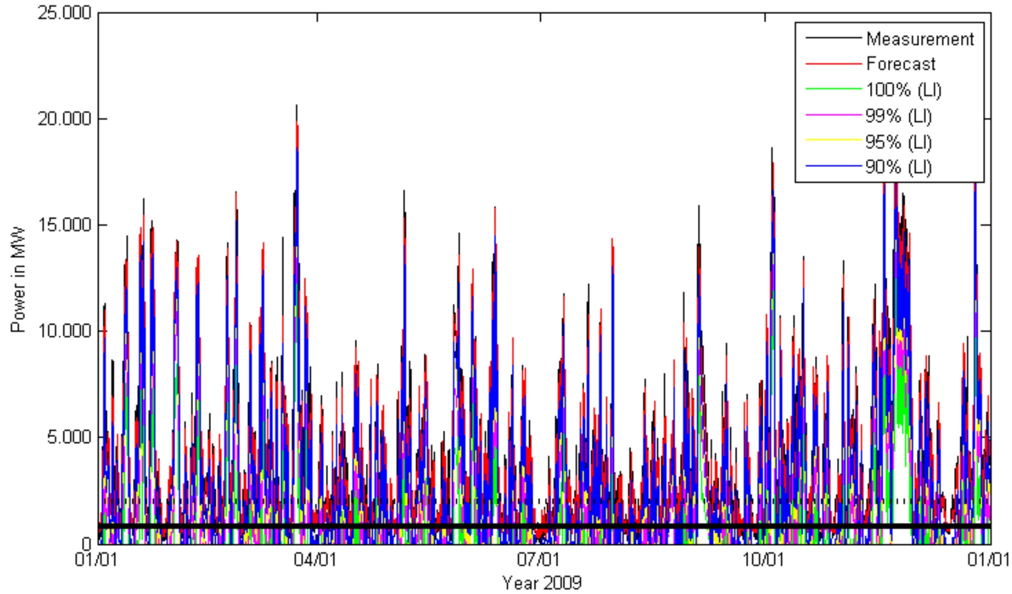


Figure 49 – LI calculation for wind power forecast in Germany during 2009

An example and a better description of the available information from the calculated Lower Intervals is included in Figure 50 and Figure 51. The black line represents the current needed primary power reserve volume (800 MW) and the black dotted line represents the secondary power reserve volume (2000 MW).

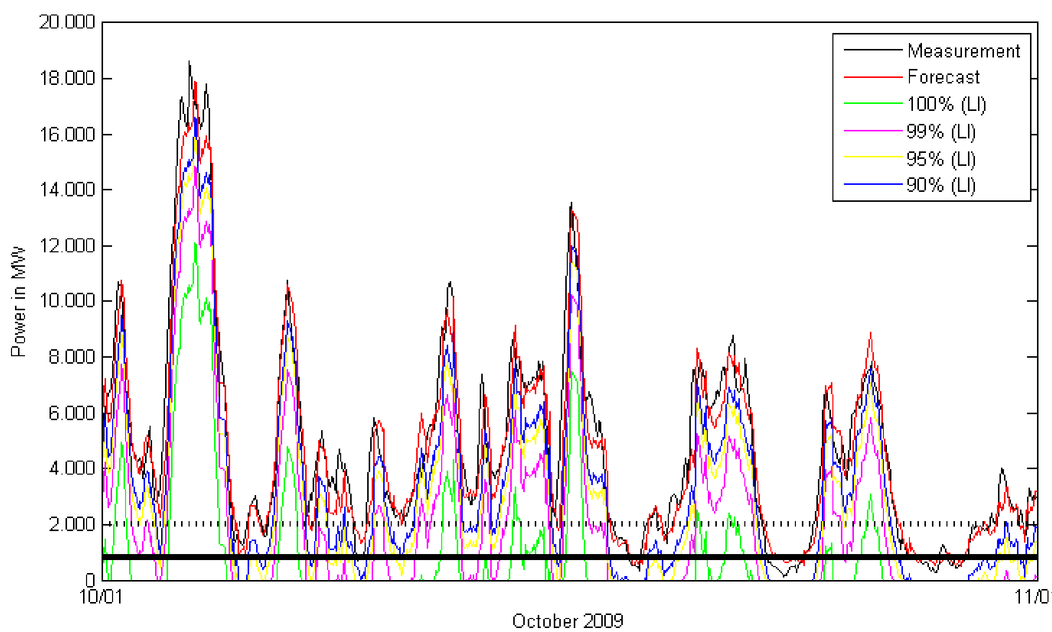


Figure 50 – LI calculation for wind power forecast in Germany, October 2009

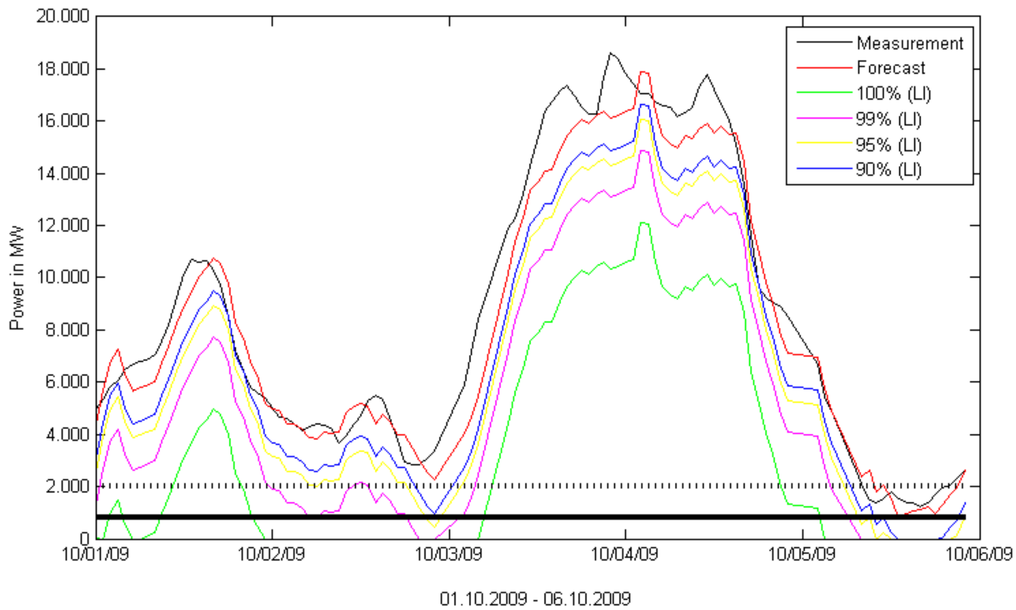


Figure 51 – LI calculation for wind power forecast in Germany, 01.10.2009 – 06.10.2009

The developed methodology was applied to the German wind power production time series in 2009. Based on the lower intervals from the wind power forecast it was calculated for which % of the year primary and secondary power reserve provision could have been provided by wind power. Lower intervals with reliability factors of 90, 95, 99 and 100% were calculated. The results can be observed in Table 25, Table 26 and Table 27. For both, primary and secondary power reserve, the relevant reliability factors are 95 and 99% (more realistic ones if the natural characteristics of wind power are considered).

In Table 25 it can be observed that primary power reserve provision (800 MW) could have been provided by wind power with a 99% of certainty during 3656 hours (41,74%) in 2009.

Primary power reserve (800 MW)	
Reliability	Potential power reserve provision during 2009
100 %	19,58 %
99 %	41,74 %
95 %	57 %
90 %	66,22 %

Table 25 – Potential primary power reserve provision with wind power in Germany

Secondary power reserve provision results can be observed in Table 26. These results show that wind power could have provided with a 99% of certainty 2000 MW of power reserve during 2580 hours (29,46%) in 2009.

Secondary power reserve (2000 MW)	
Reliability	Potential power reserve provision during 2009
100 %	13,95 %
99 %	29,46 %
95 %	41,97 %
90 %	47,98 %

Table 26 – Potential secondary power reserve provision with wind power in Germany

Finally, Table 27 shows the calculation results from both, primary and secondary power reserve, together. It can be observed that both kinds of power reserves could have been provided by wind power with a 99% of certainty during 2096 hours (23,93%) in 2009.

Primary and Secondary power reserve (2800 MW)	
Reliability	Potential power reserve provision during 2009
100 %	11,49 %
99 %	23,93 %
95 %	33,38 %
90 %	39,08 %

Table 27 – Potential primary and secondary power reserve provision with wind power

5.6 Summary chapter 5

This chapter presents the implementation results from the methodology described in chapter 4. The validation is based on real data from 5 wind farm clusters. Two simulation scenarios were built in order to test the developed methodology and data flow. Finally, the same methodology was implemented considering the wind power production time series from 2009. It was calculated for how long and with which certainty level primary and secondary power reserve could have being provided by wind power. Results have shown that wind power could have contributed to primary power reserve[17] during 41,74% of the year with a 99% of certainty. It can also be observed that secondary power reserve[18] could have been provided by wind power during 29,46% of the year with a certainty level of 99%. The next chapter presents the control capabilities of real wind farm clusters based of different tests performed in Germany and Portugal.

[17] Considering that 800 MW are required for primary power reserve in Germany (ENTSO-E).
[18] Considering that 2000 MW are requiered for secondary power reserve.

6. Capability of wind farm clusters to provide power reserve

Developing a concept to provide active power reserve with wind energy requires also testing the capabilities of real wind farms to contribute with this service. In some cases, the already implemented technologies at wind farm level are not fully being used and the capability of wind farms to be controlled is already there.

Several scientific tests were carried out based on the developed control strategies for active power control considering the structure of wind farm clusters developed by Fraunhofer IWES [2] as well as the need of sharing data between TSO control systems and dispatch centres.

During the projects “Integration großer Offshore-Windparks in elektrische Versorgungssysteme” [41] and “Wind on the Grid” [29], control strategies for wind farm clusters management were implemented and evaluated. Wind farms located in Germany and Portugal were proposed as real test fields being online monitored and controlled by the WCMS during the tests phases of the already mentioned projects.

Concrete R&D results are analyzed as well as the test field scenarios are described[19] where tests were performed.

6.1 Project “Integration großer Offshore-Windparks in elektrische Versorgungssysteme”

6.1.1 Project description and main objectives

The overall aim of the project was to increase the economic value of wind power by improving the integration of large offshore wind farms into the electrical power supply system.

Wind power feed-in from both on- and offshore wind farms lead to load flows in the transmission grid on land. These were quantified and evaluated with respect to necessary grid extensions. The results show a clear need for increased transmission capacity especially for connections between the transmission grids. To be able to integrate large

[19] All information regarding real tests performed in the frame of the “Wind on the Grid” project is being published in this chapter due to the kind permission of REN and Enercon.

amounts of wind power into the grid the “Wind Farm Cluster Management System” (WCMS) was developed, which allows controlling real time the active and reactive power generation of the wind farms by sending control commands at cluster and wind farm level.

The WCMS was implemented in two different countries showing how large amounts of wind power could be integrated in the power supply system by means of optimised operational control and information technology. By aggregating wind farms to clusters, which are units adjusted to the grid topology, the WCMS was able to make the geographically spread wind farms controllable for the requirements of the grid operator [41].

6.1.2 Project partners

No.	Organization name
1	ISET - Institut für Solare Energieversorgungstechnik e.V.
2	E.ON Netz GmbH
3	Vattenfall Europe Transmission GmbH
4	Universität Kassel
5	Wobben Research & Development GmbH
6	Deutscher Wetterdienst DWD
7	Enertrag AG

Table 28 – Project partners “Integration Offshore-Windparks in elektrische Versorgungssysteme”

6.1.3 Test scenario

The proposed cluster for this testing phase is connected to the transformer station Bertikow (see Figure 52) controlled by TSO Vattenfall Europe Transmission. The geographic distribution of the involved wind farms is also shown in Figure 53.

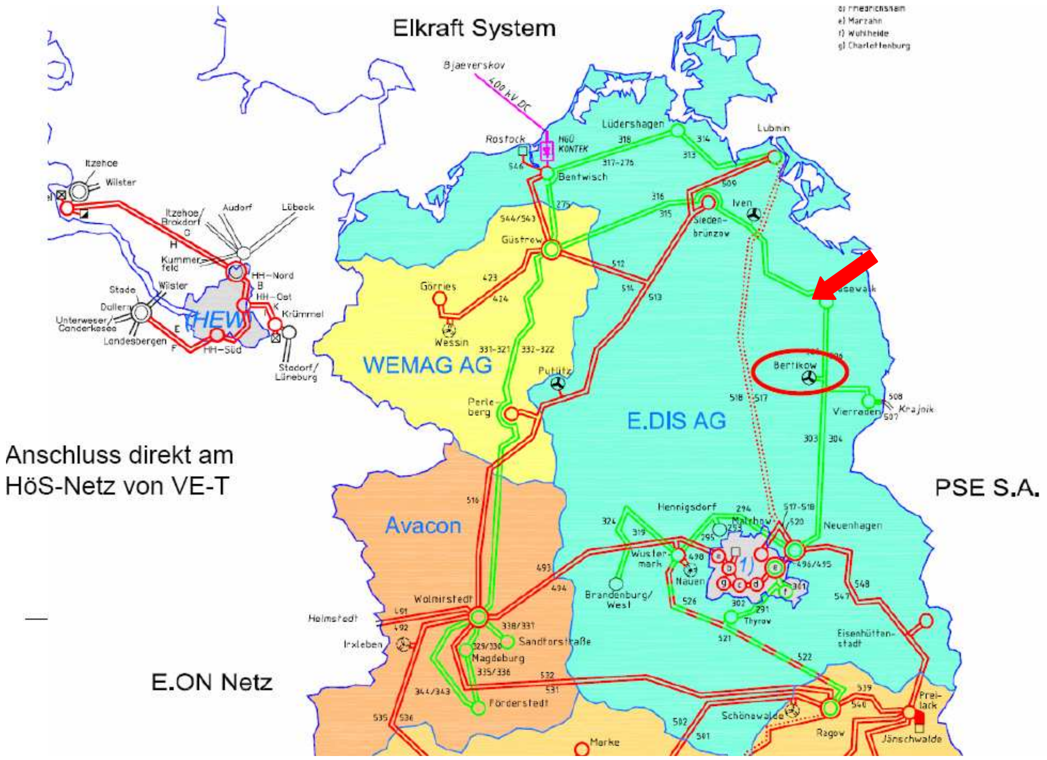


Figure 52 – Location of the wind farm cluster "Bertikow"

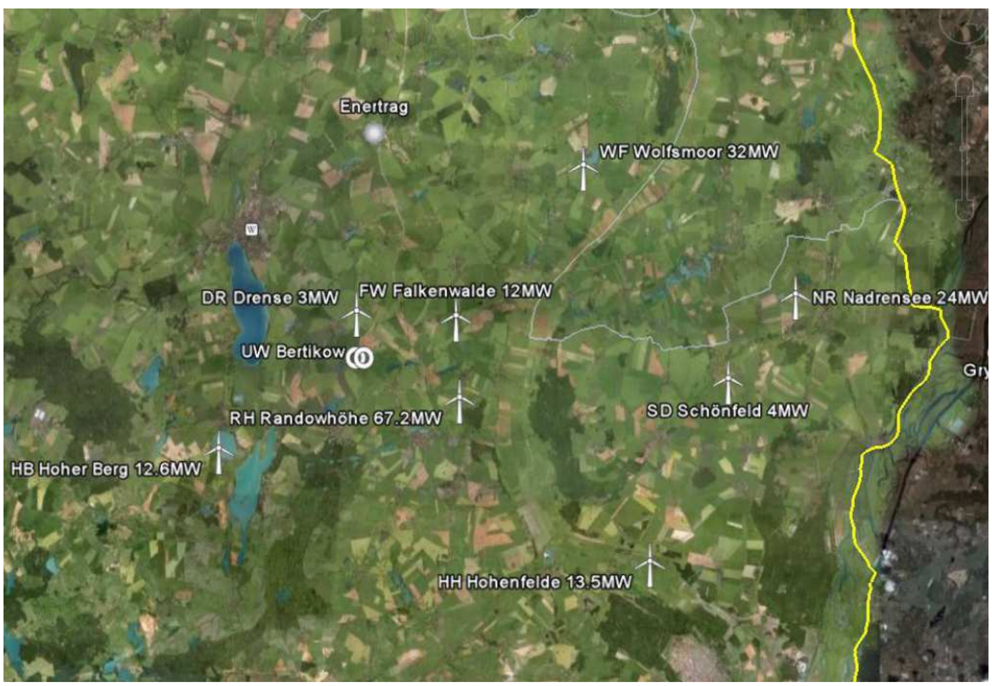


Figure 53 – Bertikow wind farm cluster

The wind farm cluster "Bertikow" consist of 8 wind farms connected to the 110 kV High Voltage line in the transformer station "Bertikow", which belongs to "Vattenfall Europe Transmission". Figure 54 shows the grid characteristics of the cluster as well as Table 29 describes the characteristics of each wind farm included into the cluster.

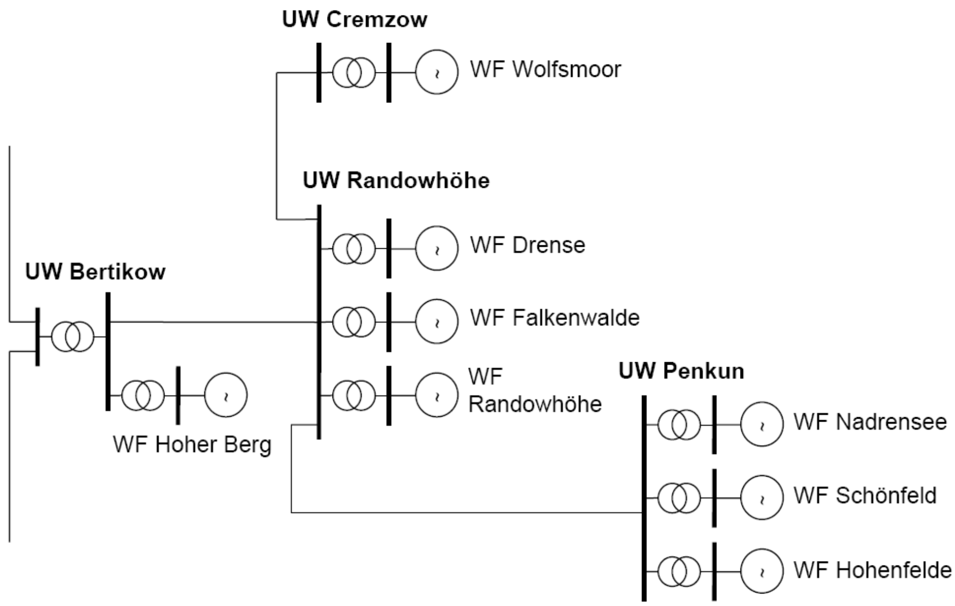


Figure 54 – Grid description of the wind farm cluster Bertikow

Wind farm	Transformer station	Install capacity (MW)
DR Drense	UW Randowhöhe	3.000
HB Bietikow	UW Bertikow	12.600
HH Hohenfelde /Randowhöhe	UW Penkun	13.500
NR Nadrensee / Randowhöhe	UW Penkun	24.000
RH Randowhöhe	UW Randowhöhe	67.200
SD Schönfeld	UW Penkun	4.000
WF Wolfsmoor	UW Cremzow	32.000
FW Falkenwalde / Randowhöhe	UW Randowhöhe	12.000
Groß Pinnow		34.000

Table 29 – Technical characteristics of the “Bertikow” wind farm cluster

6.1.4 Positive power reserve tests in the wind farm cluster “Bertikow”

Positive power reserve tests[20] were carried out during the test phase of the project at wind farm cluster “Bertikow”. It was analyzed the time response capacity of the cluster once a control command is sent, the stability of the set point during its activation period and the

[20] Due to the main topic of this PhD, active power control tests were analyzed considering the capacity already shown by the different wind farm clusters to contribute with positive and negative power reserver in different countries.

power release capacity once the set point is finished. It was also checked how long it takes to the cluster to achieve the desired value once the set point is received.

Tests performed on August 18th 2009

During August 18th 2009, four tests were carried out in the wind farm cluster "Bertikow" as it is described in Table 30. After these tests were performed it was proved that wind power could react to a certain set point reaching a desired operational value, as it is shown in Figure 55. Despite of that, the desired active power limitation during the set point was not kept completely stable in all cases. As it can be seen in Figure 56 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.

	10:41:00	**11:10:00**	**11:30:00**	**15:20:00**
Set point duration (min)	20	10	10	10
Active power before the set points (MW)	110,7	136,6	116	129,9
Set point target (MW)	100	108	71	120
Operational level requested (%)	90,3	79,1	61,2	92,4
Aimed reduction [%]	95	80	60	90
Set point target (MW)	105,2	109,3	69,6	116,9
Active power after the set point	120	128	100	122

Table 30 – Test description from 18.08.2009

It was also observed during the tests that it is possible for wind power to contribute with positive and negative power reserve if gradient limitations are adapted to the needed time response for power reserve provision.

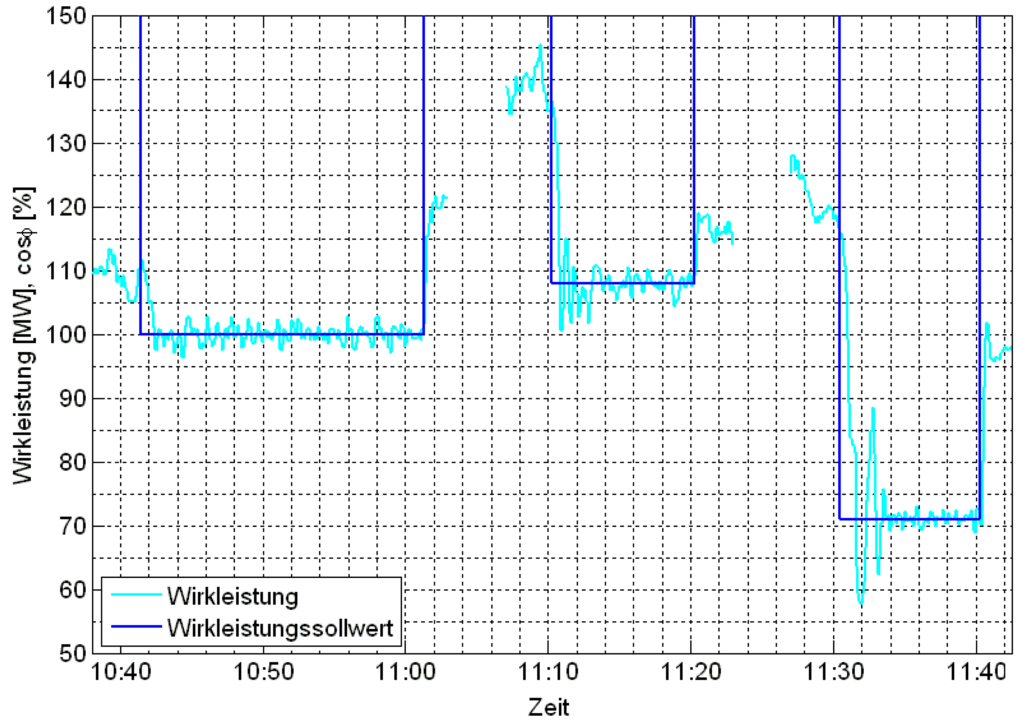


Figure 55 – Positive power reserve tests in Bertikow wind farm cluster (18.08.2009)

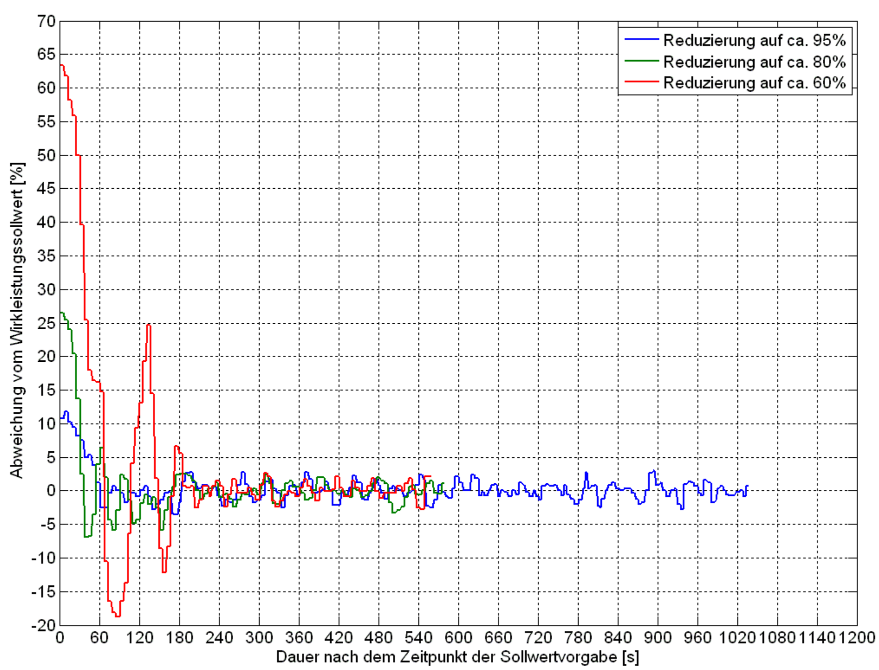


Figure 56 – Wind farm cluster response during positive power reserve tests

For a better evaluation of the wind power capabilities, a longer power limitation set point of 158 MW was sent to the wind farm cluster. For this specific test, active power measurements at wind farm cluster level were taken each 6 seconds. As it is shown in

Figure 57, “Bertikow” wind farm cluster has reacted and during the set point period the limit of 158 MW was kept.

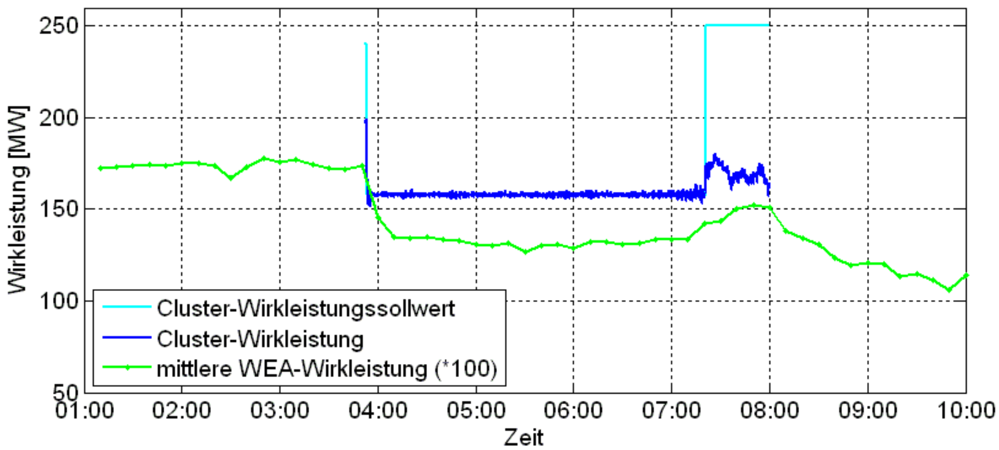


Figure 57 – Positive reserve power test of three hours during March 23rd 2009

Figure 58 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.

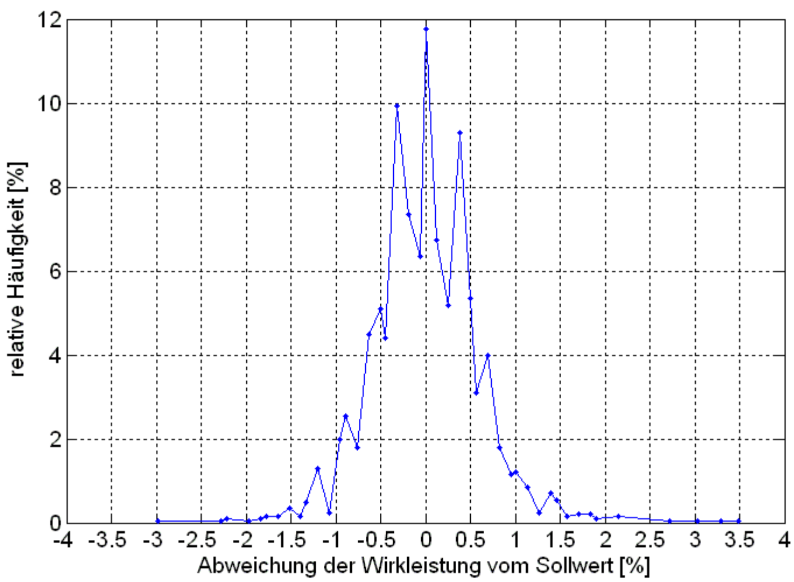


Figure 58 – Active power deviations during tests on August 18th 2009

6.1.5 Results of the project

Controllability of the wind farm cluster was successfully tested as well as oscillations were registered which should be deeper analyzed and in the future minimized.

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 of a set point.

An optimised grid connection is one of the questions arising from a massive expansion of offshore wind power. A co-ordinated and consistent planning approach for the high voltage power transmission system to connect all offshore wind farms to the grid was found to be very beneficial.

6.2 Project "Wind on the Grid"

6.2.1 Project description and main objectives

Wind on the Grid, initiative supported by EU Commission-DGTREN, is a project focused on preparation of the European electricity network for the large-scale integration of wind farms through the design, development and validation of new tools and devices for its planning, control and operation in a competitive market.

WINDGRID addresses the "Large-scale integration of renewable energy sources into energy supplies", since its general research objectives are closely linked to the transition towards future sustainable energy supply based on a large share of renewable energy sources in production, by contributing integrally and in a reliable manner large-scale wind power sources to high-voltage transmission networks.

It is the first time in European history that such a group (see Table 31) representing the largest investment drive for the integration of wind farms in the European electricity network, have joined force in a project like WINDGRID. These companies are some of the most important in the wind power industry and belong to countries with a significant volume of installed wind capacity.

6.2.2 Project partners

No.	Organisation name	Country
1	Red Eléctrica de España, S.A.(REE)	Spain
2	Enercon GmbH (ENERCON)	Germany
3	Gamesa Wind Engineering	Spain
4	Fraunhofer IWES	Germany
5	Iberdrola Energías Renovables II S.A.U. (IB)	Spain
6	Deloitte, S.L.(DT)	Spain
7	Rede Eléctrica Nacional, S.A. (REN)	Portugal
8	Korona Power Engineering d.d. (KORONA)	Slovenia

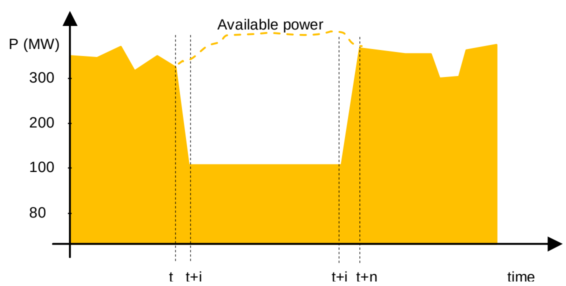
Table 31 – Project partners "Wind on the Grid"

6.2.3 Control strategies development

The aim of a control strategy is to receive a command sent by the TSO to a certain wind farm cluster and calculate the set points to be sent to each wind farm which belongs to the cluster in order to fulfil the grid requirements of the TSO. As it is shown in Figure 59, the developed control strategies were divided into two groups:

- Active power control strategies.
- Reactive power control strategies.

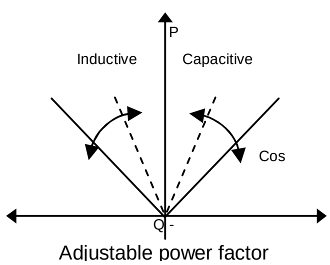
Active power regulation



Active power control strategies:

- Congestion management.
- Power limitation.
- Gradient control.
- Reserve power.
- Frequency control.

Reactive power regulation



Reactive power control strategies:

- Reactive power range forecast.
- Reactive power control.
- Power factor control.
- Voltage changes control.

Figure 59 – Control strategies

Once developed and tested, each control strategy was included into the Wind Farm Cluster Management System (WCMS).

Considering the aim of this PhD, the analysis of R&D results is oriented to the active power control tests and the behaviour of the deployment times, which are the most important technical parameters for frequency-related ancillary services, and can be described as following:

- The maximum amount of time that can elapse between the request from the TSO and the beginning of the response by the service provider.

- The maximum time that can elapse between the moment when the provider receives the request and the moment at which it delivers its full response.

6.2.4 Test scenario in Portugal (REN)

The Portuguese wind farm clusters “Gardunha” and “Pinhal Interior” belonging to the company GENERG were selected by REN to test the control strategies developed during the different R&D activities of the project (see Figure 60).

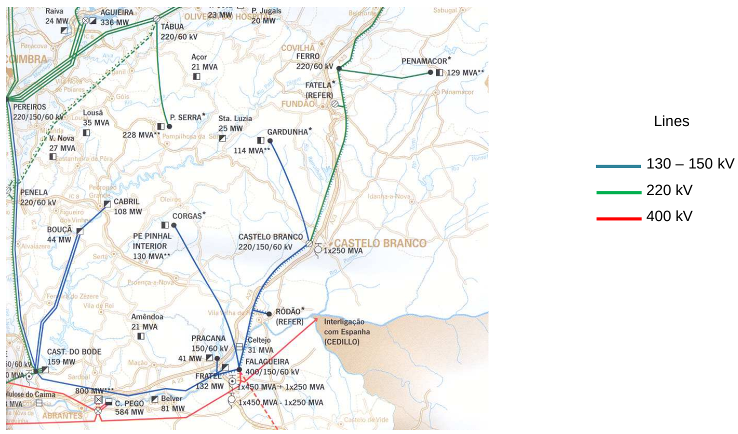


Figure 60 – Wind farm clusters locations in the Portuguese grid (Source: REN)

The control capability tests that were planed are the following:

- Active Power limitation[21].
- Phi Set-point.
- Reactive Power Set-point.
- Voltage Set-point.

Table 32 describes which kind of control strategy is expected to be performed by each of the selected clusters. The reference point for both clusters is on the High Voltage network (150 kV).

Gardunha	Pinhal Interior	Cluster
Limited Active Power	Limited Active Power	
φ Set point	φ Set point	φ Set point
Reactive Power Set-point	Reactive Power Set-point	Reactive Power Set-point
Voltage Set-point		

Table 32 – Control strategies by wind farm clusters

[21] The wind farm cluster must operate below its operational limit.

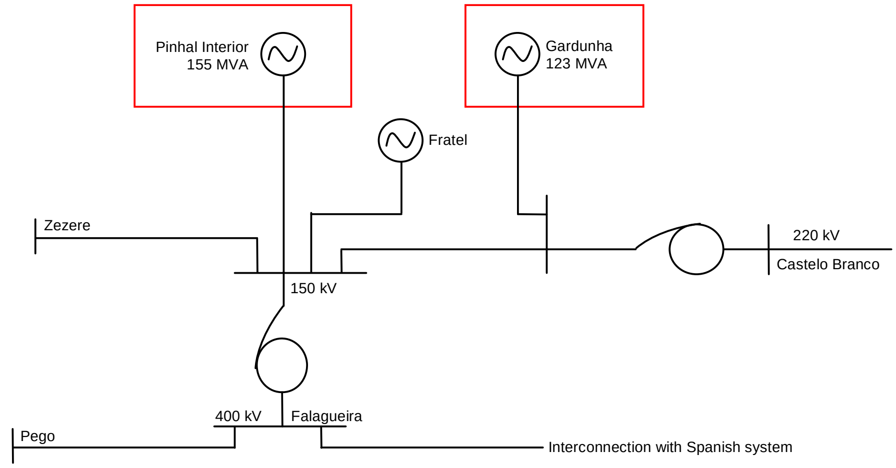


Figure 61 – Reference point on the High Voltage network (150 kV) observed by REN.

Enercon was the wind turbine manufacturer participating in the Portuguese part of the project. Therefore only Enercon wind farms owned by the company GENERG were monitored and controlled during “Wind on the Grid” project. The controllable part of Pinhal Interior was 90 MW and in Gardunha was 114 MW (see Table 33). The wind farms included into the “ENEOP2” were none controlled due to the Portuguese grid code.

	Pinhal Interior	**Gardunha**	Total
Enercon	90	114	204
Vestas	54		54
ENEOP2	24		24
Total	168	114	282
Test %	54%	100%	72%

Table 33 – Controlled MW per wind farm cluster in Portugal

These two wind farm clusters were selected by REN due to their complexity in terms of grid layout and also considering that not all wind farms were available during the “Wind on the Grid” project. Therefore, is was a need of the project to consider all these restrictions during the planning phase and to perform all calculations in order to be sure that any set point, sent to the controllable cluster, could reach the desired operational point by the TSO in the cluster grid node.

6.2.5 Electrical characteristics of the tested wind farm clusters

- **Gardunha**

Gardunha wind power plant was built exclusively with Enercon wind turbines (55 E-82 + 2 E-70). The total active power output is 57x2 MW = 114 MW.

- **Pinhal Interior**

Pinhal Interior was built with Enercon wind turbines (25 E-82 + 32 E-70) and Vestas wind turbines (18 V-90). The total active power output is 57x2+18x3 MW = 168 MW. Since during the project only Enercon wind turbines belonging to GENERG were controllable, the total power under control is 45x2= 90 MW. The reference point for this wind farm cluster is the 150 kV busbar at Pinhal Interior substation. The wind farms Proença, Furnas, Seladolinho and Fundeiro belong to Pinhal Interior and could be controlled.

6.2.6 Description of the active power limitation tests in Portugal

The minimum required active power to perform these tests was 10% of the install capacity of each involved wind farm. The active power forecast was requested to confirm if the wind conditions were enough to guarantee this minimum requirement during the duration of the tests.

These tests were performed in a working day, during working hours. To be able to measure the impact of the limitation on the active power, the limit was a minimum reduction of 5% of the installed capacity.

The expected time response of the Enercon wind farms after receiving the new set point was 1 minute. As it can be seen in topic “6.2.7 Analysis of active power control tests in Portugal” the time response of the wind farms was below the expected limit of 1 minute.

6.2.7 Analysis of active power control tests in Portugal

During the test phase of “Wind on the Grid” project, three active power control tests were performed in Portugal during September 22nd and 23rd, and November 25th 2009. The aim of these tests was to prove the capability of the selected wind farm clusters to contribute with active power control, being able to provide positive and negative power reserve.

Tests were performed also under low and normal wind conditions, analyzing the capability of the different wind farms included into each cluster to operate according to their power characteristics.

- **September 22nd 2009, positive power reserve provision test in Portugal.**

This was the first test performed where WCMS and the needed IT infrastructure were checked as well as the response capability of the involved wind farm.

The main test information is described as following:

- Target: 2,2 MW positive reserve power by "Proença" wind farm
- Reached target: 2,816 MW positive reserve power
- Start: 22.09.2009 11:50:03
- Finish: 22.09.2009 11:55:27
- Expected duration: 00:05:00
- Real duration: 00:05:24

Due to the low wind conditions during this first test, it was sent through WCMS a 2,2 MW positive power reserve set point during 5 minutes to "Proença" wind farm. Just before receiving the set point "Proença´s" production was 5,161 MW. Once the set point was received, "Proença" has being working 2,816 MW below its operational limit (target was 2,2 MW) during the requested 5 minutes as it can be seen in the 3 seconds sampling Figure 62. It took to "Proença" 45 seconds to reach the set point target (2,345 MW) in a stable way and also it can be apreciated an oscilation phenomena due to the dynamic behaiviour of the machines which also has affected the reactive power production during a short period (yellow line in Figure 62).

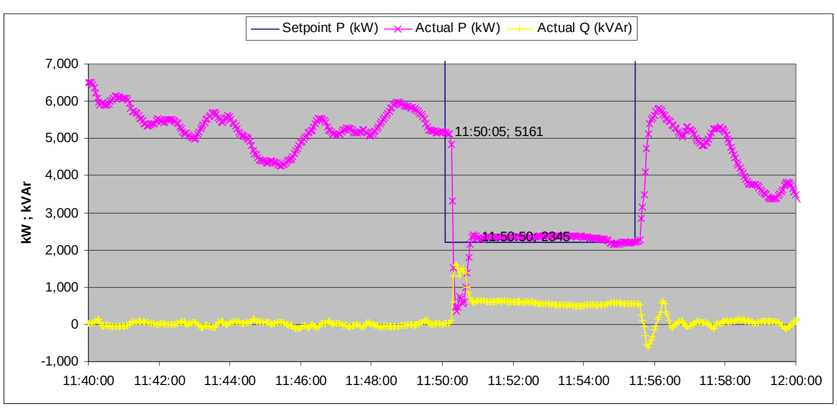
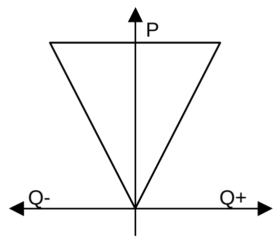


Figure 62 – P/Q monitoring from Proença wind farm (Source: Enercon)

As it can be observed in Figure 62, after receiving the set point, the active power level of Proença went down for a few seconds just before reaching the desired value of the given control command. Based on the triangular P/Q diagram of the wind farm, the need reactive power (as a funtion of the active pwoer) for keeping the Cos Phi = 0 was not available.



Schematic description of the P/Q diagram of Proença

- **September 23rd 2009, positive power reserve provision test in Portugal.**

This test was more complex since the aim was to perform an active power control with a complete wind farm cluster and also due to the particular wind conditions in the area of the cluster. Some of the wind farms included into the controlled cluster were influenced by a normal wind condition while at the same time an extreme low wind situation was affecting one of them ("Seladolinho" wind farm).

The set point was sent from REN facilities through the WCMS to the wind farm cluster "Pinhal Interior", splitting this cluster set point to the wind farms "Proença", "Furnas", "Seladolinho" and "Fundeiro".

The main test information is described as following:

- Target: 9 MW positive reserve power provision at cluster level
- Start : 23.09.2009 11:35:00
- Finish: 23.09.2009 11:43:00
- Expected duration: 00:08:00
- Cluster set point: 9 MW

Wind farm	Real test duration	Set point (MW)
Seladolinho	00:08:08	1,149
Proença	00:07:51	5,5
Fundeiro	00:08:07	1,25
Furnas	00:07:54	1,2

Table 34 – Technical details from test performed on September 23rd 2009

Figure 63 shows the behaiviour of each wind farm during the test. The wind farm cluster has succesfully fullfilled the TSO requirements sent through WCMS and at the same time all wind farms have reached the target after recieving the control command calculated by WCMS for each of them, as it is shown in Table 34.

A particular situation could be observed with one of the wind farms included into the “Pinhal Interior” wind farm cluster. Due to extreme low wind conditions on its area, “Seladolinho” wind farm was initially below the requested set point value (see Table 34) and as a concequence no active power control could be observed until 11:42:00 when due to the increasing wind situation and the already active set point the “Seladolinho” wind farm was regulated below its operational limit until the end of the control command sent by REN.

This situation could happend in other cases when the wind condition is too low or unstable, therefore wind power forecast, its lower interval and the capability of each wind farm to report real power and also available power is relevant and deeply described in chapter 4 “Power reserve provision with wind farms”.

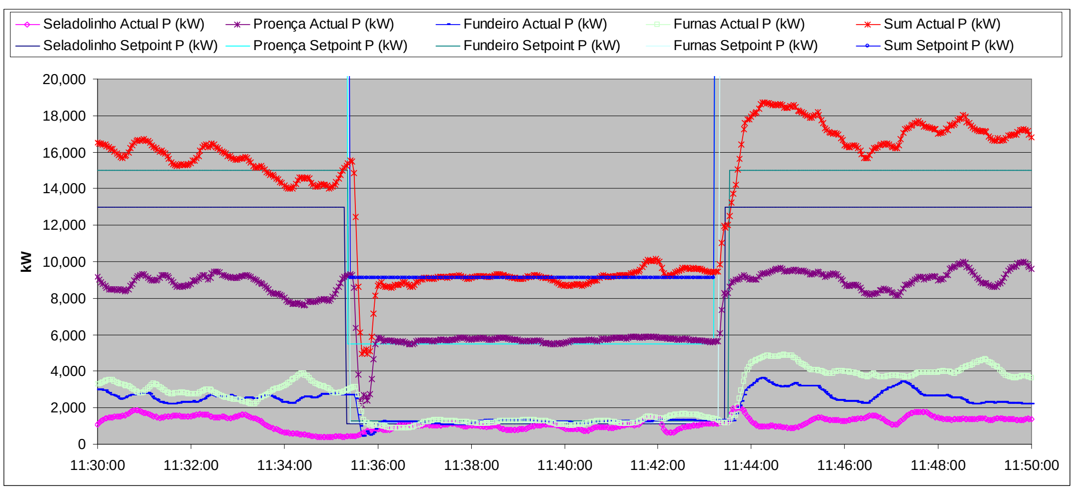


Figure 63 – Second active power control test (Source: Enercon)

Figure 64 shows the interface of the WCMS during the testing phase. It can be observed the behaviour of the wind farm cluster “Pinhal Interior” during the set point execution. In yellow it can be seeing the active power control and 9 MW of positive power reserve provided by the cluster during 8 minutes, as it was requested by the TSO. In red it is shown the reactive power provided by the cluster during the test. Even when the amount of provided reactive power is low, it can be observed a particular behaviour which is coincident with the set point time frame.

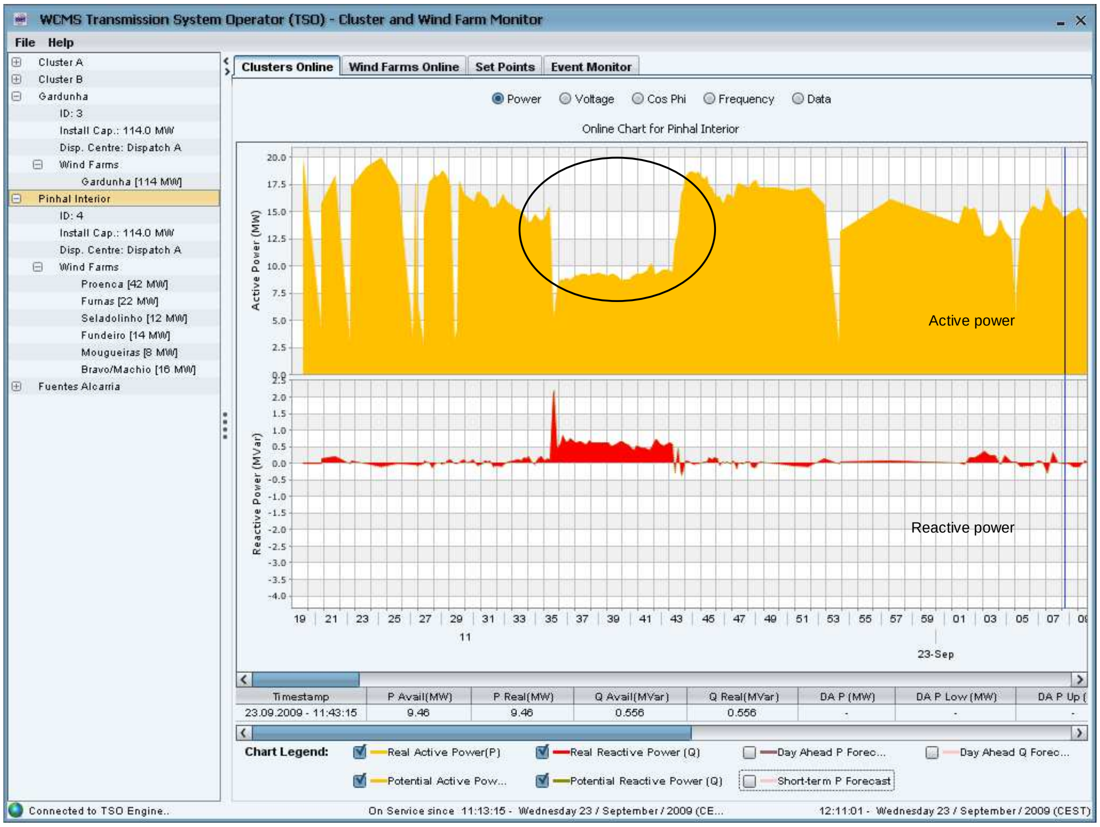


Figure 64 – Wind farm cluster “Pinhal Interior” (Source: IWES)

In Figure 65, Figure 66, Figure 67 and Figure 68 it can be observed the behaviour of each wind farm belonging to the “Pinhal Interior” wind farm cluster. Each wind farm has received a control command sent by the TSO (see Table 34) and contributes with the wind farm cluster behaviour showed in Figure 64. Due to the already mentioned different wind conditions, the contribution from each wind farm to the overall result of the test is different in terms of positive power reserve provided.

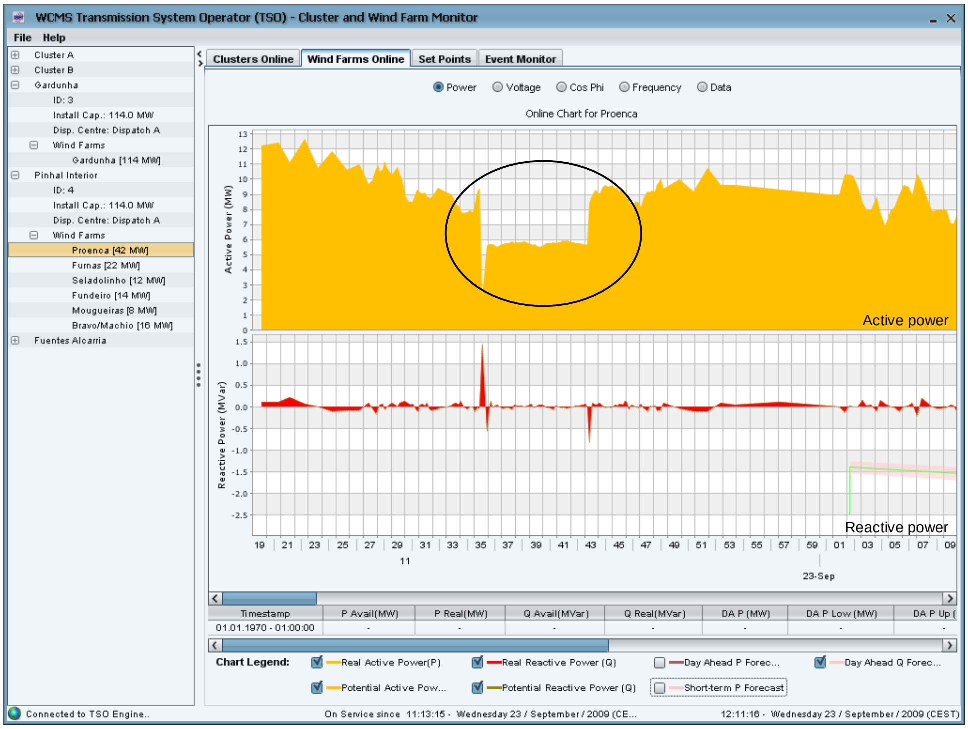


Figure 65 – Wind farm “Proença”, wind farm cluster “Pinhal Interior” (Source: IWES)

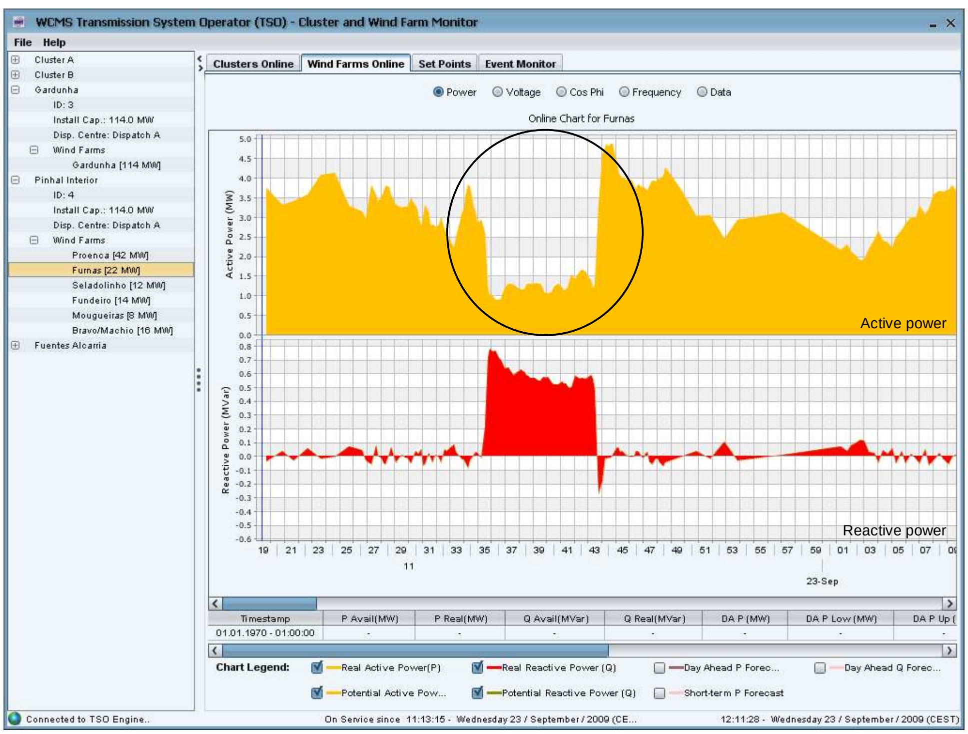


Figure 66 – Wind farm “Furnas”, wind farm cluster “Pinhal Interior” (Source: IWES)

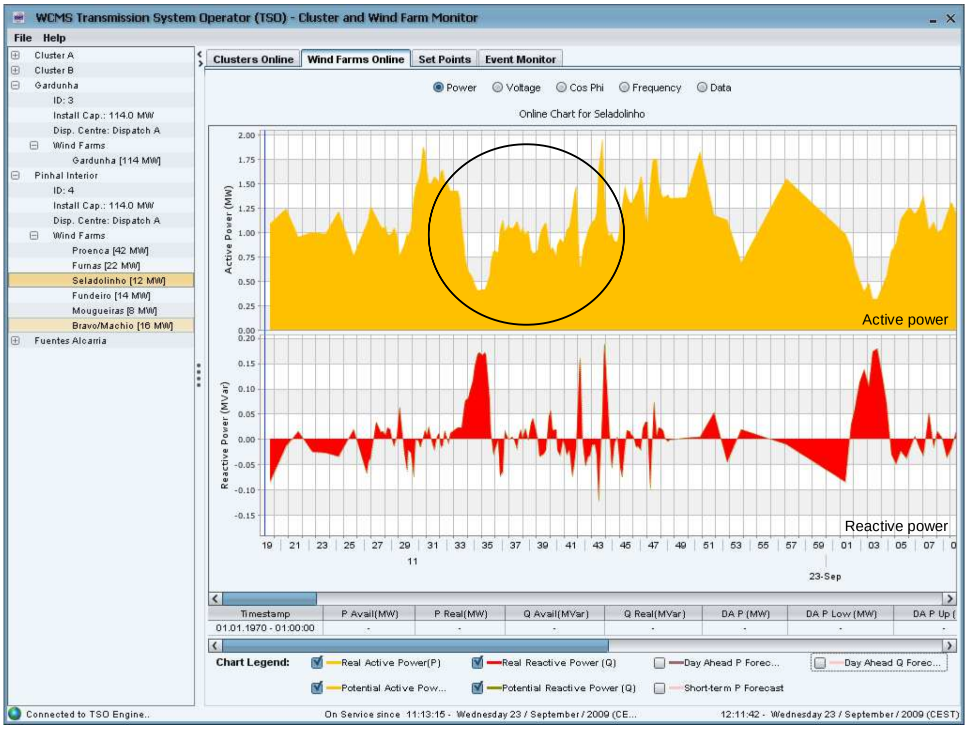


Figure 67 – Wind farm “Seladolinho”, wind farm cluster “Pinhal Interior” (Source: IWES)

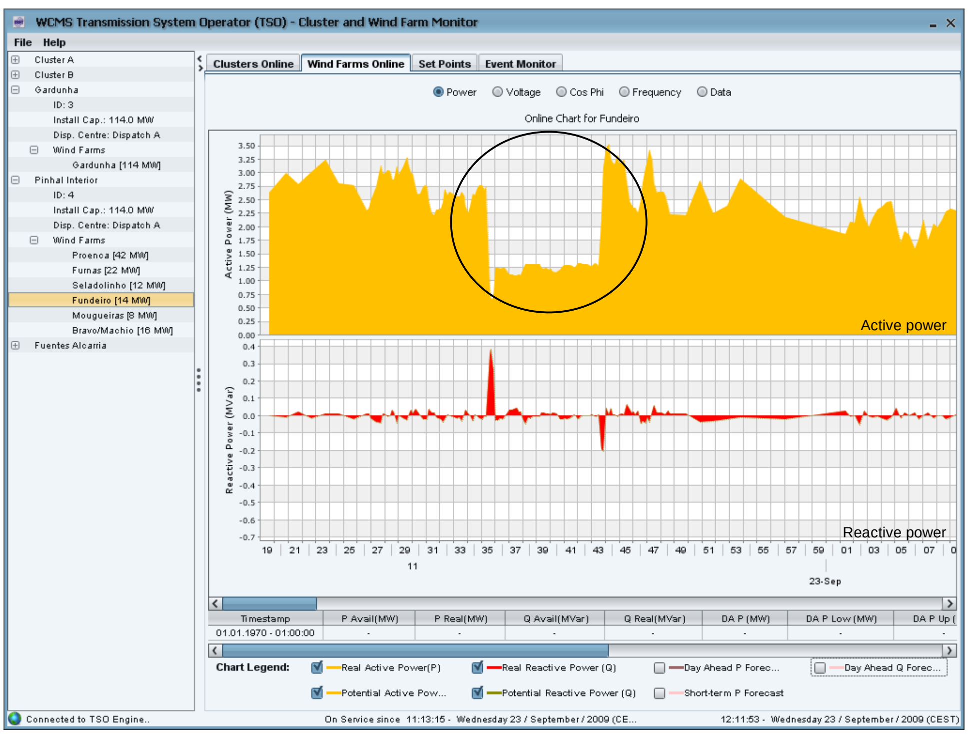


Figure 68 – Wind farm “Fundeiro”, wind farm cluster “Pinhal Interior” (Source: IWES)

- **November 25th 2009, positive power reserve provision test in Portugal.**

For this test a better wind condition was expected for the wind farm cluster area. Therefore a bigger volume of positive power reserve was planned to be requested to the cluster for a longer period.

The aim of this test was to prove the capability of a wind farm cluster under good and stable wind conditions to provide positive power reserve as well as to keep this reserve power provision stable during a longer period than the other performed tests.

The main test information is described as following:

- Target: 10 MW positive reserve power provision at cluster level
- Start: 25.11.2009 15:42:00
- Finish: 25.11.2009 15:52:00
- Expected duration: 00:10:00
- Cluster set point: 13,939 MW

Wind farm	Real test duration	Set point (MW)
Seladolinho	00:10:15	2,388
Proença	00:10:41	4,632
Fundeiro	00:10:30	1,646
Furnas	00:10:06	5,273

Table 35 – Technical details from test performed on November 25th 2009

In Figure 69 and Figure 70 it can be observed the behaviour of each wind farm before, during and after the 10 minutes set point. The reaction time to the control command of all wind farms is below 1 minute. Some of them have also reduced their power generation faster than the others due to different situations which are described as following:

- "Furnas" wind farm is composed by two groups of wind turbines ("Furnas" + "Moradal") separated by a distance of approximately 20 km. The response time of the wind farm could show many different figures depending on the wind distribution through the turbines.
- "Seladolinho" wind farm is one single wind farm with a dedicated control device. Its time response has shown nearly no delays.

After the 10 MW reduction requested by the TSO and the 10 minutes duration of the set point, power is restored above 35 MW, proving that positive reserve power was provided and the success of the test.

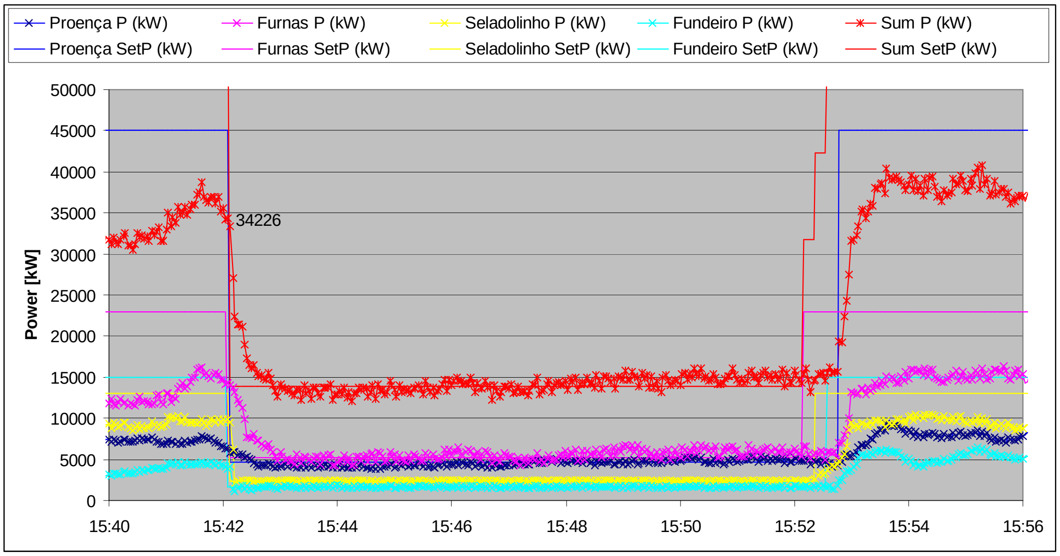


Figure 69 – Third active power control test (Source: Enercon)

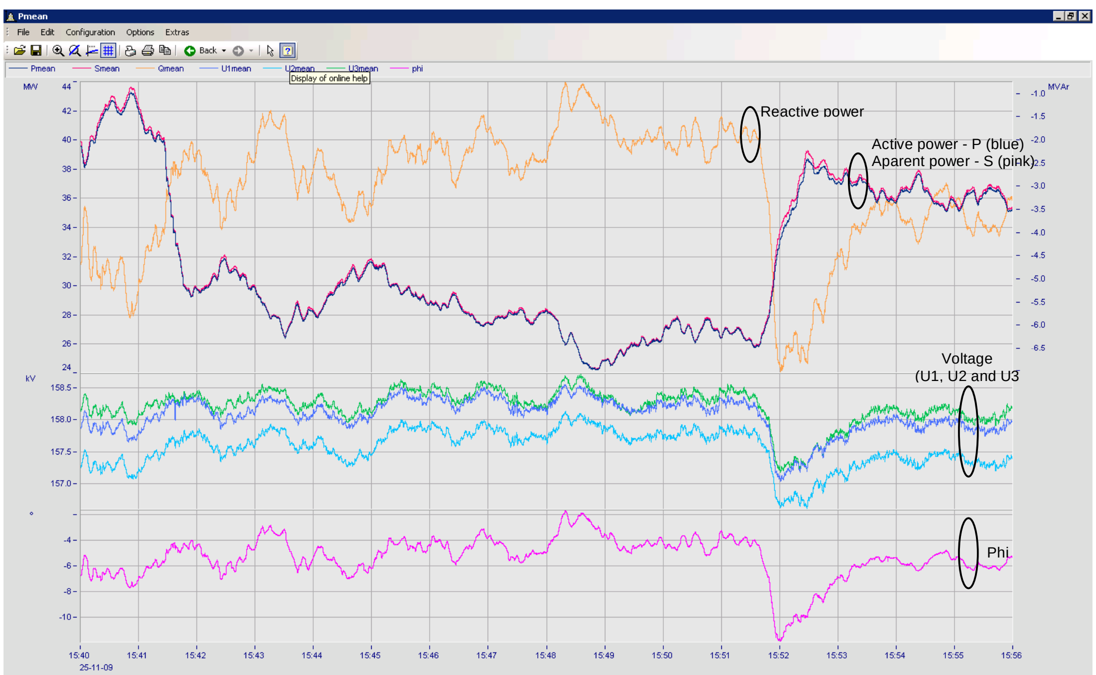


Figure 70 – Real time control wind farm cluster “Pinhal Interior” (Source: Enercon)

The behaviour of each wind farm during the set point execution can be appreciated in Figure 71 (“Proença”), Figure 72 (“Furnas”), Figure 73 (“Seladolinho”) and Figure 74 (“Fundeiro”), where the WCMS interface shows how each of them has received a single set point and reached the desired value, according with Table 35.

In Figure 72 and Figure 73 it can be appreciated the difference between the behaviour of "Furnas" and "Seladolinho", where "Seladolinho" has reacted faster than "Furnas" due to the already described differences between these two wind farms.

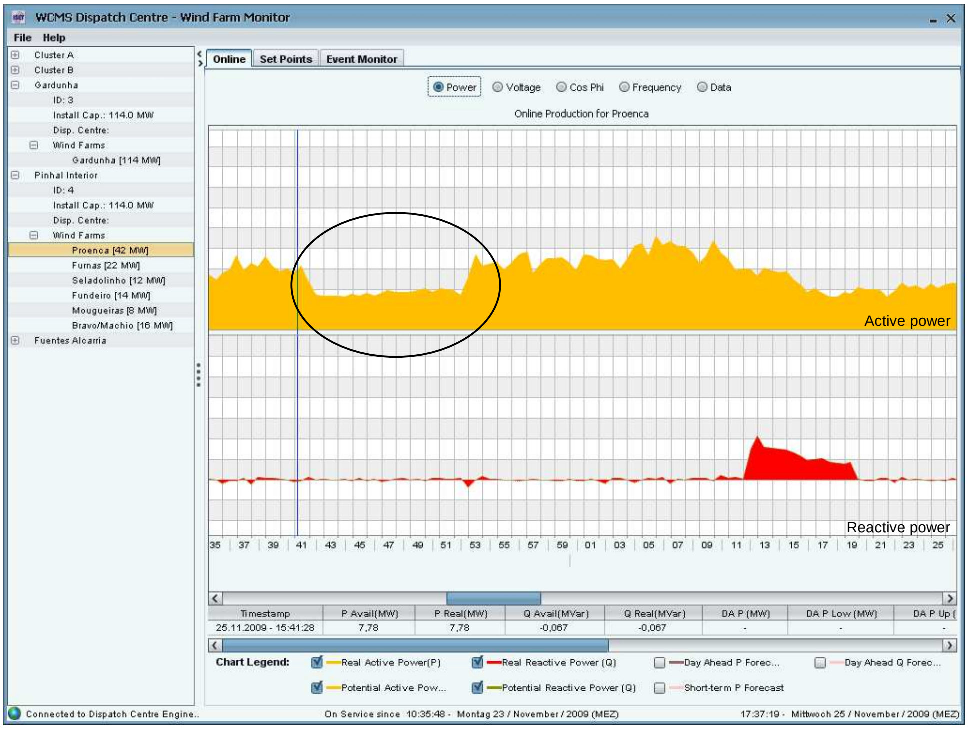


Figure 71 – RTC wind farm "Proença", Cluster "Pinhal Interior" (Source: IWES)

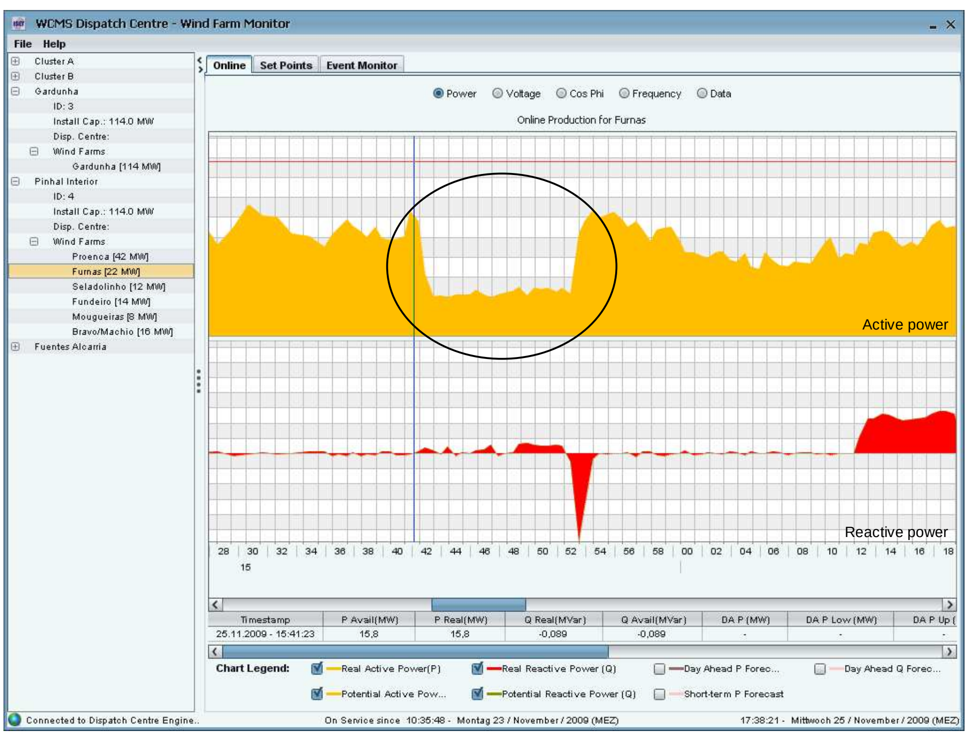


Figure 72 – RTC wind farm "Furnas", Cluster "Pinhal Interior" (Source: IWES)

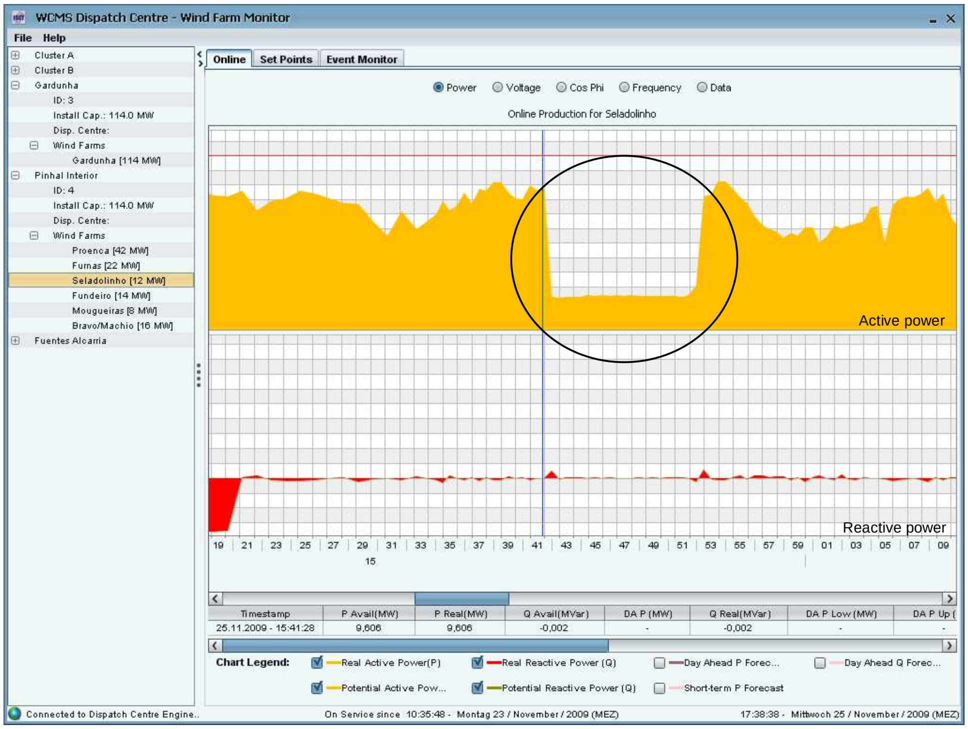


Figure 73 – RTC wind farm “Seladolinho”, Cluster “Pinhal Interior” (Source: IWES)

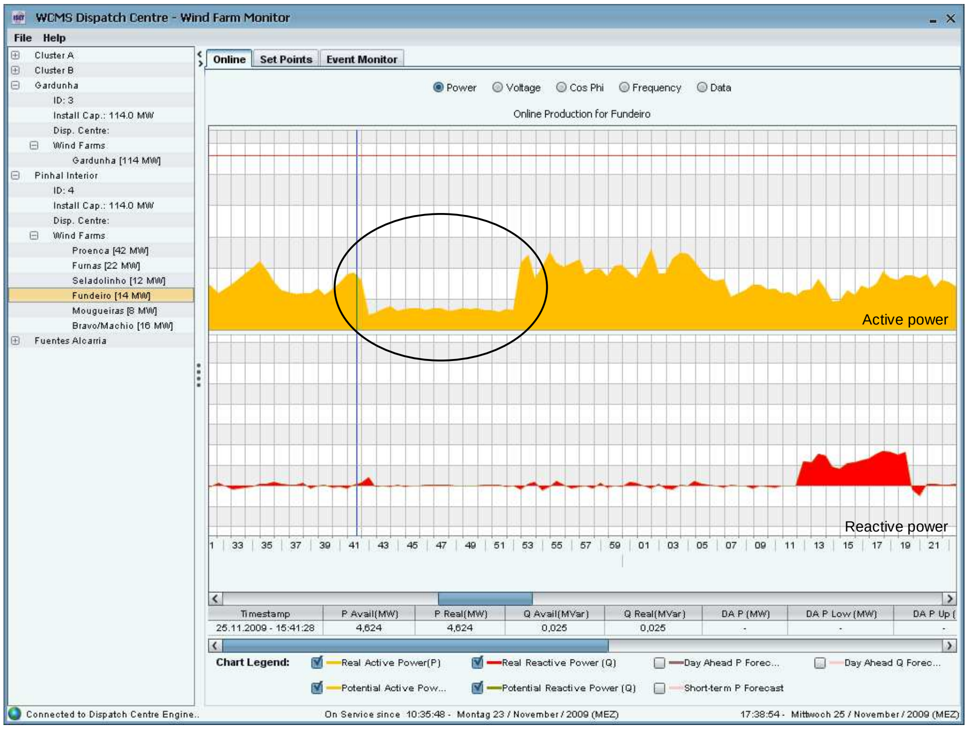


Figure 74 – RTC wind farm “Fundeiro”, Cluster “Pinhal Interior” (Source: IWES)

6.2.8 Results of the project

The results of the “Wind on the Grid” project regarding active power control have shown the capability of wind power of reacting to a given control command and keeping it stable during the period of the set point. Said in other words, according to the project results wind power is technically capable to provide positive and negative power reserve.

It was also essential to analyze and describe the differences between the structures of the different wind farm clusters in order to better study the R&D results of the different tests performed in Portugal.

Tests under low and normal wind conditions were performed showing that under low wind conditions it is difficult to guarantee power availability in order to offer power reserve.

The two layers structure for wind power control, TSO and dispatch centre layer, which are currently being implemented by some European countries (Spain and Denmark, for example), were also considered during the performed tests, showing that the developed control strategies implemented into the WCMS could run into these structures.

6.3 Summary of chapter 6

During this chapter concrete control capabilities of wind farms are being reported based on several tests performed in Germany and Portugal. Tests scenarios as well as their grid description are also presented. Promising results, based on second level measurements campaigns, are shown where wind farms are being successfully controlled, and power reserve provision capability is tested.

Finally, control commands were sent to the selected wind farm clusters, and their control capabilities were demonstrated. The active power deviations from the original set point were also analyzed.

7. Conclusions and recommendations for further research

7.1 Conclusions

This chapter summarizes the findings of the present PhD “Power reserve provision with wind farms”.

Wind power is, admittedly, different from other power technologies and integrating large amounts of it in the existing power systems is a challenge that requires innovative approaches to keep the sustainability of the power system operation. In the coming years the contribution of wind power to the system security will become mandatory.

Nowadays the Transmission System Operators (TSOs) are managing and operating the electric power transmission grids based on ancillary services procurement from the free market. The trend goes towards more decentralized structures and an increase in complexity due to a higher number of market participants. The provision of this kind of services also by wind energy requires innovative technical solutions.

The planned construction of numerous wind farms of the magnitude of conventional power plants calls for a new strategy in their operational management. In terms of the monitoring, connection and control conditions, wind farms should be equivalent to conventional power stations. Particularly related to the ancillary services provision, it is proved that wind farms could take over the tasks currently carried out by conventional generators.

As it has being described during this PhD, wind power can not only be decreased but also be increased within a time frame of seconds. Widespread use of this method of operation can result in a significant frequency-supportive power reserve provided by wind farms.

The contribution of wind energy into power reserve market leads to new market rules, legal and regulatory frameworks. Furthermore, in order to achieve its wide application and participation throughout Europe, these new rules and frameworks will need to be highly compatible and partly even harmonized in the European Internal Electricity Market (IEM).

This new context, characterized by complex regulations, an increasing number of actors and the services that they require, asks for more intelligent control systems that can manage both the electrical and financial operation of the grid and new interactions between grid participants.

Many different visions have been proposed for future power systems. Each of these visions depends on equipment, regulations, legal structures, environmental factors and many more, all with specific control needs.

The consensus no longer exists with regard to the question how a future power grid should be controlled, or what should be intermediate steps towards that direction. A new research area is currently forming on the border between electrical power engineering, industrial automation, control engineering, energy economics, communications technology and intelligent systems. The first large research projects in this area have already been launched. Some countries like Denmark or Spain, have already implemented the proposed “two layers” concept (TSO and dispatch centres), showing that wind power is controllable and predictable enough to allow larger penetration levels, according the world wide trends.

The necessity of the wide use of renewable generation is nowadays self evident. However, it is not the need of ancillary services provision based on renewable energies. Large wind farm clusters will be centrally controlled in order to coordinate and adjust the operation of many individual wind farms distributed in the field.

This research has been focused on the development, implementation and validation of an innovative methodology oriented to wind power being able to provide positive and negative power reserve. The following steps have been taken:

1. A clear description of the problem as well as the research objectives and main focus.
2. Literature review regarding the existing grid code requirements for wind power in Europe[22]. Particularly, it was analyzed the current requirements for active power control with wind farms.
3. A development of a methodology for power reserve provision with wind power. This methodology considers the natural characteristics of wind power, the current available forecasting structures and their uncertainties as well as the security requirements of the TSOs.

[22] The ENTSO-E recomendations were considered as a guide line for power systems and technical requirements.

4. The developed methodology is implemented based on real data. The behaviour of the developed algorithms and structures is tested in two different environment simulations of positive power reserve provision.
5. Based on the German wind power production time series from 2009, the proposed methodology is implemented and power reserve provision offers from wind farms are simulated considering different wind power forecast certainty scenarios.
6. Technical capabilities of wind farms were analyzed and tested in real test fields in Germany and Portugal. These results are analyzed considering the needed requirements for wind power being able to provide power reserve.

The project has been oriented to the technical aspects of power reserve provision with wind power. The results of this PhD are divided into the following topics:

1. Literature review and wind power controllability

During the last two decades wind power was considered a non controllable energy source fully dependent on unstable weather conditions. As the main conclusion after the analysis from several European grid codes, it can be stated that nowadays wind power is considered as controllable power source. It is already documented, at grid code level, that wind farms should fulfil several technical requirements in order to be connected into the European grids. The main aspects with regard to active power control which are reviewed during this PhD are controllability and control range, ramping and limitation, reduction due to over frequency and reduction for protection schemes and frequency control.

It can also be observed that traditional schemes from grid codes oriented to conventional generation are not directly transferable to wind power. The trend goes in the direction that wind power plants are expected to be fully controllable as conventional power plants.

In some cases the needed technologies are already installed in the field or available to be delivered by the wind turbine manufacturers. The regulatory mechanisms are pushing the development of innovative methodologies in order to make use of the available technologies and fulfil the grid codes requirements.

2. Methodology for power reserve provision with wind farms

Existing barriers, available technologies and design parameters have been considered for the development of an innovative methodology in order to allow wind power to provide primary and secondary power reserve in a secure and flexible way.

For an effective management of the wind power input into the electricity supply systems, wind power forecasts are essential, therefore the main algorithm includes the use of wind power forecast and the lower boundary of its confidence interval. At the same time, it is also considered the interaction between the TSO, the wind power generation companies and the SCADA system of each wind farm.
The structures included into the developed algorithm are “Offer Validation Matrix”, “Hour Stability Factor” and “Offer Stability Factor”.

3. Methodology validation

In order to validate the developed methodology, two simulations of power reserve provision with wind power were carried out based on real wind farm clusters. More than 650 MW of install capacity were considered for the simulations development and the implementation of the developed methodology.

The behaviour of the validation structures during the different steps of the process was also analyzed as well as the effectiveness of the complete model with regard to its control capability and the possibility of wind power to provide power reserve in a stable and secure way.

Finally, it was studied the concrete capability of wind power to provide primary and secondary power reserve during one year. The analysis was performed based on the German wind power production time series from 2009. The results of the validation process can be described as following:

- The innovative developed methodology allows increasing the power quality at low costs from those electrical systems which may have a strong penetration of wind power.
- The structure of wind farm clusters is recommended in order to reduce limitations due to potential unavailability of single units by grouping wind farms into clusters.

- Wind farms should be prequalified in order to be able to provide ancillary services as happens nowadays with conventional generators.
- Due to the needed time response, an automatic algorithm is needed to monitor and control the different steps until the power reserve is finally provided by the selected wind farms.
- For the year 2009 it was calculated for how long and with which certainty level primary and secondary power reserve could have being provided by wind power. Results have shown that wind power could have contributed to primary power reserve[23] during 41,74% of the year with a 99% of certainty. It can also be observed that secondary power reserve[24] could have been provided by wind power during 29,46% of the year with a certainty level of 99%.

4. Capability of wind farm clusters to provide power reserve

Developing an innovative concept to provide power reserve with wind power requires also testing the technical capabilities of real wind farms. In some cases, the already implemented technologies at wind farm level are not fully being used and the capability of wind farms to be controlled is already there.

Several scientific tests were carried out based on control strategies for active power control considering the structure of wind farm clusters developed by Fraunhofer IWES as well as the need of sharing data between TSO control systems and dispatch centres.

During the projects "Integration großer Offshore-Windparks in elektrische Versorgungssysteme" and "Wind on the Grid", control strategies for wind farm clusters management were implemented and evaluated. Wind farms located in Germany and Portugal were proposed as real test fields being online monitored and controlled by the Wind Farm Cluster Management.

Concerning the performed tests, the obtained results are described as following:

- Wind farms have showed the capability of reacting to a given control command.
- Controllability of wind farm clusters was successfully tested.
- Power oscillations were registered. They should be deeper analyzed in order to be minimized.

[23] Considering that 800 MW are required for primary power reserve in Germany (ENTSO-E).
[24] Considering that 2000 MW are requiered for secondary power reserve.

- 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 of a set point.

7.2 Recommendations for further research

The global solution to the energy problem requires new developments oriented to the integration and management of the renewable energies as a whole.

The concept of “Virtual Power Plant” as a cluster of renewable energy sources will be essential in order to allow a secure and flexible management of those renewable energies integrated into the different power systems. At the same time renewable energies should also be able to contribute to the system security, which currently is handled by conventional power plants.

The provision of ancillary services based on “Virtual Power Plants” should be deeper analyzed considering the different natural characteristics from each renewable energy source and their capabilities to be forecasted in the short and long term.

The large scale integration of renewable energies also requires analyzing which storage facilities are going to be needed in the near future. The storage technologies which are currently being studied and should be matter of further research are listed as following:

- Electrical vehicles.
- Batteries.
- Water pumping stations.
- Hydrogen.

Better correspondence of the load with the generation could be achieved in the future by the use of dynamic tariffs, known as demand side management. It could make it possible to shift big (industry) as well as small (citizen) load from the peak to the low load time. The “Smart Grids” concept is also currently being developed in this direction. One other option is the use of plug-in-hybrid vehicles, which can be also considered as electric energy storage (“prosumers” concept).

Also economical and regulatory models should be matter of research in order to promote ancillary services to be provided by renewable energies (not only by wind power).

8. Acknowledgments

This PhD was carried out while I was working as Research Engineer at Fraunhofer IWES in the area “Energy Meteorology and Wind Power Management” at the “R&D Division Energy Economy and Grid Operation”.

I do believe that there is nothing more valuable than theoretical knowledge and practical experience together. A combination of these two factors is what I have gained as part of my experience as Researcher at Fraunhofer IWES. At this point I want to express my sincere gratitude to a number of people for their support and assistance during the development of my research.

I would like particularly to thank my PhD supervisor, Prof. Dr.-Ing. Siegfried Heier, from the Department of Power Supply Systems, Faculty of Electrical Engineering and Computer Science, University of Kassel. Prof. Heier gave me the sole responsible research through his constant advice and encouraging discussions.

Especially, I would like to express my gratitude to the co-supervisor of this PhD, Dr.-Ing. Kurt Rohrig, head of the “R&D Division Energy Economy and Grid Operation” from Fraunhofer IWES. Dr. Rohrig hired me giving me the opportunity of starting my carrier as researcher at Fraunhofer IWES. His advisory help, his vision with regard to my research topic and his unremitting belief in the success of this work were extremely valuable for me.

I would like to take the opportunity to thank Dr.-Ing. Bernhard Lange head of our group “Energy Meteorology and Wind Power Management” and all my colleagues from the “R&D Division Energy Economy and Grid Operation”. I have shared with them many working hours in a professional and kind atmosphere. It is great for me to be part of such a professional team. I would like to thank the collaboration from Mrs. Katharina Lesch and Mr. Michael Durstewitz. Particularly, I would like to thank also Mr. Jan Dobschinski for his support with issues related to wind power forecast technologies.

Then, there are a number of people and institutions that I would also like to thank for providing me expert information that has enabled me to direct my research well and to move forward in the right direction.

First and foremost, I would like to thank Mr. Knud Johansen for sharing his large experience and knowledge with me. With his constant contributions and ideas he added an enormous value to my PhD. I am extremely thankful to him for his kindness, generosity and for the time he has taken from his personal life to support me.

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I also look back to the highly interesting and useful discussions I have had with Mr. Luis Coronado Hernandez (REE, Spain) and with Mr. Rui Pestana (REN, Portugal). Their vision from a TSO point of view as well as their concerns with regard to the subject of this PhD was highly valuable for me in order to keep my research in the right direction.

In many ways I am deeply indebted to all people who contributed to this work.

Finally, I owe my gratitude to my parents, my family, my parents-in-law and friends for all their love and support during my personal and professional education.

I have some words to the person being closest to me. A very big “thank you” is reserved to my wife, Verónica, for her love, encouragement and unconditional support during the last 11 years, when sometimes I was “away” fully dedicated to my studies, my work and also travelling around the world. She was always there, supporting me patiently. Without her I could have never completed my work.

I dedicate this work to our son Santiago Alejandro Gesino.

Kassel, 22 November 2010 Alejandro J. Gesino

Appendix I: Project support for the thesis

Parts of this thesis were supported by funding of the following projects:

- Project "**Integration großer Offshore-Windparks in elektrische Versorgungssysteme**". This project has received funding from the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

- Project "**Wind on the Grid**", initiative supported by EU Commission-DGTREN. This project has received funding from the European Union's Sixth Framework Programme.
  http://www.windgrid.eu/

Only the author is responsible for the contents of the thesis.

Appendix II: Wind Farm Cluster Management System (WCMS)

The Wind Farm Cluster concept was created as a natural evolution for wind energy. In the past, wind turbines were grouped into wind farms. Nowadays wind farms are being grouped into wind farm clusters. The aim of clustering wind farms is to allow the TSOs to administer wind energy as a conventional power source thereby avoiding some of its impact on the grid due to the fluctuating nature of the wind, the wide distribution of the wind farms and the existence of different generator technologies, among other issues.

Based on this innovative concept, the Wind Farm Cluster Management System (WCMS) was developed making joint use of advanced techniques in high-tech wind farm control strategies as well as wind energy forecast technologies. With all these elements combined, the WCMS is able to perform active and reactive power control, congestion management, gradient control, voltage control as well as power factor control in order to fulfil the requirements of operational flexibility and security required by grid operators.

WCMS Architecture

The WCMS architecture was designed with the structure of the current wind energy market, from both a technological and economical point of view, in mind Figure 75. The existence of different company profiles and control levels were considered as well as different business and commercial concerns regarding energy production and trading markets.

Two main layers of operation were identified, namely the “TSO layer” and the “dispatch centre” layer. This structure allows the TSOs to efficiently monitor all wind farms operating in their control zones as well as being able to reliable distribute control commands to all required wind farm clusters, independent from the dispatch centre to which each belongs. Both layers can be described as following:

- TSO layer: is mainly responsible for grid security issues and the decision making process regarding control commands for wind farm clusters. Its main requirements are real time information at wind farm level as well as its own forecasting and grid calculation tools. Based on this information, the wind power production that may be fed into the power system at any given time is calculated. This is done using historical data, the characteristics of the generators and the current state of the system.

When a control command must to be sent to a given wind farm cluster, it is initially forwarded to the connected dispatch centres which re-transmit it to the wind farms under their control.

- Dispatch centre layer: its main function is to supervise and control the power production of all wind farms which are connected at this level. Dispatch centres should guarantee the interconnection between the TSO and the wind farms forwarding monitoring values at wind farm level to the TSO and control commands sent by the TSO to each wind farm. A dispatch centre also articulates the integration of the wind power production in a way which is compatible with the system security. The information is collected from the control units of each wind farm. Measurements, such as active and reactive power, voltage, connectivity, temperature and wind speed are taken from each wind farm every second.

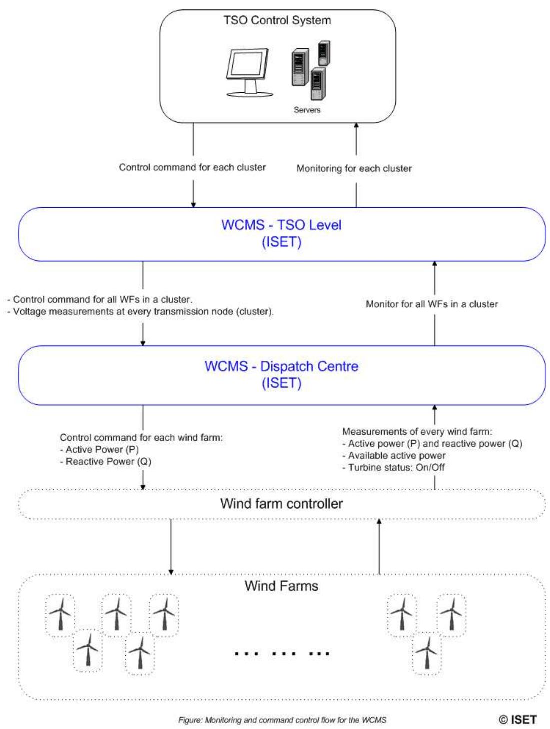

Figure 75 – WCMS data flow

Data flow: control commands and data monitoring

Figure 76 depicts two data flow directions: the “control command” direction and the “data monitoring” direction. The control command (set point) is sent from the “WCMS TSO” to the “WCMS Dispatch Centre”, which process the incoming information and finally delivers the processed instruction to the “Wind Farm Controller”. At the same time, monitoring data at wind farm level is sent from "WCMS Dispatch Centre" to "WCMS TSO" at the highest available frequency.

The generated set point at the WCMS TSO level includes grid security parameters, which were calculated by the TSO. Those parameters include, among others, shot-circuit estimations, maximum wind power admissible and grid transmission capacity. Once the calculations are completed, the settings are transformed into active and reactive power set points which are then sent from the TSO to the dispatch centre level.

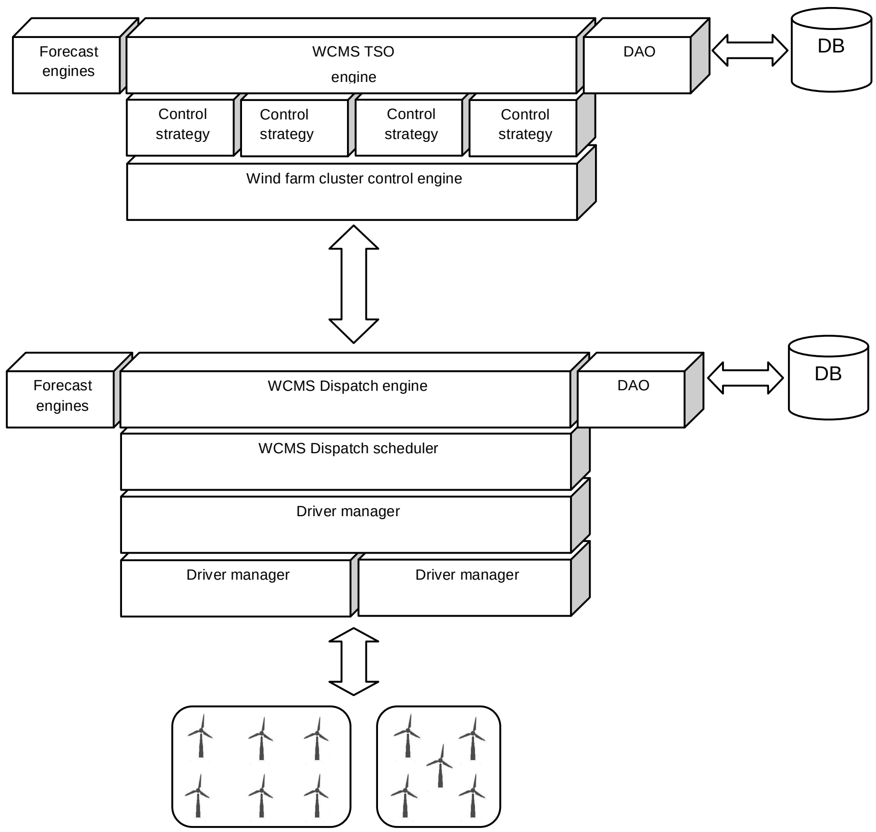

Figure 76 – WCMS architecture

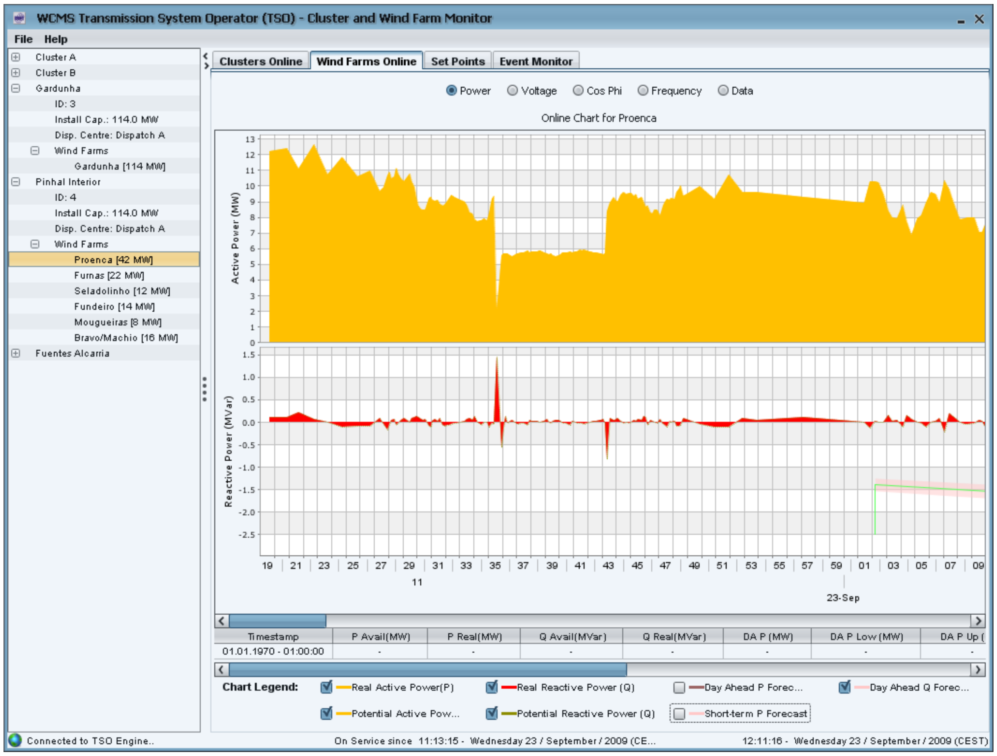

Figure 77 – Wind Farm Cluster Management System

Appendix III: Pre-qualification rules for wind farms

Introduction

The aim of the pre-qualification rules is to set up a list of rules that any power generator which aims to be connected to public electricity supply grid should be able to fulfil. The power generator needs to participate in a procedure under which its technical capabilities are reviewed by the TSO or by an independent body. After following successfully a pre-qualification procedure, the supplier is entitled to participate in the tendering process (see Figure 78).

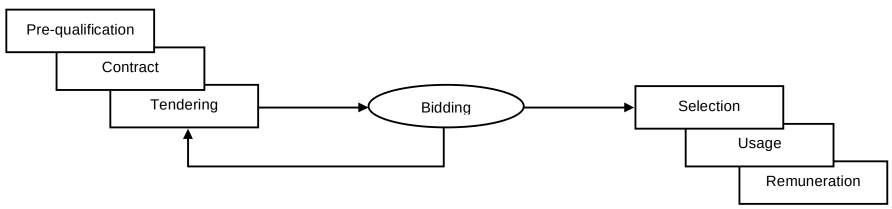

Figure 78 – Tendering model schema after pre-qualification

Previously, only large power station units undertook the tasks relating to regulation and stabilization of the power system. As nowadays power production is increasingly based on wind power, all production units, including wind farms, will have to contribute to the system security through the ancillary services provision. As a consequence, pre-qualification rules which were developed exclusively for conventional generation should be also adapted to wind farms.

Pre-qualification rules for wind farms

In the past wind turbines were approved under relatively low technical grid constraints. The primary objective in the operation of these units grouped into wind farms consisted in maximising the energy yield. Now, however, in order to ensure a secure grid operation, it has become necessary for wind farms to accept new constraints within their capabilities. New binding grid connection rules for wind farms should be defined by the TSOs. These rules include the minimum power output per unit (wind farm) and the properties which the power units must incorporate and retain during their service life.

From the responsibilities point of view, the pre-qualification rules should be written by the TSO and the wind farm owner should be responsible for ensuring that the wind farm observes the requirements of the regulation. Once the wind farm owner submits to the TSO the proper documentation as well as the wind farm simulation model, the permission to the normal operation of the wind farm should be granted by the TSO as soon as the pre-qualification tests are successful.

The new set of rules has to ensure that the wind farms have the regulation properties and dynamic properties essential for power system operation[25].

Besides the technical prequalification rules, wind farms shall observe other applicable regulations, as market and system operation regulations. This ensures that wind farms connected to the power system can contribute sufficiently to its operational reliability.

Energinet.dk has published the "Technical regulation for the properties and regulation of wind turbines" [77] where active and reactive power regulation capabilities are described and summarized as following:

- **Active power regulation**

For each wind farm a joint function is to ensure remote control of the total active power production. The "farm controller" has to ensure that control commands submitted to the wind farm are met in the connection point. Each wind farm shall cover the following regulation functions for active power:

Type of regulation	Purpose	Primary regulation aim
Absolute production constraint	Limit the wind farm's current power production in the connection point to a maximum, specially indicated MW value. Constraints may be necessary to avoid overloading of the power grid.	Limit production to optional MW_{max}
Delta production constraint	It must be possible to reduce the power production of the wind farm by a desired power value compared to what is possible at present, thereby setting aside regulating reserves for the handling of critical power requirements.	Limit production by MW_{delta}
Balance regulation	The power production of the wind farm must be adjusted to the current power requirement.	Change current production by

[25] The described pre-qualification rules do not deal with economic aspects associated with the use of regulation properties.

		-MW / +MW with the set gradient and maintain the production.
Stop regulation	The wind farm must to keep the power production at the current level (if the wind makes it possible). The function results in stop for upward regulation and production constraints if the wind increases.	Maintain current production.
Power gradient constrainer	For system operational reasons it may be necessary for wind farms to limit the maximum speed at which the power output changes in relation to changes in wind speed. The power gradient constrainer is to ensure this.	Power gradients do not exceed the maximum settings.
System protection	System protection is a proactive function which must be able to automatically downward regulate the power production of the wind farm to a level which is acceptable to the power system. In the case of unforeseen incidents in the power system, the power grid may be overloaded at the risk of power system collapse. The system protection regulation must be able to rapidly contribute to avoiding system collapse.	Downward power production automatically on the basis of an external system protection signal.
Frequency control	At frequency deviations in the power system all production units must to be able to contribute with rapid automatic power control to support the restoration of the normal frequency (50 Hz).	Regulate power production on the basis of the local frequency.

Table 36 – Active power regulation

Finally, to ensure that the various regulating and constraint functions do not interfere with each other, the following priority ranking shall be observed where function 1 has preference over function 2, etc.

1. System protection.
2. Frequency control.
3. Stop regulation.
4. Balance regulation.
5. Power gradient constraint.
6. Absolute gradient constraint.
7. Delta production constraint.

- **Reactive power regulation**

The wind farm owner shall supply a P-Q diagram showing the regulation capability for reactive power in the connection point. The amount of reactive power that the wind farm can supply shall be made available to the system operator for control of the power system's reactive power requirement. The wind farm shall contribute as far as possible to maintaining the agreed MVar exchange or voltage level in the reference point. Reactive power regulation shall be done by the "farmer controller" function. It shall be possible to order reactive power regulation requirements via remote control.

Type of regulation	Purpose	Primary regulation aim
MVar regulation	Automatically ensure that the wind farm supplies the desired MVar exchange in the reference point.	Maintain the desired MVar value in the reference point.
Voltage regulation	Automatically ensure the desired voltage in the reference point by the reactive power regulation of the wind farm.	Maintain the desired voltage in the reference point.
Reactive regulation according to minimum requirements	The reactive production of the wind farm shall observe the permitted reactive characteristics in the connection point.	

Table 37 – Reactive power regulation

As it can be observed in Table 36 and Table 37 active and reactive power are required to be controlled as happens with conventional generation.

Appendix IV: Economical consideration of providing power reserve with wind power

Introduction

Markets liberalization coincided with an increasing awareness for environmental concerns, technological progress and security of supply considerations as well as an increased need for reliable and high-quality power, which jointly with the fact that wind energy is starting to replace conventional generation leads to the need of wind energy to provide ancillary services. This brings new entities which should interact together keeping at the same time the basic security requirements of TSOs.

Liberalization and deregulation of the industry led to the introduction of competition in the segments of generation and supply. One of the consequences of liberalization is the new way in which the now separated entities interact with each other [53] as well as new methodologies are developed in order to rule the relation between them. Some of these methodologies regarding positive and negative power reserve provision are particularly described in this chapter.

Electricity exhibits a combination of attributes that makes it distinct from other products: non-storability (in economic terms), real time variations in demand, low demand elasticity, random real time failures of generation and transmission, and the need to meet the physical constraints on reliable network operations [59].

Market access on equal terms is a prerequisite for the establishment of a level playing field between conventional generation and wind power. Current electricity market design does not take into account the specific characteristics of wind energy in several respects, thereby delimiting the realisation of its potential contribution in terms of active power provision and the provision of ancillary services.

Nowadays no real monetary incentives exist for a direct RES ancillary service market access (see Figure 79). Corresponding to the current law in Germany (EEG) RES units are not required to schedule their energy and contribute to ancillary services [52].

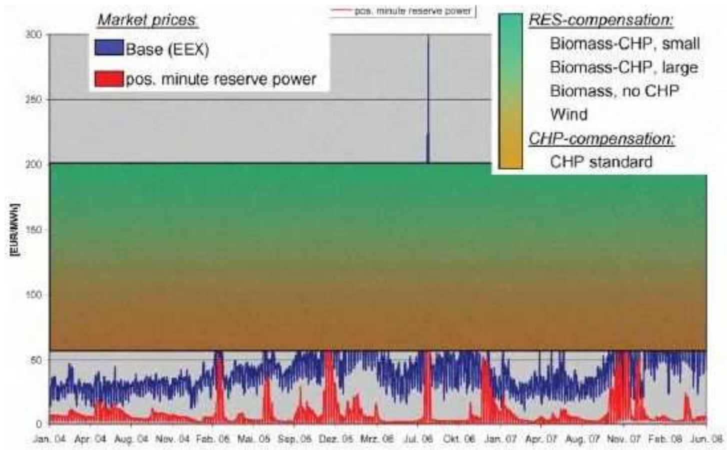

Figure 79 – Price of the direct market access vs. RES and CHP-compensation [52]

Economical and market barriers for power reserve provision with wind power

- Down regulation is mostly not a problem; up regulation however is difficult without jeopardizing economics. The properties of different generators determine their capability to participate in either or both primary and secondary control.
- The fixed price practice for wind energy: an adapted model should be developed in order to allow maintaining wind energy prices as well as enabling the ancillary services market participation in parallel.
- Participation on the positive power reserve markets may be profitable for power producers with high fuel costs only. This situation excluded the participation of wind power plants because of the missing fuel costs for wind power on the other side.
- The provision of negative power reserve will become mandatory to avoid power surplus in the future. A regulatory framework will require switching-off the surplus of power during the weak load times.
- Wind energy does not participate on the liberalized market. Its fix price is much higher than the low end prices for energy or power reserve. Consequently there is no incentive to contribute with positive or negative power reserve.

Electricity market

The "electricity market" is in fact not one market, but rather consists of a set of submarkets that operate both sequentially and in parallel. Except for the real-time market, all electricity markets are financial markets: the delivery of power is optional and the seller's only real obligation is financial. Typically, market participants conclude contracts through **bilateral trading** already weeks or months in advance. Thereafter, they trade on institutional markets (power exchanges or pools) to balance their portfolios. The former usually comprise a day ahead market, an hour-ahead market, and a real-time or balancing market. The **day-ahead market** takes the form of an auction. Generators, traders, retailers and large industrial customers submit bids specifying price/volume pairs of electricity they will sell or buy for each of the 24 hours of the following delivery day. The bids are "frozen" at a fixed deadline on the trading day and prices are determined according to the rules of the power exchange or pool. Finally, accepted bids are settled at the calculated prices [53].

The **hour-ahead market** allows market participants to improve their physical electricity balance after gate closure of the day-ahead market through continuous trading until one hour before delivery. In the hour of actual operation, the balancing of power is either done on the basis of bilateral contracting or by means of a **balancing or real-time market**. In order to ensure instantaneous balancing of supply and demand, real-time markets are run as centralized markets, even in fully deregulated systems. The system operator acts as a Single Buyer and is responsible for upward and/or downward regulation, which may be done via regulating bids under an exchange or pool approach [53].

Economic decisions are made individually by market participants and system-wide reliability is achieved through coordination among parties belonging to different companies. In other words, in the past all grid participants pursued the same goal: the objectives of the individual entities were congruent with the objectives of the system. This has changed: today, the multitude of independent agendas does not necessarily guarantee decisions that are effective and sustainable for the power system as a whole. Coordination is therefore necessary [53].

Mechanisms to procure ancillary services

Four major methods through which system operators procure ancillary services can be distinguished: **compulsory provision**, **bilateral contracts**, **tendering** and **via a spot market** [27].

For wind power, remuneration is focused on active power, therefore as far as providing power reserve consist in wind farms being operated below their operational limits in order to allow them to inject additional power on demand, costs of this ancillary service should be determined, in order to allow producers to participate in such markets.

As with any commodity, creating a market for ancillary services is a way of resolving the conflict between buyers and sellers to their mutual benefit. TSOs would like to obtain the resources they need to maintain the security of the system at the minimum cost, while providers seek to maximize the profit they make from the sale of ancillary services. However, because ancillary services are not simple commodities, the already mentioned forms of trading are analyzed as following [27]:

Compulsory provision means that a certain class of network users (typically large conventional generators) is required as part of their connecting conditions to provide upon request from the TSO up to a certain amount of a given ancillary service. Compulsory provision is "fair" because all the users belonging to a certain class must provide the same absolute or relative amount of ancillary services. However, for the sake of fairness and transparency, the requirements for compulsory provision are often expressed in a manner that does not catch all the complexity of the issue. This simplification has two main consequences. First, the volume of ancillary services provided may exceed what is needed, imposing unnecessary costs on the providers. Second, compulsory provision does not necessarily minimize costs because potentially low costs providers are treated on the same basis as more expensive ones.

When a TSO procures an ancillary service using **bilateral contracts,** it negotiates with each provider the quantity, quality and price of the service to be provided. Bilateral contracts have disadvantages. First, since their terms are usually not disclosed to third parties, this form of procurement lacks the transparency that is desirable when one of the parties is a monopoly (the TSO). Second, the bilateral negotiations can be long, complex and costly. Third, because of the high transaction cost of bilateral contracts, price and volume are often fixed for a long time. This will inevitable be detrimental to one of the parties if market conditions change [27].

The third and fourth procurement methods involve the development of a tendering process or the creation of a spot market. The **spot market** is used to denote a market where standardized products with a short duration are exchanged. A tendering process involves less standardized products. They have high data management costs and may facilitate the exercise of market power by some participants [27].

Regarding the remuneration, there are also different kinds of remuneration methods. Ancillary services can be **non-remunerated** or paid according to one of three types of price: **a regulated price**, a **pay bid price** or **a common clearing price** [27].

While **a non-remunerated** system is very convenient for the TSO, it is unlikely to be economically optimal because the costs that the providers incur end up bundled in the price of other products such as electrical energy [27].

By definition, **a regulated price** is set by the regulator or the TSO and is usually the same for all providers. This form of remuneration is particularly justified when market power is an issue. In general, however, a regulated price is not desirable as it reflects very imperfectly the actual costs of providing an ancillary service, particularly when this cost changes with time or circumstances [27].

In **a pay as bid system**, the supplier receives the price of its accepted offer. This type of remuneration method is suitable when the quality of the ancillary services offered is highly differentiated and those offers are thus not easily comparable. However, pay as bid price does not give providers an incentive to bid their marginal cost, except when market concentration is low [27].

In a common clearing price system, all the successful providers are paid the price of the most expensive accepted or the least expensive rejected offer. This form of pricing gives real incentives to suppliers to offer their marginal cost. On the other hand, it is not adapted to differentiated products because all the offers have to be comparable [27].

The market size and the development of the power reserve services in Germany are demonstrated in Figure 80 [54].

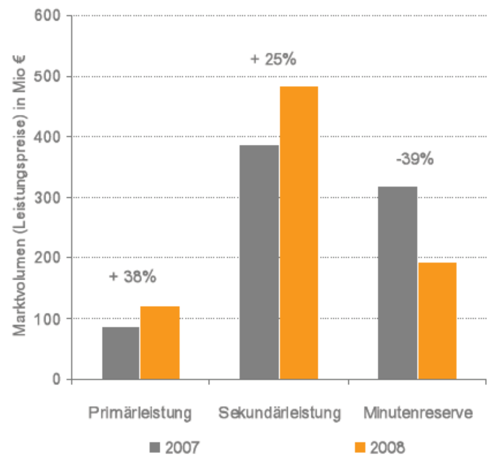

Figure 80 – Market size of reserve power in Germany

Profit expectation for power reserve provision

Generators have the potential to participate as reserve capacity. However, as the marginal costs are usually low, there is little incentive to participate. This effect is often aggravated by subsidies which are being given per unit of produced energy to generators of renewable energy [51].

For reserve capacity, two main payment strategies are in use [60]. These are:

Payment for Power Delivered

In this case, reserve capacity is only rewarded if it is actually used. The payment consists of a price per unit of energy sold as reserve capacity. Generators choose to keep reserve capacity when the price per unit of energy for reserve capacity (λ_r) is larger than the price for normal production (λ).

Payment for Reserve Allocated

In the second case, withholding reserve capacity is always rewarded. The generator will receive a payment per unit of energy of lost production. Since most of this electricity will never be produced, little production costs are made and the price for allocation (λ_r) of the reserve capacity can be lower than the price for normal production (λ).

Next to the decision whether to have a payment for power delivered or a payment for reserve allocated, also a decision needs to be taken how to determine the price for the product. In the marginal pricing system, all selected bidders receive the same price whereas in the pay-as-bid system, all selected bidders receive their own individual bidding price.

In case the portfolio of the producer exists only a single generator the expectation of the profit for the power producer can be described as following [60]:

$$E(\Pi) = E(\Pi_s + \Pi_{r+} + \Pi_{r-} - C)$$

Equation 8 – Profit expectation of a power producer

In which:

$$\Pi_s = (1 - r^-)\lambda P_s$$
$$\Pi_{r+} = r^+ \lambda_{r+} (P_t - P_s)$$
$$\Pi_{r-} = r^- \lambda_{r-} P_s$$
$$C = -a((1 - r^-)P_s + r^+(P_t - P_s))^2 - \ldots$$
$$\ldots - b((1 - r^-)P_s + r^+(P_t - P_s)) - c$$

Where:

- $E(\Pi)$ is the expectation of the profit of a producer.
- Π_s corresponds to the income resulting from production of normal energy and selling it to the normal price.
- Π_{r+} corresponds to the income originating from the production and selling of positive reserve capacity during the shortage of energy. The maximum reserve capacity is determined as the difference between P_t and P_s.
- Π_{r-} corresponds with the income proceeding from deployment of negative reserve capacity. This means that part of the production P_s is decreased in order to receive the price for negative reserve capacity.
- r^+ and r^- are the probabilities of providing negative and positive reserve capacity.
- λ is the electricity price at the moment. λ_{r-} and λ_{r+} are the prices of negative and positive reserve capacities.
- C corresponds with the costs for production of the required amount of electricity. A 2nd order polynomial cost function is selected.

For the power producer (see Equation 8) should be treated as an optimization problem (see Equation 9) to optimize the expected profit given certain values for r^+, r^-, λ_{r+}, λ_{r-}, λ, a, b, and c.

$$\max_{Ps} \mathrm{E}(\Pi)$$

Equation 9 – Optimization problem

Influences of the incentives for renewable generation on the equation for the profit of a generator

In many countries, subsidies are given to producers as an incentive to invest in distributed or renewable generation. Often these subsidies are paid per unit of energy, delivered by the generator of renewable energy. This changes the equations for the profit of a generator by adding the subsidy price (λ_{sub}) [51].

$$E(\Pi) = E(\Pi_s + \Pi_{r+} + \Pi_{r-} - C)$$

Equation 10 – Profit of a generator by adding the subsidy price

In which:

$$\Pi_s = (1 - r^-)(\lambda + \lambda_{sub})P_s$$
$$\Pi_{r+} = r^+(\lambda_{r+} + \lambda_{sub})(P_t - P_s)$$
$$\Pi_{r-} = r^- \lambda_{r-} P_s$$
$$C = -a((1 - r^-)P_s + r^+(P_t - P_s))^2 - \ldots$$
$$\ldots - b((1 - r^-)P_s + r^+(P_t - P_s)) - c$$

As a result the conditions to withhold capacity for the use of either positive or negative reserve capacity changes into:

$$\lambda_{r+} > \lambda + \lambda_{sub}$$
$$\lambda_{r-} > \lambda + \lambda_{sub}$$

In case of perfect competition and liquid markets for both power and reserve capacity, the prices λ_{r+} and λ_{r-} will evolve such that $r^+\lambda_{r+}=\lambda$ and $r^-\lambda_{r-}=\lambda$ [61]. Since λ_{sub} is assumed to be positive, the variable P_s for the optimization will change to P_t. This means that both conditions will never be fulfilled and that it is not beneficial for subsidised generators to provide either positive or negative reserve capacity [51].

Summary

Wind power plants do not have a dependency between production costs and generation. Therefore and as far as no new markets are created, currently it is more advantageous to sell the maximum energy than to provide power reserve. However, due to the constant increase of the wind power penetration into the power systems, ancillary services which typically were offered by conventional generation are starting to be requested to be provided also by wind power.

Proving power reserve with wind power means that during certain periods, wind farms should run below their operational limits. This way of operation is not possible, without the proper market framework which should be compatible with the current regulatory models for wind power.

In this Appendix, the mechanisms to procure ancillary services and the economical and market barriers for power reserve provision with wind power are analyzed. Finally after describing the profit expectation for power reserve provision, the influence of the incentives for renewable generation is addressed.

Appendix V: References

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[1] European Union, "A European Strategy for Sustainable, Competitive and Secure Energy", Brussels, Belgium, 8th March 2006. Internet reference: http://europa.eu/scadplus/leg/en/lvb/l27062.htm (Last accessed: 04.05.2009).

[2] Braun M., Dobschinsk J., Gesino A., Lange B., Mackensen R., Mata J. L., Quintero C., Pestana R., Rohrig, K., Wessel A., Wolff M., "Wind Power Plant Capabilities - Operate Wind Farms like Conventional Power Plants", European Wind Energy Conference 2009, Marseille, France, 16 - 19 March 2009. Internet reference: http://www.ewec2009proceedings.info/allfiles2/272_EWEC2009presentation.pdf (Last accessed: 06.01.2009).

[3] Rohrig K., "Online-monitoring and prediction of wind power in German transmission system operation centres", World Wind Energy Conference, Cape Town, South Africa, 2003.

[4] Gesino A., Lange B., Mackensen R., Quintero C., Rohrig K., Wolff M., "Wind farm Cluster Management System", XV Energie Symposium, Fachhochschule Stralsund, Stralsund November 6 – 11th 2008.

[5] UCTE AD-HOC Group, "Frequency quality investigation", Final report, 30th August 2008.

[6] Horne J., "Wind Farms Can provide Frequency Response – Experience of Great Britain Transmission System Operator", 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms, Madrid 26 – 27 May 2008. Internet reference: http://www.electricitycommission.govt.nz/pdfs/submissions/pdfscommonqual/freq-reg/NZWEA1.pdf (Last accessed: 16.06.2009).

[7] Heier S., Waddington R., "Grid Integration of Wind Energy – Conversion Systems", 2nd Edition 2007.

[8] Heier S., "Windkraftanlagen – Systemauslegung, Netzintegration and Regelung", 2005.

[9] Heier S., "Nutzung der Windenergie", 2007.

[10] UCTE, "50 Hertz: a delicate balance". Internet reference: http://www.ucte.org/_library/knowledgecenter/UCTEKnowledgeCenter_Article09_50Hertz.pdf (Last accessed: 04.05.2009).

[11] ELIA, "The primary reserve: a solution for stabilizing the frequency in the European interconnected system", 23.01.2008.

[12] UCTE Operation Handbook, “Load-frequency control and performance”, Appendix 1, 16.06.2004. Internet reference: http://www.ucte.org/_library/ohb/appendix1_v19.pdf (Last accessed: 15.06.2009).

[13] Dany G., “Power reserve in interconnected systems with high wind power production”, 2001. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=00964802 (DRS4-402) (Last accessed: 15.06.2009).

[14] Zacharias P. (editor), “Use of Electronic-Based Power Conversion for Distributed and Renewable Energy Sources”, 2008.

[15] Manwell J.F., McGowan J.G., Rogers A.L., “Wind energy explained – Theory, design and application”, 2002.

[16] EWEA book, “Wind energy – The facts”, 2009.

[17] UCTE Operation Handbook, “Load-frequency control and performance”, Policy 1, 20.07.2004. Internet reference: http://www.ucte.org/_library/ohb/policy1_v22.pdf (Last accessed: 15.06.2009).

[18] UCTE, “Glossary”, 24.06.2004. Internet reference: http://www.ucte.org/_library/ohb/glossary_v22.pdf (Last accessed: 15.06.2009).

[19] RWE Transportnetz Strom, “Procurement of control power and energy in Germany”. Internet reference: http://www.rwetransportnetzstrom.com/web/cms/en/132518/rwe-transportnetz-strom/system-usage/ancillary-services/control-energy/ (Last accessed: 15.06.2009).

[20] RWE Transportnetz Strom, “Criteria”. Internet reference: http://www.rwetransportnetzstrom.com/web/cms/en/132268/rwe-transportnetz-strom/system-usage/ancillary-services/control-energy/criteria/ (Last accessed: 15.06.2009).

[21] Vattenfall, “Compensation energy”. Internet reference: http://www.vattenfall.de/www/trm_en/trm_en/941683compe/index.jsp (Last accessed: 15.06.2009).

[22] Chown, G., Coker M., “Interim report on frequency relaxation project”, August 2000. Internet reference: http://www.sapp.co.zw/docs/frequency%20relaxation.pdf (Last accessed: 06.01.2009)

[23] Eckard Quitmann, Stephan Wachtel, Alfred Beekmann, Enercon GmbH, “Wind Farms with power plant capabilities”, Kasseler Symposium Energie-Systemtechnik 2009, 24-25 September 2009.

[24] CIGRE Working Group 08 of Study Committee C6, “Grid Integration of Wind Generation”, July 2009.

[25] Yann Rebours, Daniel Kirschen and Marc Trotignon, “Fundamental Design Issues in Markets for Ancillary Services”, The Electricity Journal, July 2007, Vol. 20, Issue 6. Internet reference: http://www.eee.manchester.ac.uk/research/groups/eeps/docs/kirschen_2007B.pdf (Last accessed: 06.01.2009).

[26] Yann G. Rebours, Daniel S. Kirschen, Fellow, Marc Trotignon and Sébastien Rossignol, “A Survey of Frequency and Voltage Control Ancillary Services - Part I: Technical Features”, IEEE Transactions on power systems, Vol. 22, No. 1, February 2007. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4077135&isnumber=4077088 (Last accessed: 06.01.2010).

[27] Yann G. Rebours, Daniel S. Kirschen, Fellow, Marc Trotignon and Sébastien Rossignol, “A Survey of Frequency and Voltage Control Ancillary Services Part II: Economic Features”, IEEE Transactions on power systems, Vol. 22, No. 1, February 2007. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4077136&isnumber=4077088 (Last accessed: 06.01.2010).

[28] Reinhard Mackensen, Bernhard Lange, Florian Schlögl, “Integrating Wind Energy into public power supply systems - German state of the art”.

[29] Wind on the Grid, Final Report. Internet reference: http://www.windgrid.eu/ (Last accessed: 07.09.2010)

[30] EWEA, “Wind Directions – The impossible reality of grid integration”, Bimonthly Magazine – Volume 27 No. 5. September/October 2008.

[31] R. Mackensen, Dr. K. Rohrig, “Das regenerative Kombikraftwerk”, Abschlussbericht, April 31st 2008. Internet reference: http://www.kombikraftwerk.de (Last accessed: 11.01.2010).

[32] Gerlinde Hammer, Rolf Röhrig, “Qualification Requirement Analysis Offshore Wind Energy Industry” – Final Report – Bremerhaven/Bremen July 2005. Internet reference: http://www.offshore-power.net/Files/Dok/final_report_qrs.pdf (Last accessed: 12.01.2010).

[33] J.Dobschinski, A.Wessel, B.Lange, K.Rohrig, L. v. Bremen, Y.M.Saint-Drenan, “Estimation of wind power prediction intervals using stochastic methods and artificial intelligence model ensembles”, Dewek 2008.

[34] Jeremie Juban, Nils Siebert, George N. Kariniotakis, “Probabilistic short-term wind power forecasting for the optimal management of wind generation”. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=04538398 (Last accessed: 12.01.2010).

[35] M. Lange: "Analysis of the Uncertainty of Wind Power Predictions", PhD dissertation, Carl von Ossietzky University, Oldenburg, 2003. Internet reference: http://oops.uni-oldenburg.de/frontdoor.php?source_opus=263 (Last accessed: 12.01.2010).

[36] Enercon, "Enercon data sheet grid performance E-82", 01.04.2009.

[37] European TP Wind Project, "Strategic research agenda. Market deployment strategy. From 2008 to 2030", July 2008. Internet reference: http://www.windplatform.eu/ (Last accessed: 15.01.2010).

[38] Verband der Netzbetreiber - VDN – e.V. beim VDEW, Holger Berndt (E.ON Netz GmbH), Mike Hermann (VDN – Verband der Netzbetreiber e.V.), Horst D. Kreye (Vattenfall Europe Distribution Berlin GmbH and Vattenfall Europe Distribution Hamburg GmbH), Rüdiger Reinisch (Vattenfall Europe Transmission GmbH), Ulrich Scherer (EnBW Transportnetze AG), Joachim Vanzetta (RWE Transportnetz Strom GmbH), "TransmissionCode 2007 - Network and System Rules of the German Transmission System Operators", August 2007. Internet reference: http://www.vde.com/de/fnn/dokumente/documents/transmissioncode%202007_engl.pdf (Last accessed: 18.01.2010).

[39] Eurelectric, Sub-group "Connection Rules for Generation and Management of Ancillary Services within WG "Network Issues", Ref: 2000-130-0003, "Connection rules for generation and management of ancillary services", May 2000. Internet reference: http://www.eurelectric.org/CatPub/Document.aspx?FolderID=1513&DocumentID=5908 (Last accessed: 21.01.2010).

[40] IEC, "Wind turbines - Part 12-2: Power performance of electricity producing wind turbines based on nacelle anemometry", 18.07.2008.

[41] ISET - Institut für Solare Energieversorgungstechnik e.V., E.ON Netz GmbH, Vattenfall Europe Transmission GmbH, Universität Kassel, Wobben Research & Development GmbH, Deutscher Wetterdienst DWD and Enertrag AG, "Integration großer Offshore-Windparks in elektrische Versorgungssysteme, Abschlussbericht", August 2009.

[42] BMU, "Strategie der Bundesregierung zur Windenergienutzung auf See im Rahmen der Nachhaltigkeitsstrategie der Bundesregierung", Januar 2002. Internet reference: http://www.bmu.de/files/pdfs/allgemein/application/pdf/windenergie_strategie_br_020100.pdf (Last accessed: 03.02.2010).

[43] Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems", second edition. (December 2006)

[44] ENTSO-E, "Requirements for Grid Connection Applicable to all Generators".

[45] EWEA, “Grid code format for wind power generation”, September 23rd 2009. Internet reference: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/position_papers/080307_WGGCR_final.pdf (17.02.2010)

[46] Energinet.dk, “Grid code for wind energy”.

[47] Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Germany, “Benefits and costs of wind energy”. Internet reference: http://www.erneuerbare-energien.de/inhalt/42721/ (Last accessed: 17.02.2010).

[48] European Union, “European Wind Integration Study (EWIS) Towards a Successful Integration of Wind Power into European Electricity Grids”, January 2007. Internet reference: http://www.wind-integration.eu/downloads/library/EWIS-phase-I-final-report.pdf (Last accessed: 17.02.2010).

[49] V. Buehner, B. M. Buchholz, “Provision of ancillary services by RES”, CIGRE 2010.

[50] T. Kapetanovic, B. M. Buchholz, B. Buchholz, V. Buehner, “Provision of ancillary services by dispersed generation and demand side response – needs, barriers and solutions”, CIGRE session 2008, Paris, France, 2008. Internet reference: http://www.springerlink.com/content/dp3h792nt3666436/fulltext.pdf (Last accessed: 10.03.2010).

[51] J. Frunt, Student Member, IEEE, and A. Kechroud, Student Member, IEEE, nd W. L. Kling, Member, IEEE, and J. M. A. Myrzik, “Participation of Distributed Generation in Balance Management”, Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05281990 (Last accessed: 01.03.2010).

[52] Volker Biihner (EUS / Kisters - Germany), Wolfgang Glaunsinger (ETG/VDE - Germany), Zbigniew A. Styczynski (University Magdeburg - Germany), “Economic and regulatory framework conditions for integration of renewable energy sources into the liberalised market”, CIRED, 20th International Conference on Electricity Distribution. Prague, 8-11 June 2009, Paper 0906. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=05255863 (Last accessed: 01.03.2010).

[53] Oliver Gehrke, Stephanie Ropenus, Philippe Venne, “Distributed Energy Resources and Control: A power system point of view”, RISO-R-1608. Internet reference: http://130.226.56.153/rispubl/reports/ris-r-1608_248-257.pdf (Last accessed: 01.03.2010).

[54] Angela Pietroni, “Zusatzgeschäft Regelenergie”, Zeitungsartikel: Enervis, Powernews – 04/2009. Internet reference:

http://www.enervis.de/images/stories/enervis/pdf/publikationen/fachpresse/enervis_Publikation_04.2009.pdf (Last accessed: 02.03.2010).

[55] Bart Christian. Ummels, "Power System Operation with Large-Scale Wind Power in Liberalised Environments," Ph.D. dissertation, Dept. Elec. Eng., Delft Univ. of Technology, 2009. Internet reference: http://www.uwig.org/Ummels_PhDThesis.pdf (Last accessed: 05.03.2010).

[56] M. Shahidehpour, Y. Wang, "Communication and Control in Electric Power Systems: Applications of Parallel and Distributed Processing", Book, Wiley-IEEE Press, 2003.

[57] F.F. Wu, K. Moslehi, A. Bose, "Power System Control Centres: Past, Present, and Future", Proceedings of the IEEE, p.1890-1907, Vol. 93, No. 11, November 2005. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1519722&userType=inst (Last accessed: 10.03.2010).

[58] B. Tyagi, S. Srivastava, "A decentralized automatic generation control scheme for competitive electricity markets", IEEE Transactions on Power Systems, p. 312-320, Vol. 21, 2006. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01583690 (Last accessed: 10.03.2010).

[59] P. Joskow, "Electricity restructuring: Lessons Learned", Latin American Economic Review, p. 548-558, No. 121, December 2003. Internet reference: http://econ-www.mit.edu/files/1170 (Last accessed: 10.03.2010).

[60] E. H. Allen, M. D. Ilic, "Price-Based Commitment Decisions in the Electricity Market, Advances in Industrial Control", Book, Springer-Verlag, 1999, pp. 5-97.

[61] F.I. Denny, D.E. Dismukes, "Power System Operations and Electricity Markets", Book, vol. I. Boca Raton: CRC Press, 2002, chapter 9. Internet reference: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01226739 (Last accessed: 10.03.2010).

[62] Reiner Schinn, University of Kassel, Masterarbeit, "Vorschläge zur Anpassung des deutschen Regelenergie-Strommarktes zur verbesserten Teilnahme der Erneuerbaren Energien".

[63] EWEA, "Wind in power - 2009 European statistics - February 2010". Internet reference: http://www.ewea.org/fileadmin/ewea_documents/documents/statistics/general_stats_2009.pdf, (Last accessed: 15.03.2010).

[64] GWEC, "Global wind power". Internet reference: http://www.ewea.org/fileadmin/ewea_documents/documents/statistics/gwec/GWEC_-_Table_and_Statistics_2009.pdf (Last accessed: 15.03.2010).

[65] EWEA, “Wind energy – The facts”, ISBN: 978-1-84407-710-6. Internet reference: http://www.wind-energy-the-facts.org (Last accessed: 16.03.2010).

[66] GWEC, “Energy supply security”. Internet reference: http://www.gwec.net/index.php?id=138 (Last accessed: 22.03.2010).

[67] GWEC, “Wind energy makes sound economic sense”. Internet reference: http://www.gwec.net/index.php?id=137 (Last accessed: 22.03.2010).

[68] GWEC, “Wind energy and the environment”. Internet reference: http://www.gwec.net/index.php?id=139 (Last accessed: 22.03.2010).

[69] EWEA, “European Grid Code Requirements for Wind Power Generation”, Brussels February 2008. Internet reference: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/position_papers/080307_WGGCR_final.pdf (Last accessed: 05.06.2010)

[70] ENTSO-E, “WG EPS – Pilot for Grid Connection of Generators with special focus on Wind Generation”.

[71] H. Holttinen, “Optimal electricity market for wind power”, Energy Policy 33 (2005) 2052-2063. Internet reference: http://lib.tkk.fi/Diss/2004/isbn9513864278/article8.pdf (Last accessed: 25.06.2010)

[72] WWEA (World Wind Energy Association), “World Wind Energy Report 2009”, March 2010. Internet reference: http://www.wwindea.org/home/images/stories/worldwindenergyreport2009_s.pdf (Last accessed: 05.07.2010)

[73] Jan Dobschinski1, Ennio De Pascalis, Arne Wessel, Lüder von Bremen, Bernhard Lange, Kurt Rohrig, Yves-Marie Saint Drenan, “The potential of advance shortest-term forecasts and dynamic prediction intervals for reducing the wind power induced reserve requirements”, EWEC 2010. Internet reference: http://www.ewec2010proceedings.info/papers/1251755017.pdf (Last accessed: 08.07.2010)

[74] IEA Wind Energy, “Final report – Phase one 2006 - 08”, IEA Wind Task 25. Internet reference: http://www.ieawind.org/AnnexXXV/PDF/Final%20Report%20Task%2025%202008/T2493.pdf (Last accessed: 17.08.2010)

[75] IEA Wind Energy, “Annual report 2008”, July 2009, ISBN 0-9786383-3-6. Internet reference: http://www.ieawind.org/AnnualReports_PDF/2008/2008%20AR_small.pdf (Last accessed: 17.08.2010)

[76] EWEA, “Pure power. Wind energy targets for 2020 and 2030”, 2009 update. Internet reference:

http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Pure_Power_Full_Report.pdf (Last accessed: 18.08.2010)

[77] Energinet.dk, "Technical regulation for the properties and the regulation of wind turbines", 2004 update. Internet reference: http://www.energinet.dk/NR/rdonlyres/E4E7A0BA-884F-4E63-A2F0-98EB5BD8D4B4/0/WindTurbinesConnectedtoGridswithVoltageabove100kV.pdf

List of Acronyms and Abbreviations

- AC: Alternative Current
- ACE: Area Control Error
- AGC: Automatic Generation Control
- AEY: Annual Energy Yield
- AI: Artificial Intelligence
- ANN: Artificial Neural Networks
- ATC: Available Transfer Capacity
- B: Belgium
- BRP: Balance Responsibility Party
- CCT: Critical fault Clearing Time
- CET: Central European Time
- CF: capacity factor
- D: Germany
- DC: direct current
- DFIG: Doubly-Fed Induction Generator
- DG: Distributed Generation
- DNO: Distribution Network Operator
- DSO: Distribution System Operator
- DWD: Deutscher Wetterdienst (German Weather Service)
- EC: Economic optimization
- ENTSO-E: European Network of Transmission System Operators
- EU: European Union
- EWEA: European Wind Energy Association
- F: France
- FCAS: Frequency Control Ancillary Services
- FiT: Feed-in Tarif
- FRT: Fault Ride-Through
- FRTC: Fault Ride-Through Capability
- Fraunhofer IWES: Fraunhofer-Institut für Windenergie und Energiesystemtechnik
- GB: Great Britain
- GW: gigawatt
- GWe: gigawatts of electricity
- GWh: gigawatt hours
- HVDC: high voltage direct current
- Hz: hertz

- IEA: International Energy Agency
- IPP: Independent Power Producer
- ISET: Institut für Solare Energieversorgungstechnik
- ISO: Independent System Operator
- kV: kilovolt
- kW: kilowatt
- kWh: kilowatt hour
- LFC: Load Frequency Control
- LOEE: Loss Of Energy Expectation
- LOLE: Loss Of Load Expectation
- LOLP: Loss Of Load Probability
- MAE: Mean Average Error
- MW: Megawatt
- MWh: Megawatt hours
- NL: The Netherlands
- NOR: Norway
- NRMS: Normalised Root-Mean-Square error
- NTC: Net Transfer Capacity
- NWP: Numerical Weather Prediction
- O&M: Operation and Maintenance
- P: active power
- PP: Perfect wind power Prediction
- PRAT: Power Reserve Activation Time
- PRP: Program Responsible Party
- Q: reactive power
- REE: Red Eléctrica de España
- REN: Redes Energéticas Nacionais, SGPS, S.A. (Portugal)
- RES: Renewable Energy Sources
- RMS: Root-Mean-Square error
- RoCoF: Rate of Change of Frequency
- RTC: Real Time Control
- RTO: Regional Transmission Operator
- SCADA: Supervising Control and Data Acquisition
- SO: System Operator
- SPLD: System Peak Load Demand
- TSO: Transmission System Operator
- TWh: terawatt hours

- UCTE: Union for Co-ordination of Transmission of Electricity
- UTC: Universal Time Coordinated
- WCMS: Wind Farm Cluster Management System
- WF: Wind Farm
- WFC: Wind Farm Cluster
- WPMS: Wind Power Management System
- WT: Wind Turbine

Wind power is, admittedly, different from other power technologies and integrating large amounts of it in the existing power systems is a challenge that requires innovative approaches to keep the sustainability of the power system operation. In the coming years its contribution to the system security will become mandatory as far as the trend goes towards more decentralized structures and an increase in complexity due to a higher number of market participants.

This PhD addresses one of the fundamental ancillary services researching about a secure and flexible methodology for power reserve provision with wind farms.

Based on the current needs and security standards of those highly developed European grid codes, a new model for power reserve provision with wind power is developed. This methodology, algorithms and variables are tested based on real scenarios from five German wind farm clusters.

Finally, once the methodology for power reserve provision with wind power has been tested, real control capabilities from already installed wind farms in Germany and Portugal are analyzed. Their capabilities of following control commands as well as an error deviation analysis are also presented.

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