Wind Turbine Contribution to Ancillary Services under increased Renewable Penetration levels

Master Thesis Project

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Wind Turbine Contribution to Ancillary Services under Increased Renewable Penetration levels

By

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Abstract

Wind constitutes a dominant form of sustainable energy that is expected to grow rapidly in the years to come. Increased inverter-based wind power penetration may however endanger grid stability and reliability, if not enriched with the capability to provide crucial ancillary services to the grid, such as frequency regulation.

In order for the wind turbine technology to participate in the ancillary service provision, a more in depth understanding of the wind turbine dynamic behavior is required. Therefore, this Master Thesis Project was formulated to study how the wind turbine technology can assist in providing ancillary services under increased renewable penetration levels with a concentration on the frequency support.

This project proposes the frequency controllers both at the single wind turbine level and the wind farm level to facilitate the provision of ancillary services. The power system transient simulation package PSCAD™/EMTDC™ V4.6.2 is used for the controller design and the simulation study. The single wind turbine frequency controller enables the provision of the necessary positive or negative active power reserves in proportion to the measured grid frequency, via the kinetic energy stored in the rotating masses and pitch control. Thus, the wind turbine generator power output is enabled to increase or decrease respectively. The full potential offered by the technology is exploited, while the limitations associated with the provision of active power reserves are identified and respected by the implemented controller. The wind farm controller allows for the coordination and control of the available wind turbines within a wind farm, despite several barriers identified in this project. A list of parameters is used to this end, which can be varied to achieve a more sustained frequency response, despite the barriers introduced by the available limitations of the electrical and mechanical components of the wind energy conversion system.

An offshore wind farm case study was performed to test the performance of the implemented controllers and investigate the impact of the wind farm frequency response on the grid frequency, in various scenarios. The successful response of the implemented controllers is proven, while no violation of physical or safe limits is identified thanks to the frequency controller designed in this project. The allowable ranges within which the controller parameters can be varied without unwanted situations are analytically discussed and summarized as important lessons learned. Finally, the active power product that can be provided within the Ancillary Service Market is quantified and described, while recommendations are made at the Ancillary Service Market level that reflect the capabilities of the wind turbine technology, if enriched with the designed controller.

Overall, a positive effect of the frequency response provided by the wind turbine technology on the grid frequency is observed. Significant improvements have been achieved on the frequency nadir and the rate of change of frequency by the wind farm controller parametrization under different severity of the frequency deviations. In general, the frequency response that can be achieved through the wind turbine technology is in any case proportional to the amount of power that is generated by a certain wind farm (i.e. proportional to the wind speed conditions). The response provided can last for several seconds, thus constituting a “Fast Frequency Response” service the most appropriate option for the wind turbine technology. A trade-off between the maximum reserves provided and the duration of the response provided is seen. However, in the cases that a certain wind turbine needs to recover following a period of reserves provision, a compromise between the aggressiveness and the duration of the recovery period is also observed.

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AC	Alternative Current
DC	Direct Current
DFIG	Doubly-Fed Induction Generator
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
FRR	Frequency Restoration Reserve
FSC	Full-scale Converter
FSO	Frequency Supporting Operation
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
PCR	Primary Control Reserve
PEC	Power Electronic Converter
PFC	Primary Frequency Control
PI	Proportional-Integral
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RMS	Root Mean Square
ROCOF	Rate of Change of Frequency
RR	Restoration Reserve
SCIG	Squirrel Cage Induction Generator
SFC	Secondary Frequency Control
TFC	Tertiary Frequency Control
TSO	Transmission System Operators
TSR	Tip Speed Ratio
VSC	Voltage Source Converter
VSWT	Variable Speed Wind Turbine
VSWTG	Variable Speed Wind Turbine Generators

WECS	Wind Energy Conversion System
WF	Wind Farm
WPP	Wind Power Plant
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator
WT	Wind Turbine
WTG	Wind Turbine Generator

1. Introduction

1.1. Research Theme

Maintaining the security of supply in the most economical way under a reliable grid operation scenario constitutes one of the most important responsibilities undertaken by the Transmission System Operators (TSOs) [1]. The stable operation of the modern power system depends on the frequency and voltage stability, which are respectively linked to active and reactive power [2][3]. The traditional power system stability is mainly maintained by the conventional power plants through the provision of the necessary ancillary services. The behavior of the power system is still largely governed by the synchronous generators, even though Renewable Energy Sources (RES) have already started to acquire a larger share of the total generation mix.

Renewable penetration levels are expected to increase rapidly in the years to follow reaching a share of almost 50% of the total installed capacity by the year of 2040, as per the New Policies Scenario of IEA, World Energy Outlook of 2016 [4]. As a result, new challenges are expected to arise in the future operation and control of the electricity network due to the intermittent nature of renewable generations. The future grid stability may be endangered, unless the control and operation of the power system is also adapted to ensure the security of electricity supply with the increased RES penetration levels.

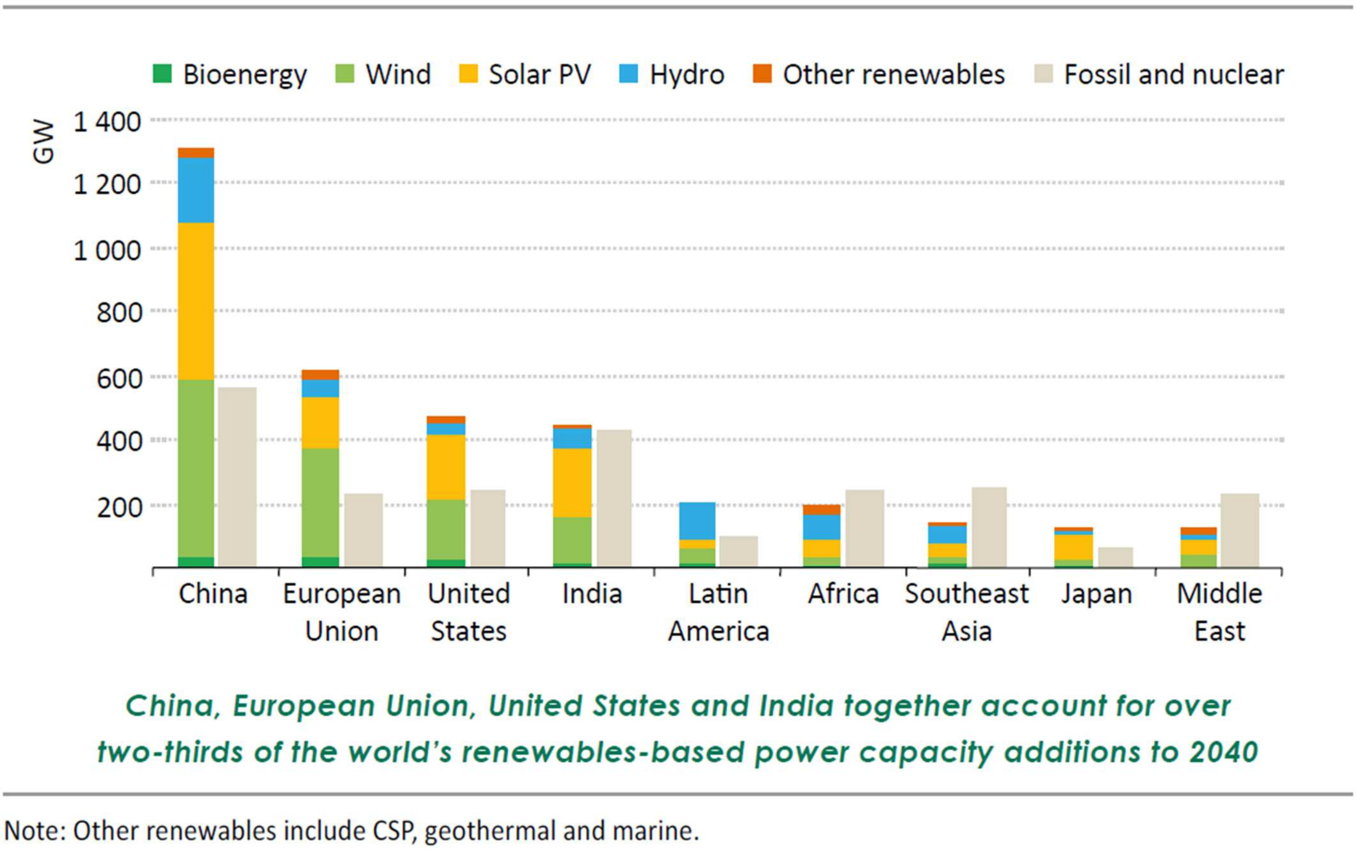

Figure 1: Additions of power capacity by region and type according to the New Policies Scenario of IEA, World Energy Outlook, 2016 [4].

More specifically, the increased inverter-based generation has raised serious concerns in the power industry as it results in reduction of the available inertia and primary frequency response [3]. It is argued that even though the conventional generation is capable of economically providing the required ancillary services, it may not be sufficient to ensure the system stability at all time in the future. Hence, an active participation of the renewable energy sources via the ancillary services is essential to operate the electricity network in a safe and reliable manner, despite the increased uncertainty and volatility in the balancing market. Among the ancillary services that are traditionally provided by the synchronous generators, frequency control ranks on top to accomplish in the context of an increased renewable penetration levels scenario, where inverter-based renewable generation will not inherently contribute to frequency support.

Frequency control constitutes the means used by TSOs to ensure frequency stability, which strongly depends on the balance of demand and supply [5][6]. Frequency control is performed in different time-steps with the corresponding reserve services. These services can be provided through appropriate options in the Ancillary Service Market. One of the frequency control mechanisms is inertial response, which constitutes an inherent, automatic response of the synchronous generators. The inertia available in the system strongly affects the power system stability. More specifically, the total system inertia determines the level of vulnerability of the power grid to a disturbance (i.e. the severity of the frequency excursions). However, inverter-based generations do not possess an inherent inertial response. Thus, increased RES penetration levels may lead to decreased system inertia and if the occurring frequency deviations become excessive they may lead to load shedding, damage of the grid-connected machine, system instability and sometimes even a blackout [3].

Within the global generation mix from RES, wind appears to be a dominant sustainable energy technology that is expected to grow rapidly. Specifically, within European Union wind power is expected to be the most important source of electricity supply after 2030 [4]. The more the share of wind power in the world’s power mix increases, the more challenging its integration becomes both from a technical as well as from a market perspective. The inherently different characteristics of wind energy conversion systems will start altering the behavior of the power system. The unpredictable nature of wind and its dependence on the weather conditions may result in imbalances between supply and demand and therefore, to frequency oscillations. Thus, the characteristics of wind impose a limitation on the maximum wind penetration level within a power system’s generation mix that can be allowed without jeopardizing the grid’s stability and reliability.

In order to increase the wind power penetration levels without endangering grid stability, wind power plants need to participate in the provision of crucial ancillary services, such as the frequency support. Variable speed wind turbine generators (VSWTGs), currently the dominating technology regarding the market share, possess some very interesting capabilities in terms of Ancillary Service provision capability. More specifically, VSWTGs through the use of Power Electronic Converters (PECs) are able to support variable speed operation and thus achieve more effective power capture. Power Electronic based wind turbine generators also allow for active and reactive power to be controlled independently. Moreover, through appropriate adjustments in the PEC control loops they can assist to the provision of Ancillary Services [7][8][9], including frequency support. In this way, wind turbines can contribute to power system stability, thus enabling higher wind penetration levels to be achieved.

Various methodologies have been proposed in the literature to achieve that. However, a more in-depth understanding of the dynamic behavior of the wind turbine is still required. This will allow to take advantage of the full potential offered by the wind turbine technology in terms of ancillary service provision, while respecting the associated limitations imposed by this technology. The development of the appropriate wind turbine controllers for the provision of ancillary services is crucial to compensate for the absence of synchronous generators, due to the progressive phase out of conventional power plants.

The successful provision of Ancillary Services in general, and of frequency supporting services in particular, by the wind turbine technology is expected to allow increased wind power penetration levels within the generation mix. This will allow for a more efficient and sustainable power system with decreased CO_2 emissions. Thus, the demand in electricity can be satisfied to a larger extend through renewable energy sources, resulting in an important societal and environmental impact.

1.2. State-of-the art & Scientific Gap

Different approaches have been proposed to enable the provision of the necessary active power reserves by the means of the wind turbine technology, to support the grid frequency. The most popular and common method constitutes the de-loaded operation [10] of wind turbines that allows for the necessary reserves to be available the moment that a frequency deviation occurs. However, this method demands the wind turbines to continuously operate at decreased power output to ensure the necessary reserves to be available at all time. Hence, de-loaded operation typically results in significant economic losses due to low electricity generation efficiency.

Other approaches have been suggested in the literature, such as the "*Virtual Synchronous Machine*" concept [11] where a model of the synchronous machine is used in the inverter control scheme, in order to enrich a power electronic based wind turbine with the behavior of a synchronous machine, in terms of inertial response. However, in this case, the controller, instead of adjusting its response according to the wind turbine state of operation, responds to consequences. An alternative approach for contributing to fast frequency control during over-frequency events, by dissipating the surplus power through the chopper, is introduced in Mohammad et al [12]. Supporting over-frequency events though, is significantly simpler compared to supporting under-frequency events, which is the real challenge when it comes to frequency response from the wind turbine technology. Moreover, an appropriate control design should allow for both positive as well as negative reserves to be provided, when required.

In general, both *synthetic inertia* as well as *droop control* are frequently discussed in the literature, however the exact way in which the required reserves are satisfied and the control design differ among the available studies [3]. The limitations that are associated with the provision of the necessary reserves constitute one of the most important points in such a study though, and these are not adequately addressed by the available literature.

A more precise study that also considers the limitations of the technology and attempts to include them within the control design has been performed by Ervin Bossanyi [13], where the kinetic energy of the rotating masses and the surplus power normally discarded through pitch control are the used sources for providing the necessary positive reserves. An important advantage of this approach constitutes the fact that, the wind turbine state of operation as well as the limitations associated with the provision of active power reserves from the wind turbine technology are considered in the control design. Additionally, the provision of the required reserves becomes possible both for below as well as for above rated wind speed conditions.

A more thorough comparison of the different methods available is outside of the scope of this project, however the approach suggested by Ervin Bossanyi [13] is used as a basis for this project, due to the offered advantages.

1.3. Scope of the Project & Research Questions

Based on the problem definition, the state-of-the-art on the topic of Ancillary Service provision by Wind Turbines, with focus on frequency support, as well as on the identified gaps in the available literature, the scope of the work has been defined, which is explored through the study of four main research questions.

The main goal of this project constitutes the study of *how the existing Wind Turbine Technology can be used to assist in providing Ancillary Services*. The focus is placed on *frequency support*, since this constitutes an important challenge that TSOs will have to face in the future power grid, where the increased inverter-based wind power results in reduced system inertia and insufficient spinning reserves.

Four research questions have been formulated to address the main objective:

1. What are the required modifications at the Wind System level to enable the provision of Ancillary Services?
2. What are the associated limitations for the provision of Ancillary Services by Wind Turbines?
3. What are the associated challenges and arising benefits by the simultaneous provision of Ancillary Services by multiple Wind Turbines in a Wind Farm?
4. Considering the theoretical analysis and the simulation results, what recommendations can be made at the Ancillary Service Market level with respect to the provision of Ancillary Services by Wind Turbines and Wind Farms?

1.4. Research Approach & Project Description

For the purposes of this project, PSCAD™/EMTDC™ [15] power system transient simulation package is used, as it enables the representation of the electrical parts important for such type of study, as well as for sufficient representation of the mechanical parts (such as the aerodynamic model and pitch control) that are also essential. In this way, the necessary controllers for enriching an inverter-based wind turbine with the ability to support the frequency can be implemented, while the result of such a response from wind turbines on the grid frequency can also be observed. Moreover, this software is more appropriate for modeling fast phenomena, compared to other softwares commonly used (e.g., PowerFactory, Matlab), that entail time limitations and may result in very long initialization times, especially at the wind farm level.

The Full-Scale Converter (FSC) design that uses a direct-driven Permanent Magnet Synchronous Generator (PMSG) is used for this study, as it is the type most commonly used from wind turbine manufacturers for the large wind turbines, that are also preferred for large scale Wind Farm applications, such as offshore wind farms. The provision of Ancillary Services, and more specifically of frequency support, becomes more interesting for such large-scale applications, due to the additional benefits that are offered by the coordinated support of frequency through multiple wind turbines within a wind farm.

A model of a direct-driven PMSG is available within the PSCAD library, which was used as a base for this study. Even though this model contains a detailed model of the converters, it is lacking an appropriate representation of essential parts, such as pitch control and the variable speed operation principle, that constitutes the model appropriate for operation at different wind speed values. Therefore, the first step was to implement the necessary improvements in the wind turbine model, to constitute it appropriate for the type of studies required for this project. The implemented changes follow the rules of the wind turbine modelling. The used controllers are analytically explained in section 3.3.

In the following, the required modifications at the wind system level that enable the contribution of the wind system to frequency support, as well as the associated limitations that need to be respected have been identified. To this end, a thorough literature review has been conducted, both on the different components available within the full-scale converter design, as well on the mechanical parts used during the frequency supporting operation of the wind system. According to the results and the conclusions drawn from this step, the necessary adjustments in the power electronic converter control loops have been implemented, that enrich the wind system with the ability to support the grid frequency, while ensuring the appropriate and safe operation of the wind turbine.

Afterwards, the model has been scaled up to the wind farm level, where 120 wind turbines with a rated power of 5 MW each, were used to acquire a realistic representation of a Wind Farm with total capacity of 600 MW. For the connection with the grid, an generic offshore wind farm topology has been proposed, that is thoroughly described in chapter 5.1. In this step, the associated challenges as well as the benefits that can be achieved by the simultaneous provision of active power reserves from multiple wind turbines within a wind farm to support the grid frequency are revealed. An alternative strategy is suggested that allows for the wind turbines to be arranged in groups and thus, to participate in reserve provision successively. This allows for a more sustained response to be achieved for certain modes of operation, where the existing limitations would otherwise result in much shorter responses. Moreover, the benefit of such a response on the grid frequency is also presented and discussed.

Finally, the results obtained from the simulations as well as from the literature review conducted, have been used to make recommendations at the Ancillary Service Market level, that reflect the potential offered by the modern wind turbine technology, and will thus encourage the participation of Wind Power Plants in the Ancillary Service Market.

1.5. Project Contributions & Boundaries

The project contributions as well as the boundaries for this study, are analytically explained in this section for the added value and the priorities set to become clear.

Project Contributions

The most important contributions of this project compared to the available literature, that are based on the scientific gap identified during the literature review, are summarized in the following paragraphs, in order for the importance of this study to become more clear:

- Since operating wind turbines at de-loaded power output results in economic losses, this project uses the kinetic energy of the rotating masses and pitch control to provide the necessary reserves. This allows to maximize the total economic benefits that can be achieved by a wind farm, both from selling electricity to the grid as well as from providing frequency supporting services to the Ancillary Service Market.
- The implemented control design allows for the necessary reserves to be provided according to the frequency deviation sensed, while considering the operating state of the wind turbine. Additionally, it respects all associated limitations. The safe operation of the wind turbine is set as the most important priority of the controller in all cases.
- Both types of frequency deviation (over-frequency and under-frequency events) can be supported under the different operating modes that can be distinguished for the wind turbine. Moreover, the full potential offered by the wind turbine technology is explored and utilized.
- The limitations associated with frequency response from wind power plants are thoroughly discussed, in order for a more in depth understanding of the existing boundaries (power available in the wind, minimum rotor speed, management of rotor recovery, converter maximum power transfer capability, impact on the electrical and mechanical components, slow response of pitch control, time limitation) and of the implications resulting from violations of the identified limitations (e.g., aerodynamic stall, overheating of converter components, decreased lifetime of components) to be acquired. The limitations (minimum rotor speed, aggressiveness of recovery period, converter maximum power transfer capability, time limitation) that can be considered through the use of

the PSCAD software, that is used for the purposes of this study, are all integrated in the controller design. Other limitations that would require additional measurements (e.g., temperature measurements) not available in this study, or a software that would more adequately represent the mechanical components present within the wind energy conversion system, are explained in depth to be used as a basis for future studies.

- The amount of reserves that can be provided by a realistic wind farm application is specified under various scenarios (different frequency events, parameter settings and wind speed conditions). The important factors influencing critical aspects, such as the amount of reserves provided, the duration of the frequency response provided and the aggressiveness of the recovery period, are analytically explained and presented in a large number of simulation results.
- The benefit of the wind farm frequency response, as well as the implications resulting due to rotor recovery on the grid frequency, are presented under several scenarios. This allows for a more in depth understanding to be acquired regarding the most beneficial strategies to be used for deploying reserves under the different wind turbine operating modes and frequency events.
- Detailed guidelines for the allowed range of the controller parameters are provided together with lessons learned at the final chapters of this report.
- The product that can be provided to the Ancillary Service market is quantified as clearly as possible, and suggestions are made at the Ancillary Service Market level that reflect the potential frequency supporting service that can be provided by the wind turbine technology.

Since this project in a way constitutes a continuation of the study performed by Ervin Bossanyi [13], it is also important to highlight the contributions of this thesis project compared to this base study.

In the base study, a wind turbine modelling software that is appropriate for modeling the mechanical parts and controllers of the wind turbines, Bladed, has been used. However, the impact of the wind turbine response on the grid frequency cannot be obtained in such a study. Therefore, a more analytical representation of the electrical parts (converters and the connection to the grid), are important to reveal the impact of such a response from wind turbines on the grid frequency. Such a step is of high importance, because the suggested method allows for the potential offered by the wind turbine technology to be explored to a higher extend, by more clearly identifying and considering the existing limitations within the control design.

An alternative way for managing the recovery period is suggested in this thesis, and the impact of the rotor recovery on the grid frequency can also be observed, which constitutes an important contribution of this project. Moreover, priority is always placed on the proper operation of the system, thus unwanted situations or limit violations do not in any case occur in the control design implemented for the purposes of this thesis project. Hence, this study has progressed beyond simply observing when unwanted situations occur, to implementing a control design that prevents them from happening.

Additionally, the analytical representation of the electrical parts of the system allow for the provided reserves to be calculated according to the frequency deviation sensed, which is the current trend of the Ancillary Service Market. Moreover, the study of the additional benefits offered through the provision of frequency supporting services by multiple wind turbines within a wind farm becomes possible. This constitutes a very interesting point, since only at the wind farm level does the contribution offered by the wind turbine technology become significant. In this way, the true capability of the wind turbine technology, in terms of frequency support, can be revealed and the product that can be provided to the Ancillary Service Market can be more clearly quantified.

Project Boundaries

The scope of the project could be rather extensive, thus the boundaries of the project have been clearly set in order for the priorities to become clear and for the limitations associated with the available time frame as well as the modelling limitations to be identified.

First of all, the wind turbine technology can assist to different ancillary service options, such as voltage control, fault ride through, power oscillation damping, etc.. However, the focus of this project is placed on frequency regulation, as it is considered a challenging service to be achieved by the wind turbine technology. A more thorough comparison of the different approaches that have been suggested in the literature to enable the support of the grid frequency by wind power plants falls outside of the scope of this project. It was decided from the very early steps of the project, that this study would serve as a continuation of the work already conducted by Ervin Bossanyi on this topic, while the important gap to be filled constitutes to focus on the electrical behavior of the system and the effect of the suggested strategy on the grid frequency. Moreover, the arising benefits and challenges by the simultaneous contribution of multiple wind turbines within a wind farm on frequency response was considered a very interesting topic to be addressed through the final steps of this study. Finally, the results that can be obtained from such studies will allow for recommendations at the ancillary service market level to be made that will attempt to more clearly quantify the product that can be offered through this technology.

Regarding the existing limitations of the wind turbine technology for the provision of frequency response, limitations exist both on electrical as well as on mechanical components. However, the software used allows the focus to be placed on the electrical behavior of the system, with the essential mechanical components, such as pitch control, to be adequately represented. A more thorough study of the effect of the mechanical stresses on the lifetime of the components is outside of the scope of this study, since it cannot be investigated with the used software and the followed approach. The same applies for the effect of the frequency supporting operation of wind turbines on the lifetime of the mechanical and electrical components. Nevertheless, all identified limitations are at least theoretically explained in detail, to lay the foundation for future investigation.

1.6. Stakeholder Groups

The most important stakeholder groups for this project are presented in the following, and the contributions of this project for each one of them is discussed.

Transmission System Operators

Transmission System Operators are responsible for ensuring the stable and reliable operation of the power system. Under a future scenario of increased renewable penetration levels, TSOs may be faced with grid stability problems, unless the RES satisfying demand start to also participate more actively in providing the necessary ancillary services, that will ensure grid stability.

This project aims at providing the necessary know-how regarding the capabilities of the wind turbine technology in terms of ancillary service provision. The focus is placed on frequency support, since it is considered one of the most challenging ancillary service options to be successfully provided by wind turbines. Enabling the wind turbine technology to provide frequency supporting services within the ancillary service market, will offer more options to the TSOs to use for ensuring grid stability.

Wind Turbine Manufacturers

In order for the wind turbine technology to assist to frequency regulation, it is first of all important to acquire a more in depth understanding of the wind turbine dynamic behavior, as well as of the limitations for providing a frequency response from wind turbines and wind farms.

In this study, the required modifications that will enrich the wind turbine technology with the capability to assist to frequency support as well as the associated limitations that need to be respected within the control design for no limit violations to occur are identified and analytically discussed. Moreover, the corresponding single wind turbine and wind farm frequency controller are implemented and also presented in detail.

Thus, this study provides thorough guidelines for wind turbine manufacturers to use as a starting point for designing wind systems that also include appropriate frequency controllers.

Wind Farm Operators – Aggregators

In order to take advantage of the full potential of the wind turbine technology as well as of the opportunities that exist in providing frequency supporting services from multiple wind turbines within a wind farm, it is important that a party performs the necessary studies. In this way the potential of a certain wind farm in terms of frequency support can be determined . These studies may for example include:

- The use of the expected mean wind speed and turbulence within a certain wind farm site and the wind speed variations at different times of the year to specify whether a site is appropriate for providing active power reserves, as well as the amount of reserves that can be provided to the Ancillary Service Market.
- A wide range of studies that will allow to decide which is the most appropriate strategy according to which the available wind turbines within a wind farm should be coordinated and controlled to take advantage of the full potential offered by a wind farm and to maximize the economic benefits. Moreover, it is also important to ensure that the offered product complies to the technical specifications of the Ancillary Service Market option of interest.

This party could be the wind farm operator, that can be different for each wind farm. However, it can also be the case that the studies required to specify the potential offered by a wind farm to provide the necessary reserves to the Ancillary Service market for frequency regulation purposes, opens the door for an “aggregator” to take over all necessary actions for a number of wind farms, that can participate in the ancillary service market.

This thesis provides useful information and guidelines on how the available wind turbines within a wind farm should be controlled under different case scenarios, as well as the ranges within which the available parameters within the implemented controller can be varied without causing unwanted situations.

Finally, the theoretical analysis of the limitations that are associated with the wind turbine technology regarding frequency response, constitutes important information that should be considered before using any wind turbine or wind farm for this purpose.

Ancillary Service Market Operators

Considering a scenario of increased RES integration, the Ancillary Service Market operators may need to include more options within the Ancillary Service Market, that will also be suitable for the participation of RES into the market, since the current options available mainly reflect the capabilities of conventional generation. In order to achieve that, they first need to acquire a more in depth understanding of the capabilities of each renewable energy technology, and use the conclusions as a basis for the specification of the technical requirements of each option.

This thesis project focuses on wind turbine technology and frequency support. Thus, it provides significant information regarding the active power product that can be offered by this technology to the ancillary service market. Considering both the theoretical analysis as well as the simulation results, recommendations are made to the Ancillary Service Market that attempt to specify the appropriate option that will facilitate the participation of the wind turbine technology to frequency support.

1.7. Master Thesis Outline

In this section a brief description of the chapters of this report is provided.

Chapter 1: Introduction

First of all, an introduction to the project is provided, where the research theme, the urgency for such a project and the societal impact are discussed. Moreover, the stat-of-the art is presented and the scientific gaps are identified. The scope of the project and the main research questions are presented. A more thorough description of the project follows, while the most important contributions of this project are highlighted and the boundaries are set, for the priorities of the study to become clear. Finally, the main interested stakeholder groups are identified, and the outline of the report is given.

Chapter 2: Frequency Stability & Control

In this chapter, the conventional frequency control mechanisms are presented and an overview of the German Ancillary Service Market is provided, with the available options related to frequency support discussed in more details.

Chapter 3: Wind Turbine Technology

In this chapter, the wind system together with its main components are discussed in detail and an overview of the various wind energy conversion configurations is provided. Afterwards, the dynamic model of the full-scale converter design that uses a PMSG is presented in detail with all the available controllers.

Chapter 4: Required Modifications & Limitations for Ancillary Service provision

The required modifications and limitations for ancillary service provision by the wind turbine technology, with focus on frequency support, are identified and discussed in this chapter. Additionally, the control design implementation at the single wind system level is analytically presented and explained.

Chapter 5: Wind Farm Topology & Wind Farm Controller

In this chapter, the wind farm topology used for this study as well as the wind farm control logic and the implementation of its design are analytically explained.

Chapter 6: Case Studies & Simulation Results

In the following chapter, simulation results for several scenarios are presented and discussed in detail. In this way it is proven that the designed controller performs appropriately, while important conclusions are drawn regarding the frequency response that can be achieved through a wind farm and the capabilities of the wind turbine technology in general.

Finally, the most important lessons learned from the simulation results are summarized at the end of the chapter, and guidelines are provided for the correct settings of the wind farm controller parameters that achieve the most beneficial response.

Chapter 7: Recommendations at the Ancillary Service Market level

In this chapter, the theoretical analysis together with the simulation results and the lessons learned are used to make recommendations at the ancillary service market level, that reflect the capabilities of the wind turbine technology.

Chapter 8: Conclusions

The most important conclusions obtained through this study are summarized in this chapter. The research questions of the project are answered, with references to the corresponding chapters that contain more analytical information related to each research question.

Chapter 9: Suggestions for Future Work

In this chapter, the most important topics to be further studied are highlighted and briefly explained, to serve as a guidance for the continuation of this project.

2. Frequency Stability & Control

The modern power system comprises of a complex network of electrical components that ensures the generation, transmission and distribution of electric power. The power system needs to be properly designed and controlled to ensure its efficient and reliable operation at all time. Therefore, its operation should comply to certain fundamental requirements. More specifically, the power system needs to be able to continuously meet the needs in electricity demand, to ensure the supply of energy at the minimum possible cost and with the minimum possible impact on the environment, as well as the quality of the power supply [2].

Since electricity cannot be stored in sufficiently large quantities, it is important that the power system ensures that the necessary spinning reserves are available at all time. In this way, it will be able to meet the continuously changing demand in active and reactive power. The design and operation of the power system in a way that power system stability and reliability are ensured at minimum cost constitutes a complex problem that needs to take many factors into consideration. The reason is that the power system constitutes a nonlinear system and its dynamic performance is affected by the large number of the components from which it is comprised. All these components have different characteristics and responses.

Power System Stability constitutes an important property of the power system, and it can be defined as the ability of the system to maintain a state of equilibrium under normal operating conditions, as well as its ability to regain an acceptable state of equilibrium following a disturbance [2].

Instability in the power system may occur in different ways. However, in traditional power systems stability mainly constitutes a problem of maintaining synchronous operation among the synchronous machines. The synchronous machines are responsible for the generation of the necessary electrical power to meet the needs in active and reactive power demand. Loss of synchronism may occur either between groups of machines or between a single machine and the rest of the power system.

The control of active power is related to the control of frequency, while the control of reactive power is related to the control of voltage [2]. Frequency control aims at *frequency stability*, which represents the ability of the power system to maintain the frequency within the predefined boundaries that reflect the power system operation limits, through deploying the necessary reserves. On the other hand, voltage control aims at *voltage stability*, which constitutes the power system ability to maintain steady voltages within the permissible ranges at all system buses both during normal operating conditions as well as following a disturbance.

2.1 Conventional Frequency Control Mechanisms

Within an AC power system, where the largest percentage of load demand is covered by synchronous generators, the grid frequency is determined by their rotational speed. Since stability constitutes an equilibrium between opposing forces, synchronous machines aim at restoring forces whenever the equilibrium is in any way disturbed [2]. The input mechanical torque together with the output electrical torque of a synchronous machine are in equilibrium under steady state conditions. This results in constant speed of the machine.

An imbalance between the energy consumption and generation is translated into an imbalance between the electrical power output and the mechanical power input of the synchronous generators respectively. Such an imbalance will cause the rotational speed of the power system synchronous generators to change, resulting in a frequency deviation [16]. The acceleration or the deceleration of the machine rotors after a certain point may result in decreased power transfer and eventually can lead to instability.

More specifically, in the presence of a change in consumption (e.g., increased load) or in generation (e.g., loss of a generation unit) the grid frequency will also change. This will happen because the mechanical power that is applied to the shaft of the synchronous generators cannot instantly change, since the inertia of the synchronous generators functions as an energy buffer between the mechanical generation and the electrical consumption. To this end, the only source of energy in the beginning of a frequency deviation constitutes the energy that is stored within the synchronous generators' magnetic fields. Hence, the imbalance between generation and consumption will impact on their rotational speed, causing acceleration or deceleration, as well as on the rotor angles that will start to change [16].

In order to secure the stable and reliable operation of the power system the TSO needs to ensure, among others, that the grid frequency is appropriately controlled in order to maintain it within its predefined boundaries at all times. *Frequency stability* represents the ability of the power system to maintain the frequency within the predefined boundaries that reflect the power system operation limits through deploying the necessary reserves. The safe, stable and reliable power system operation strongly depends on maintaining nearly constant frequency. In the synchronous European power network the nominal value of frequency is 50 Hz. The allowable frequency range under normal operating conditions has a lower limit of 49.8 Hz and an upper limit of 50.2 Hz. Thus, the maximum frequency deviation tolerated during normal grid operation is 200 mHz [1].

Regulation mechanisms exist that are activated to restore the balance between generation and consumption in the power grid. Thus, the grid frequency is maintained within the allowable operation limits. The different mechanisms that take over the restoration of the grid frequency back to its nominal value are activated in different time steps. These are *Inertial Response*, *Frequency Containment Reserves (FCR)*, also known as Primary Frequency Control, *Frequency Restoration Reserves (FRR)*, also known as Secondary Frequency Control, and *Restoration Reserves (RR),* also known as Tertiary Frequency Control.

The two main performance indicators used for frequency control constitute the rate of change of frequency (ROCOF) and the frequency nadir. The frequency nadir is defined as the bottom point of the frequency deviation. Higher inertia levels within a power system are expected to be accompanied by lower ROCOF values as well as higher frequency nadir values. In general, the inertia of a power system should be adequately high to provide sufficient time to the available synchronous generators to adjust their power output in the presence of a frequency deviation.

2.1.1 Inertial Response

The first rotor swings only last for a few seconds, thus the deviation of the rotor angles is soon settled and all the generators are in synchronism, while all the rotating masses either decelerate or accelerate with the same negative or positive acceleration:

$$\Delta\dot{\omega}_i = \Delta\dot{\omega}_n = -\frac{\Delta P_{el\,i}}{2H_i} = -\frac{\Delta P_{el\,n}}{2H_n} = -\frac{\Delta P_L}{2H_{sys}} \quad (1)$$

Where $\Delta\dot{\omega}$ is the rotor acceleration/deceleration , ΔP_{el} is the change in the generator's electrical output , H is the inertia of a single synchronous generator, H_{sys} is the total inertia of the grid and ΔP_L is the change in load (consumption).

Thus, the power output of each synchronous machine mainly depends on its inertia constant H_i and is defined by the following equation:

$$\Delta P_{el\,i} = \frac{H_i}{H_{sys}} \cdot \Delta P_L \quad (2)$$

This behavior is known as *inertial response* and it constitutes an inherent characteristic of the synchronous generators [16]. The average rate of change of the grid frequency depends on the system inertia constant H_{sys} as well as on the change in load ΔP_L.

2.1.2 Frequency Containment Reserves

In every synchronous generator, a governor (speed controller) is present that, if activated, can detect the speed deviation. Thus, it will start to change the production of the prime mover to stabilize the speed. In this way, the grid frequency is controlled. The response of the governor of the prime mover in the presence of a change in the grid frequency is known as *Primary Frequency Control* or *Frequency Containment Reserves*.

The governor response is proportional to the change in the speed and will result in the stabilization of the grid frequency at a steady-state with an offset error remaining from the nominal frequency value. Primary Frequency Control acts within the first few seconds after a frequency deviation occurs and is responsible for adjusting the active power output of the synchronous generators in proportion to the speed and thus the frequency change that is sensed [2][16]. This is achieved though adjusting the fuel that is supplied to the turbine. Usually, the synchronous generators are not operated at full load, thus the rest of their capacity is used as spinning reserves to support the grid frequency through the Primary Frequency Control mechanism.

2.1.3 Frequency Restoration Reserves

After the provision of frequency containment reserves further actions are taken for reducing the offset that exists in the grid frequency and restore the frequency back to its nominal value. This is accomplished by a further action on the prime movers which results in appropriately adjusting the active power output of the synchronous generators. This response is known as *Secondary Frequency Control* or *Frequency Restoration Reserves* and acts on a slower time scale and from a more centralized perspective [16].

This mechanism constitutes an automatically activated control reserve that also considers responsibilities for imbalances and operates from a more centralized system perspective. It acts within a few minutes after an event has occurred with the main aim to bring the frequency back to its nominal value. At the same moment the primary control reserves used are released [17][18].

2.1.4 Restoration Reserves

If the system imbalances have a longer duration, *Tertiary Frequency Control*, also known as *Restoration Reserves*, is activated. It is not considered useful or beneficial to maintain secondary control reserves for longer lasting disturbances [18]. Tertiary Frequency Control is implemented through either automatic or manual changes at the generators operation points in an effort to provide sufficient restoration reserves. With appropriate management of the available resources the remaining offset on the grid frequency can be eliminated within time durations not longer than 15 minutes [16]. The actions taken for the provision of restoration reserves consider economic considerations or the optimal power flow to ensure the minimum possible cost of the power plants operating [17].

2.2 Frequency Control in the European Ancillary Service Market

The security of power supply within the power system at the minimum possible cost and in a way that the most environmental benefits can be achieved is ensured through efficient balancing and ancillary service markets. Ancillary Services constitute a number of functions procured by the TSO for power system security to be guaranteed.

These services have been, and are still at their major part, being provided by Conventional Power Plants. Conventional generation constitutes a more economical way to provide ancillary services at the time being. However, we are entering an era with increased integration of Renewable Energy Sources. Thus, allowing the TSOs to have access to the necessary services from a more broad range of providers is expected to enable more flexibility and more efficient decisions to be made [19].

Currently, the ancillary service markets within Europe are under continuous development [18], while a tendency towards increased harmonization of the rules that apply on balancing and ancillary services is observed. Harmonization within the markets will enable a more effective pan-European competition and will allow for increased efficiency to be achieved [19].

Within Europe, an *international Primary Control Reserve (PCR) (Frequency Containment Reserves) cooperation* between the Ancillary Service Markets of Germany, Belgium, the Netherlands, Switzerland and Austria has been formulated. The strength of this cooperation was recently increased by the entrance of the French market, while the participation of the Danish power system operator is also planned [20]. Such a scheme allows for increased liquidity on the market from the part of the TSOs, while it opens the way for new sale opportunities among the involved parties.

Since a tendency towards harmonization is observed which centers the German Ancillary Service Market, this is used as a basis for this project. The main options available within the German Ancillary Service Market that aim at frequency regulation are *Primary Control Reserves*, *Secondary Control Reserves* and *Minute Reserves*. The main technical and deployment requirements of each one of those are presented in Table 1 and are explained in more details in the following paragraphs. No option for provision of *inertial response* is currently available within this market. The reason constitutes that fact that sufficient amount of inertia still exist in the European interconnected network from the amount of conventional generation used to satisfy the load.

Table 1: Comparative table with the main requirements of the available frequency control options of the German Ancillary Service Market [20].

Requirements	Frequency Control options in the German Ancillary Service Market		
	Primary Control Reserves	Secondary Control Reserves	Minute Reserves
Auction period:	Week	Week	Day
Product type:	1 symmetric product	4 products: peak & off-peak, separate positive & negative reserves	12 products, 4-hour blocks, separate positive & negative reserves
Minimum bid size:	1 MW	5 MW	5 MW
Capacity payment:	Yes	Yes	Yes
Energy payment:	No	Yes	Yes

Payment system:	Pay-as-bid	Pay-as-bid	Pay-as-bid
Activation time:	30 seconds	5 minutes	15 minutes
Delivery time:	15 minutes	10 minutes	15 minutes

2.2.1 Primary Control Reserve & International PCR Cooperation

Through coupling the different markets within the International PCR Cooperation the largest market for frequency containment reserves is formulated within Europe, that achieves a total demand that exceeds 1250 MW. Parties that are interested in providing reserves within this option can take part in weekly tenders with a minimum bid size of $\pm 1\ \mathrm{MW}$ with increments of $1\ \mathrm{MW}$. The participants must be available to provide the contracted MWs during the whole week (100% availability is required). The product type is *symmetric*, which means that the participants need to be able to provide both positive as well as negative active power reserves to support both under-frequency as well as over-frequency deviations respectively. The selection among the participants in the market follows a *merit order of capacity prices*. The selected suppliers are being paid according to the offered bid price in $€/\mathrm{MW}$ which is known as “paid-as-bid” system. In case that a supplier fails to provide the contracted capacity the received premium is reduced in proportion to the amount of PCR power that was not provided as well as the time period for which the supplier failed to provide the contracted capacity. In case that such an occasion is repetitive the operator may impose a penalty equal to ten times this amount after having announced to the supplier the intention to do so.

For frequency deviations less than 10 mHz no response is required by the supplier. For frequency deviations of more than $\pm 200\ \mathrm{mHz}$ the full contracted power $P_{contracted}$ needs to be activated by the supplier. For frequency deviations in the range of $10\ \mathrm{mHz} \leq |\Delta \mathrm{f}| \leq 200\ \mathrm{mHz}$ the requested performance of the supplier $P_{RESERVES}$ needs to be proportional to the frequency deviation (equation 3).

$$P_{RESERVES}\ [MW] = \begin{cases} 0 & , \quad \Delta f \leq 10\ mHz \\ -\dfrac{\Delta f}{200\ mHz} \cdot P_{contracted} & , 10\ \mathrm{mHz} \leq |\Delta \mathrm{f}| \leq 200\ \mathrm{mHz} \\ P_{contracted} & , \quad \Delta f \geq 200\ mHz \end{cases} \quad (3)$$

The provided reserves need to be fully activated within 30 seconds and to be maintained for 15 minutes, while a 15-minute pause is allowed in between the reserve provision cycles (Figure 2). The provision of the PCR power must be maintained until the steady-state error in the frequency is completely offset by the activation of the secondary and tertiary control reserve mechanisms.

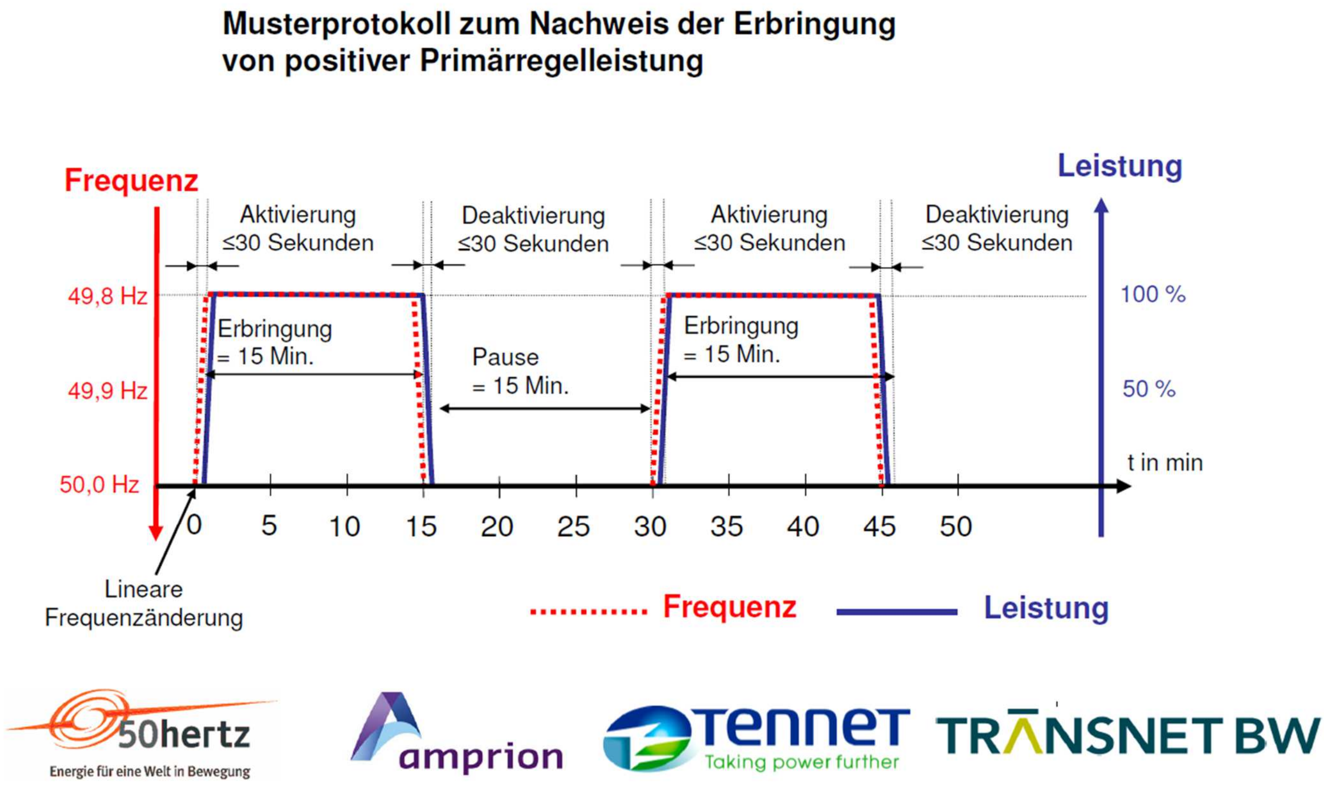

Figure 2: Deployment of positive Primary Control Reserves in the in the International PCR Cooperation [20].

2.2.2 Secondary Control Reserve in the German Ancillary Service Market

The parties that are interested in providing reserves in the Secondary Control Reserve scheme can take part in weekly tenders with a minimum bid size of $\pm 5\ \mathrm{MW}$ with increments of $1\ \mathrm{MW}$. Separate tenders exist for *positive* and *negative reserves*. Two product time-slices can be distinguished, the *peak* (from Monday to Friday between 8 a.m. and 8 p.m.) and *off-peak* (remaining time periods), which are procured as different products [20][21]. Thus, in total four different products are procured through this scheme.

The provision of control reserve capacity and deployed control energy is separately awarded. As a result, a *capacity price bid* as well as an *energy price bid* need to be specified by the participants. The selection among the participants in the market follows a *merit order of capacity prices*. Energy price bids are only considered in case that marginal bids with identical capacity prices exist. The selected suppliers are being paid according to the offered bid price in $€/\mathrm{MW}$ which is known as "*paid-as-bid*" system [20][21].

The provided reserves need to start being activated within 30 seconds following a disturbance and be fully activated within 5 minutes (Figure 3). The reserves need to be maintained for 10 minutes and then be deactivated within 5 minutes. A 10-minute pause is allowed in between each cycle of reserve provision.

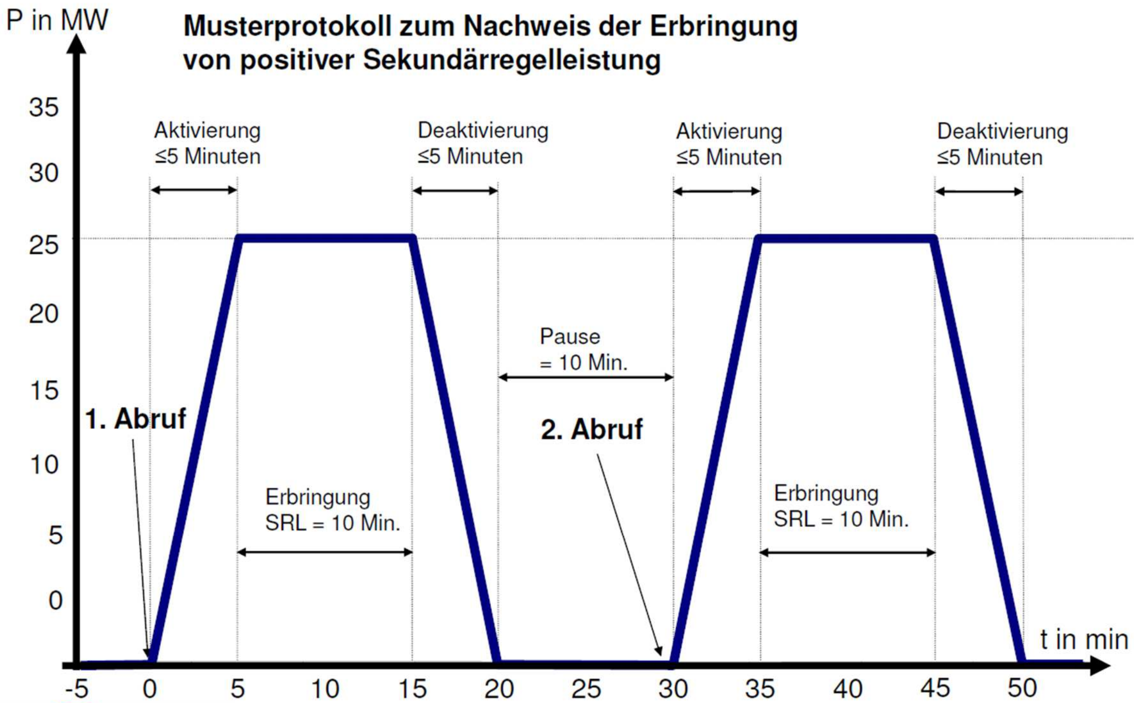

Figure 3: Deployment of positive Secondary Control Reserves in the German Ancillary Service Market [20].

2.2.3 Minute Reserve in the German Ancillary Service Market

The parties that are interested in providing reserves in the Minute Reserve scheme can take part in daily tenders with a minimum bid size of $\pm 5\ \mathrm{MW}$ with increments of $1\ \mathrm{MW}$. Separate tenders exist for *positive* and *negative reserves.* Six product time-slices can be distinguished consisting of four hours each. Thus, this ancillary service option is characterized by a *larger product scale* as well as *shorter tendering periods* [20][21].In total twelve products are procured through this scheme.

The provision of control reserve capacity and deployed control energy is separately awarded. As a result, a *capacity price bid* as well as an *energy price bid* need to be specified by the participants. The selection among the participants in the market follows a *merit order of capacity prices*. Energy price bids are only considered in case that marginal bids with identical capacity prices exist. The selected suppliers are being paid according to the offered bid price in $€/\mathrm{MW}$ which is known as "*paid-as-bid*" system.

The provided reserves need to be activated within 15 minutes, be sustained for 15 minutes, and be then deactivated within another 15 minutes, while 15-minute pauses are allowed in between every cycle of reserves provision (Figure 4).

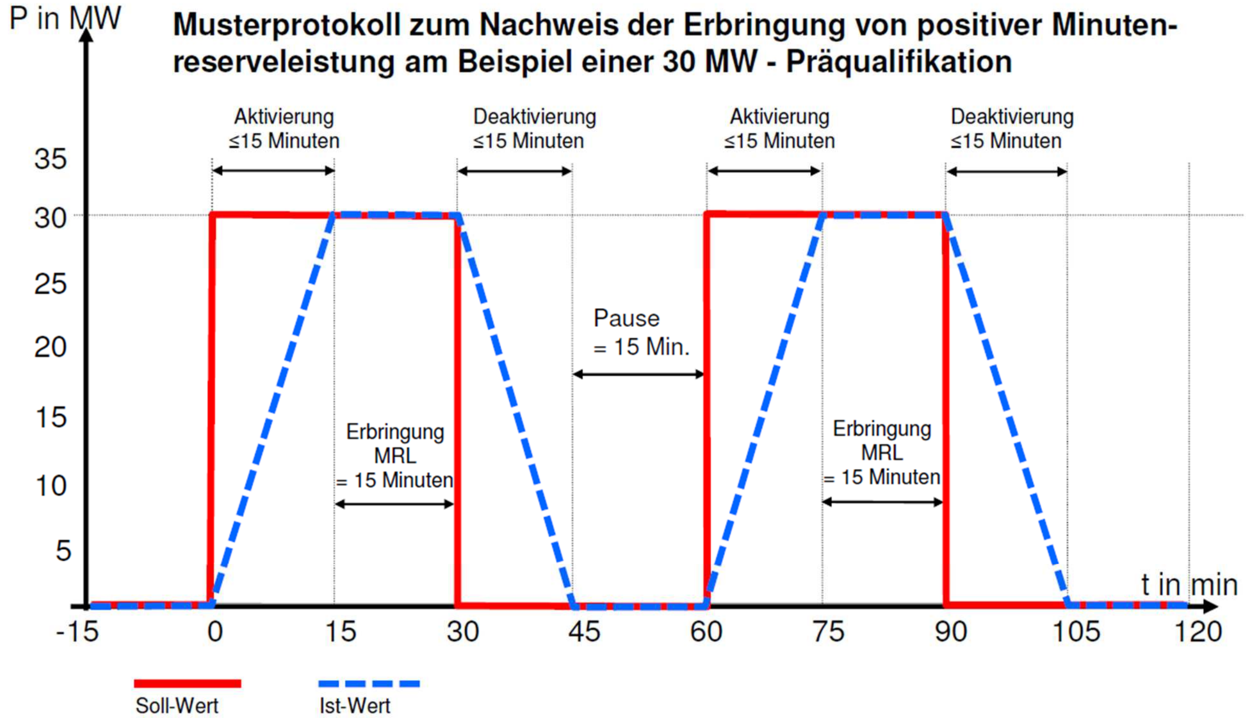

Figure 4: Deployment of positive Minute Reserves in the German Ancillary Service Market [20].

3. Wind Turbine Technology

Wind constitutes a dominant form of sustainable energy that has shown a rapid growth among the available renewable energy sources used for electricity generation [22]. It is considered one of the most cost effective means of electricity generation among RES [22]. The integration of wind power within the power mix is expected to experience an important growth in the near future. Moreover, the development of the technology is expected to boost its cost competitiveness.

A variety of combinations of Wind Turbine Generators (WTGs) and Power Electronic Converters have been used in commercial wind turbine designs for enabling the wind turbine operation with a fixed speed, a semi-variable speed or a full-variable speed [23]. The trend in WTG designs is upgrading from stall-controlled, fixed speed WTGs with drive trains that include a gearbox, towards pitch-controlled variable speed and often gearless designs, due to increased efficiency, reduction of mechanical stresses on turbines as well as improved power quality, reduced maintenance requirements, increased lifetime and capability to comply with grid code requirements, that the modern designs offer.

Variable speed operation is enabled by the use of PECs. Thus, converter-based WTG designs, also known as Variable Speed Wind Turbine Generators, are dominating the market at the time being. The important feature of VSWTGs constitutes the capability to control the operational speed to increase the aerodynamic efficiency, thus enabling more effective power capture up to 15% [22].

Among the variable speed wind turbine generator designs, doubly-fed induction generators, that use partial scale converters, and direct-driven permanent magnet synchronous generators, that use full-scale converters, constitute the most preferred ones from manufacturers, due to their advantages when compared to other Variable Speed Wind Turbine (VSWT) designs. As the size of WTGs increases more and more to support large Wind Farm applications either onshore or offshore, direct-driven PMSG appear to be the leading design type, due to the many advantages offered. These include improved reliability, reduced weight and maintenance, and ability to comply with Grid Code Requirements.

3.1 Wind Energy Conversion System & Main Component Description

The *wind turbine* constitutes a rotating engine that has the ability to capture the kinetic energy that is available in the wind and convert it into mechanical power through the aerodynamic process. The electrical generator afterwards takes over the conversion of the rotational mechanical energy into electrical energy that is usually injected to the grid.

Several configurations of wind energy conversion systems have been used by the various wind turbine manufacturers. In each one of these several components are required to achieve reliable and efficient conversion of the kinetic energy of the wind into electric energy that can be effectively controlled. The required components can be divided in three main categories, the *mechanical components*, the *electrical components* and the *control systems*.

The *mechanical components* comprise of the tower, the nacelle, the rotor blades and hub, the gearbox, the pitch and the yaw drives, the wind speed sensors, the drive-train as well as the mechanical brakes. The tower, the nacelle and the blades of the rotor are the visible parts of the wind turbine, while the rest of the components are usually placed within the wind turbine. The *electrical components* comprise of the wind turbine generator, the power electronic converter, that is used in certain WTG designs, the step-up transformer, filters for harmonics attenuation and the grid. *Control systems* are used both for the mechanical as well as for the electrical conversion systems [23][25][26]. The basic configuration of a wind turbine that is connected to the grid is presented in Figure 5.

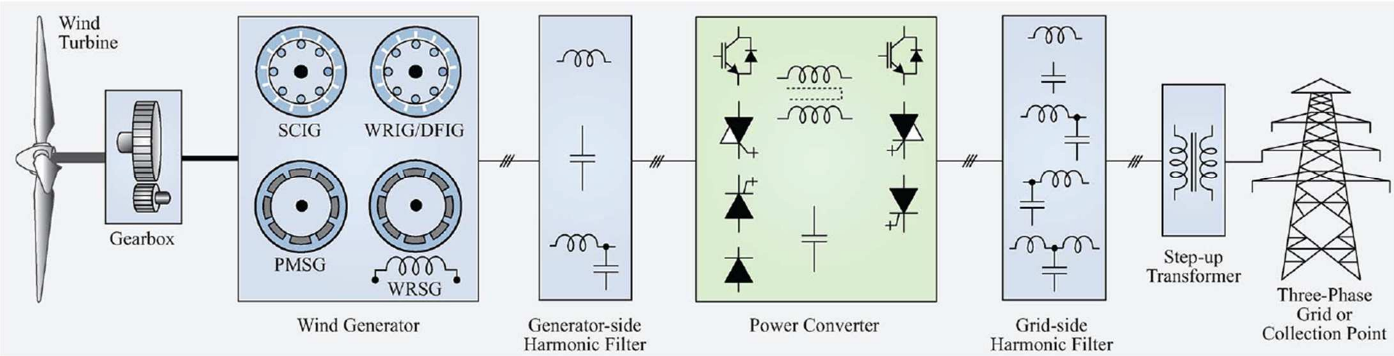

Figure 5: Basic configuration of a Wind Energy Conversion system connected to the grid [23].

The wind turbine tower that bears the nacelle and the wind turbine rotor that comprises of the rotor blades and the hub formulate the *wind energy conversion system*. The nacelle usually includes the necessary equipment for measuring the speed and direction of wind, such as anemometers and wind vane. The nacelle also contains the gearbox, the mechanical brake, the generator, the control system, the yaw drive, etc. (Figure 6). The blades are responsible for the transformation of the kinetic energy of the wind into mechanical power, while the tower, the nacelle and the rotor hubs provide the necessary mechanical support to the rotor blades. Yaw drive is responsible for moving the blades along with the nacelle towards the wind. In this way the maximization of the energy extraction is achieved.

The gearbox is used to couple the shaft of the turbine, which usually operates at low speed and high torque values, to the shaft of the wind turbine generator, that usually operates at high speed and low torque. The gearbox is accompanied by increased costs, noise, need for maintenance and decreased efficiency. However, the gearbox can be eliminated through matching the speed of the generator to the speed of the turbine. In this way, the problems faced due to the use of gearbox can be overcome. This is specifically important for offshore applications.

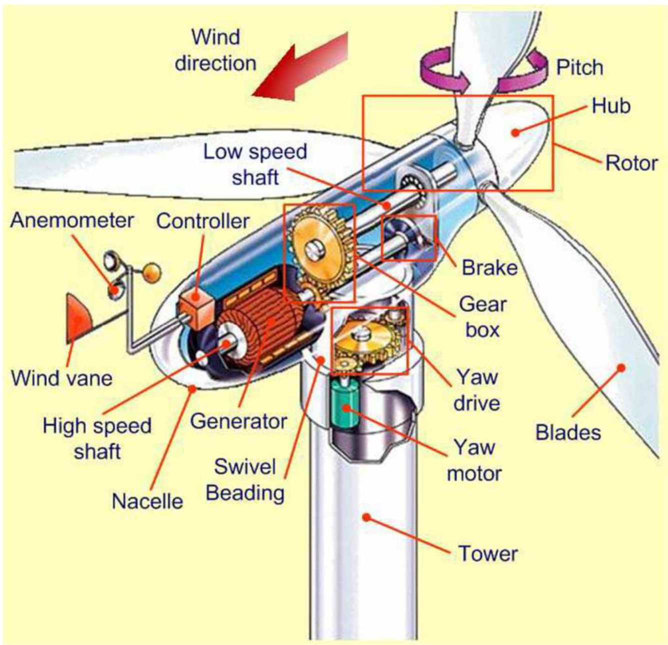

Figure 6: Wind turbine main components [22].

The electrical generator is used for the conversion of the rotational mechanical energy into electrical energy, while its output frequency and voltage are continuously adjusting to the sensed wind speed conditions. Different Wind Turbine designs exists that use different generator types, such as squirrel-cage induction generator (SCIG), wound rotor induction generator (WRIG), doubly-fed induction generator (DFIG), permanent magnet synchronous generator (PMSG) or wound rotor synchronous generator (WRSG). The generator can either be directly coupled to the grid or connected through the use of PECs. The use of PECs results in switching frequency harmonics. Thus, filters are required for harmonic attenuation both at the generator as well as at the grid side. On the generator side the harmonic filter assists in the reduction of harmonics on the generator currents and voltages, while on the grid side it assists in reduction of harmonics on the grid side and thus, in complying with the grid code requirements. Afterwards, the wind system is connected to the three-phase grid through the use of a step-up transformer.

The power capture strongly depends on the wind speed conditions. However, it is essential that the wind system is able to limit and control the power capture, especially at high wind speed conditions. This allows for the equipment not to be damaged. Different methods are available to achieve this depending on the used configuration [22]. These are [24]:

- *Stall control*, where the rotor blades' design allows for a fixed position of the blades and therefore results in decreased aerodynamic efficiency at increased wind speed values above rated, causing stall.
- *Pitch angle control*, which allows for the blades to be turned out of the wind at increased wind speed values to disoptimize the power capture with the use of either hydraulic mechanisms or electric motors.
- *Active stall*, constitutes a combination of the two above mentioned methods. It allows for the blade angle to be adjusted, hence causing stall along the blades.

3.2 Wind Energy Conversion Configurations

Various designs of Wind Turbine Generator types have been used by the available manufacturers. In general, four main types can be distinguished according to which the available designs are usually categorized. These are presented and briefly discussed in the following paragraphs.

3.2.1 Type 1: Fixed-speed Wind System with a Squirrel Cage Induction Generator (SCIG)

This constitutes the oldest technology that was developed for wind turbines and uses an asynchronous squirrel cage induction generator that is directly connected to the grid through a soft-starter and a step-up transformer (Figure 7). The generator speed is almost fixed at the synchronous speed, with a variation of only 1% allowed[23]. The difference between the wind turbine speed and the wind turbine generator speed is usually corrected through the use of the gearbox. This design draws reactive power from the grid. Hence, additional equipment for reactive power compensation is required, such as the use of capacitor banks [22].

This configuration constitutes the most simple and low cost option. However, it is characterized by lower efficiency, while any wind speed variation is directly reflected to the grid since it results in fluctuations of the mechanical and thus of the electrical power.

Such wind turbine generator types are still in operation. However, they are not preferred nowadays due to their disadvantages compared to the rest of the available designs. These include inability to support variable speed operation which would enable more efficient power capture as well as the requirement for a stiff grid connection with a fixed frequency and voltage.

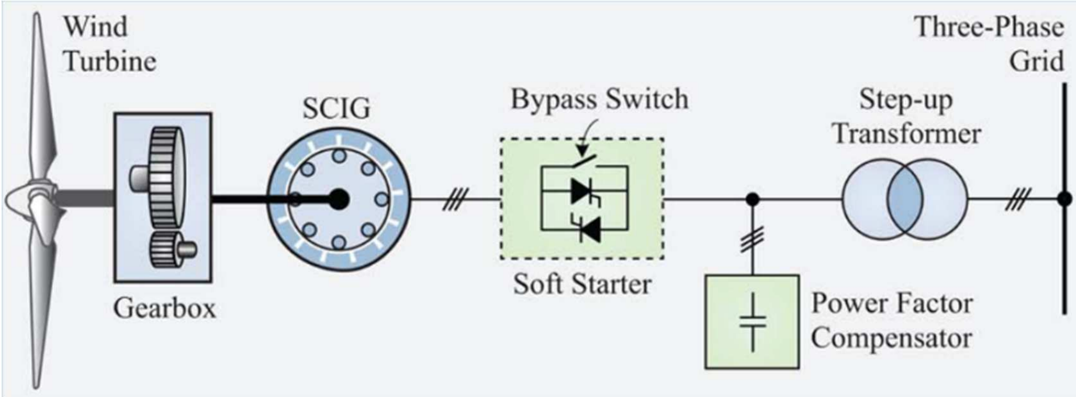

Figure 7: Fixed-speed Wind System with a squirrel-cage induction generator [23].

3.2.2 Type 2: Semi-variable speed Wind System with a Wound Rotor Induction Generator (WRIG)

This configuration uses a wound rotor induction generator and a variable generator rotor resistance to enable variable-speed operation through altering the torque-speed characteristic of the electric generator (Figure 8). Thus, the generator speed can vary at around $\pm 10\%$ of its rated value, with the exact range determined by the size of the resistance connected in series with the rotor windings [22][23].

For adjusting the rotor resistance a power converter is used that consists of a diode rectifier as well as a chopper. The soft starter enables smoother grid connection. Variable speed operation enables more efficient power capture. However, this configuration results in losses in the rotor resistance and a capacitor bank is required for reactive power compensation purposes.

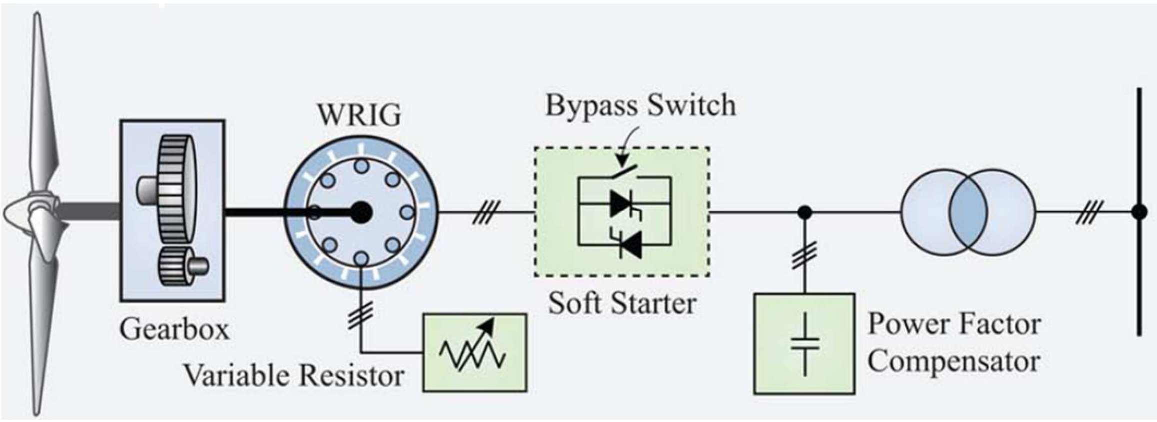

Figure 8: Semi-variable speed Wind System with a wound rotor induction generator [23].

3.2.3 Type 3: Semi-variable speed Wind System with a doubly-fed Induction generator (DFIG) and a partial-scale Converter

Another semi variable configuration uses a Doubly-fed Induction Generator and a partial-scale converter in the rotor circuit to enable variable speed operation at a range of $\pm 30\%$ of the rated speed (Figure 9). In this configuration, the power of the electric generator is injected to the grid both through the stator as well as the rotor windings. The partial-scale converter used has a power rating of about 30% of the generator capacity and is feeding the rotor winding. The rotor winding controls the rotor frequency and as a result the rotor speed. The stator winding is directly connected to the grid [22][23].

The use of the partial-scale PEC is responsible for the increased speed range operation and its rating determines the allowable speed range. The maximization of the power capture allows for increased efficiency. Moreover, the converter allows for reactive power control as well as smoother grid connection. Additionally, the dynamic performance of the system is enhanced, higher robustness in case of disturbances is offered, while the smaller converter constitutes this configuration more economically attractive.

The offered advantages establish this configuration as one of the dominant designs that are available in the market. However, certain grid code requirements, such as Fault ride through, are limited for this configuration due to the use of a partial-scale converter. Moreover, the use of the gearbox results in higher cost, maintenance requirements and weight. Such drawbacks constitute this configuration less appropriate for offshore applications [23].

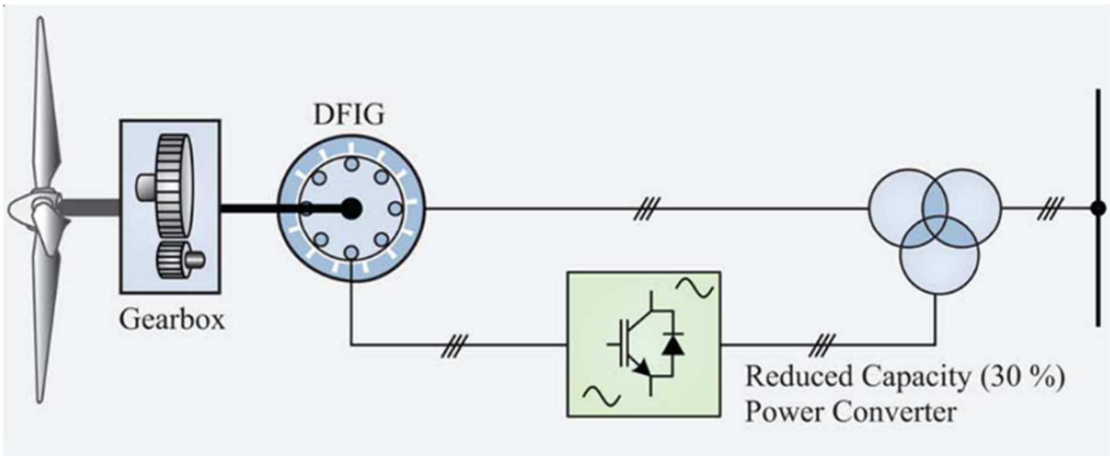

Figure 9: Variable-speed Wind System with a doubly-fed induction generator [23].

3.2.4 Type 4: Variable-speed Wind System with a full-scale Converter

The direct-in-line full variable speed wind turbine uses a synchronous generator that is connected to the grid through a full-scale Power Electronic Converter (Figure 10). The full-scale converter is connected in series with the electric generator and is responsible for transforming the variable frequency AC power that is produced by the WTG into fixed frequency AC power [22]. Moreover, the FSC allows for complete decoupling of the Wind Turbine Generator from the grid frequency and therefore enables variable speed operation at the full speed range [23][21] for optimal power capture. All the power produced flows through the full-scale converter to the grid. Such a configuration allows for independent control of the active and reactive power as well as for smooth grid connection.

For the Wind Turbine Generator an electrically excited type can be used (Wound Rotor Synchronous Generator) or a permanent magnet excited type (Permanent Magnet Synchronous Generator). The advancements in the power electronic technology enable the use of the Squirrel Cage Induction Generator. The use of the gearbox is optional as the full-scale converter design allows for the Wind Turbine Generator to operate at very low speeds [22].

The main drawbacks of this design constitute the higher costs due to the full-scale converter and the output filter that result in increased losses and thus reduced system efficiency. However, the cost of the converter is only a small part of the total system cost. Moreover, the use of the full-scale PEC allows for the highest efficiency among all available designs to be achieved as well as for reactive power control and smooth grid connection. Moreover, certain grid code requirements, e.g., Fault ride through, can be achieved in the best possible way from this configuration [23]. Finally, the gearless construction allows for reduced maintenance requirements. Overall, the characteristics of this configuration constitute it a very interesting solution for the large offshore applications [22].

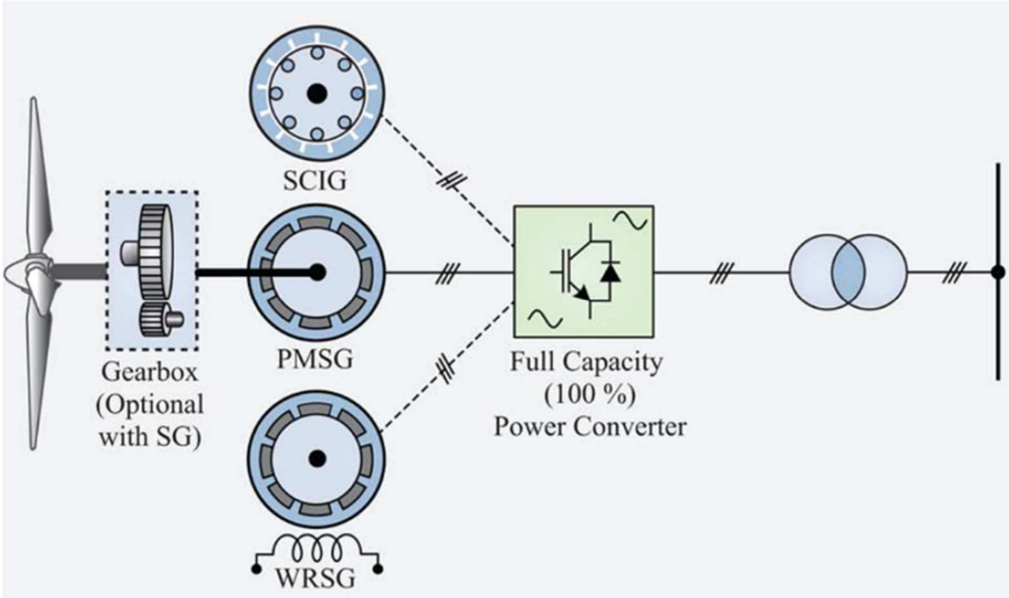

Figure 10: Variable-speed Wind System with a full-scale converter [23].

3.3 Dynamic Model of full-scale Converter Design with a direct-driven Permanent Magnet Synchronous Generator

This study focuses on the investigation of the potential offered by the Wind Turbine Technology in terms of Ancillary Service provision with the main interest placed on frequency support. Since variable speed wind turbine generators are the ones that dominate the market at the time being, due to the increased efficiency offered, the most interesting configurations are the VSWTGs. Moreover, the use of converters allows for active and reactive power to be independently controlled and thus for certain Ancillary Services to be provided. This characteristic constitutes VSWTs very interesting for this project.

From the available VSWTs the full-scale converter design that uses a direct-driven Permanent Magnet Synchronous Generator constitutes the most interesting option due to the optimal efficiency offered, the advantages of the full-scale converter that enables the provision of ancillary services in the best possible way as well as the decreased need for maintenance. It is also the preferred configuration from manufacturers for the large wind turbines used nowadays especially for large offshore applications. Therefore, the direct-driven PMSG that uses a full-scale converter is used for this study.

An initial model offered by the library of PSCAD was used as a basis for this study. This model includes a detailed model of the converters. However, it was only able to operate at rated wind speed, since the rotor speed controller and a correct pitch angle controller were not available within this model. For the purposes of this study it is essential to test the model at various wind speed conditions. Moreover, speed and pitch angle control constitute very important parts for this project. Thus, the necessary additions and improvements have been implemented to enable variable speed operation.

The operation of the Wind System constitutes a challenging and complicated topic. Various controllers interact with each other to achieve the overall goal, which is to manage the power injection to the grid in a way that the maximum possible power output can be achieved. The main parts and controls of the final model of full-scale converter that is used for this study are shown in Figure 11 and are discussed in detail in sections 3.3.1 to 3.3.6.

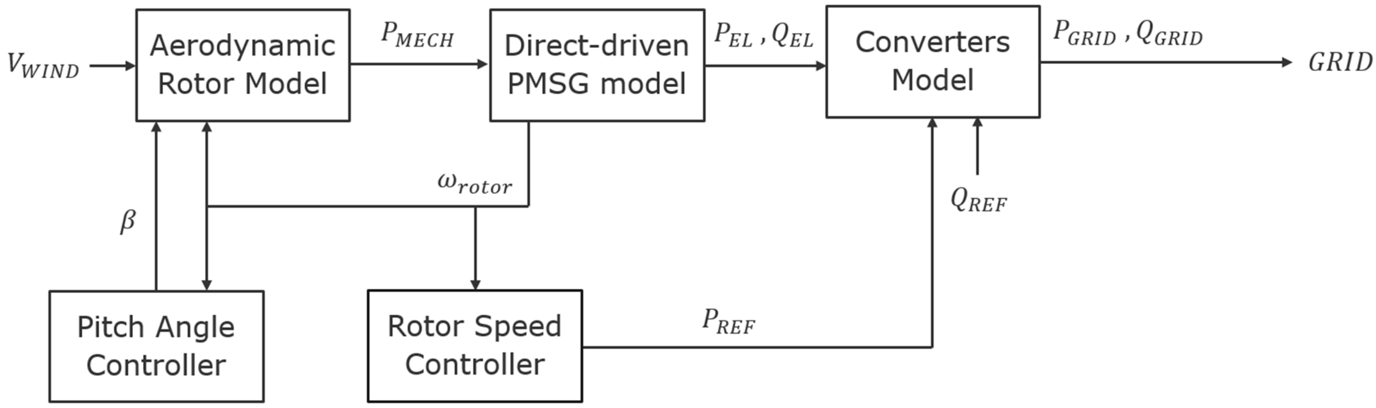

Figure 11: General structure of the full-scale converter with a PMSG model.

3.3.1 Aerodynamic Rotor Model

The wind turbine rotor constitutes a complex aerodynamic system. Its main aim is the extraction of the kinetic energy that is available in the wind and its conversion into mechanical power through the aerodynamic process.

Ideally, the rotor model required for the calculation of the mechanical torque and power obtained from the wind is based on the *Blade Element Theory*. However, such an approach requires an in depth knowledge of the aerodynamics as well as of the wind turbine geometry. Therefore, when the focus is the electrical behavior of the system a quasi-static rotor model is often used, in which an algebraic relationship is assumed between the wind speed and the mechanical power that is extracted from the wind [24].

The mechanical power that is extracted from the wind through the rotor can be calculated by the following equation:

$$P_{MECH} = \frac{1}{2} \cdot \pi \cdot R^2 \cdot \rho \cdot C_p \cdot {V_{WIND}}^3 \; [W] \; (4)$$

Where R is the turbine radius in meters, ρ is the air density in kg/m^3 , C_p is the power coefficient and V_{WIND} is the wind speed in m/s.

The *Power Coefficient* can be expressed as a function of the *pitch angle* β and the *tip speed ratio (TSR)* λ. For the calculation of the Power Coefficient, the mathematical representation for the C_p curves that is provided by GE Energy [29] is used, which is given by the following equation:

$$C_p(\beta, \lambda) = \sum_{i=0}^{4} \sum_{j=0}^{4} a_{i,j} \cdot \beta^i \cdot \lambda^j \;\; (5)$$

This curve fit constitutes a good approximation for tip speed ratio values of $3 < \lambda < 15$, and thus are an appropriate choice for all blade configurations and models.

The *tip speed ratio (TSR)* λ is an important design characteristic of a Wind Turbine, and can be calculated by the following equation:

$$\lambda = \frac{\omega_M \cdot R}{V_{WIND}} \;\; (6)$$

where ω_M is the mechanical speed of the wind turbine in rad/s, which is linked to the electrical speed of the wind turbine generator as follows:

$$\omega_M = \frac{\omega_E}{p} \left[\mathrm{rad}/_{sec} \right] (7)$$

Where p is the number of pair poles.

In the gearless type VSWTG, that is used for this study, the electrical speed and frequency of the wind turbine generator are completely decoupled from the synchronous speed and frequency of the grid. More specifically, the electrical speed of the generator is much slower compared to the network synchronous speed. The electrical base frequency of the wind turbine generator has to be set equal to the rated speed of the wind turbine:

$$f_{AC} = p \cdot \frac{RPM_{TUR}}{60} \; [Hz] \; (8)$$

The electrical speed of the wind turbine generator can be calculated as follows:

$$\omega_E = 2\pi f_{AC} = 2\pi \cdot \frac{RPM_{TUR}}{60} \cdot p \left[{}^{\mathrm{rad}}\!/_{sec} \right] (9)$$

where RPM_{TUR} is the rated speed of the wind turbine in *rpm*.

Therefore, under steady state conditions, the TSR can be calculated as follows:

$$\lambda = \frac{2\pi \cdot \frac{RPM_{TUR}}{60} \cdot R}{V_{WIND}} \cdot p \;\; (10)$$

Thus, the TSR value is calculated as follows:

$$\lambda = \frac{2\pi \cdot \frac{RPM_{TUR}}{60} \cdot R \cdot \omega_{M_{pu}}}{V_{WIND}} \cdot p \;\; (11)$$

where $\omega_{M_{pu}}$ is the mechanical speed in *pu*.

The generator and the rotor speed are linked through the gearbox ratio $r_{gearbox}$:

$$\omega_{gen} = \omega_{rotor} \cdot r_{gearbox} \left[{}^{\mathrm{rad}}\!/_{sec} \right] (12)$$

Since a gearless design is used, $r_{gearbox} = 1$ and thus:

$$\omega_{gen} = \omega_{rotor} = \omega_M \left[{}^{\mathrm{rad}}\!/_{sec} \right] (13)$$

3.3.2 Rotor Speed Controller

The wind turbine is optimally designed to operate at its rated wind speed, at which it generates its rated power output. For wind speeds below and above the rated wind speed two different operation modes can be distinguished where different control goals apply. For wind speeds lower than the cut-in wind speed not enough energy is available in the wind to successfully overcome the friction and stably operate the wind turbine. On the other hand, for very high wind speeds the energy that is available in the airflow is too high, resulting in increased structural loads on the turbine. Thus, the wind turbine is taken out of operation [24].

At below rated speed wind turbine operation there is not enough power available in the wind for the Wind Turbine to produce its rated power output. Therefore, the goal is to maximize the power capture from the wind and to generate as much power as the wind allows. In this way the aerodynamic efficiency is maximized over a wide range of wind speeds. This is achieved by adjusting the rotor speed to the wind speed conditions [27] and it constitutes an important characteristic of the Variable Speed Wind Turbine Generators, to which the full-scale converter design belongs. This characteristic is enabled through the use of power electronic converters that allow for decoupling the frequency and thus the Wind Turbine Generator rotational speed from the grid frequency. Therefore, the air-gap torque or the power of the wind turbine generator can also be controlled.

Maximum aerodynamic efficiency is achieved at the optimum tip speed ratio value $\lambda = \lambda_{opt}$ at which the power coefficient C_p obtains its maximum value $C_{p_{max}}$. The relationship between the optimal rotor speed and the wind speed is given by the following equation:

$$\omega_{opt} = \frac{\lambda_{opt}}{R} \cdot V_{WIND} \left[{}^{\text{rad}}/_{sec}\right] \quad (14)$$

Since the rotor speed is proportional to the wind speed value the maximum mechanical (or aerodynamic) power that can be captured from the wind can be calculated by the following equation:

$$P_{MECH}{}^{max} = P_{MPPT} = \frac{1}{2} \cdot \pi \cdot \rho \cdot R^5 \cdot \frac{C_p{}^{MAX}}{\lambda_{opt}{}^3} \cdot \omega_{opt}{}^3 \ [W] \ (15)$$

In steady-state operating conditions, the optimum tip speed ratio can be achieved by setting the generator power to balance the aerodynamic power. Alternatively, the generator torque can be set to balance the aerodynamic torque since these two are proportional by the rotor speed. This is known as *power or torque control*. This can be achieved by a Proportional-Integral (PI) controller that is acting on the error between the measured rotor speed and the optimal rotor speed value. In this way, a generator power demand is calculated that will be tracking the optimal rotor speed. The operation of the WTG at the optimal speed value that achieves maximum aerodynamic efficiency is also known as the Maximum Power Point Tracking (MPPT) principle.

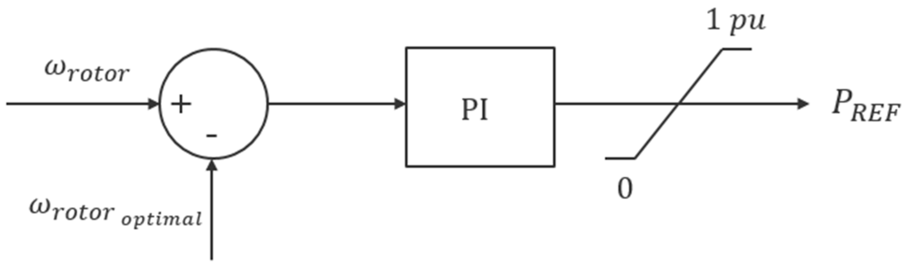

Figure 12: Rotor speed controller.

At above rated wind speed wind turbine operation there is more power available in the wind than the rated power output of the wind turbine generator. Thus, the torque or power is not sufficient any more to control the rotor speed from substantially increasing. To this end, *pitch control* is activated to regulate the rotor speed. Therefore, the power that is extracted from the wind is reduced with the main aim to keep the power constant at the rated power of the wind turbine generator. This is achieved by means of the pitch control which ensures that the wind turbine will continuously generates its rated power.

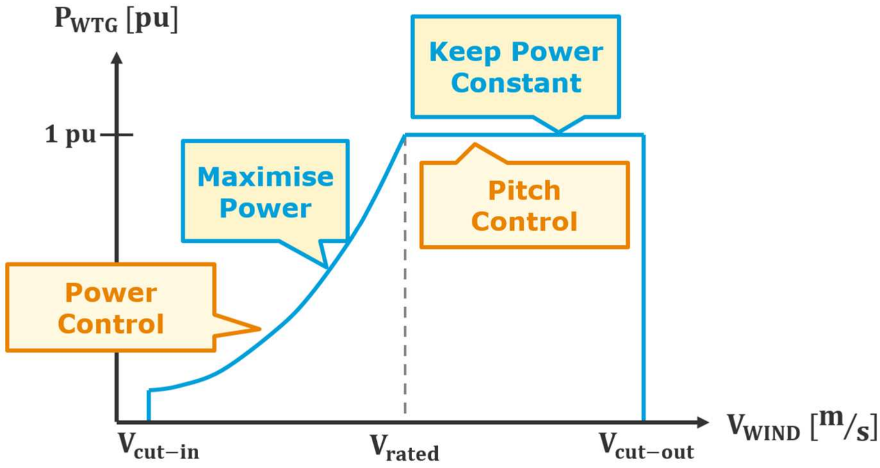

Figure 13: Power Curve of full-scale converter Wind Energy Conversion System.

3.3.3 Pitch Angle Controller

Pitch Angle Control constitutes is mechanically activated. It adjusts the pitching of the blades at high wind speeds to disoptimize the power capture from the wind, leading to decreased aerodynamic efficiency. Pitch control is only active during high wind speed conditions and its contribution is necessary, since rotor speed cannot be effectively controlled by increasing the generated power. Further increasing the generated power at above rated wind speed conditions would result in overloading the converters and the generator.

More specifically, pitch control increases the pitch angle β, also known as the *angle of attack*, which is the angle at which the relative wind strikes the blades. Pitch angle is adjusted with main aim the limitation of the rotor aerodynamic efficiency. The value of the pitch angle ranges between zero and a maximum value. The increase of the pitch angle results in a decrease of the aerodynamic torque T_{AERO}. This results in discarding the surplus power that is available in the wind but exceeds the rated power output of the Wind Turbine Generator.

The activation of the pitch control is accomplished through sensing a deviation of the measured rotor speed from its maximum allowed value that constitutes the activation point of pitch control. The activation point of pitch control is usually set close to the rated rotor speed. A Proportional – Integral (PI) Controller is often satisfactory for this application. However, since pitch control is mechanically activated, it is generally slow and it entails a maximum rate of change limitation. Thus, the value of the pitch angle and as a result the pitching of the blades cannot change instantly.

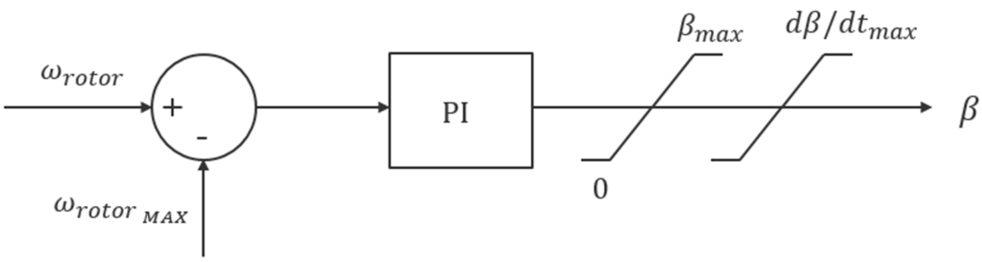

Figure 14: Pitch Angle Controller Model.

When designing the power (rotor speed) and the pitch controller, it is essential to ensure the correct switching from power to pitch control to prevent these two controllers from interfering with each other and simultaneously trying to control the speed. Such a situation may occur because maximum allowed rotor speed may be reached for wind speeds close but slightly lower than the rated speed. This would cause the pitch control to be activated (and thus discarding some power that is available in the wind) to maintain the rotor speed to its reference without the wind turbine producing its rated power output [27]. One simple and satisfactory way to avoid such a situation is to set the activation point of pitch control a little bit higher. Moreover, in order to avoid continuous change of the pitch angle due to slight decreases of the rotor speed, a *hysteresis loop* is used for the activation of pitch control.

3.3.4 Direct-driven Permanent Magnet Synchronous Generator Model

A synchronous generator is described by the following equations, when neglecting the stator transients [30]:

$$\psi_{ds} = -(L_{ds} + L_{\sigma s}) \cdot i_{ds} + L_{ds} \cdot i_{fd} \quad (16)$$

$$\psi_{qs} = -(L_{ds} + L_{\sigma s}) \cdot i_{qs} \quad (17)$$

$$\psi_{fd} = L_{fd} \cdot i_{fd} \quad (18)$$

$$v_{ds} = -R_s \cdot i_{ds} - \omega_r \cdot \psi_{qs} \quad (19)$$

$$v_{qs} = -R_s \cdot i_{qs} + \omega_r \cdot \psi_{ds} \quad (20)$$

$$v_{fd} = R_{fd} \cdot i_{fd} + \frac{d\psi_{fd}}{dt} \quad (21)$$

Where ψ is the flux linkage, v is the voltage, i is the current, ω is the frequency, R is the resistance and L is the inductance. The indices *d* and *q* stand for the d and q axis component respectively, *s* and *fd* stand for the stator and field quantities, while *r* and σ stand for the rotor and leakage respectively.

For a permanent magnet rotor equation (18) disappears, while equation (16) becomes:

$$\psi_{ds} = -(L_{ds} + L_{\sigma s}) \cdot i_{ds} + \psi_{pm} \quad (22)$$

Where ψ_{pm} represents the flux of the permanent magnets that are mounted on the rotor linked by the stator winding.

For the generated active and reactive power the following equations apply:

$$P = T_{el} \cdot \omega_r \quad [W] \; (23)$$

$$T_{el} = \psi_{ds} \cdot i_{qs} - \psi_{qs} \cdot i_{ds} \quad [N \cdot m] (24)$$

$$Q = v_{qs} \cdot i_{ds} - v_{ds} \cdot i_{qs} \quad [Var] \; (25)$$

Where the indexes *el* and *r* stand for electrical and rotor respectively.

3.3.5 Shaft Dynamics

The single mass equivalent model is used in this model where the wind turbine and the wind turbine generator are rotating through the same shaft. These two masses are mutually coupled through a shaft of finite stiffness. It can be the case that torsional oscillation will result between these two predominant masses. If it is required to see the turbine and generator torsional characteristics the *shaft dynamics* need to be considered.

For the representation of the shaft dynamics the *multi-mass torsional shaft model* can be used. This model is based on the shaft system model and equations [28]. However, since the full-scale converter design is used, where the wind turbine generator is directly connected to the grid through the power electronic converters, the shaft properties are barely reflected at the grid connection. This is because the power electronic converter fully decouples the wind turbine generator speed (and thus frequency) from the grid frequency. Therefore, the single mass equivalent can be used where the shaft dynamics are neglected.

For a stiff drive train and if the dynamics of the frequency converter are ignored, the torque balance gives [27]:

$$J \cdot \frac{d\omega_M}{dt} = T_{aero} - T_{gen} \quad (26)$$

Where J is the lamped inertia of the rotor, the drive train and the generator, T_{aero} is the aerodynamic torque and T_{gen} is the torque of the generator.

In reality, there is a loss in the mechanical torque of the drive train, which is a function of the rotational speed and torque, however this is neglected for this project.

3.3.6 Converter Model

The overall objective of the Wind Energy Conversion System control constitutes the management of power that is injected to the grid. This is achieved by the Generator and the Grid Side Converters that connect the Wind Turbine Generator to the grid. These two converters, that are linked through the DC Link capacitor, formulate a *frequency back-to-back converter*. Both converters are Voltage Source Converters (VSC) that in practice use Pulse Width Modulation (PWM) for the switching action. VSC can control the output AC current through the switching [31]. For the purposes of this project the average model has been used for the converters. Thus, no switching events are calculated. This results in significant reduction of the simulation time.

The main goal of the *Generator Side Converter* is to maximize the power extraction from the wind, which is afterwards injected to the DC Link. This converter controls the active power injection of the wind energy conversion system as well as the AC voltage, through appropriate control of the d and q components of the ac grid current. The d component of the output AC current controls the active power injection to the grid, while the q component of the output AC current controls the stator AC voltage. The active power reference signal is provided by the rotor speed control loop, while the reference for stator AC voltage is generally set at its rated value to avoid over-voltages due to over-speeds.

The main goal of the *Grid Side Converter* is to keep the DC Link voltage fixed. This converter controls the DC Link voltage and the reactive power injection of the wind energy conversion system, through appropriate control of the d and q components of the AC grid current. The d component of the output AC current controls the DC Link voltage, while the q component of the output AC current controls the reactive power injection to the grid. The reactive power reference signal is usually set to zero for the Wind Turbine System to inject as much active power as possible to the grid and to operate at close to unity power factor. Through the control of the DC Link Voltage the active power transfer to the grid is also control.

The DC Link Capacitor provides a means of energy storage between the Generator and the Grid Side Converter. Any change in the power production will be reflected in voltage variations across the DC Link Capacitor. These voltage variations need to be compensated through charging or discharging processes.

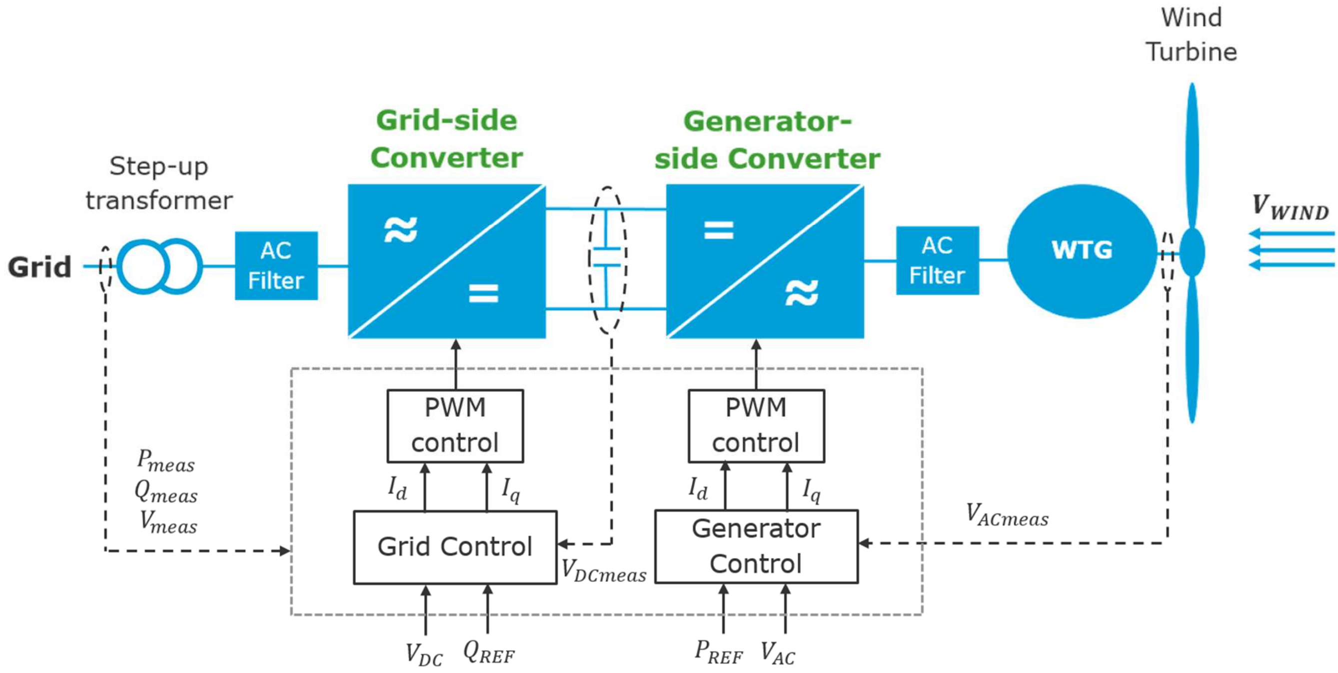

Figure 15: Converter Control scheme.

4. Required Modifications & Limitations for Ancillary Service Provision

4.1 Wind Turbine Technology Potential for Ancillary Service Provision

The power electronic converters used in the Variable Speed Wind Turbine Generators and thus, in the full-scale converter design that is used in this project, allow for active and reactive power injection of the system to be separately controlled. Therefore, Wind Turbines have the potential to be controlled in a way to contribute to Ancillary Service provision through the appropriate control of the power injection to the grid.

In this work, the main Ancillary Service option considered is frequency regulation. In order to support the grid frequency the wind turbine system needs to provide active power reserves. The main motivation for Wind Turbines to contribute to frequency support constitutes the participation in the Ancillary Service Market and thus the economic benefit that can be achieved through such a scheme (Figure 16).

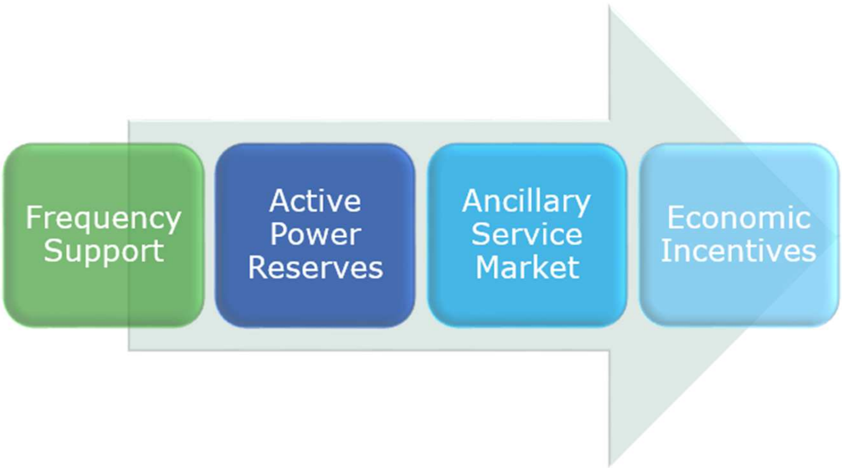

Figure 16: Motivation for participation to frequency support.

In order for the full potential that can be achieved from Wind Turbines in terms of frequency support to be more accurately estimated, it is important to study the dynamic behavior of the wind system to conclude to how this technology can be used to support the grid frequency, how much it can provide and for how long.

The first step towards answering these questions constitutes the analysis or the *required modifications* that will enrich the wind system with the ability to assist to frequency support, with the use of the chosen approach, as well as the identification of the *limitations* that need to be respected during providing the necessary active power reserves. Finally, the appropriate controller is designed based on the results and lessons learned from this first step. All the above are thoroughly explained in the following sections.

4.2 Required Modifications for Frequency Support

What are the required modifications at the Wind system level to enable the provision of Ancillary Services?

The first research question of this project constitutes the identification of the required modifications at the wind system level that will enable the provision of Ancillary Services. The focus of this project is placed on frequency support, thus the modifications required will allow for the wind system to provide the necessary active power reserves to support the grid frequency when a frequency deviation is sensed. To this end, an analytical explanation of the power flow under different conditions is provided within this section that will allow for an in depth understanding of the processes that take place during the provision of active power reserves by the wind system to be acquired. The knowhow obtained by the end of this section constitutes the basis for the design of the corresponding frequency controller.

The contribution of Wind Turbines to frequency support constitutes a challenging topic. For its successful implementation special care should be taken at the wind energy conversion system to first clearly understand how the provision of active power reserves influences its main operation and control under normal operating conditions. Careful consideration should be taken in order not to result in any unwanted situations during or after the provision of the requested reserves.

First of all, it is important to discriminate between an under-frequency and an over-frequency event. During an over-frequency event supply exceeds demand, thus the Wind Turbine Generator will be requested to reduce its active power output to provide the necessary *negative active power reserves.* This will assist in restoring the balance between supply and demand and thus the grid frequency back to the set-point of 50 Hz. On the other hand, during an under-frequency event the generated power is not sufficient to meet the needs in demand. Thus, there is need for *positive active power reserves* (Figure 17). This is the most critical situation for the grid and also the most difficult to achieve from the Wind Turbine. In order for the Wind Turbine Generator to satisfy the required positive active power reserves it needs to increase its active power output sufficiently.

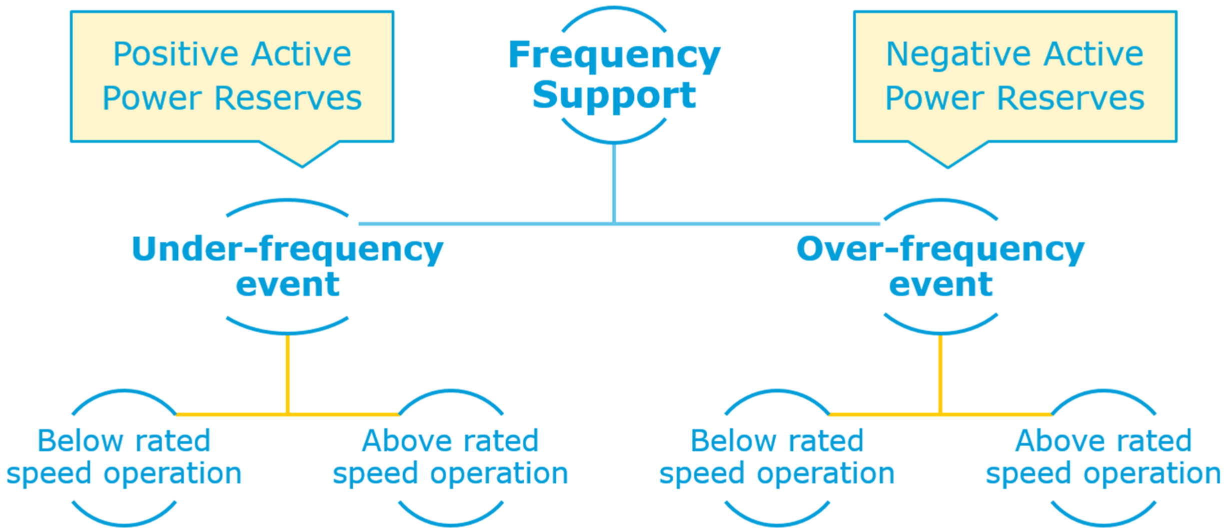

Figure 17: Discrimination between the different types of frequency deviation and the reserves required from a Wind System in each case.

Many challenges exists for the successful provision of positive active power reserves. The limitations associated with the provision of the required reserves by the Wind Turbine Technology need to be very carefully considered during the design of the corresponding controllers. In general, for the provision of active power reserves it is important to discriminate between above and below rated wind speed wind turbine operation, due to the different operating principles and control goals that apply under these two modes of operation. As a result, different approaches are required and different strategies need to be implemented to successfully provide the necessary reserves under each mode of operation, while ensuring the safe operation of the Wind Turbine.

4.2.1 Below rated speed Wind Turbine Operation

During below rated speed wind turbine operation and under normal operating conditions there is not enough power available in the wind for the Wind Turbine Generator to produce its rated power output. Therefore, the wind system is operated and controlled with the main objective to achieve optimal power capture from the wind (Figure 18). Thus, the wind turbine generates as much power as the wind allows:

$$P_{WTG} = P_{WIND} = P_{MPPT} \, [W] \; (27)$$

Where P_{WTG} represents the active power output of the wind turbine generator, P_{WIND} represents the power that is available in the wind under the given wind speed conditions, and P_{MPPT} represents the active power reference set point calculated according to the Maximum Power Point Tracking principle, with main aim the optimal power capture.

Optimal (maximum) power capture is achieved when the rotational speed obtains its optimal value. Thus, some kinetic energy will be stored in the rotating masses. The amount of the available kinetic energy depends on the wind speed conditions and thus on the rotational speed value.

The kinetic energy that is stored in the rotating masses both of the wind turbine as well as of the wind turbine generator rotor is given by the following equation:

$$K_{ROTOR} = \frac{1}{2} \cdot J \cdot \omega_{rotor}^2 \, [J] \; (28)$$

Where J is the lumped inertia of the wind turbine and the wind turbine generator rotor in $seconds$ and ω_{rotor} represents the rotor speed in ${}^{\mathrm{rad}}/_{sec}$, which is the same as the generator speed for a gearless design.

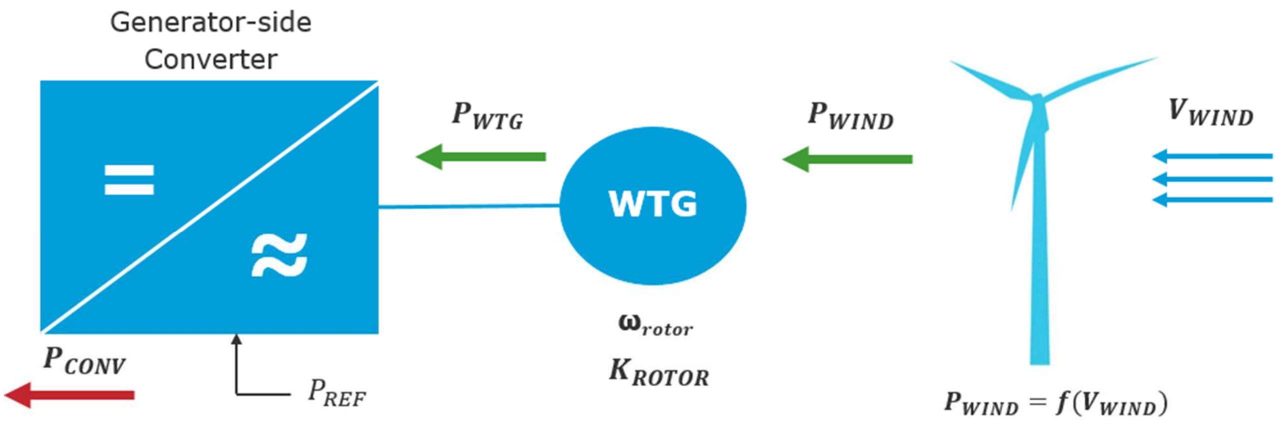

Figure 18: Normal power flow under below rated wind speed conditions.

The means to provide the necessary active power reserves in the presence of a frequency deviation are explained in the following paragraphs.

Under-frequency Event

If an under-frequency deviation is sensed the Wind Turbine Generator will be asked to increase its active power injection to the grid to provide the necessary positive active power reserves $P_{RESERVES}$. To achieve this, the active power reference signal P_{REF} that is sent to the Generator Side Converter needs to be increased by the amount of the additional reserves required.

$$P_{REF} = P_{WIND} + P_{RESERVES}\ [W](29)$$

As a result, the Generator Side Converter will try to follow the active power reference signal, thus drawing more power from the WTG than the amount of power that is being captured from the wind. In order for the demand in active power coming from the Generator Side Converter to be satisfied, the kinetic energy that is stored in the rotating masses K_{ROTOR} will automatically be released to provide the additional active power required, resulting in a decrease of the rotor speed [13](Figure 19):

$$P_{WTG} = P_{WIND} + P_{K_{rotor}}\ [W]\ (30)$$

Where $P_{K_{rotor}}$ represents the amount of power provided as reserves through releasing the kinetic energy stored in the rotating masses in $Watt$.

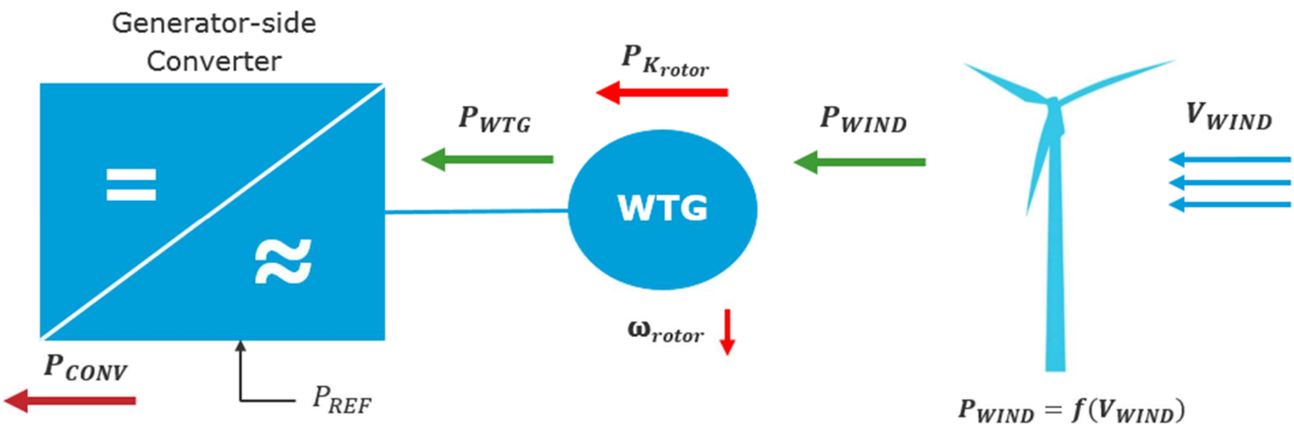

Figure 19: Power Flow under below rated wind speed conditions when the Wind Turbine provides positive active power reserves.

Over-frequency Event

If an over-frequency deviation is sensed, the Wind Turbine Generator will be asked to reduce its active power injection to the grid to provide the necessary negative active power reserves. To achieve this, the active power reference signal P_{REF} that is sent to the Generator Side Converter needs to be decreased by the amount of the negative reserves $P_{RESERVES}$ required.

$$P_{REF} = P_{WIND} + P_{RESERVES}\ [W]\ (31)$$

As a result, the Generator Side Converter will try to follow the active power reference signal, thus drawing less power from the WTG than the amount of power that is being captured from the wind. In order for the demand in active power coming from the Generator Side Converter to be satisfied, the surplus power that is captured from the wind, but not injected to the grid, will be stored as kinetic energy K_{ROTOR} in the rotating masses. This will result in an increase of the rotor speed (Figure 20).

If the rotor speed increases above the activation point of pitch control, pitch control will take over and increase the pitch angle to disoptimize the power capture from the wind and thus provide the necessary negative reserves without resulting in over-speeds.

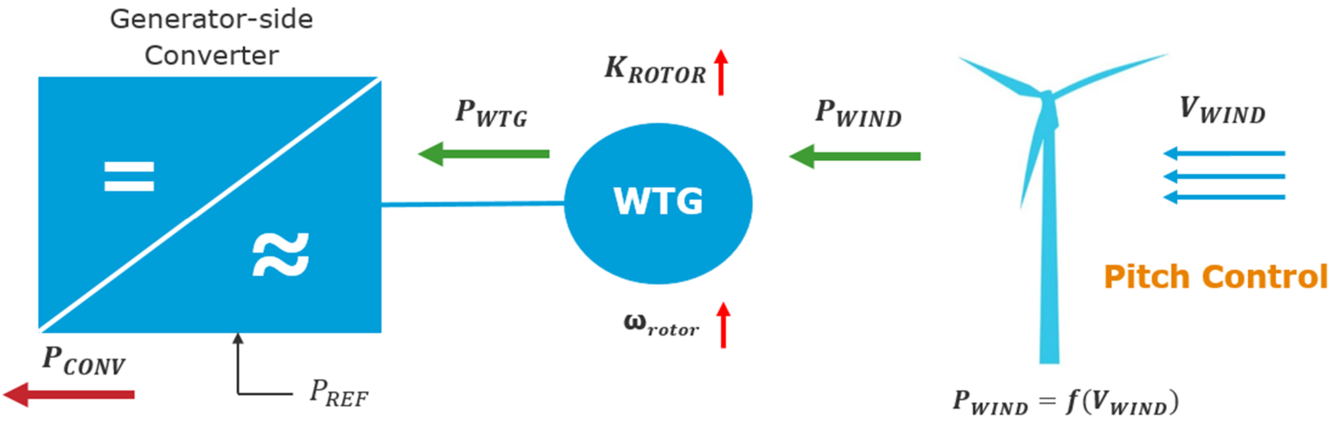

Figure 20: Power Flow under below rated wind speed conditions when the Wind Turbine provides negative active power reserves.

Rotor Recovery

Under below rated speed operation mode, the means used to support the frequency by providing the necessary reserves is by increasing or decreasing the kinetic energy K_{ROTOR} stored in the rotating masses. This results in an increase or decrease of the rotor speed ω_{rotor}. However, it is the optimal value of the rotor speed that allows the Variable Speed Wind Turbine Generators to achieve optimal power capture from the wind. Thus, it is very important to afterwards recover the rotor speed back to its optimal value. This is achieved by increasing or decreasing the active power injection to the grid a short time later to release the additional kinetic energy stored in the rotating masses or to recoup the kinetic energy lost during the frequency supporting operation of the wind turbine.

This procedure is defined as *"rotor recovery"* and will result in a second frequency deviation. Hence, it is important to be appropriately managed to be as smooth as possible. The successful management of the rotor recovery constitutes one of the most important challenges of this project.

4.2.2 Above rated speed Wind Turbine Operation

At above rated speed wind turbine operation, the Wind Turbine Generator produces its rated power output $P_{WIND_{rated}}$. Any surplus power $P_{SURPLUS}$ that is available in the wind is being discarded by means of pitch control resulting in a non-zero value of the pitch angle.

$$P_{WTG} = P_{WIND} - P_{SURPLUS} = P_{WIND_{rated}} \; [W] \; (32)$$

Under-frequency Event

If an under-frequency deviation is sensed, the Wind Turbine Generator will be asked to increase its active power output P_{WTG} to provide the necessary positive active power reserves $P_{RESERVES}$. To achieve this, the active power reference signal P_{REF} that is sent to the Generator Side Converter needs to be increased by the amount of the additional reserves required $P_{RESERVES}$:

$$P_{REF} = P_{WIND_{rated}} + P_{RESERVES} \; [W] \; (33)$$

As a result, the Generator Side Converter will try to follow the active power reference signal, thus drawing more power from the WTG than the amount of power that is being captured from the wind $P_{WIND_{rated}}$. The imbalance between the power demanded by the converter and the power captured from the wind will automatically cause some kinetic energy to be released in an effort to satisfy the additional demand in active power. Thus, the rotor speed will be slightly decreased. However, under this mode of operation pitch control is active and regulates the rotor speed at its maximum value. Thus, the slight decrease of the rotor speed will cause pitch control to optimize again the power capture from the wind. This will decrease the pitch angle and maintain the rotor speed close to its maximum allowed value. In the end, the additional demand in active power will be satisfied by the surplus power captured from the wind $P_{SURPLUS}$ for high wind speeds (Figure 21).

$$P_{WTG} = P_{WIND_{rated}} + P_{SURPLUS}\ [W]\ (34)$$

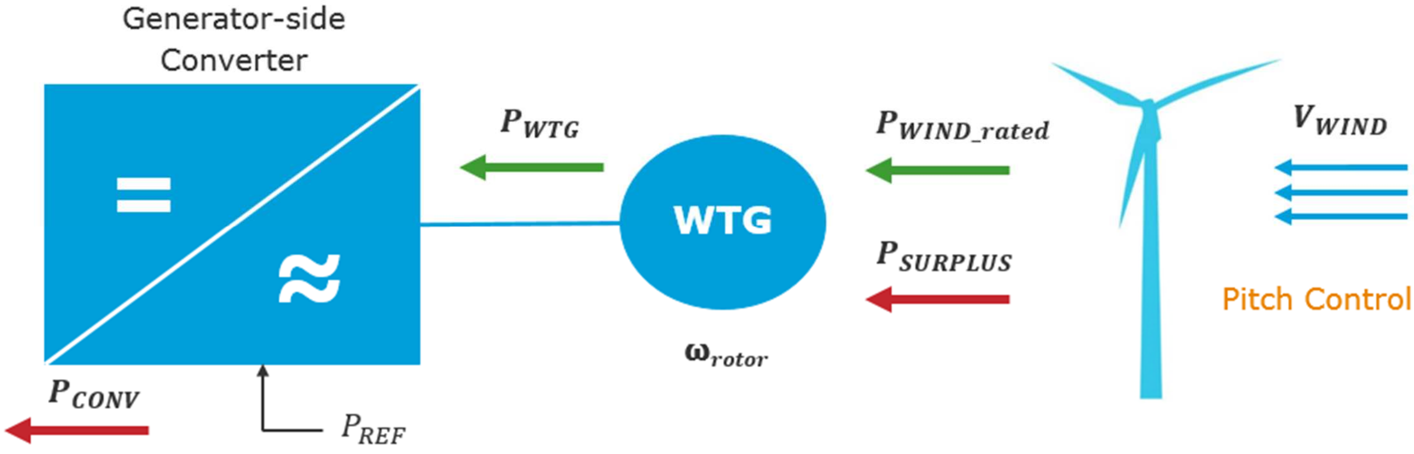

Figure 21: Power Flow under above rated wind speed conditions when the Wind Turbine provides positive active power reserves by means of pitch control.

For wind speeds close to rated where the surplus power that is available in the wind is low or if the additional demand in active power exceeds the surplus power that is available in the wind, some of the kinetic energy that is stored in the rotating masses K_{ROTOR} can also be released to provide the additional active power required. This will result in a decrease of the rotor speed ω_{rotor} (Figure 22):

$$P_{WTG} = P_{WIND_{rated}} + P_{SURPLUS} + P_{K_{rotor}}\ [W]\ (35)$$

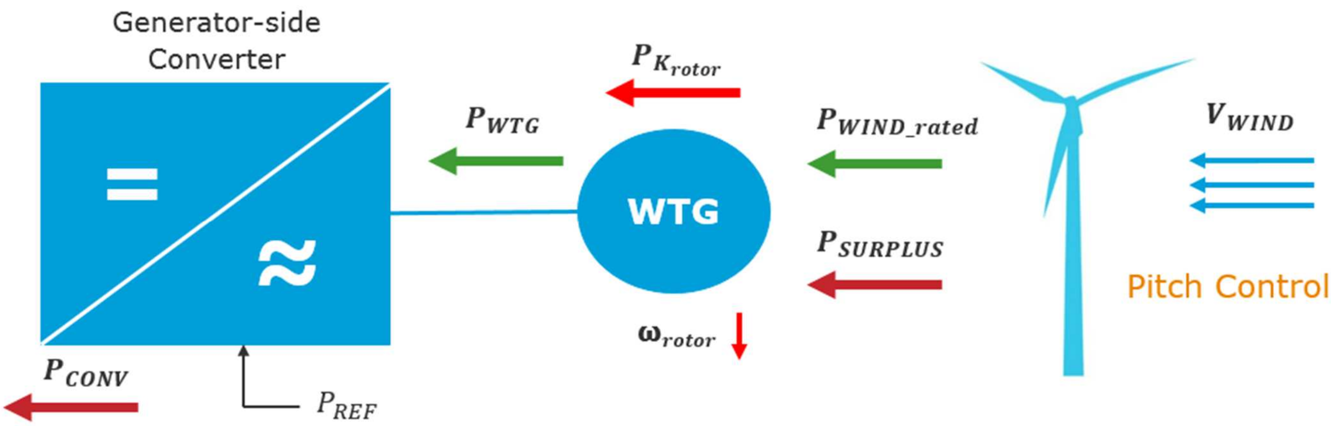

Figure 22: Power Flow under above rated wind speed conditions when the Wind Turbine provides positive active power reserves by means of pitch control and the kinetic energy that is stored in the rotating masses.

Therefore, after the necessary reserves have been provided, the rotor speed needs to be recovered back to its optimal value similarly to the below rated speed wind turbine operation.

Over-frequency Event

If an over-frequency deviation is sensed, the Wind Turbine Generator will be asked to reduce its active power output P_{WTG} to provide the necessary negative active power reserves. To achieve this, the active power reference signal P_{REF} that is sent to the Generator Side Converter needs to be decreased by the amount of the negative reserves required $P_{RESERVES}$.

$$P_{REF} = P_{WIND_{rated}} + P_{RESERVES}\ [W]\ (36)$$

As a result, the Generator Side Converter will try to follow the active power reference signal, thus drawing less power from the WTG than the amount of power that is being captured from the wind. Therefore, less power will be injected to the grid compared to the power captured from the wind. The surplus power will start to automatically be stored in the rotating masses. This will cause the rotor's kinetic energy to increase and the rotor speed to also slightly increase. However, pitch control is regulating the rotational speed under this mode of operation. Thus, pitch control will react with a further increase of the pitch angle to disoptimize the power capture from the wind and provide the necessary negative active power reserves, while maintaining rotor speed around its maximum allowed value and avoiding excessive increase of the rotational speed.

$$P_{WTG} = P_{WIND_{rated}} - P_{discarded} \ [W] \ (37)$$

Where $P_{discarded}$ represents the additional power that is discarded by means of pitch control for the necessary negative active power reserves to be provided.

4.3 Limitations for Frequency Support

What are the associated limitations for the provision of Ancillary Services by Wind Turbines?

The second research question of this project constitutes the identification of the associated limitations for the provision of Ancillary Services through the Wind Turbine Technology. The focus of this project is placed on frequency support. Thus, the limitations of interest are related to the provision of the necessary either positive or negative active power reserves. These are analytically explained in this section to provide the required insight for the controller design. It is important to respect the existing limitations when designing the frequency controller to ensure that the frequency response provided by the wind system will not result in any unwanted situations, that may in the end cause more severe frequency excursions. Hence, the knowhow obtained by the end of this section is used as an input for the design of the corresponding frequency controller.

While providing the necessary active power reserves from a wind system to support the grid frequency, the normal operating and control principles are being altered. Therefore, it is essential to ensure the Wind Turbine proper operation during the provision of the required reserves, and hence to respect the limitations associated with the use of the Wind Turbine Technology for frequency supporting purposes. The identified limitations are explained in the following paragraphs and will serve as an input for the design of the corresponding frequency controller.

4.3.1 Limit of the Power Available in the wind

The power that is available in the wind under certain wind speed conditions constitutes one of the most important limitations, since it will always restrict any possible power increase as well as any possible power decrease. The power that is available in the wind can be calculated by the following equation:

$$P_{WIND} = \frac{1}{2} \cdot \rho \cdot A \cdot {V_{WIND}}^3 \ [W] \ (38)$$

Where ρ is the air density, A is the area swept by the blades and V_{WIND} is the wind speed.
A wind turbine cannot capture all the power that is available in the wind. The maximum power extraction that can be achieved by an ideal wind turbine is limited to 59.26% of the available power, which is also known as the *Betz limit* [17]. The mechanical power captured by a wind turbine can be calculated with the help of the power coefficient

C_p , which constitutes the ratio between the amount of the power extracted from the wind turbine and the amount of power that is available in the wind.
The power that is extracted from the wind is defined by the following equation:

$$P_{MECH} = \frac{1}{2} \cdot \pi \cdot R^2 \cdot \rho \cdot C_p \cdot V_{WIND}{}^3 \; [W] \; (39)$$

The amount of energy that the wind turbine can capture from the wind and thus the amount of generated power depends on the turbine power versus wind speed characteristic as well as on the distribution of the wind speed at the wind turbine or wind farm site. The power curve of a variable speed wind turbine, that shows the relationship between the wind turbine generator power output P_{WTG} and the wind speed V_{WIND} ,is shown in Figure 23.

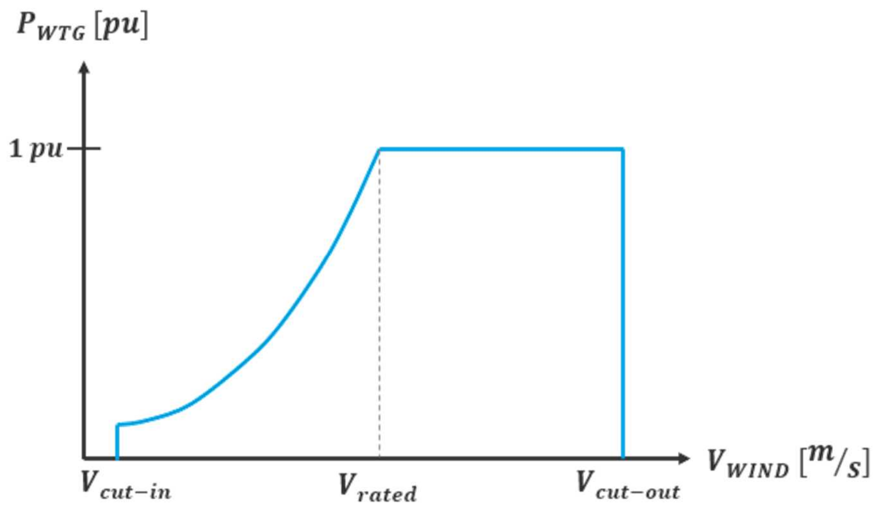

Figure 23: Power Curve of variable speed wind turbine generator.

For the provision of the necessary positive or negative active power reserves the normal power output that can be found through such a power curve is altered to satisfy the demand in active power according the frequency deviation sensed.

Even though the normal power curve does not directly show the capabilities of a wind system in terms of reserve provision, it can in a way serve as an indication of the reserves that can be provided at different wind speed conditions.

More specifically, the higher the wind speed conditions the more the positive active power reserves that can be provided, if the only limitation considered constitutes the available resources in the wind. At lower wind speed values though below rated the only source of energy constitutes the kinetic energy stored in the rotating masses. This can be released to satisfy the additional demand in active power. The available kinetic energy (equation 28) is though proportional to the rotational speed that increases with the wind speed. Thus, the amount of positive reserves that can be provided are directly dependent on the wind speed conditions.

4.3.2 Minimum Rotor Speed Limit

When releasing the kinetic energy of the rotating masses the rotational speed will decrease. Thus, it is essential to make sure that the amount of kinetic energy that is released will not cause the rotational speed to drop below a certain minimum value. The minimum rotor speed constitutes a limit of the minimum tip speed ratio λ_{min} and it is important to be respected to avoid *aerodynamic stall*.

The relationship between the minimum rotor speed and the minimum tip speed ratio value is given by the following equation:

$$\omega_{rotor_{min}} = \frac{\lambda_{min} \cdot V_{WIND}}{R} \ \left[{}^{\mathrm{rad}}/_{sec}\right] \quad (40)$$

Aerodynamic stall can occur if there is not enough kinetic energy left in the rotation masses to overcome the existing friction and thus to stably operate the wind turbine. If aerodynamic stall occurs, it will result in a steep drop of the rotational speed and eventually of the wind turbine generator active power output. If such a situation occurs, the impact on the grid frequency will be much more substantial compared to the benefit provided through the frequency supporting operation of the wind turbine. Hence, preventing aerodynamic stall must be set as a priority during the design of the frequency controller.

Other than the minimum rotor speed, one other factor that may affect the minimum rotor speed limit that needs to be imposed constitutes the way in which the total active power term provided by a certain wind turbine is calculated. More specifically, it is important to realize that when releasing the kinetic energy stored in the rotating masses the rotor speed will inevitably decrease. Thus, continuing to transfer the normally injected amount of active power under lower rotational speed values will already deteriorate the decrease of the rotor speed. The lower the wind speed conditions are, the more evident this phenomenon will become. This may result in aerodynamic stall occurring for tip speed ratio values higher than the minimum tip speed ratio under low wind speed conditions.

Various methods can be used to calculate the correct minimum rotor speed value that needs to be respected by the frequency controller when releasing the kinetic energy of the rotating masses. The speed controller design as well as the design of the frequency controller play an important role when choosing the appropriate approach. In the end, any control design that ensures that aerodynamic stall is avoided is considered acceptable, however the level at which the potential offered by the wind turbine technology under a certain control design will differ.

4.3.3 Limits of the Electrical Components of Wind Energy Conversion System

When adjusting the power output of the wind energy conversion system to meet the demand in active power during a frequency event, it is important to ensure that the design specifications of the electrical components are not exceeded. The critical situation that needs to be considered constitutes the increase of the power output above the rated power of the system, since this will cause the components to heat up. However, components such as the generator and the transformer are characterized by longer time constants, ranging from 30 minutes to several hours, and are thus not considered sensitive for such type of applications. Cables may have shorter time constants but still in the order of minutes. Thus, they are also not expected to be affected by such a transient response. Converters however, consist of semiconductor devices that are characterized by critical time constants of around one second. Such devices are usually operated close to their limits for cost reasons [13].

More specifically, the maximum power that can be transferred through the converters is translated in a maximum AC current that the converters can switch [13][32]. As a result, they can only withstand very transient increases of the transferred power. A continuous power transfer above the converter rated power (100%) will cause the electrical components to heat up. However, the maximum power transfer limitation is in fact defined as a maximum junction temperature. It is also dependent on the design of specific components and on structural loading. This allows the implementation of slightly longer power increases as long as the maximum temperature limit is not violated. The more accurate the temperature measurements, the more we can temporarily increase the maximum power transfer limit. Therefore, it is possible to temporarily overload the converters at around 110% or 125% of the rated power. The more the converter is overloaded the more the temperature will increase.

However, even if the necessary restrictions are made for immediate failure of the components not to occur due to the increased temperatures experienced, it is expected that overloading the converters on a frequent basis will have a negative impact on the lifetime of the insulation of the electric components. Finally, a converter with increased rating can also be used if the economic benefit that can be achieved by such a scheme justifies the additional costs.

4.3.4 Management of Recovery Period

The recovery of the rotor constitutes the most important challenge in supporting the grid frequency. The way in which it is accomplished will in essence determine whether this is a beneficial response from Wind Turbines or not. Care should be taken that the wind system will not introduce a larger disturbance to the network during the rotor recovery than the one it is trying to solve. The importance of the recovery period becomes more evident when the same response is provided by multiple wind turbines within a wind farm, thus causing an important second frequency deviation during the recovery phase. Therefore, three main goals exist with respect to a successful rotor recovery:

- Priority is placed on a successful recovery of the rotational speed that first of all respects all limitations.
- The recovery of the rotor needs to be achieved in a smooth and gradual way, for conventional power plants to be able to more easily adjust to the second frequency deviation that will occur during the rotor recovery, due to the increase or the decrease of the wind system power output required to restore the rotor speed back to its optimal value.
- The recovery of the rotor should if possible occur when the frequency will have recovered back to the set-point of 50 Hz or at least closer to it. The provision of a higher amount of reserves that will result in an early rotor recovery should be avoided, since the second frequency deviation caused during the recovery period may be more severe than the first one.

Overall, the goal is to keep the frequency within the allowable range in exchange of smaller and preferably smoother additional frequency deviations that can be more easily handled by the grid and will not result in unwanted situations.

4.3.5 Pitch Control Limitation

Pitch control is mechanically activated. Thus, when used as a mechanism to provide the necessary active power reserves it is important to consider that the pitching of the blades cannot instantly change. Pitch control is a slower mechanism compared to releasing or storing kinetic energy and it entails a rate of change limitation. Thus, sudden and steep changes in the active power output of the Wind Turbine Generator that need to be satisfied by means of the pitch controller may result in more significant variations of the rotational speed before pitch control can take over the provision of the required reserves. This may result in over-speeds if a sudden decrease of the active power output of the Wind Turbine Generator is requested, and should thus be avoided.

4.3.6 Time Limitation

It is important to take into account that there is a time limitation regarding the provision of additional active power reserves from Wind Turbines. This is due to two main reasons:

- The kinetic energy that is released during below rated speed Wind Turbine Operation is not unlimited and will only last for a few seconds. It is however possible to choose between releasing it all at once or to provide less reserves for a few more seconds. In general, a *trade-off* between the duration of the response provided and the amount of reserves provided can be observed.
- The converters can be overloaded only temporarily, since the increased current flowing through the converters will cause the components to heat up in time. The components' temperature increases with the time and with the amount of power above rated that is transferred through the converters. If more accurate

temperature measurements are taken slightly longer responses may be possible, as long as the junction allowed temperature is not exceeded. If however temperature measurements are not possible, a more conservative time limit should be imposed in the frequency response provided by the wind system to ensure the proper system operation under all cases.

4.3.7 Limits of the Mechanical Components of Wind Energy Conversion System

The designed controller that adjusts the power output according to the frequency deviation will have a direct effect on the wind turbine behavior and on the loads that it experiences. For example, there is a *trade-off* in the pitch actuator activity that can be tolerated and the good control of the wind turbine generator power output achieved by the controller, since repetitive action on the pitch may result in reduced lifetime of the components.

The overall effect of the frequency controller on the pitch actuator lifetime is proportional to the frequency of its usage for reserve provision. The balancing product is expected though to be less frequent compared to the normal operation of pitch control. Thus, the effect on pitch control is expected to be negligible. Nevertheless, more thorough studies would be required to prove this in practice.

Moreover, it is estimated that changes in the fatigue loads experienced by the wind turbine will not have an important impact [13]. Fatigue and extreme loading conditions should ideally also be considered. The most important source of increased loads lies in the provision of positive active power reserves at high wind speed conditions.

The software used for this project focuses on the electrical behavior of the system and thus the impact on the mechanical components cannot be studied through this project. Therefore, the impact on the mechanical components is not considered in the design of the frequency controller.

4.4 Frequency Controller Design Implementation

In this section, the *frequency controller* that has been designed to enrich the wind system with the capability to support the grid frequency is presented in detail. The controller design follows the theoretical analysis presented in sections 4.2 “Required Modifications for Frequency Support” and 4.3 “Limitations for Frequency Support” . The operation of the wind system in a way that the identified limitations are not violated is always set as the priority of the controller.

The controller within the wind system that needed to be appropriately modified to enrich the Wind Turbine with the capability to support the grid frequency constitutes the *speed controller*. Speed control is undertaken by the *power controller or rotor speed controller*, for below rated speed values. For above rated wind speed values it is undertaken by the *pitch angle controller*.

Normal pitch control will automatically respond when needed. However, changes are required in the power control loop through which the active power reference signal that is sent to the Generator side converter is calculated, resulting in effective control of the active power injection to the grid.

It is pointed out that within the implemented control design, for low wind speed values close to the cut-in wind speed value when the active power output of wind turbine generator is less than 0.35 pu, the wind system is not allowed to provide any reserves in the presence of frequency deviation. It is not considered sensible to provide frequency response from wind turbines at low wind speed values as the amount of kinetic energy that can be safely released will in any case be quite low. Moreover, even if a very small amount of kinetic energy is released under such low wind speed conditions, it becomes much more challenging to guarantee that aerodynamic stall will be successfully prevented. The reason lies in the increased losses under low wind speed conditions as well as the significantly decreased rotor speed value that will be requested to realize an increased active power injection. Thus, it becomes highly possible that if the wind system were to participate in frequency support under such wind speed conditions, the kinetic energy left within the rotating masses may soon not be sufficient to overcome the friction and stably operate the wind turbine. Additionally, the small amount of kinetic energy that can be potentially released as reserves by a single wind turbine or even a wind farm will cause a very short response from the wind system. Thus will possibly result in an early recovery and hence, a more severe frequency deviation. Finally, a wind farm operating at low wind speed conditions will in any case not be substantially contributing to the load. Thus, it will not be causing decreased system inertia levels, since conventional generation (or other means of power supply) will be used to satisfy the load. To this end, under low wind speed conditions close to the cut-in wind speed value it is not really required, neither advised, to provide a frequency response from wind turbines and wind farms.

The block diagram of the modified model that includes the frequency controller that has been designed for the purposes of this Master Thesis project is depicted in Figure 24.

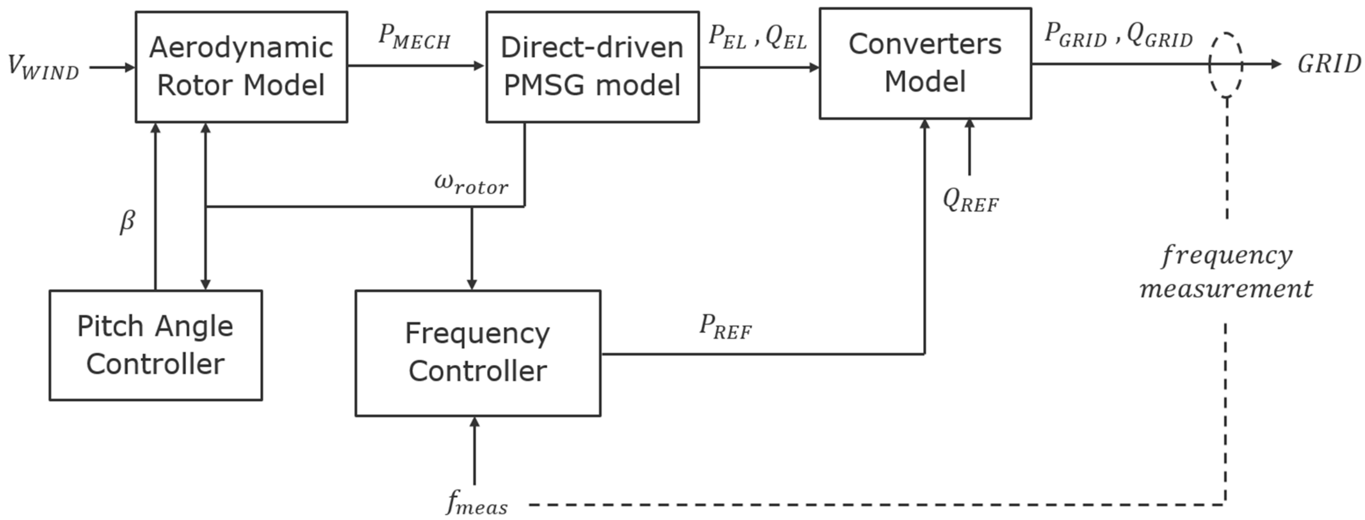

Figure 24: Block diagram of the full-scale converter model with a PMSG modified to enable frequency support.

The block diagram of the implemented frequency controller with its main sub-controllers is presented in Figure 25. There are three main sub-controllers used within the corresponding frequency controller, with each one of those taking over a different task. These are: the modified *rotor speed controller*, the *reserves controller* and the *recovery controller*, which calculate the normal active power reference signal P_{REF_NO} , the reserves active power reference signal $P_{RESERVES}$ and the recovery active power reference signal $P_{RECOVERY}$ respectively. The input to the rotor speed controller and the recovery controller constitutes the rotational speed, while the input to the reserves controller constitutes the measured frequency.

The three active power reference signals created by the sub-controllers are afterwards added to produce the total active power reference signal P_{REF}, which is limited to 125% of the rated power of the Wind Turbine Generator, before sent to the Generator Side Converter to respect the converter maximum power transfer capability.

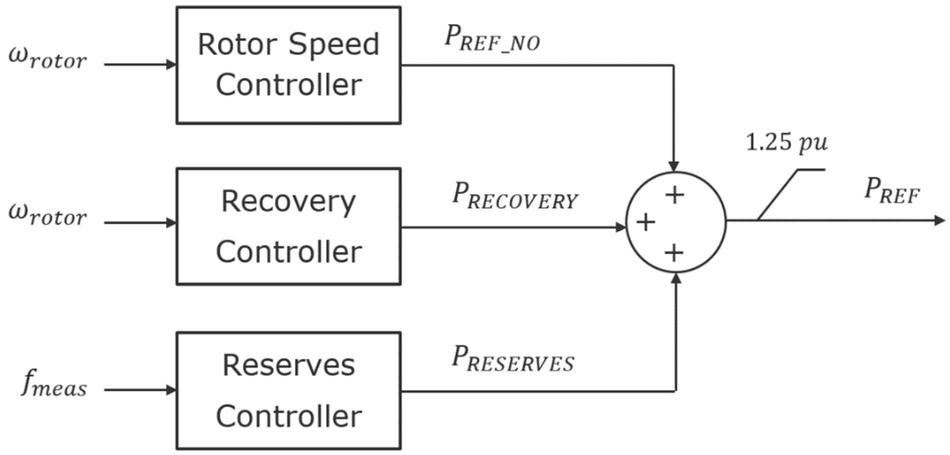

Figure 25: Block diagram of the implemented Frequency Controller.

The tasks undertaken by the different parts of the controller are analytically described in the following paragraphs.

4.4.1 Modified Rotor Speed Controller

The normal rotor speed control loop is appropriately adjusted to allow the provision of the necessary active power reserves during a frequency deviation. The modified rotor speed controller is depicted in Figure 26. This controller results in an active power reference signal that is sent to the Generator Side Converter. Thus, the active power injection to the grid is managed. Its implementation is described in more detail in the section 3.3.2 “Rotor Speed Controller”.

In the presence of an altered active power injection to the grid that that, for below rated wind speed conditions, would result in a rotor speed value different from the optimal rotor speed value, the rotor speed controller would inherently try to counteract any reserves that need to be provided to maintain the rotor speed at its optimal value. Hence, it is important that such an action is prevented to take full advantage of the potential that can be offered by the Wind Turbine technology.

One way to achieve that constitutes freezing the PI used in this part of the controller from the moment that active power reserves start to be provided (which for now corresponds to the time instant that a frequency deviation is sensed) and until the moment the rotor speed has been recovered back to its optimal value. In this way, P_{REF_NO} will always be the signal that would have otherwise be sent to the Generator Side Converter, under normal operating conditions, if the Wind Turbine was not providing active power reserves to support the grid frequency. The recovery of the rotor speed will be handled by a different controller.

If the wind turbine is set to provide zero reserves, then the rotor speed controller PI is never frozen, even though a frequency deviation is sensed. In such a case, the wind turbine operates normally to produce as much power as possible.

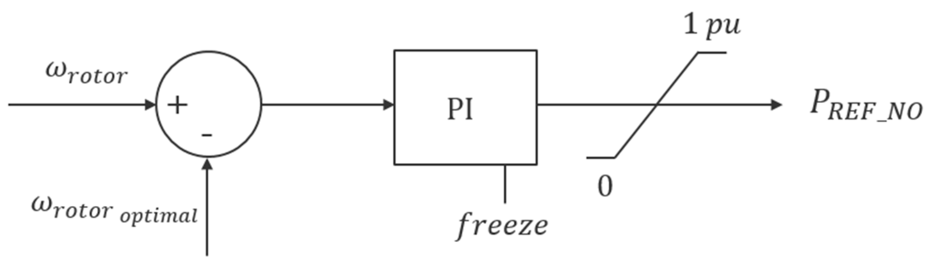

Figure 26: Modified Rotor Speed Controller to enable frequency support.

4.4.2 Reserves Controller

The additional reserves required to support the grid frequency are calculated by the *reserves controller*. The implemented reserves controller is depicted in Figure 27.

The method that is used for the calculation of the required reserves is *droop control*. Thus, the additional reserves required are proportional to the frequency deviation sensed by a gain droop constant K_{droop}, which is a parameter that can be varied to control the amount of reserves provided. Droop control was preferred compared to inertial control that would produce a power term proportional to the rate of change of the grid frequency, as it has already been proved from the available literature that the optimal inertial constant obtains a value close to zero. Thus, even a synthetic inertia strategy would basically result in a fast droop control strategy [14].

The calculated reserves are afterwards multiplied by minus one for positive active power reserves to be provided during an under-frequency deviation and for negative active power reserves to be provided during an over-frequency deviation.

A deadband of 10 mHz is allowed, for which no reserves are requested from the wind turbine (following the current trend in the Ancillary Service Market). Moreover, no reserves are provided for low wind speed values close to the cut-in wind speed to avoid undesirable situations, as explained in the above. The limit for this model is set to 7.6 m/s, which results in a wind turbine generator active power output of 0.35 pu.

For frequency deviations above 200 mHz, the reserves controller is adjusted to provide a constant amount of reserves. Thus, the frequency deviation measured is substituted by a constant frequency deviation equal to 200 mHz (following the current trend in the Ancillary Service Market).

The total amount of reserves that needs to be provided is afterwards appropriately limited.

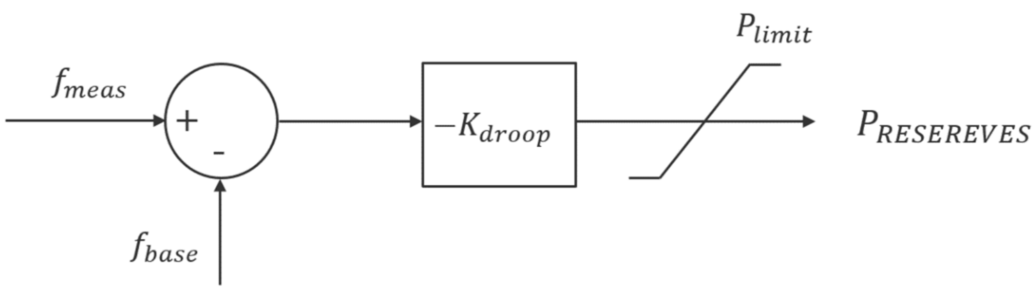

Figure 27: Reserves Controller.

For *low wind speed values,* below the rated wind speed, the limit P_{limit} is the maximum possible kinetic energy that can be released within a certain time-period $\Delta t_{release}$ without reducing the rotor speed below its minimum allowed value.

$$P_{limit} = P_{K_{rotor}} \, [W] \quad (41)$$

The minimum allowed rotor speed constitutes a limit of the *tip speed ratio* for wind speed values above 8.9 m/s. For lower wind speed values a different limit needs to be imposed that only allows for the rotational speed to decrease by 15% from its optimal value to effectively prevent aerodynamic stall. This is necessary because the rotor speed controller freezes during the frequency supporting operation of the wind system. Thus, a lower rotational speed is requested to,not only provide the additional reserves required, but also to maintain the normal active power output of the wind turbine generator under the given wind speed conditions.

Thus, the minimum rotor speed can in total be calculated as follows:

$$\omega_{rotor_{min}}[{}^{rad}/_{sec}] = \begin{cases} \dfrac{\lambda_{min} \cdot V_{WIND}}{R}, & V_{WIND} \geq 8.9\ m/s \\ 0.85 \cdot \omega_{opt}, & V_{WIND} < 8.9\ m/s \end{cases} \quad (42)$$

The minimum tip speed ratio value depends on the wind turbine design. For this study, a minimum tip speed ratio value λ_{min} equal to 5.5 is used, following the example of the study performed by Ervin Bossanyi [13], where a wind turbine design with the same characteristics was used.

From the minimum rotor speed, the maximum kinetic energy of the rotor that can be released can be obtained as follows:

$$K_{ROTOR} = \frac{1}{2} \cdot J \cdot \left(\omega_{rotor}^2 - \omega_{rotor_{min}}^2\right) [J] \ (43)$$

The power limit P_{limit} in Watt is then obtained by dividing the calculated amount of kinetic energy that can be safely released by a time period $\Delta t_{release}$[sec] that represents the time period within which the available kinetic energy will be released. This is a parameter that can be varied.

$$P_{K_{rotor}} = \frac{K_{ROTOR}}{\Delta t_{release}} = \frac{\frac{1}{2} \cdot J \cdot (\omega_{rotor}^2 - \omega_{rotor_{min}}^2)}{\Delta t_{release}} \ [W](44)$$

On the other hand, for *high wind speed values* above the rated wind speed where pitch angle obtains a non-zero value, the limit constitutes the sum of the maximum kinetic energy of the rotor that can be safely released within a certain time frame without reducing the rotor speed below its minimum value, $P_{K_{rotor}}$, and the amount of the surplus power that is available in the wind and is normally discarded through pitch control, $P_{SURPLUS}$.

$$P_{limit} = P_{K_{rotor}} + P_{SURPLUS} \ [W] \ (45)$$

The surplus power available in the wind that can be captured by a change on the pitching of the blades, $P_{SURPLUS}$, can be calculated as follows:

$$P_{SURPLUS} = \frac{1}{2} \cdot \pi \cdot R^2 \cdot \rho \cdot C_{p_{opt}} \cdot V_{WIND}{}^3 \ [W] \ (46)$$

Where $C_{p_{opt}}(\lambda, \beta)$ constitutes the optimum power coefficient that is calculated for a zero value of the pitch angle β and the tip speed ratio value λ that is obtained from the simulation. For a zero value of the pitch angle the wind turbine achieves the highest possible power capture for the given wind speed conditions.

In fact, for very high wind speed values the surplus power that is available in the wind is usually more than enough to satisfy the additional reserves required during an under-frequency deviation. The hard limit for the maximum reserves that can be provided in such a case constitutes the limit of the maximum converter power transfer capability. This limit is imposed to the total active power reference signal P_{REF} that is sent to the Generator Side Converter, and for this study is set to 1.25 pu. However, for wind speed values around the rated value (slightly below as well as slightly above rated, since pitch control is activated for wind speed values slightly below rated wind speed as explained in section "*3.3.3 Pitch Angle Controller*"), the pitch angle has a very low value as there is only very little surplus power available in the wind that is being discarded by means of pitch control. Thus, it is important that some of the rotor's kinetic energy is also allowed to be used to take advantage of the full potential offered by the Wind Turbine technology under the given wind speed conditions to satisfy the required active power reserves.

All the above-mentioned quantities are afterwards converter to pu values, with the use of the appropriate base values.

4.4.3 Recovery Controller

The recovery of the rotor speed back to its optimal value, that is required after the provision of the necessary reserves for below rated speed wind turbine operation, is handled by the *recovery controller*. The implemented recovery controller is depicted in Figure 28.

The recovery controller is also comprised by a PI controller with input the error between the measured and the optimal rotor speed. However, the output of this controller will only be added to the total active power reference signal sent to the Generator Side Converter during the recovery period of the rotor. Moreover, the Recovery Controller PI has different saturation limits, $P_{increase_{max}}$ and $P_{decrease_{max}}$, compared to the Rotor Speed Controller PI.

Finally, the output of the recovery controller PI is limited by a rate of change limiter that ensures that no steep increases or decreases of the power output of the wind turbine generator will be facilitated at the start or the end of the recovery period.

It is important to make sure that the rate of change limit is not very low, since that may cause aerodynamic stall to occur due to insufficient kinetic energy withheld to restore the rotor speed following an under-frequency deviation at low wind speed conditions.

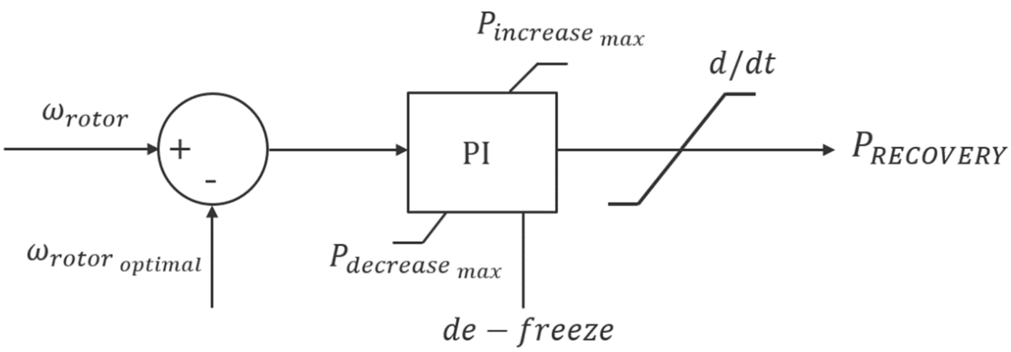

Figure 28: Recovery Controller.

The purpose of the recovery controller is to decrease or increase the normal active power reference signal by a small percentage of the rated power output of the Wind Turbine Generator during the recovery of the rotor. This will allow this small amount of power that is being captured but not injected to the grid to be used to recover the rotor speed to its optimal value after an under-frequency event, or slowly releasing the surplus power that has been stored in the rotating masses during an over-frequency event. A smoother recovery period that will last longer can be achieved by using a small percentage of the rated power, while a faster but also more aggressive rotor recovery can be accomplished if the step in the active power output obtains an increased value.

The recovery controller is only active during the recovery period, while for any other time instant its output will be zero. The recovery period may start:

- When the frequency is restored back to the set-point of 50 Hz with only a small offset f_{ss} remaining, which is normally restored by the activation of Secondary Frequency Control or Frequency Restoration Reserves. For this study this is set equal to 25 mHz. In this situation, the rotor recovery may be delayed by a delay time period T_{delay}.
- When the time limit of the frequency supporting operation T_{FSO} is exceeded. In this way, a time limit for the provision of active power reserves that exceed the rated power output of the converter is imposed to avoid overheating the converter components above their maximum junction temperature. Such an activation of the

recovery period will be imposed only for above rated wind speed values and after an under-frequency deviation has been sensed.

- When the rotor speed reaches its minimum value, thus the recovery of the rotor is forced to avoid aerodynamic stall. The rotor speed is only allowed to approach and not to actually reach the minimum rotor speed value in order to ensure that no undesirable situations occur. Thus, the recovery of the rotor will start for a rotor speed only slightly higher than the minimum rotor speed.

The moment that any of the above-mentioned conditions is satisfied, the rotor recovery will immediately start through the activation of the Recovery Controller. If no reserves are provided by the wind turbine for any reason (zero gain droop constant or wind speed values very close to the cut-in wind speed value), this controller is not activated at all.

Finally, this controller is only used for below rated wind speed conditions, while for above rated wind speed conditions the rotor recovery is undertaken by the normal pitch control. Thus, no additional controller is required and the normal active power output does not need to be affected after the requested reserves have been provided.

5. Wind Farm Topology & Wind Farm Controller

What are the associated challenges and the arising benefits by the simultaneous provision of Ancillary Services by multiple Wind Turbines in a Wind Farm?

The third research question of this project constitutes the identification of the main challenges and benefits that are associated with the simultaneous provision of ancillary services by multiple wind turbines within a wind farm. The focus is placed on frequency support. Thus, the most important question that needs to be answered constitutes how can multiple wind turbines within a wind farm be controlled to achieve the most beneficial frequency response from the wind farm in total, in terms of duration and maximum reserves provided as well as in terms of optimal rotor recovery. Two steps are required for successfully answering this question. First an appropriate wind farm controller needs to be designed. Afterwards, a realistic wind farm application needs to be modelled to test the performance of the total single wind turbine and wind farm frequency controller in the presence of various frequency deviations and parameter settings.

The amount of reserves that can be provided by a single wind turbine may be small, however the use of multiple wind turbines within a wind farm to support the grid frequency can have an important impact on the grid frequency. The coordination of many wind turbines to maximize the potential offered by this technology is an interesting topic, but also a challenging and complicated one.

In order to observe the results of such a response from wind turbines to the grid frequency as well as to study the associated challenges and the arising benefits that can be achieved by the simultaneous provision of active power reserves by multiple wind turbines within a wind farm, the model has been scaled up to the wind farm level. Moreover, the controller has been enriched with additional capabilities that will allow for better coordination among the wind turbines of the wind farm. The wind farm topology used as well as the overall control logic and the implementation of its design are presented and thoroughly discussed within the following sections.

5.1 Wind Farm Topology

In order to draw accurate conclusions regarding the benefit of the provision of frequency supporting services from the wind turbines within a wind farm and its impact on the grid frequency, a realistic representation of the connection to the grid is required to take into account the power lost in the transmission network. Therefore, the offshore wind farm topology that is depicted in Figure 29 has been implemented.

An offshore wind farm application has been chosen, since offshore wind farms usually have high capacity, therefore significantly contributing to the load. In such cases, where the amount of wind power is satisfying an important share of the consumption, the importance of supporting the grid frequency becomes more vital. Additionally, the amount of active power that can be provided as reserves to the ancillary service market is expected to increase for increased wind farm installed capacity.

The *wind farm application* considered for this project consists of 120 wind turbines with a rated power of 5 MW each, thus formulating a 600 MW wind farm. For the connection of the wind farm to the grid two identical sides (Side A and Side B) comprising of step-up transformers, cables and reactors for reactive power compensation are available. In this way, if one of the two sides is for any reason disconnected the wind farm still remains connected to the grid.

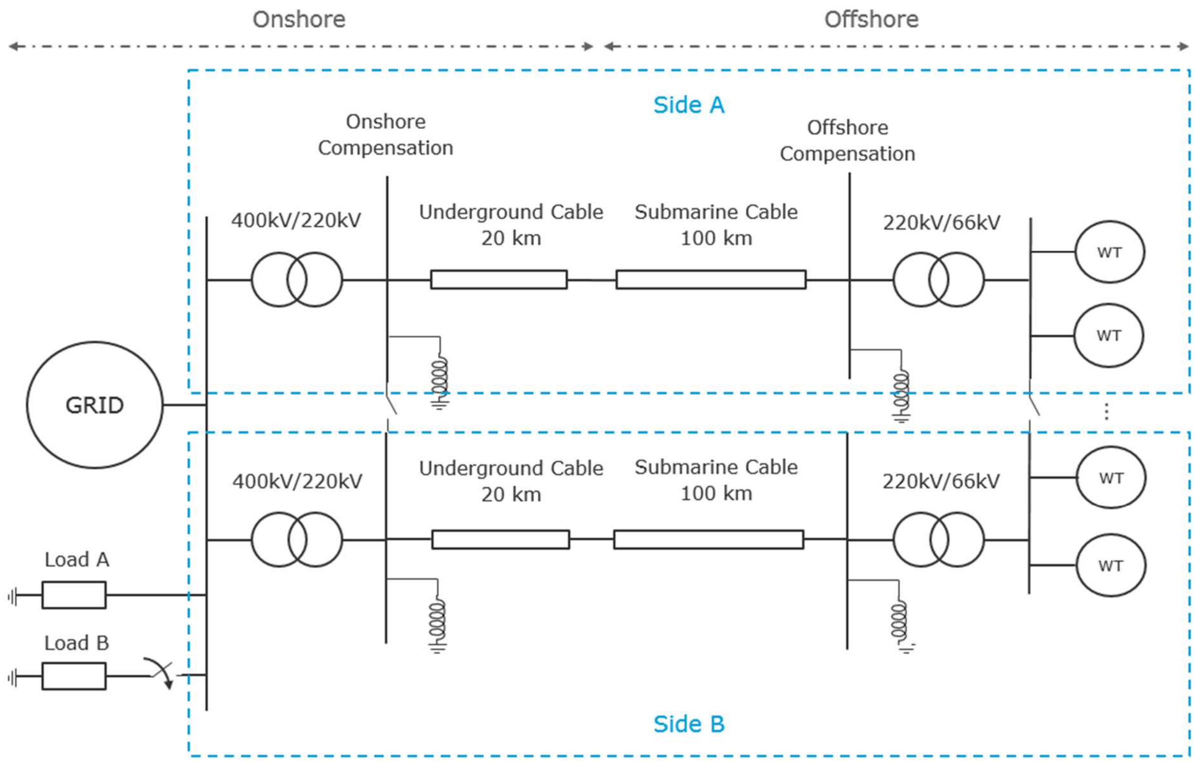

Figure 29: Offshore Wind Farm Topology.

Each one of the two sides comprises of the onshore and the offshore part for the connection to the grid. For Sides A and B, the *onshore part* consists of:

- A 400 kV bus that is connected to the grid and the loads.
- A 400 kV / 220 kV step-up transformer.
- A 220 kV bus that connects the underground cable to the transformer.
- An underground cable (3x1x1200 Cu) with total length equal to 20 km.
- A 220 kV, 212 MVar reactor, to compensate for the excessive reactive power produced by the cables.

For Sides A and B, the *offshore part* consists of:

- A submarine cable (1x3x1000 Cu) with total length equal to 100 km.
- A 220 kV bus that connects the submarine cable to the transformer.
- A 220 kV / 66 kV step-up transformer.
- A 66 kV bus, where the wind turbines are connected.
- A 220 kV , 212 MVar reactor, to compensate for the excessive reactive power produced by the cables.

The grid is represented by a synchronous generator with a hydro-governor, which is characterized by a slow response in the presence of a frequency deviation. The consumption is represented by a load with power factor equal to 0.85 (Load A), which is always connected to the grid, and its value could be varied to create scenarios of different renewable penetration levels. In order to create a frequency deviation, a second load (Load B), with power factor also 0.85, is either connected or disconnected at a time instant t_{dis} . The values of this load can also be varied in order to create smaller or more severe disturbances.

The resistance and the inductance of the loads are calculated as follows:

For a power factor PF equal to 0.85, if P is the desirable active power to be consumed by the load in MW:

$$|S| = \frac{P}{PF}\ [MVA]\ (47)$$

$$|S| = \frac{V^2}{|Z|} \Rightarrow |Z| = \frac{V^2}{S}\ [\Omega]\ (48)$$

$$P = \frac{V^2}{|Z|^2} \cdot R \Rightarrow R = \frac{P \cdot |Z|^2}{V^2}\ [\Omega]\ (49)$$

$$Z = \sqrt{R^2 + X^2} \Rightarrow X = \sqrt{Z^2 - R^2}\ [\Omega]\ (50)$$

$$X = 2 \cdot \pi \cdot f \cdot L \Rightarrow L = \frac{X}{2 \cdot \pi \cdot f}\ [H]\ (51)$$

Where S is the apparent power of the load in MVA, V is the bus voltage (line-to-line RMS) to which the load is connected in kV, Z is the load impedance in Ω, R is the resistance of the load in Ω, X is the reactance of the load in Ω, L is the inductance of the load in H, and f is the grid frequency, which for this study is 50 Hz.

5.2 Wind Farm Controller

It is important to optimize the control of the available wind turbines within a wind farm and to achieve the best possible wind farm frequency response, in terms of duration and amount of reserves provision, as well as in terms of the smoothness of the rotor recovery. To this end, a certain wind farm control logic has been designed, that allows for the wind turbines to be arranged in groups, to which different signals can be sent through the wind farm controller.

The capabilities of the implemented wind farm controller, the available parameters that can be varied to achieve the desirable frequency response, as well as the wind farm controller design implementation are presented and analytically explained in the following paragraphs.

5.2.1 Wind Farm Controller logic & parameters

The Wind Farm Controller shapes the response provided by the wind farm during a frequency deviation by controlling a set of parameters (signals) that are send to the different wind turbines. The wind farm controller signals sent to the different wind turbines within the wind farm are:

1. The *gain droop constant* $\boldsymbol{K_{droop}}$ $[\mathbf{1/Hz}]$ that controls the *amount of reserves provided* by a single wind turbines in the presence of a frequency deviation. By increasing this parameter, more reserves are provided by a single wind turbine.
2. The *time period* $\boldsymbol{\Delta t_{release}}$ $[\mathbf{sec}]$ *within which the kinetic energy of the rotor will be released*, in case that an under-frequency deviation occurs under low wind speed conditions.
3. The *time limit* $\boldsymbol{T_{FSO}}$ $[\mathbf{sec}]$ that needs to be imposed to the duration of the Frequency Supporting Operation (FSO) of the wind turbine, in case the active power injection of the wind turbine exceeds its rated power output. In this way, overheating the semiconductor components of the converter due to the increased currents flowing is avoided.
4. The *delay time* $\boldsymbol{T_{delay}}$ $[\mathbf{sec}]$, which represents *the time-period for which the recovery of the rotor will be delayed*, unless the rotor speed reaches its minimum allowed value, in which case the recovery of the rotor will be forced to prevent aerodynamic stall.
5. The *saturation limits of the recovery controller* $\boldsymbol{\Delta P_{recovery_{max}}}$ $[\mathbf{pu}]$ *and* $\boldsymbol{\Delta P_{recovery_{min}}}$ $[\mathbf{pu}]$ that obtain a value of a small percentage of the rated power of the wind turbine generator, by which the *active power*

output of the wind turbine will be increased/decreased during the rotor recovery, when reserves are provided under low wind speed conditions.

The effective management of these parameters from the Wind Farm Controller Operator can have an important effect on the response provided by the wind farm during a frequency deviation.

Different settings can be applied to different wind turbines or to different groups of wind turbines, in order to facilitate a slightly longer response (through decreased K_{droop} values or increased $\Delta t_{release}$ values), or a more smooth response (through imposing different T_{delay} values to different (groups of) wind turbines or through decreased $\Delta P_{recovery}$ values) during the recovery period that is required for reserve provision under lower wind speed conditions.

In order to achieve a *more sustained frequency response* from the wind farm during an under-frequency deviation, that constitutes the most critical situation and the most difficult to deal with, the coordination of different wind turbine groups within the wind farm is enabled. The implemented strategy allows for every next group (other than the first group), to be used to compensate for the amount of reserves that the previous group in line was not able to provide, due to the existing limitations.

Such an approach can assist in avoiding unwanted bigger deeps in the frequency as the FSO of the wind turbines and as a result of the wind farm is either restricted (due to the limited kinetic energy) or stopped (due to the time limit under high wind speed conditions). The available wind turbines can be arranged in groups and the FSO of some of them can be triggered at the time instant at which the FSO of the previous group is either restricted or stopped.

To facilitate such a scheme, three additional parameters have been added to the wind farm controller:

1. The *FLAG parameter,* that discriminates the first group of wind turbines used to support the grid frequency (Group A), from the rest of the available groups. For Group A this parameter obtains a value equal to 1, while for all other groups it obtains a zero value. Through this parameter, coordination among different groups of wind turbines is enabled, allowing for smarter control of the wind turbines, that leads to a more sustained frequency response.
2. The ***number of wind turbines available for this group of wind turbines*** $\boldsymbol{No_{WT_{G\_i}}}$. The total number of wind turbines available within the wind farm are divided in a number of groups. To each group, $Group\ i$, a certain number of wind turbines is assigned, $No_{WT_{G\_i}}$, and the same settings are sent to all the wind turbines within the same group.
3. The ***number of wind turbines available in the previous group of wind turbines*** $\boldsymbol{No_{WT_{G\_i-1}}}$ *that supported the frequency before this group* $Group\ i$. Every group of wind turbines, $Group\ i$, other than the first group, Group A, has a previous group in the line from which it receives the necessary *activation* and *active power demand signals*.

In more details, the total number of wind turbines within the wind farm is arranged in groups, Group A (i=1), Group B (i=2), Group C (i=3), etc. The *FLAG* parameter is set to one for Group A and to zero for the rest of the groups. The groups are used to assist to frequency support successively, starting from Group A. The amount of reserves requested from every wind turbine that belongs to Group A, ${P_{RESERVES_{req\_G\_A}}}^{single\ WT}$, is proportional to the frequency deviation by the gain droop constant assigned to this group of wind turbines according to the original control design:

$${P_{RESERVES_{req\_G\_A}}}^{single\ WT}[pu] = -\Delta f \cdot K_{droop} \quad (52)$$

The total amount of reserves requested by all the wind turbines comprising Group A, $P_{RESERVES_{req\_G\_A}}$, is defined as the amount of reserves requested by each wind turbine within Group A, $P_{RESERVES_{req\_G\_A}}{}^{single\ WT}$, multiplied by the number of wind turbines comprising Group A, $No_{WT_{G\_A}}$:

$$P_{RESERVES_{req\_G\_A}}[pu] = P_{RESERVES_{req\_G\_A}}{}^{single\ WT}[pu] \cdot No_{WT_{G\_A}} \Rightarrow$$

$$P_{RESERVES_{req\_G\_A}}[pu] = -\Delta f \cdot K_{droop} \cdot No_{WT_{G\_A}} \quad (53)$$

Due to the existing limitations that apply when providing positive active power reserves:

- *For below rated wind speed values:* Limited kinetic energy is only available in the rotating masses that will run out within a short time frame, depending on the gain droop constant K_{droop} assigned to the wind turbines, and the time frame within which the available kinetic energy is set to be released $\Delta t_{release}$.
- *For above rated wind speed values:* The converters can only be overloaded for a limited time period of a few seconds, in order to avoid reaching the maximum junction temperature that the semiconductor components within the converters can withstand.

the response provided by wind turbines during an under-frequency deviation will in any case only last a few seconds before it is either restricted or stopped to ensure the proper operation of the wind turbines. At that point in time, $t_{trans\ i}$, that the amount of reserves $P_{RESERVES_{prov\_G\_i}}$ provided by a certain group of wind turbines, $Group_i$, will be less than the amount of reserves requested $P_{RESERVES_{req\_G\_i}}$ by the same group:

$$P_{RESERVES_{prov\_G\_i}} < P_{RESERVES_{req\_G\_i}} , \qquad t = t_{trans\ i} \quad (54)$$

an ***activation signal*** will be sent to the next group of wind turbines in line, $Group_{i+1}$, to start providing a certain amount of reserves. In this way, the frequency response provided by the wind farm as a total will not to be restricted too soon following a disturbance, since such a situation could cause a second, sometimes more severe, disturbance.

Thus, the rest of the wind turbine groups, other than Group A (Groups B, C, etc.), will be used to *compensate for the amount of reserves that could not be provided by the previous groups in line* (for Group B it will be Group A, for Group C it will be Group B, etc.). To achieve that, a ***demand signal*** $P_{DEMAND_{G\_i}}$ is calculated from every group of wind turbines $Group_i$, to be sent to the next group of wind turbines in line, $Group_{i+1}$ (Figure 30).

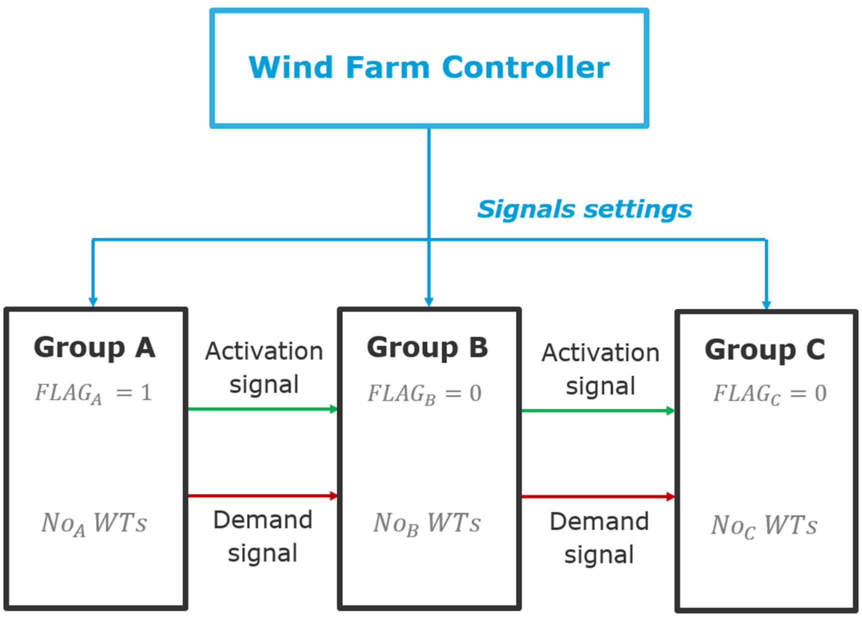

Figure 30: Wind Farm Controller logic representation.

The demand signal $P_{DEMAND_{G\_i}}$ is calculated by subtracting the amount of reserves that has been successfully provided by each wind turbine within $Group_i$, $P_{RESERVES_{prov\_G\_i}}{}^{single\ WT}$, from the amount of reserves requested from each wind turbine within $Group_i$, $P_{RESERVES_{req\_G\_i}}{}^{single\ WT}$. This will give the demand of each single wind turbine within $Group_i$, that if multiplied by the number of wind turbines available in this group, $No_{WT_{G\_i}}$, will give the total demand in active power requested from $Group_i$, to be satisfied by $Group_{i+1}$.

In case a certain group of wind turbines $Group_i$ is recovering during the frequency deviation, the active power output decrease $P_{recovery_{G\_i}}{}^{single\ WT}$ (since an under-frequency deviation event is discussed) required from each wind turbine of the group during the recovery period, is integrated in the demand coming from each wind turbine of the group.

$$P_{DEMAND_{G\_i}}[pu] = P_{RESERVES_{req\_G\_i}}{}^{single\ WT} - P_{RESERVES_{prov\_G\_i}}{}^{single\ WT} + P_{recovery_{G\_i}}{}^{single\ WT}) \cdot No_{WT_{G\_i}} \quad (55)$$

Where $P_{RESERVES_{req\_G\_i}}{}^{single\ WT}[pu] = P_{REF_i}[pu] - P_{REF_{NO_i}}[pu]$, where P_{REF_i}constitutes the sum of the active power reference signals .

Thus, for every next group in line, $Group_{i+1}$, the total amount of reserves requested from all the wind turbines formulating this group, $P_{RESERVES_{req\_G\_i,i \neq A}}$, will be set equal to the total demand coming from the previous group $Group_i$:

$$P_{RESERVES_{req\_G\_i+1}}[pu] = P_{DEMAND_{G\_i}}[pu] \quad (56)$$

The demand signal that will be sent to each of the wind turbines of $Group_{i+1}$, $P_{RESERVES_{req\_G\_i+1}}{}^{single\ WT}$, will be equal to the total demand signal $P_{DEMAND_{G\_i}}$ of the previous group divided by the number of wind turbines formulating this group $No_{WT_{G\_i+1}}$:

$$P_{RESERVES_{req\_G\_i+1}}{}^{single\ WT}[pu] = \frac{P_{DEMAND_{G\_i}}}{No_{WT_{G\_i+1}}} \quad (57)$$

Thus, every next group in line, $Group_{i+1}$, will be compensating for the amount of reserves that the previous group in line, $Group_i$, could not successfully provide, due to the associated limitations, as well as for the amount of power used to recover the rotor speed of each wind turbine formulating that group.

In total, for every group of Wind Turbines, $Group_i$, where $Group_{i-1}$ represents the previous group of wind turbines in line, the amount of power requested as reserves can be calculated as follows:

$$P_{RESERVES_{req\_G\_i}}[\mathrm{pu}] = \begin{cases} -\Delta f \cdot K_{droop} \cdot No_{WT_{Group\ i}}[pu] & , \ for\ i = 1\ (Group_i = Group_A) \\ P_{DEMAND_{Group\ i-1}}[pu] & , \ for\ i \geq 2, \ (Group_i \neq Group_A) \end{cases} \quad (58)$$

The total amount of reserves provided by the Wind Farm at the point of common coupling (PCC), as long as the combined support from the different groups available lasts, corresponds to the amount of reserves requested from the first group of wind turbines used to support the grid frequency (Group A), that is proportional to the frequency deviation by the gain droop constant assigned to this group, multiplied by the number of wind turbines available in this group, minus the losses in the cables and the filters:

$$P_{RESERVES_{WF\_PCC}}[MW] = -\Delta f \cdot K_{droop} \cdot P_{rated} \cdot No_{WT_{G\_A}} - P_{losses} \quad (59)$$

Where $No_{WT_{G\_A}}$ is the number of wind turbines that is available for the first group used to support the grid frequency, Group A.

The duration of the frequency response depends on many factors, such as:

- The severity of the frequency deviation.
- The wind speed conditions.
- The choice of the gain droop constant K_{droop}.

The use of such a coordination strategy is actually only required during an under-frequency event. During an over-frequency event only the first group of wind turbines, Group A, will be used to provide the necessary negative active power reserves, since the amount of reserves provided does not need to be restricted.

Therefore, in order to achieve a longer response during a possible under-frequency deviation, it is required to reduce the total amount of negative reserves provided during an over-frequency deviation. This is because only a part of the wind turbines available within the wind farm will be used to support the frequency during an over-frequency deviation. This constitutes an important disadvantage of this strategy. However, the support of an under-frequency deviation constitutes the most critical case and in order for a Wind Farm to be able to participate in the Ancillary Service Market at the time being, it is required that it can successfully provide the necessary positive as well as negative reserves.

Every group of wind turbines (Group A, Group B, etc.) can be comprised by a number of wind turbines, which is a parameter that can be varied by the wind farm operator. It is important though to keep in mind that the number of wind turbines formulating each group, especially the first one to be activated, cannot be adjusted in the process, but should be pre-determined. The first group (Group A), which is activated the moment the frequency deviation exceeds 10 mHz, is discriminated by the rest of the groups by the *FLAG* parameter. The *FLAG* parameter obtains a value equal to one for group A, while for all other groups it obtains a zero value.

For this study, every group of wind turbines is only used once to support the frequency. However, in a more sophisticated control design, it could be the case that the controller can check whether the rotor speed has recovered above a certain threshold (for lower wind speed conditions) or whether the converter components have been sufficiently cooled down (through temperature measurements) for the same group to be re-used in another cycle of reserves provision.

It makes sense to use a higher number of wind turbines for the first group (Group A), since it is very important to improve the *frequency nadir* during an under-frequency event. Then, the rest of the wind turbines can be arranged in smaller groups of decreasing number of wind turbines, Group B, Group C, etc., since it is expected that the frequency deviation will be reducing in time, due to the reserves provided both by the grid as well as from the wind farm. The different groups will be used successively, so that every next group compensates for the amount of reserves that is requested by the grid, but cannot be successfully provided by the previous group. In any case, all necessary limitations are kept for all groups of wind turbines, to ensure proper operation.

Using a large number of wind turbines to be activated the instant that a frequency deviation occurs will significantly benefit the frequency nadir. In the case of a more severe frequency deviation though this may result in a situation where the reserves that can be provided in total, have been deployed too soon. This may cause a worst event during the recovery or when the reserves need to stop being provided. Therefore, it is also important to maintain sufficient number of wind turbines available in the next groups (Group B, Group C, etc.) in order not to introduce a bigger disturbance to the network at the end of the frequency supporting operation. In any case, the proper operation of the wind turbines in a way that aerodynamic stall does not occur and the converter components are not heat up beyond the maximum junction temperature, should be the first priority when providing active power reserves.

5.2.2 Wind Farm Controller Design Implementation

In order for the wind farm control logic to be successfully implemented and for the wind farm controller parameters to be managed by the wind farm controller operator, certain changes have been implemented in the control loops within the wind turbines, while signals are also exchanged between the different groups of wind turbines used.

More specifically, the *activation* and *demand signals* that are exchanged among the available wind turbine groups are sent as input to the frequency controller. The frequency controller is modified to facilitate the control logic described in section 5.2.1, and, other than the active power reference signal that is sent to the converters, it also calculates and outputs the demand and activation signal for the next group in line. The block diagram of the modified model of the single wind turbine with its controls is depicted in Figure 31.

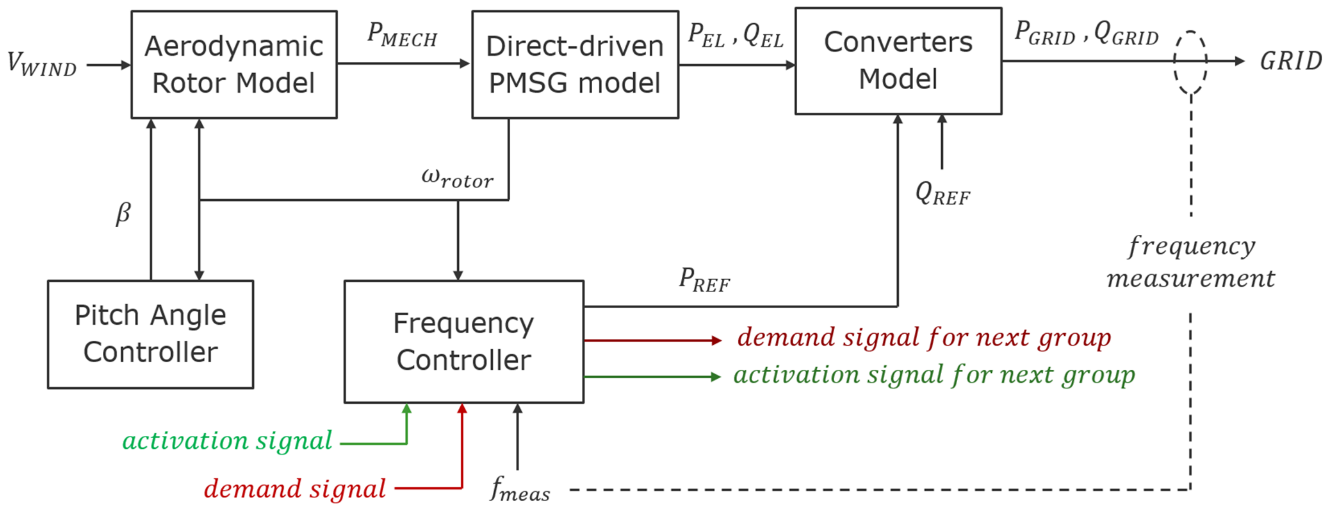

Figure 31: Block diagram of the full-scale converter model with a PMSG, modified to enable frequency support at the wind farm level.

The *modified frequency controller* is shown in Figure 32, and it comprises from the same *reserves controller*, as well as from a slightly modified *rotor speed* and *recovery controller* and a new controller, the *Demand & Activation controller*. The demand & activation controller provides the required reserve term $P_{RESERVES}$, if the *FLAG* parameter obtains a value of zero, and in any case it also calculates and provides the *demand* and *activation signals* for the next group in line.

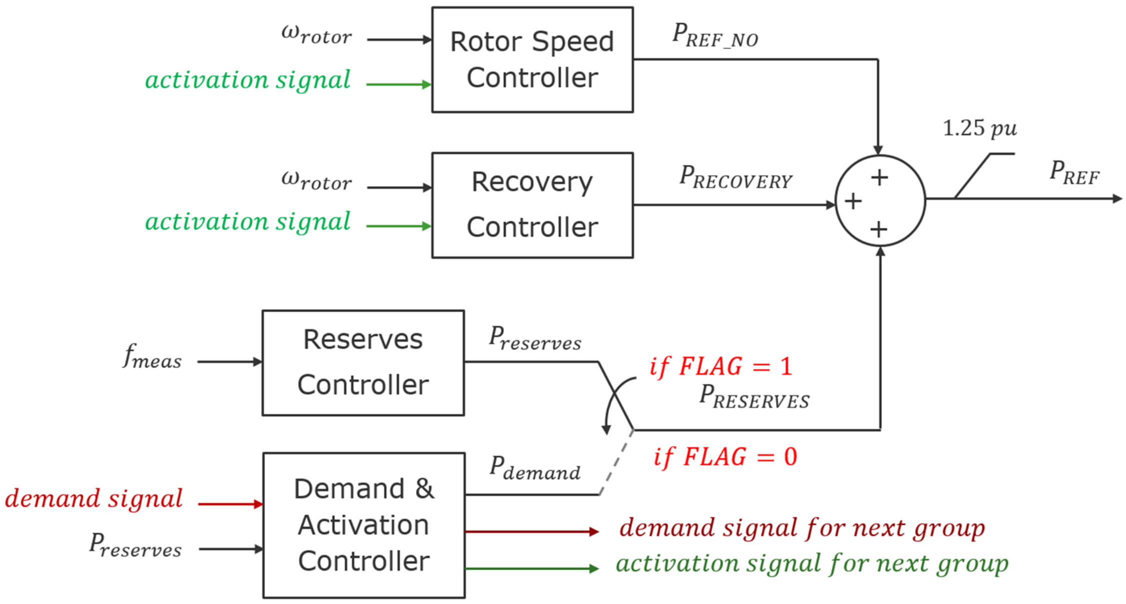

Figure 32: Block diagram of the modified Frequency Controller.

The modified rotor speed and recovery controller and the Demand and Activation controller added are further explained in the following paragraphs. The reserves controller used remains as described in section 4.4.2, and is thus not further explained.

Demand & Activation Controller

The Demand and Activation Controller (Figure 33) performs different actions depending on whether the wind turbine belongs to a group with a *FLAG* parameter equal to 1 or not.

Regardless of whether the *FLAG* parameter of this group obtains a zero or a non-zero value, the Demand & Activation controller checks whether the amount of reserves successfully provided $P_{RESERVES_{provided}}$ satisfies the amount of reserves requested $P_{RESERVES_{requested}}$, which constitutes the output of the reserves controller $P_{reserves}$. The moment that this condition becomes true, the *activation signal* that is sent to the next group in line becomes equal to 1, and a *demand signal* is calculated for the next group in line, as explained in section 5.2.1 . When this condition is false, both the demand as well as the activation signal obtain a zero value. If a certain group of wind turbines was never requested to provide reserves, then the demand and activation signals sent to this group are always zero, and the demand and activation signals for the next group in line also remain equal to zero.

If the *FLAG* parameter obtains a zero value, then the Demand & Activation controller also calculates a demand term for this wind turbine, by dividing the demand signal P_{demand} that is sent to the group of wind turbines, to which this wind turbine belongs, by the total number of wind turbines within this group, as explained in 5.2.1 .

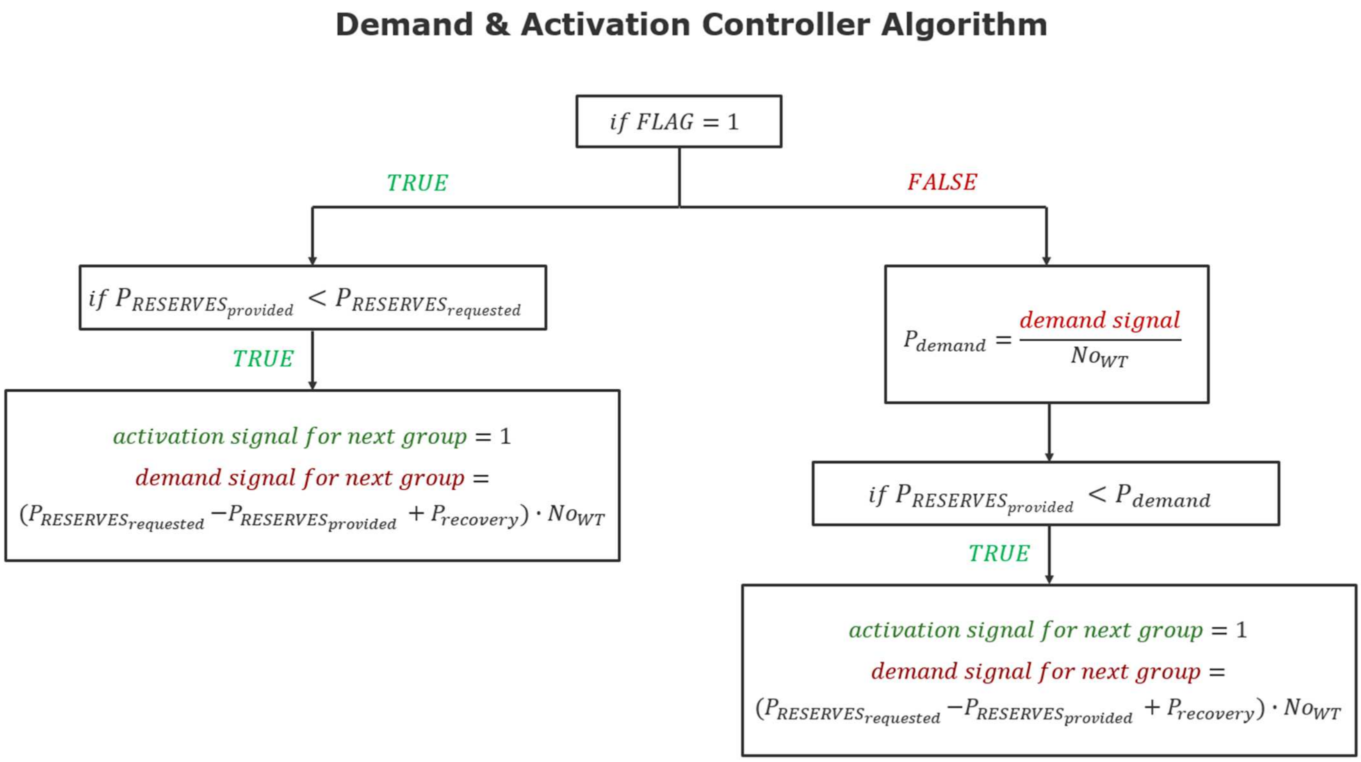

Figure 33: Demand and Activation Controller Algorithm.

Rotor Speed Controller

The rotor speed controller remains the same, as described in section 4.4.1 , with the only difference the time period within which the rotor speed controller PI is frozen. Within the wind farm controller, the available groups of wind turbines are discriminated through the *FLAG* parameter, to groups that directly provide the reserves requested by the frequency deviation sensed, and groups that compensate for the reserves that could not be successfully provided by other groups. Thus, it is important to ensure that the corresponding PI is frozen during the necessary time periods only.

In general, the speed controller PI needs to be frozen from the time instant that a wind turbine starts to provide the required reserves, and until the time instant when the rotor speed will have completely recovered back to its optimal value. If the *FLAG* parameter is set to 1 for a certain group of wind turbines, then this time instant corresponds to the time instant at which a frequency deviation of more than 10 mHz is sensed. If however the *FLAG* parameter is set to zero for a certain group of wind turbines, then this corresponds to the time instant at which the group, to which this wind turbine belongs, is activated by the previous group that was assisting to frequency support.

If the rotor speed has recovered back to its optimal value for the given wind speed conditions and there is only an offset of 25 mHz remaining in the frequency deviation, the speed controller PI is de-frozen, and returns back to its normal operation. In reality, primary frequency control is actually deactivated at the time instant at which secondary frequency control restores the frequency back to the set-point of 50 Hz, and thus even the offset is restored. However, in this study, secondary frequency control is not implemented, therefore this condition is included so that the process is finalized and the effect of the recovery on the grid frequency can be observed.

Recovery Controller

The recovery controller in general remains the same as described in section 4.4.3 . The only difference is that, if it is not requested from a specific group of wind turbines to participate to frequency support, then the recovery controller will not be activated. This may happen for example because the reserves provided by the previous group in line were sufficient to restore the frequency (in this case until the point where only an offset of 25 mHz is remaining in the frequency).

6. Case Studies & Simulation Results

In order to test the performance of the implemented *single wind turbine frequency controller* and the *wind farm controller*, a scenario of 50% RES integration has been represented within the wind farm topology presented in section 5.1. Moreover, the simulation results will allow for identifying the arising *challenges* and the *benefits* that can be achieved through the simultaneous provision of frequency supporting services by multiple wind turbines within a wind farm.

The 50% RES integration corresponds to the full capacity of the Wind Farm, thus for wind speed conditions close to or above rated wind speed. In order to apply such a scenario to the presented Wind Farm Topology the following values need to be assigned to Loads A and B:

Load A:

$$P_{LA} = 1000\ MW$$

$$S_{LA} = 1176.47\ MVA$$

$$R_{LA} = 115.6\ \Omega$$

$$L_{LA} = 0.228\ H$$

Load B:

Table 2: Load Characteristics.

Load Characteristics	Load Events			
	5% load increase/decrease	7% load increase/decrease	10% load increase/decrease	20% load increase/decrease
$\boldsymbol{P_{LB}[MW]}$	50	70	100	200
$\boldsymbol{S_{LB}[MVA]}$	58.824	82.353	117.65	235.29
$\boldsymbol{R_{LB}[\Omega]}$	2311.96	1651.43	1155.95	578.207
$\boldsymbol{L_{LB}[H]}$	4.561	3.26	2.2805	1.1402

The *rated RMS line current* of the synchronous generator that is used to represent the grid is set to 10 kA to be able to adequately supply the load and still be considered a realistic representation of a 50% RES integration scenario. The *inertia time constant* of the synchronous generator that represents the system inertia H_{sys}, is set to 5 sec.

The 120 wind turbines available within the wind farm application used are arranged in three groups to test the advantages and disadvantages of the suggested method compared to tuning all the wind turbines within the wind farm in the same way:

- *Group A:* it comprises of 60 wind turbines, and it constitutes the first group that will assist to frequency support, thus the *FLAG* parameter obtains a value equal to 1 for this group.

- *Group B:* it comprises of 40 wind turbines, and it is used to compensate for the amount of reserves that are not successfully provided by Group A. Thus, the *FLAG* parameter obtains a zero value for this group.
- *Group C:* it comprises of 20 wind turbines, and it is used to compensate for the amount of reserves that are not successfully provided by Group B. Thus, the *FLAG* parameter obtains a zero value for this group.

Since four different cases have been observed in section 4.2 that need to be addressed differently for the required reserves to be successfully provided, four corresponding case studies are considered. Different scenarios have been simulated for each one of those to test the implemented controllers, to observe the effect of the wind farm frequency response on the grid frequency as well as to understand the implications resulting during the rotor recovery. Moreover, the effect of the frequency response provided by a single wind turbine on the operation of the wind system is presented and discussed, and the boundaries regarding the possible active power product that can be provided is in all cases identified.

6.1 Case Study 1: Under-frequency deviation under below rated wind speed conditions

In order to test the performance of the implemented controllers during an under-frequency deviation as well as the draw conclusions regarding the potential offered by the wind turbine technology for positive reserve provision under low wind speed conditions, a number of scenarios have been simulated. These are presented and analytically discussed in the following paragraphs.

The simulated scenarios include a sensitivity analysis for the severity of the frequency deviation, a gain droop sensitivity analysis, the effect of the wind speed conditions on the frequency response provided, the importance of managing the recovery period and the effect of the delay time on the grid frequency and on the response provided.

Finally, a scenario where all the wind turbines are tuned in the same way is tested and afterwards compared with the results obtained from the coordination strategy suggested through this project, to conclude on the offered advantages and disadvantages of this method.

Sensitivity Analysis for the severity of the frequency deviation

The severity of the frequency deviation plays an important role on the response that can be provided by a wind turbine as well as from a wind farm in total. More reserves will be requested from the wind farm during more severe frequency deviations. Under below rated wind speed conditions such a situation may cause the available kinetic energy within the wind turbines' rotating masses to run out faster. In general, frequency deviations beyond 200 mHz rarely occur.

Moreover, the PCR option within the German ancillary service market, through which the necessary frequency containment reserves are provided, only require the provided reserves to be proportional to the frequency deviation until a 200 mHz frequency deviation. For more severe frequency deviations, the participant simply provides the full contracted power.

Thus, three events have been simulated in which an increase in the load of 5, 7 and 10 % of the initial load have been imposed at $t_{dis} = 20\ sec$, that cause frequency deviations less than or around 200 mHz.

The time period $\Delta t_{release}$ within which the kinetic energy of the rotor is released is set to 2 seconds, while during the rotor recovery the active power output of the wind turbine generator is set to be reduced by 2% of the rated power. The gain droop constant is in all cases set equal to 0.5.

The response achieved from the wind farm, the impact on the grid frequency and the effect of the recovery period can be observed in Figure 34.

The provision of the requested reserves has been interrupted due to the limited kinetic energy available in the rotating masses only for the most severe frequency deviation (10% load increase). However, even in this case the rotor recovery took place later on when the frequency had substantially recovered. In total it can be observed that the frequency nadir has been successfully kept within the range of $\pm 200\ mHz$. The frequency nadir has been significantly improved for all frequency deviations, while the more severe the frequency deviation sensed, the more beneficial the response provided by the wind farm has been for the frequency nadir. Finally, the ROCOF is in all cases smoothened when the wind farm provides a frequency response.

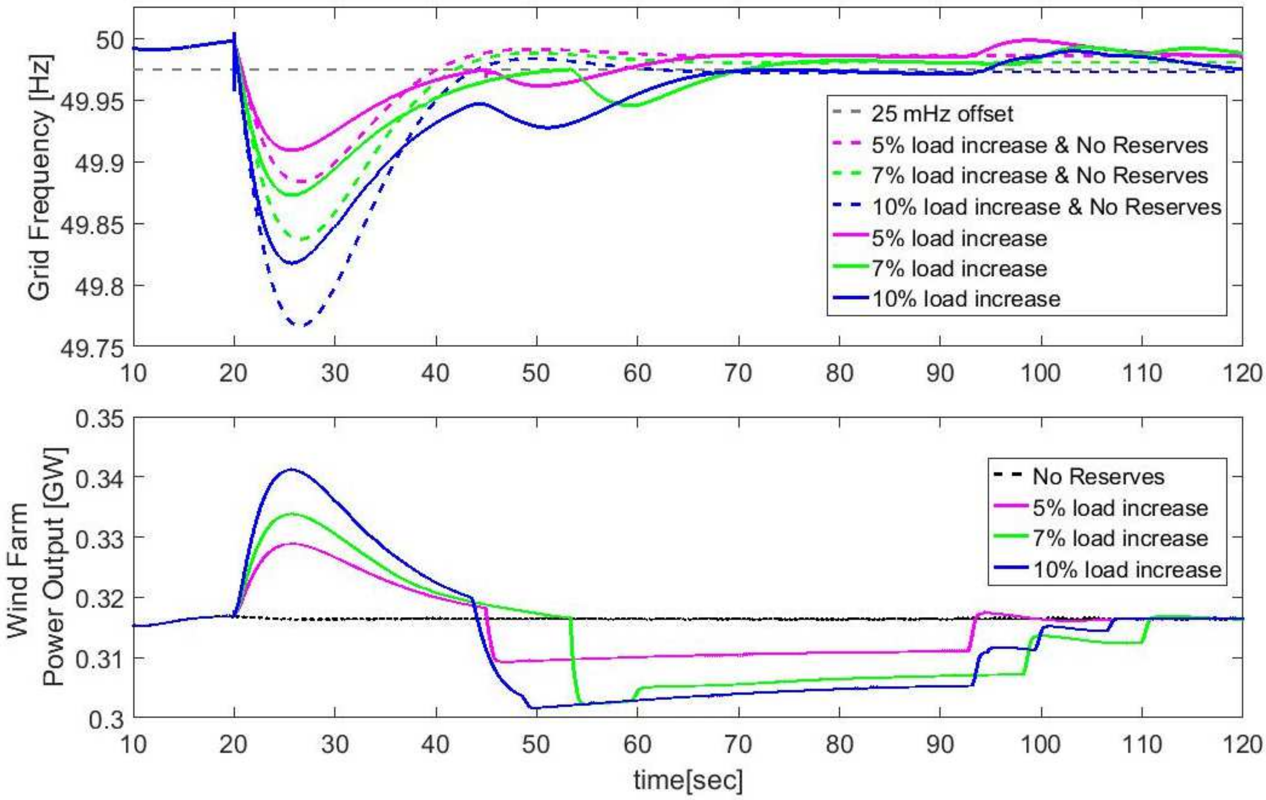

Figure 34: Sensitivity Analysis for severity of the frequency deviation sensed and the impact on the grid frequency as well as on the wind farm response.

Table 3: Performance Indicators for the Sensitivity Analysis for the severity of the frequency deviation.

Preformance Indicators	No Response from the Wind Farm ($K_{droop} = 0$)			With Frequency Support from Wind Farm ($K_{droop} = 0.5$)		
Load Increase [%]	5%	7%	10%	5%	7%	10%
Frequency Nadir [Hz]	49.884	49.837	49.767	49.908	49.872	49.818
Improvement in the Frequency Nadir [mHz]	-	-	-	24	35	51
FSO interrupted due to limitations	-	-	-	NO	NO	YES

Duration of rotor recovery [sec]	-	-	-	48	58	64
Frequency Nadir during the rotor recovery [Hz]	-	-	-	49.963	49.946	49.929
ROCOF [Hz/sec]	0.016	0.025	0.036	0.015	0.021	0.03
Maximum Reserves Provided by Wind Farm [MW]	-	-	-	12.5 (2.08%)	17.5 (2.92%)	24.5 (4.08%)

The active power output and the speed of a Wind Turbine Generator from each one of the available groups and for the different gain droop constant values, are depicted in Figure 35, Figure 36 and Figure 37. All the wind turbines that belong to the same group respond in the same way, thus the waveform for only one wind turbine of each group are provided.

In all cases, the controller responded successfully and provided the requested reserves until the moment the frequency was sufficiently restored with only an offset of 25 mHz (Figure 36 and Figure 37) remaining, or when the rotor speed approached to its minimum allowed value and thus the rotor recovery was forced to avoid aerodynamic stall (Figure 35). For the less severe frequency deviation not all groups participate to frequency support. This occurs because sufficient resources are available in Group A to support the grid frequency long enough so that is sufficiently recovers. The fact that not all groups of wind turbines are used in certain cases is a disadvantage of this strategy.

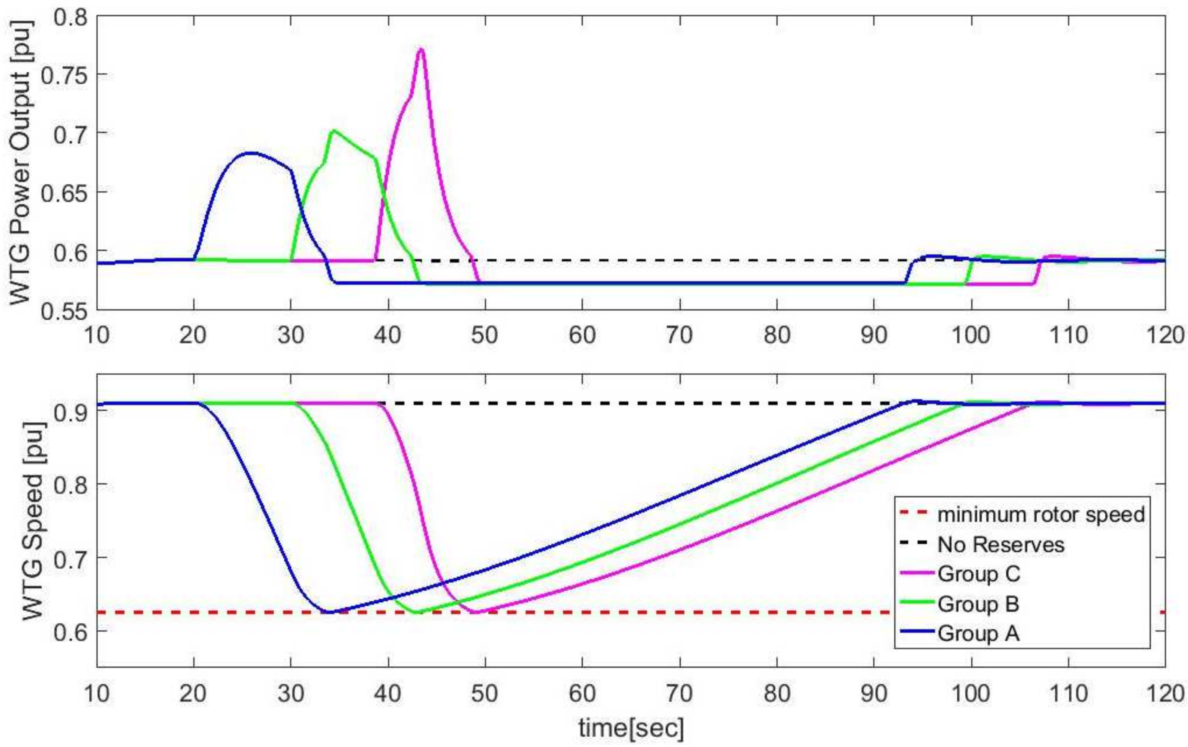

Figure 35: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 10% of the base load, for K_{droop} equal to 0.5.

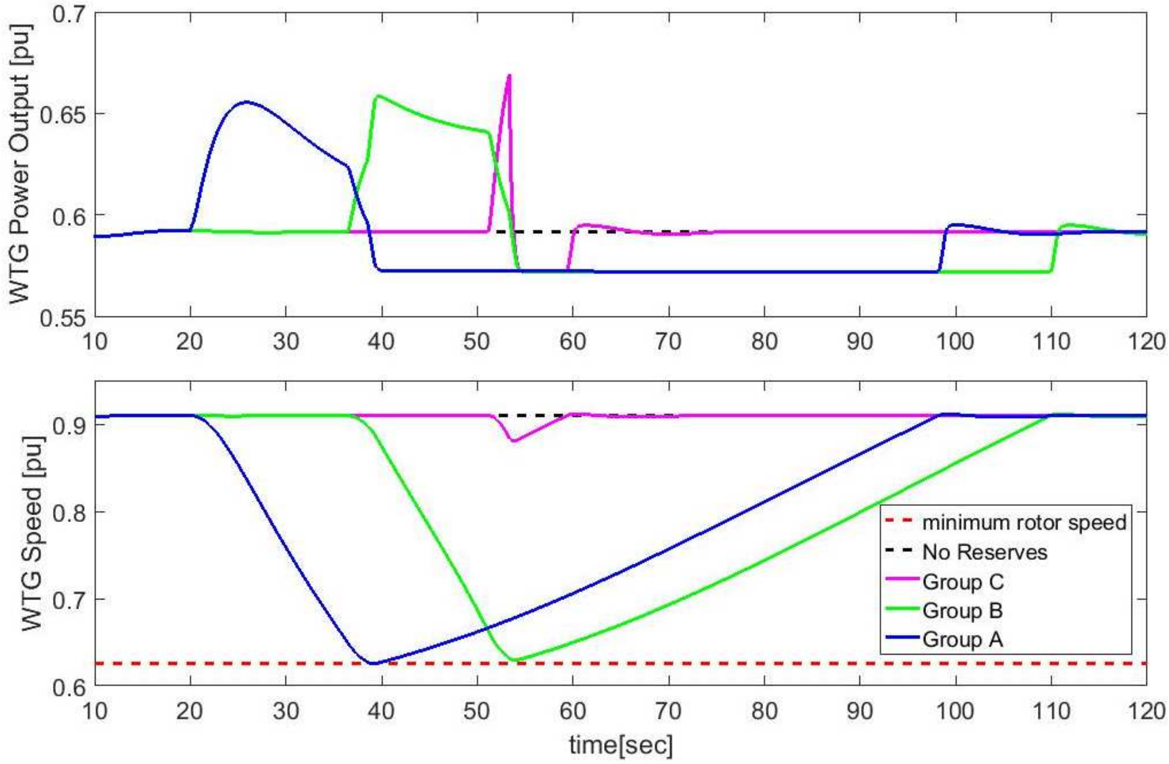

Figure 36: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 7% of the base load, for K_{droop} equal to 0.5.

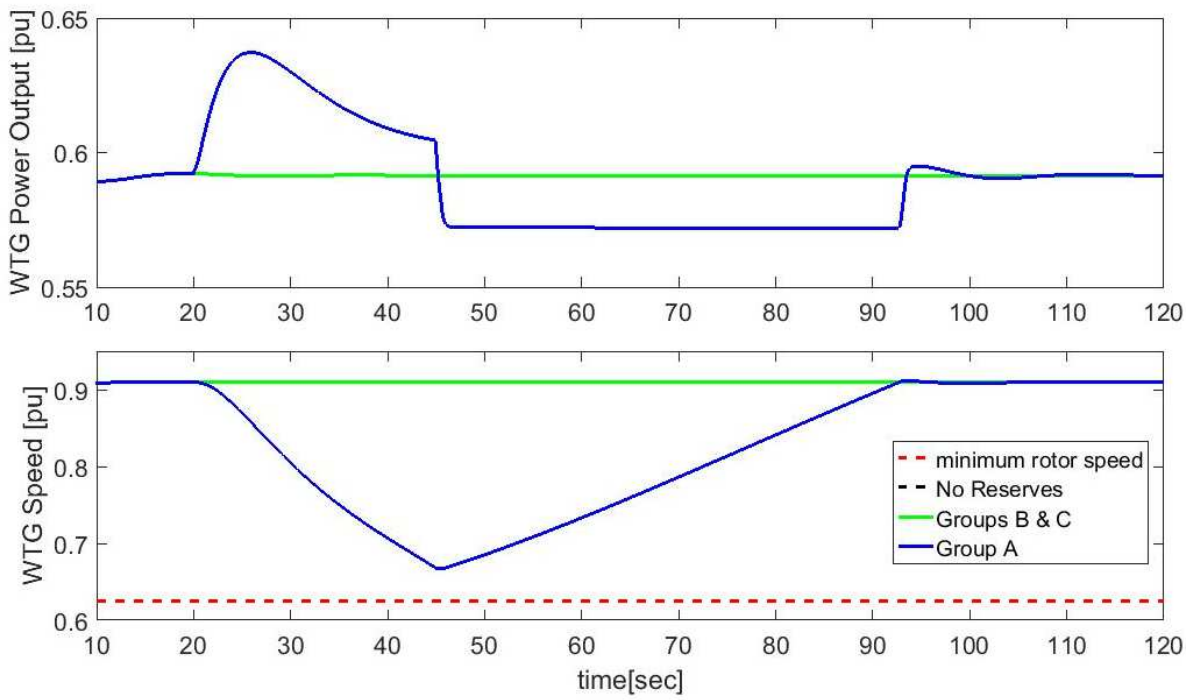

Figure 37: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 5% of the base load, for K_{droop} equal to 0.5.

Sensitivity Analysis for the gain droop constant

A sensitivity analysis of the gain droop constant $\mathrm{K_{droop}}$ has been carried out, during a 10% load increase that occurs at $t_{dis} = 20\ sec$.

The identification of appropriate gain droop constant values is important, since this will determine the bid size that a participant can offer to the Ancillary Service Market. The importance of such a study increases for the provision of positive active power reserves under below rated wind speed conditions which constitutes the most critical case.

The power that can be provided as reserves by a single wind turbine can be calculated as follows:

$$P_{RESERVES} = -\Delta f \cdot \mathrm{K_{droop}} \cdot P_{rated} = -\frac{\Delta f}{200\ mHz} \cdot P_{contracted}$$

$$\Rightarrow P_{contracted}[MW] = 0.2 \cdot \mathrm{K_{droop}} \cdot P_{rated}[MW] \quad (60)$$

Where $P_{contracted}$ represents the bid size for the market for a single wind turbine and without considering the losses in the transmission network. Thus, this term needs to also be corrected to consider the number of wind turbines used to provide reserves (with a *FLAG* parameter equal to 1) as well as the losses in the transmission network.

The time period $\Delta t_{release}$ within which the kinetic energy of the rotor is released is set to 2 seconds, while during the rotor recovery the active power output of the wind turbine generator is set to be reduced by 2% of the rated power.

The benefit of the frequency response for different values of the gain droop constant as well as the effect of the recovery period on the grid frequency are depicted in Figure 38.

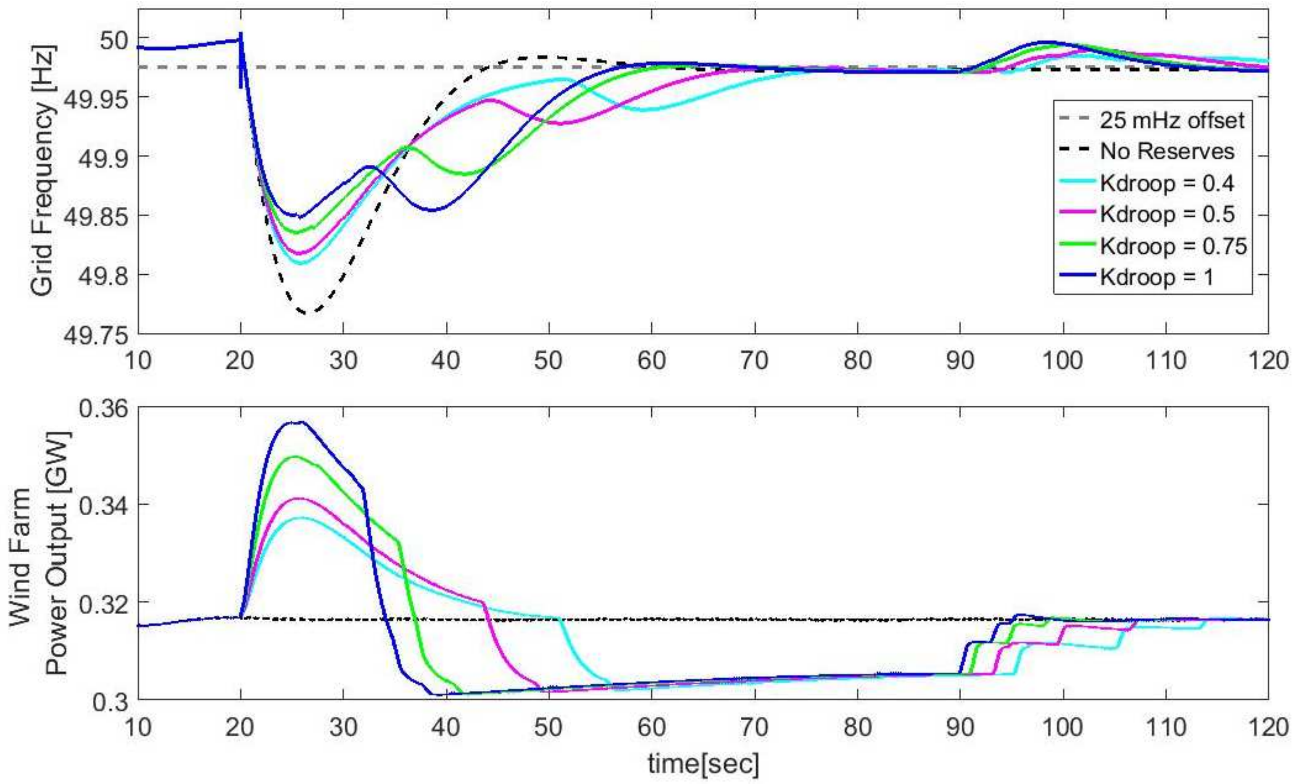

Figure 38: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load increase of 10% of the base load, Sensitivity Analysis for K_{droop}.

If the wind farm does not provide any frequency support the frequency nadir reaches the value of 49.765 Hz which is outside of the range tolerable frequency deviations ($\pm 200\ mHz$). The improvement on the frequency nadir ranges from 45 mHz to 85 mHz, while the duration of the response provided ranges from 31 seconds to 11.8 seconds for increasing values of the gain droop constant K_{droop} from 0.4 to 1. Thus, even though the improvement on the frequency nadir significantly increases with increased gain droop constant values, the duration of the response provided is negatively affected resulting in very short durations and therefore, to more severe second deeps in the grid frequency due to the early rotor recovery. The ROCOF is in all cases smoothened when the wind farm provides a frequency response. The higher the value of the gain droop constant the more the ROCOF is improved.

The maximum reserves provided range from 21 MW (3.5% of the installed capacity) to 40.1 MW (6.68% of the installed capacity). In all cases, the frequency response provided by the wind farm stopped due to limited kinetic energy that forced the rotor recovery to avoid aerodynamic stall, before the frequency had managed to sufficiently restore so that only an offset of 25 mHz is remaining, as the controller is designed. However, for gain droop constant values below 0.5 the deep caused in the frequency during the rotor recovery was less significant (above 49.9 Hz).

In all cases the rotor recovery lasts around 63 to 64 seconds. It can be observed that the frequency deviation lasts much longer when the wind farm is providing reserves compared to the case when only the grid provides frequency support, but frequency is maintained within the range of $\pm 200\ mHz$.

Table 4: Performance Indicators for the Sensitivity Analysis for the gain droop constant.

Preformance Indicators	Gain Droop Constant Values				
	$K_{droop} = 0$	$K_{droop} = 0.4$	$K_{droop} = 0.5$	$K_{droop} = 0.75$	$K_{droop} = 1$
Frequency Nadir [Hz]	49.765	49.81	49.82	49.835	49.85
Improvement in the Frequency Nadir [mHz]	-	45	55	70	85
FSO interrupted due to limitations	-	YES	YES	YES	YES
Duration of FSO [sec]	0	31	23.6	15.3	11.8
Duration of rotor recovery [sec]	-	63	63.4	63.7	64.2
Frequency Nadir during the rotor recovery [Hz]	-	49.94	49.9277	49.8848	49.8545
ROCOF [Hz/sec]	0.036	0.031	0.03	0.27	0.025
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	21 (3.5%)	24.7 (4.12%)	33.2 (5.53%)	40.1 (6.68%)

Effect of the wind speed conditions on the response provided

Under below rated wind speed conditions, the amount of kinetic energy that can be safely released from the rotating masses to support the grid frequency constitutes an important factor that determines the amount of reserves that can be provided as well as the duration of the frequency supporting operation and the impact on the grid frequency. Additionally, it highly affects the time instant at which the rotor recovery needs to take place and thus, the severity of the second deep that occurs in the grid frequency in such a case.

Therefore, simulations have been run for different below rated wind speed values to see how the response of the wind farm is affected by the wind speed conditions. For the frequency deviation, the load is increased by 10% of the base load at $t_{dis} = 20\ sec$, while the gain droop constant is set to 0.5 in all cases. The time period $\Delta t_{release}$ within which the kinetic energy of the rotor is released is set to 2 seconds, while during the rotor recovery the active power output of the wind turbine generator is set to be reduced by 2% of the rated power. The results of the simulations are depicted in Figure 39 .

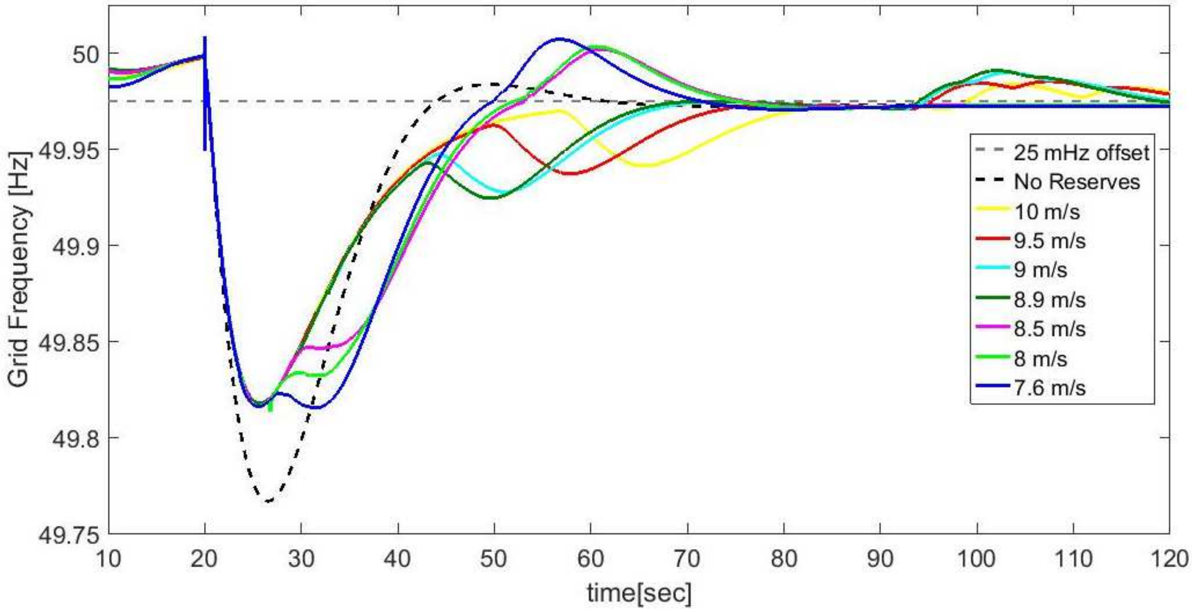

Figure 39: Effect of the wind speed conditions on the grid frequency due to the different amount of reserves that can be provided.

It can be observed that the available kinetic energy that can be released in the presence of an under-frequency deviation is highly decreased below 9 m/s, which corresponds to a wind turbine generator active power output of 0.5915 pu under normal operating conditions. For wind speed conditions below 7.6 m/s, which corresponds to a wind turbine generator active power output less than 0.35 pu, the kinetic energy that can be safely released is so little that aerodynamic stall cannot be avoided. Thus, this is the threshold below which no reserves are provided by the designed frequency controller in the presence of a frequency deviation.

The benefit on the frequency nadir is in all cases the same, what changes is the duration of the frequency response provided before the rotor recovery is forced for all wind turbines of the wind farm and the second frequency nadir that occurs during the rotor recovery. For the lower wind speed values this is very close to the first frequency nadir occurring due to the load event, since the duration of the response provided lasts less than 10 seconds.

In reality wind speed is not constant, thus the wind speed may decrease during the period of reserve provision. Thus, it may be useful not to provide reserves at wind speed conditions below 9 m/s, for this wind turbine design in order to use the available kinetic energy if such a case occurs. However, a more sophisticated control design is required to deal with variable wind speed conditions, since for this study constant wind speed conditions are considered.

Wind speed variability depends on many factors, among them the location of the wind farm, the season, the surface condition of the site, available obstacles, etc. The wind speed profile follows a *Weibull distribution* that is expressed by the following equation [33]:

$$f(V) = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1} \cdot e^{-\left(\frac{V}{A}\right)^{k}} \quad (61)$$

Where $f(V)$ is the frequency distribution, *A[m/s]* is the scale factor and k is the shape factor.

Important properties of the Weibull distribution constitute:

- The *annual mean wind speed*, that constitutes the mean value of the 10 minutes averaged wind speeds.
- The *variance* (turbulence) of the stationary 10 minutes averaged wind speeds with respect to the annual mean wind speed.

The mean wind speed and the turbulence of a wind farm (Figure 40) constitute two important factors that can be used to determine whether a site is appropriate to be used for positive reserve provision to the ancillary service market. Higher mean wind speed values and lower turbulence values are preferred, as they would allow for increased bid size with less risk of non-availability.

The turbulence experienced by onshore and offshore wind farm varies. Typical values on land constitute 10 to 15% and they decrease with the wind speed, while on sea the expected turbulence is considered generally lower, up to 5%, however it increases with the wind speed due to e.g., higher waves.

A typical Weibull distribution graph for an offshore wind farm relatively close to land is depicted in Figure 41, while the map that shows the expected mean wind speed values in different on land locations in the Netherlands is depicted in Figure 42.

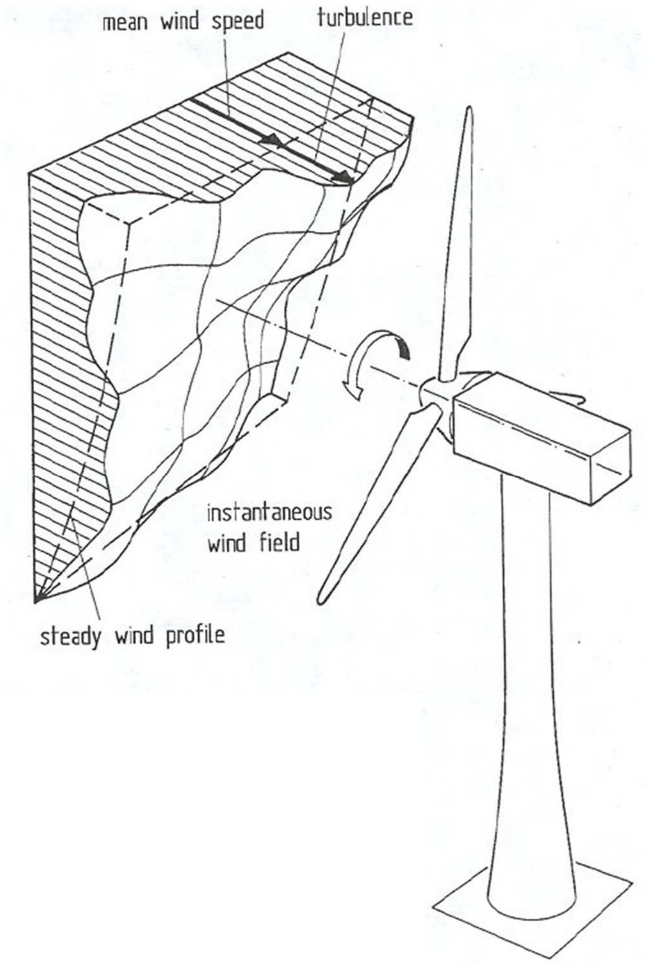

Figure 40: Mean wind speed and turbulence for wind turbine [33].

According to the simulation results, sites with mean wind speed values above 10 or 11 m/s with turbulence of around 10 to 15% are considered appropriate for positive reserve provision. This is because under such conditions, a response of around 30 seconds can be achieved with reasonable bid size that increases with the wind speed, while it is not accompanied by high risk of non-availability.

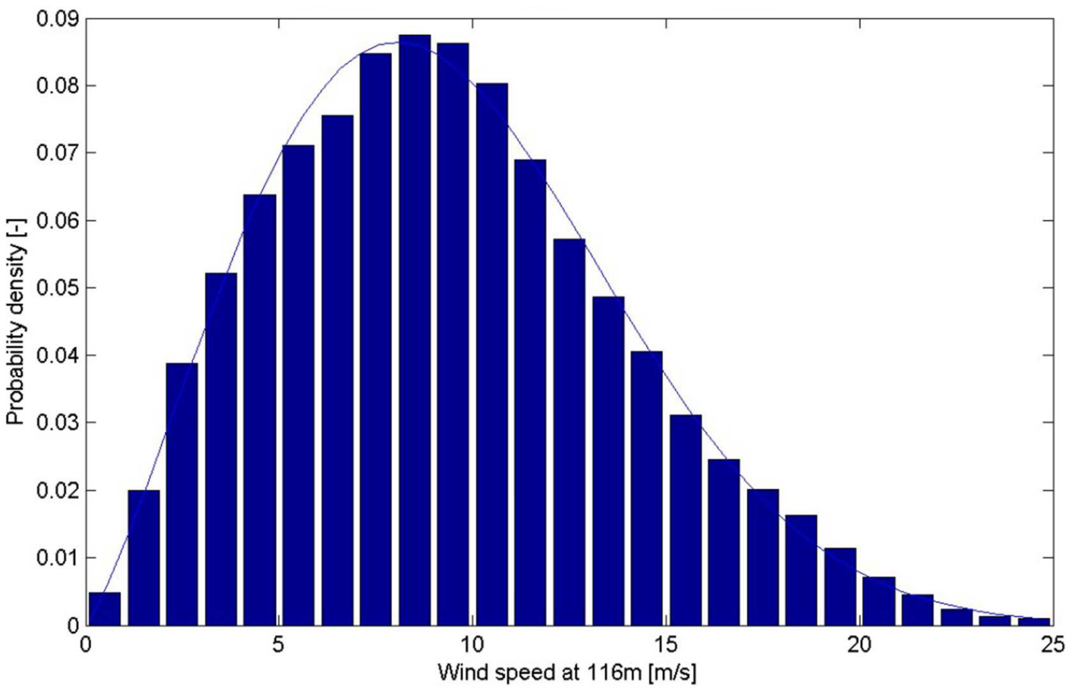

Figure 41: Weibull distribution for offshore wind farm close to land [37].

Combining the simulation results with the information about the expected mean wind speed and turbulence expected onshore and offshore it can be concluded that offshore wind farms appear as better sites to be used for supporting the grid frequency, due to the higher mean wind speed conditions and the lower turbulence expected. In most of the locations in the Netherlands for wind farms on land, the expected mean wind speed conditions are quite low and turbulence is also expected to obtain increased values constituting them less appropriate for positive reserve provision. In any case, the mean wind speed and turbulence conditions of each wind farm site vary substantially, thus general conclusions are difficult to be made.

Alternatively, other than defining a constant active power term to be provided by wind farms in the presence of a frequency deviation it can be the case that a term proportional to the size of their production at the moment of the event is provided. This would be reasonable as the amount of positive reserves that can be provided are highly dependent on the wind speed conditions. Moreover, the wind farm contribution to the load under low wind speed conditions is in any case less significant. Hence, there will be other sources of energy satisfying the biggest percentage of the load at that time which should provide a bigger percentage of the required reserves.

Nevertheless, this does not correspond to the current market design which usually expects the participants to be able to provide the offered bid size under all situations and sustain it for a pre-defined time period. Therefore, under the current market rules the worst-case scenario should be used for the specification of the bid size.

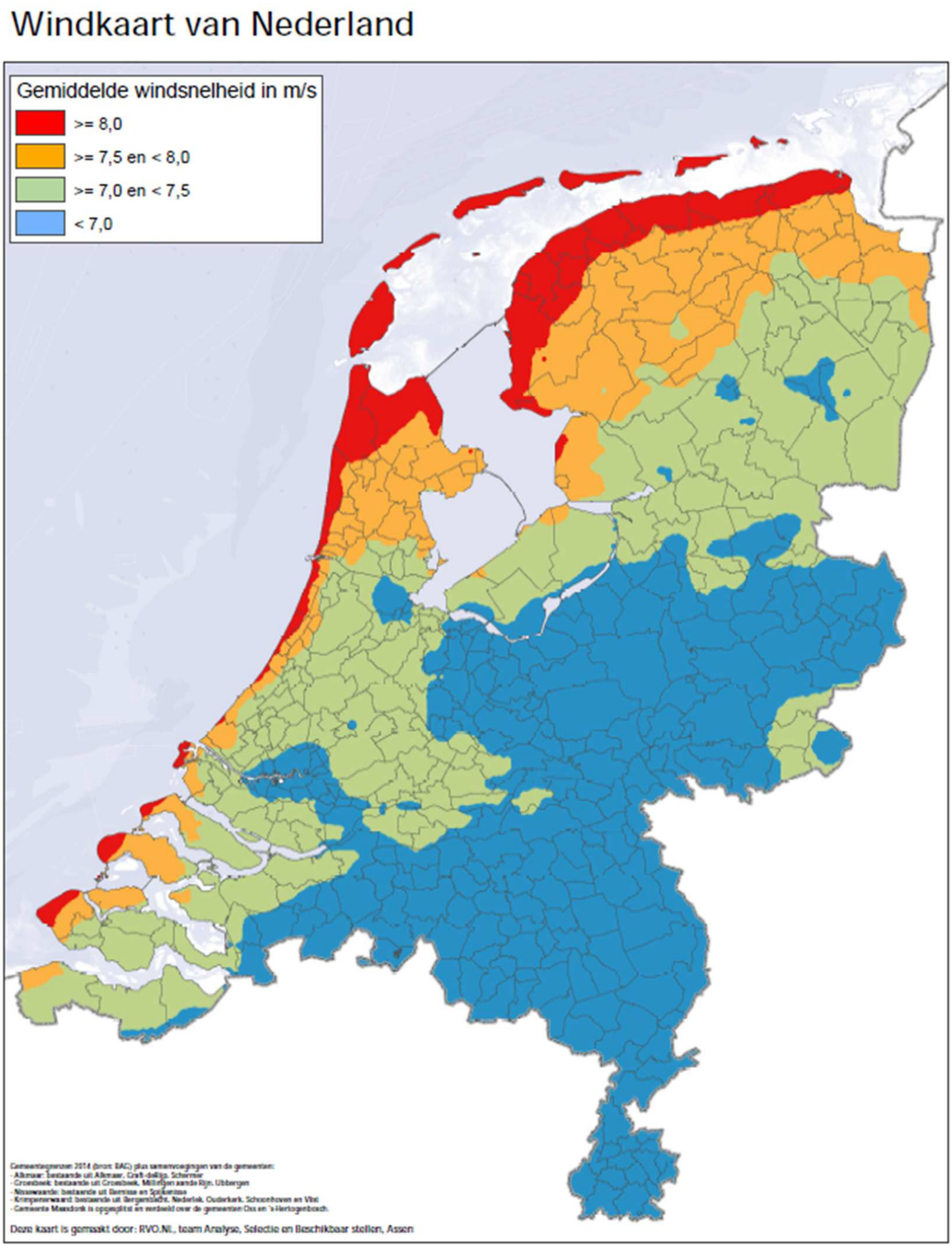

Figure 42: Map of the Netherlands with the mean wind speed values expected in different locations [34].

To this end, the controller design was extended to provide reserves proportionally to the frequency deviation until a frequency deviation as high as 200 mHz, but for more severe frequency deviations the same amount of reserves that are transferred for a frequency deviation equal to 200 mHz are only provided and not more. In this way, the trend of the ancillary service market is followed and by implementing an extremely severe frequency deviation the product that can be provided to the ancillary service market can be quantified.

The benefit of the frequency response for different values of the gain droop constant as well as the effect of the recovery period on the grid frequency are depicted in Figure 43. From the simulation results it can be observed that the gain droop constant needs to be reduced to around 0.25 for a sufficiently long response of around 30 seconds to be achieved. The maximum amount of reserves provided in such a case is 14 MW, which corresponds to 2.3% of the total installed capacity of the wind farm. Considering though the total amount of power generated (after the losses in the transmission system), under the given wind speed conditions, this amount of reserves achieves a percentage value of 4.43%.

Another important observation constitutes the fact that for frequency deviations more severe than 200 mHz the benefit on the grid frequency due to the wind farm frequency response is much less significant. This is however expected, since the amount of reserves provided stops being proportional to the frequency deviation beyond 200 mHz.

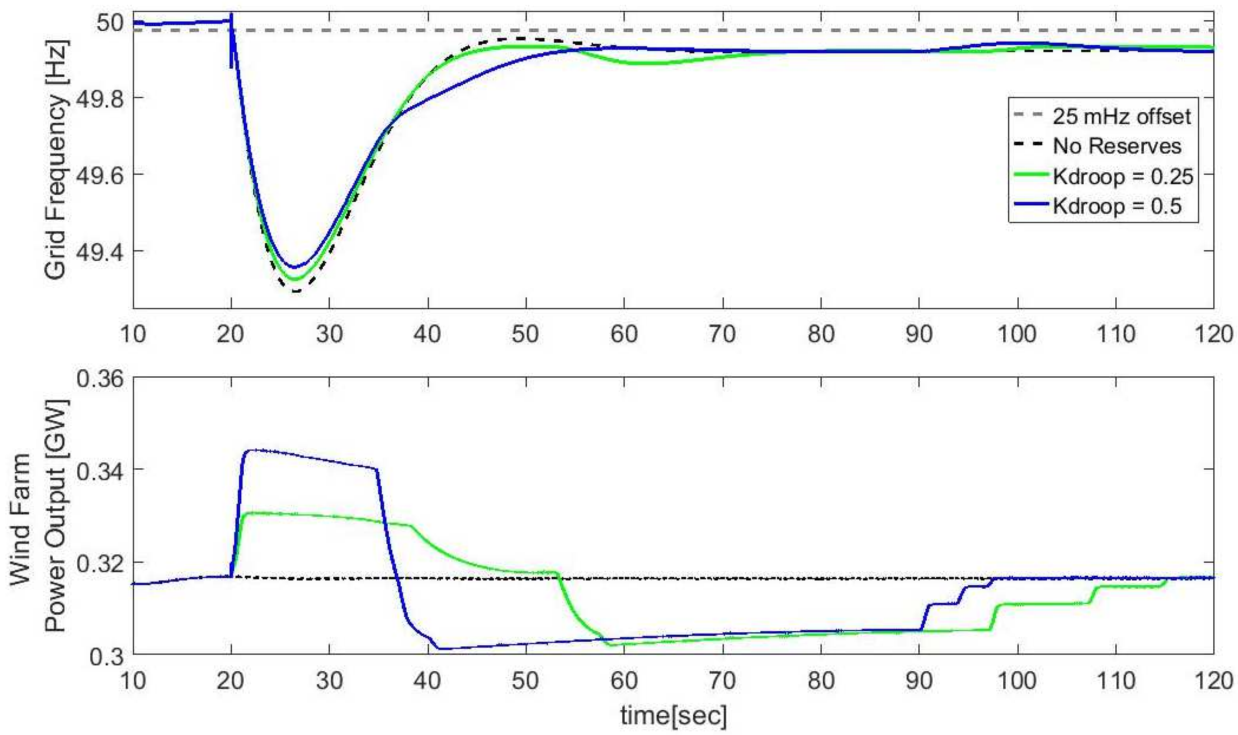

Figure 43: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load increase of 30% of the base load, Sensitivity Analysis for K_{droop}.

Importance of managing the recovery period

A sensitivity analysis for the recovery term $\Delta P_{recovery_{min}}$ has been performed to show the impact of a smoother or more aggressive rotor recovery on the grid frequency. A load increase of 10% of the base load has been imposed at $t_{dis} = 20\ sec$ to test the response of the controller under the different situations, the benefit on the grid frequency, the effect of the rotor recovery.

The time period $\Delta t_{release}$ within which the kinetic energy of the rotor is released is set to 2 seconds, while the gain droop constant is set to 0.5 for all cases.

The impact of the frequency response for different values of the recovery term as well as the effect of the recovery period on the grid frequency are depicted in Figure 44.

In all cases, the controller has provided all reserves requested, while the frequency supporting operation of the wind farm stopped because the rotor speed approached too close to the minimum allowed value to avoid aerodynamic stall. The second under-frequency event caused during the rotor recovery is less significant for decreasing values of $\Delta P_{recovery_{min}}$. However, longer recovery periods are required for decreased $\Delta P_{recovery_{min}}$ values.

Overall, a *trade-off* between the duration and the aggressiveness of the recovery period can be observed. Values higher than 0.03 pu will result in an aggressive recovery and thus, in undesirable more severe second deeps in the grid frequency.

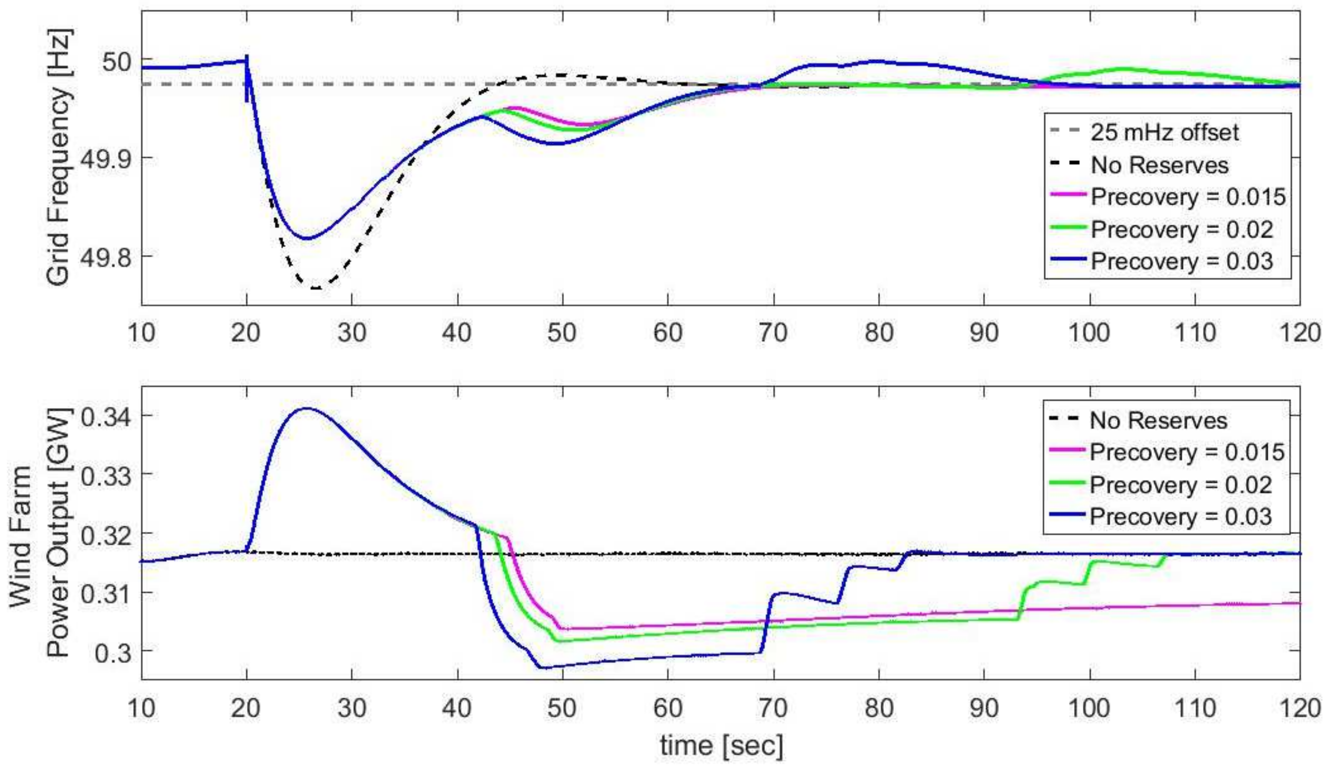

Figure 44: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load increase of 10% of the base load, Sensitivity Analysis for $\Delta P_{recovery_{min}}$.

$\Delta P_{recovery_{min}}$ values lower than 0.015 pu should in any case not be chosen, since they may result in aerodynamic stall because not enough power is kept to stop the decrease of the rotor speed and divert so that it slowly starts increasing. A value of 0.02 pu is suggested since it results in a recovery period of around 60-70 seconds and a smooth enough recovery without significant differences from the case of 0.015 pu. The duration of the recovery period should be comparable to the duration of reserve provision (around 30 seconds). Longer recovery periods will result in the wind turbines (or wind farm) not being available to support another frequency deviation that may follow.

Effect of Delay Time on the Wind Farm Frequency Response and on the grid frequency

Within the implemented control design, it is possible to delay the rotor recovery as long as the rotor speed is maintained above its minimum allowed value. This can be achieved by imposing a non-zero value to the delay time T_{delay} parameter within the wind farm controller. Potential benefits of such a strategy constitute the delay of the rotor recovery to allow the grid frequency to further restore or to delay the recovery period for certain groups of wind turbines within the wind farm to achieve a smoother recovery of the wind farm in total.

It is important to point out that a delay of the rotor recovery is only possible if the rotor speed is maintained above its minimum allowed value (for recovery following an under-frequency deviation at low wind speed conditions), since the opposite could cause aerodynamic stall. Thus, the rotor recovery can be successfully delayed only in the case that more kinetic energy is available in the rotating masses that is not released during the frequency deviation. Hence, only when the frequency response is interrupted because the grid frequency is sufficiently restored, with only an offset of 25 mHz remaining, can the recovery period be delayed. In any case, if the rotor speed approaches too close to its minimum allowed value the rotor recovery is forced to start to ensure the proper operation of the system. Such a situation is more likely to occur in the case of a less severe frequency deviation. As a result, the only actual benefit of the delay time following an under-frequency deviations constitutes the management of the recovery period by delaying the rotor recovery of certain groups of wind turbines.

The effect of imposing a delay time to different groups of wind turbines on the wind farm response and on the grid frequency can be observed in Figure 45. The wind turbines are arranged in three groups, as in the previous case studies, and a delay time of 2.5 seconds, 5 seconds and 7.5 seconds is imposed to the wind turbines within groups A, B and C respectively. The gain droop constant obtains a value equal to 0.4, both for the case of zero as well as of non-zero delay time. For the frequency deviation a load increase equal to 7% of the base load is imposed at $t_{dis} = 20\ seconds$.

It can be observed that the wind farm response is successfully sustained for another 7.5 seconds due to the delay time imposed to the last group of wind turbines, while groups B and C compensate for the recovery term required in order for Group A to recover in time to avoid aerodynamic stall. This is only possible because there is still kinetic energy left within the rotating masses at the time instant that the frequency response should normally end (no delay time scenario). If all kinetic energy was released to satisfy the required reserves, the rotor recovery would have been forced for all groups of wind turbines.

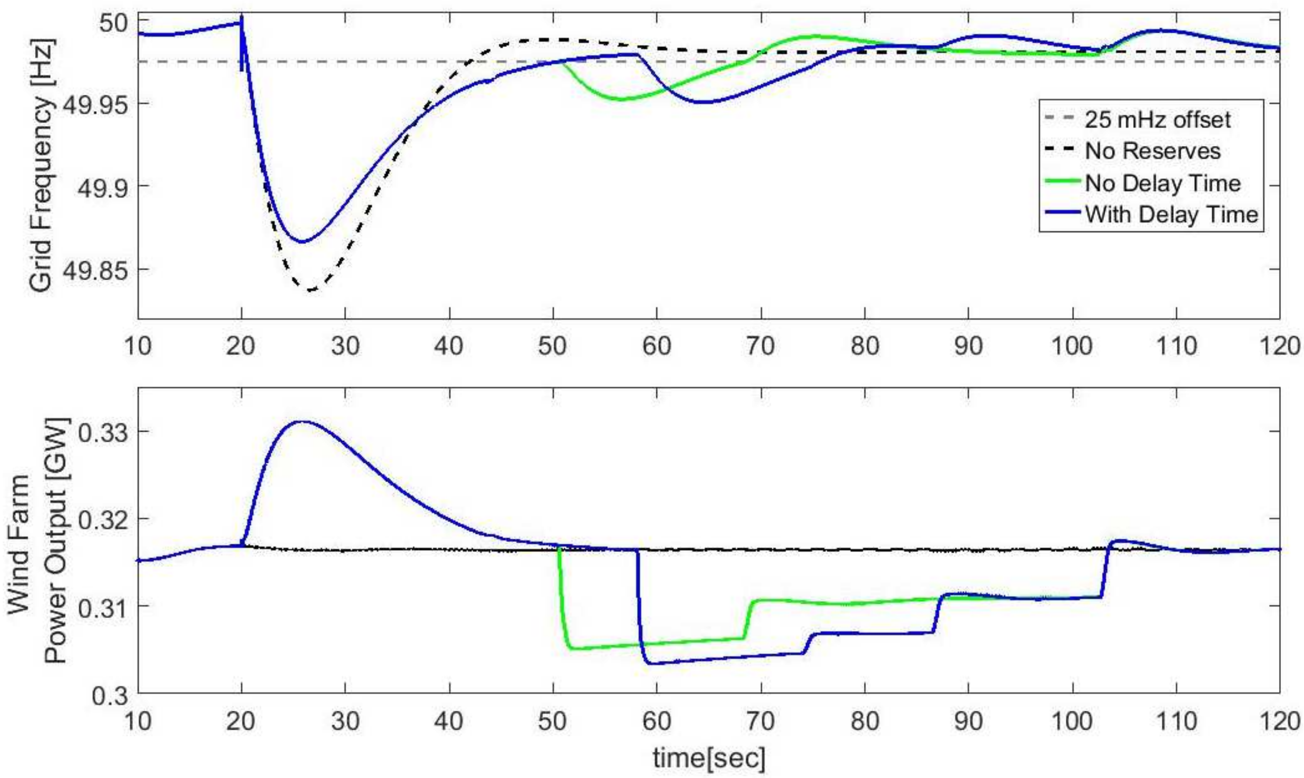

Figure 45: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load increase of 7% of the base load, Effect of delay time.

Thus, it can be concluded that imposing a delay time in different groups of wind turbines cannot guarantee a more sustained response or an actual delay of the rotor recovery. Whether the rotor recovery will actually be delayed highly depends on the amount of reserves provided during the frequency deviation. Thus, it is only expected to be possible for a smaller frequency deviation, when the frequency response is only terminated due to the frequency having sufficiently restored with only an offset of 25 mHz remaining and not because the rotor recovery was forced to start due to the limited resources available.

Sensitivity Analysis for the gain droop constant if all wind turbines are tuned in the same way

The suggested coordination strategy of the wind turbines in groups seems promising for providing more sustained responses. However, it is important to compare it with the case where all wind turbines within the wind farm are tuned in the same way to better understand the advantages and disadvantages as well as the benefits and the potential threats that we may have to face in each case.

Thus, a sensitivity analysis for the gain droop constant for the case where all wind turbines are tuned in the same way has been performed. This can be easily achieved by imposing a *FLAG* parameter with a value equal to 1 for all wind turbines within the wind farm.

For the frequency deviation, the load is increased by 10% of the base load at $t_{dis} = 20\ sec$ in all cases. The time period $\Delta t_{release}$ within which the kinetic energy of the rotor is released is set to 2 seconds, while during the rotor recovery the active power output of the wind turbine generator is set to be reduced by 2% of the rated power. Since it is important that a response that lasts approximately 30 seconds is achieved gain droop constants with slightly lower values in the range of 0.2 to 0.3 are chosen.

The impact of the frequency response for different values of the gain droop constant as well as the effect of the recovery period on the grid frequency are depicted in Figure 46.

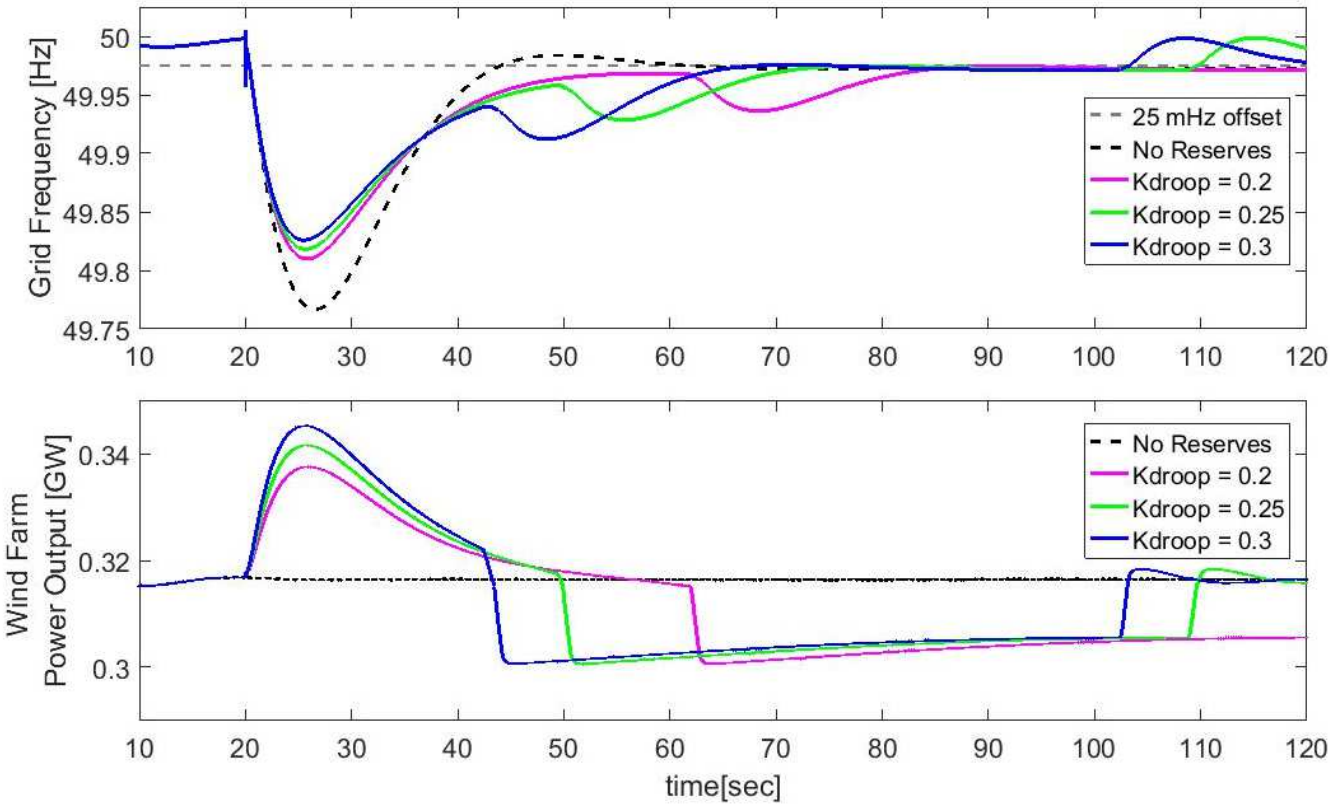

Figure 46: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load increase of 10% of the base load, Sensitivity Analysis for K_{droop}.

If the wind farm does not provide any frequency support the frequency nadir reaches the value of 49.767 Hz which is outside of the range of tolerable frequency deviations ($\pm 200\ mHz$). The improvement on the frequency nadir ranges from 43 mHz to 59 mHz, while the duration of the response provided ranges from 42 seconds to 22 seconds for increasing values of the gain droop constant K_{droop} from 0.2 to 0.3. Thus, even though the improvement on the frequency nadir increases with increased gain droop constant values the duration of the response provided is negatively affected, resulting in shorter durations and therefore,to more severe second deeps in the grid frequency due to the early rotor recovery.

The maximum reserves provided range from 22 MW (3.67% of the installed capacity) to 29 MW (4.83% of the installed capacity). In all cases, the frequency response provided by the wind farm stopped due to limited kinetic energy that forced the rotor recovery to avoid aerodynamic stall before the frequency managed to restore sufficiently so that only the offset of 25 mHz was remaining, as the controller is designed. In all cases the deep caused in the frequency during the rotor recovery was less significant (above 49.9 Hz). The rotor recovery lasts around 60 seconds, while it can be observed that the frequency deviation lasts much longer when the wind farm is providing reserves compared to the case when only the grid provides frequency support. The frequency is though maintained within the range of $\pm 200\ mHz$.

Table 5: Performance Indicators for the Sensitivity Analysis for the gain droop constant.

Preformance Indicators	Gain Droop Constant Values			
	$K_{droop} = 0$	$K_{droop} = 0.2$	$K_{droop} = 0.25$	$K_{droop} = 0.3$
Frequency Nadir [Hz]	49.767	49.81	49.818	49.826
Improvement in the Frequency Nadir [mHz]	-	43	51	59
Duration of Frequency Deviation [sec]	24	71	56	48
FSO interrupted due to limitations	-	YES	YES	YES
Duration of FSO [sec]	0	42	29	22
Duration of rotor recovery [sec]	-	>58	60	61
Frequency Nadir during the rotor recovery [Hz]	-	49.936	49.928	49.912
ROCOF [Hz/sec]	0.036	0.0313	0.03	0.029
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	22 (3.67%)	25 (4.17%)	29 (4.83%)

Comparison of different strategy scenarios

The best scenarios from all the previous study cases in the presence of a 10% load increase of the base load are depicted in Figure 47 to compare and conclude to which one achieves the best results and which are the advantages and disadvantages of each method. The following scenarios have been chosen:

- Base Scenario: No frequency response is provided by the wind farm.
- Scenario 1: All wind turbines are tuned in the same way with a gain droop constant equal to 0.25.
- Scenario 2: The wind turbines are arranged in 3 groups, with 60 wind turbines assigned to Group A, 40 to Group B and 20 to Group C. The gain droop constant obtains a value of 0.4 .

For the frequency deviation, the load is increased by 10% of the base load at $t_{dis} = 20\ sec$ in all cases. The time period $\Delta t_{release}$ within which the kinetic energy of the rotor is released is set to 2 seconds, while during the rotor recovery the active power output of the wind turbine generator is set to be reduced by 2% of the rated power.

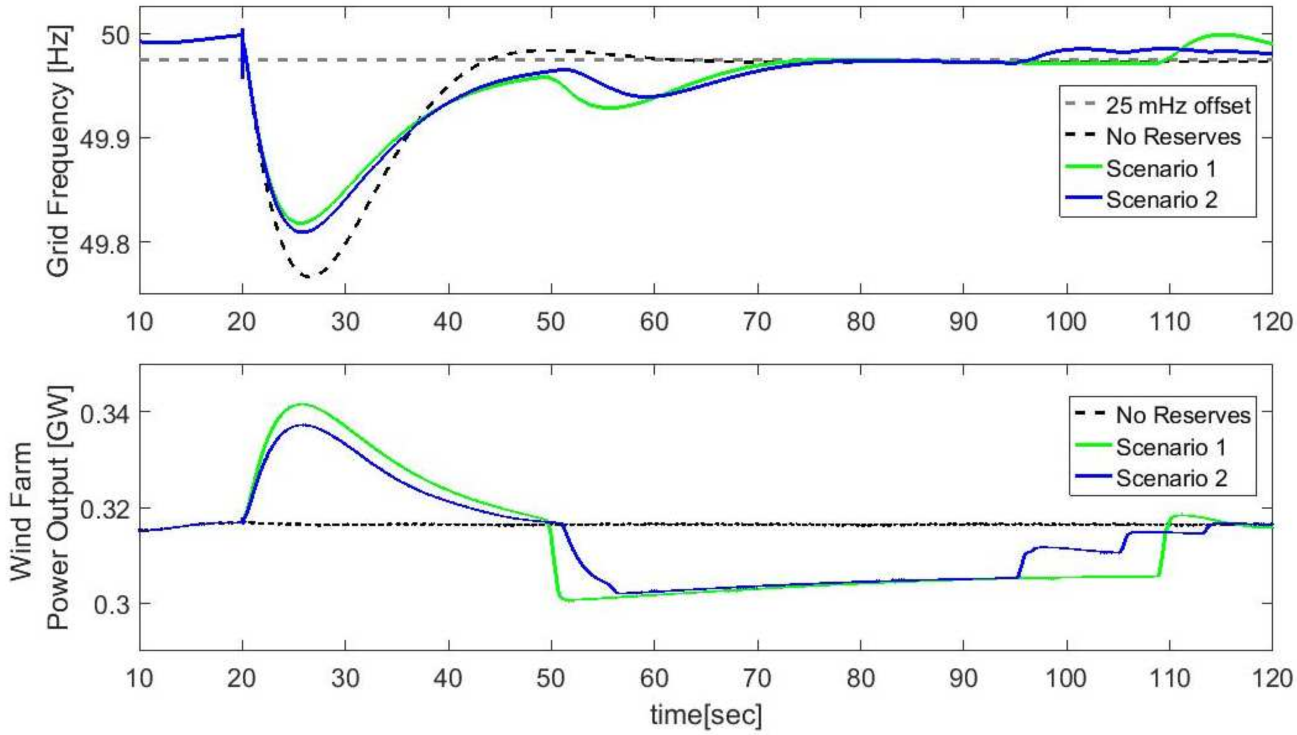

Figure 47: Comparison between the two different strategies.

In general, it can be observed that the two scenarios, that also represent different strategies for tuning the wind farm controller parameters for the available wind turbines, result in quite similar effect on the grid frequency. When all the wind turbines are tuned in the same way the benefit on the frequency nadir is slightly better, however the frequency response lasts slightly less and the effect of the rotor recovery on the grid frequency is more significant, since all the wind turbines recover simultaneously. On the other hand, arranging the wind turbines in groups may result is slightly less improved frequency nadir, however the effect of the recovery period (both at the start as well at the end time) on the grid frequency is less significant, which is considered an important advantage.

Table 6: Performance Indicators for the comparison of the different control strategies.

Preformance Indicators	Investigated Scenarios		
	Base Scenario	Scenario 1	Scenario 2
Frequency Nadir [Hz]	49.767	49.818	49.81
Improvement in the Frequency Nadir [mHz]	-	51	45
Duration of Frequency Deviation [sec]	24	56	63
FSO interrupted due to limitations	-	YES	YES

Duration of FSO [sec]	0	29	31
Duration of rotor recovery	-	60	63
Frequency Nadir during the rotor recovery [Hz]	-	49.928	49.94
ROCOF [Hz/sec]	0.036	0.03	0.031
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	25 (4.17%)	21 3.5%)

6.2 Case Study 2: Under-frequency deviation under above rated wind speed conditions

For high wind speed values above rated, even for wind speed values around the rated wind speed, there is generally more than enough power to satisfy the required reserves, especially considering that the limit of the required reserves will always be the contracted power which needs to be able to be provided under all wind speed conditions. Even for wind speed values around rated wind speed where the pitch angle obtains only small values of a few degrees, which (basically is a representative of the amount of surplus power that is available in the wind), the extra power available in the wind is already an important amount while the kinetic energy that is stored in the rotating masses can also be released if needed.

Therefore, the limitations for this case is not so much the non-availability of resources to provide the necessary reserves, but the consequences that such an action will have on the temperature of the converter components due to the increased current flowing. To avoid over-heating the converters above the junction temperature allowed, the time limit T_{FSO} has been set to 10 seconds. Therefore, each wind turbine will provide the requested reserves for a maximum of 10 seconds and afterwards it will return to its normal operation. For each wind turbine of a certain group this happens at the same time point and as a result the next group of wind turbines takes over to provide the necessary reserves for another 10 seconds, etc. The reserves provided by each wind turbine are gradually reduced which allows for a smooth waveform in the active power injection of the wind farm.

If an even more sustained response is required (more than 30 seconds) it can be achieved by simply arranging the wind turbines in more groups. The amount of reserves provided will not be highly influenced in this case (unless a very sustained response is required, which in any case will not be possible for lower wind speed values), since enough surplus power in the wind is available plus the rotors' kinetic energy is an additional resource of power that can be used in a complementary way, if needed.

Sensitivity Analysis for the severity of the frequency deviation

The impact of the frequency response for different frequency events as well as the effect of the recovery period on the grid frequency are depicted in Figure 48. Three events are simulated in which a load increase of 5%, 7% and 10% of the base load takes place at $t_{dis} = 20\ seconds$. The time limit for reserves provision is set to 10 seconds.

The provision of the reserves was maintained for a maximum of 30 seconds (since 3 groups of wind turbines were used). For smaller frequency deviations the provision of reserves was only interrupted because the frequency recovered sufficiently with only the offset of 25 mHz remaining. The more severe the frequency deviation, the more reserves are provided. In total, the frequency nadir is in all cases improved with more significant improvement observed for the more severe frequency deviations, while the ROCOF is in all cases smoothened.

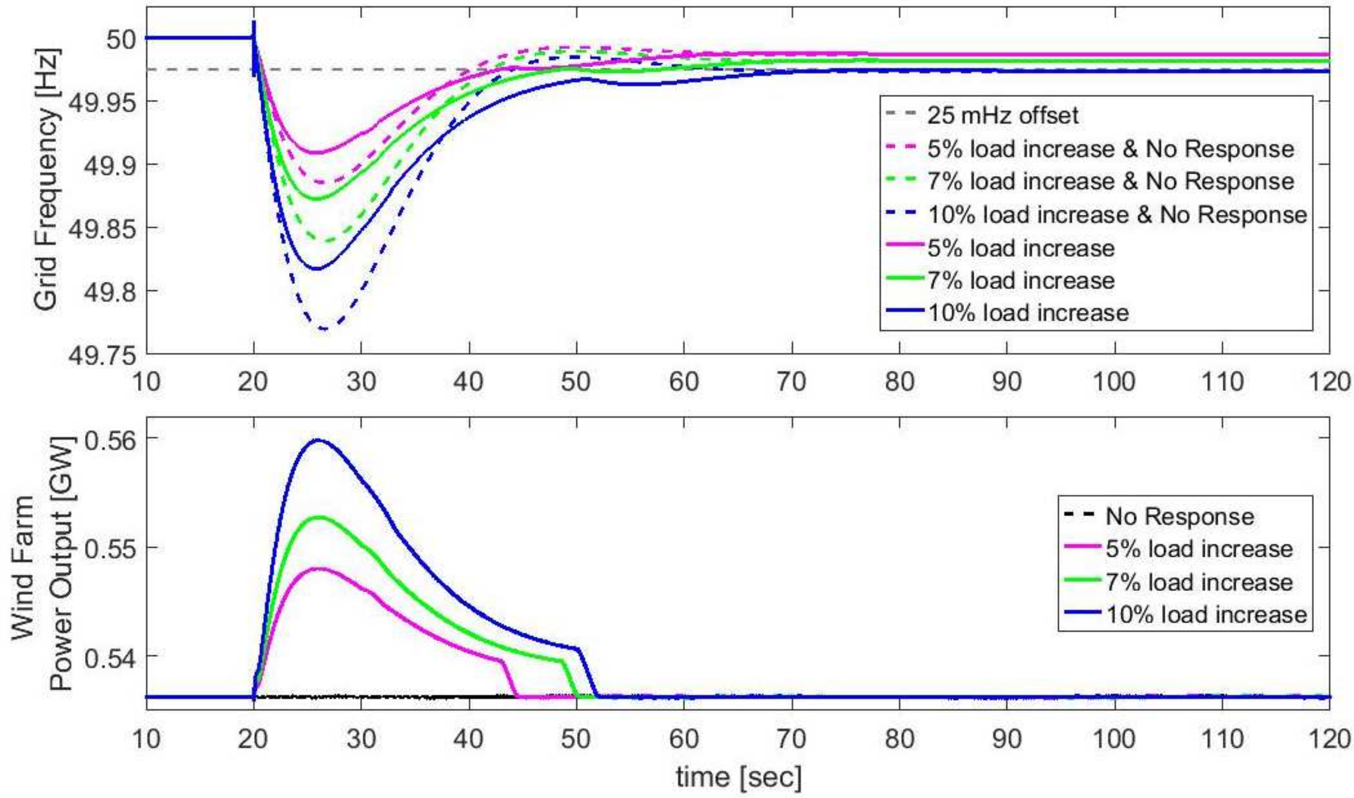

Figure 48: Sensitivity Analysis for severity of the frequency deviation sensed and the impact on the grid frequency as well as on the wind farm response, for K_{droop} equal to 0.5.

Table 7: Performance Indicators for the Sensitivity Analysis for the severity of the frequency deviation.

Preformance Indicators	No Response from the Wind Farm ($K_{droop} = 0$)			With Frequency Support from Wind Farm ($K_{droop} = 0.5$)		
Load Increase [%]	**5%**	**7%**	**10%**	**5%**	**7%**	**10%**
Frequency Nadir [Hz]	49.885	49.839	49.769	49.909	49.872	49.817
Improvement in the Frequency Nadir [mHz]	-	-	-	24	33	48
Duration of FSO [sec]	-	-	-	23	29	30
FSO interrupted due to limitations	-	-	-	NO	NO	YES
ROCOF [Hz/sec]	0.017	0.025	0.035	0.015	0.021	0.03

Maximum Reserves Provided by Wind Farm [MW]	-	-	-	12 (2%)	17 (2.83%)	24 (4%)

The power output and speed of the wind turbine generator and the pitch angle for one wind turbine in each of the available groups is presented for the three events simulated in Figure 49 (5% load increase), Figure 50 (7% load increase) and Figure 51 (10% load increase).

Even though the pitch angle only has a low value during the normal operation, which means that only a small amount of surplus power is available in the wind and discarded by pitch control, enough power was available to satisfy the requested reserves. Only for the most severe frequency deviation did the pitch angle of the wind turbines obtain a zero value during the frequency supporting operation. This basically means that all surplus power available in the wind has been utilized and some of the kinetic energy stored in the rotating masses has also been deployed to satisfy the required reserves, resulting in a decrease of the rotor speed. The recovery of the rotor speed in this case was achieved by means of normal pitch control.

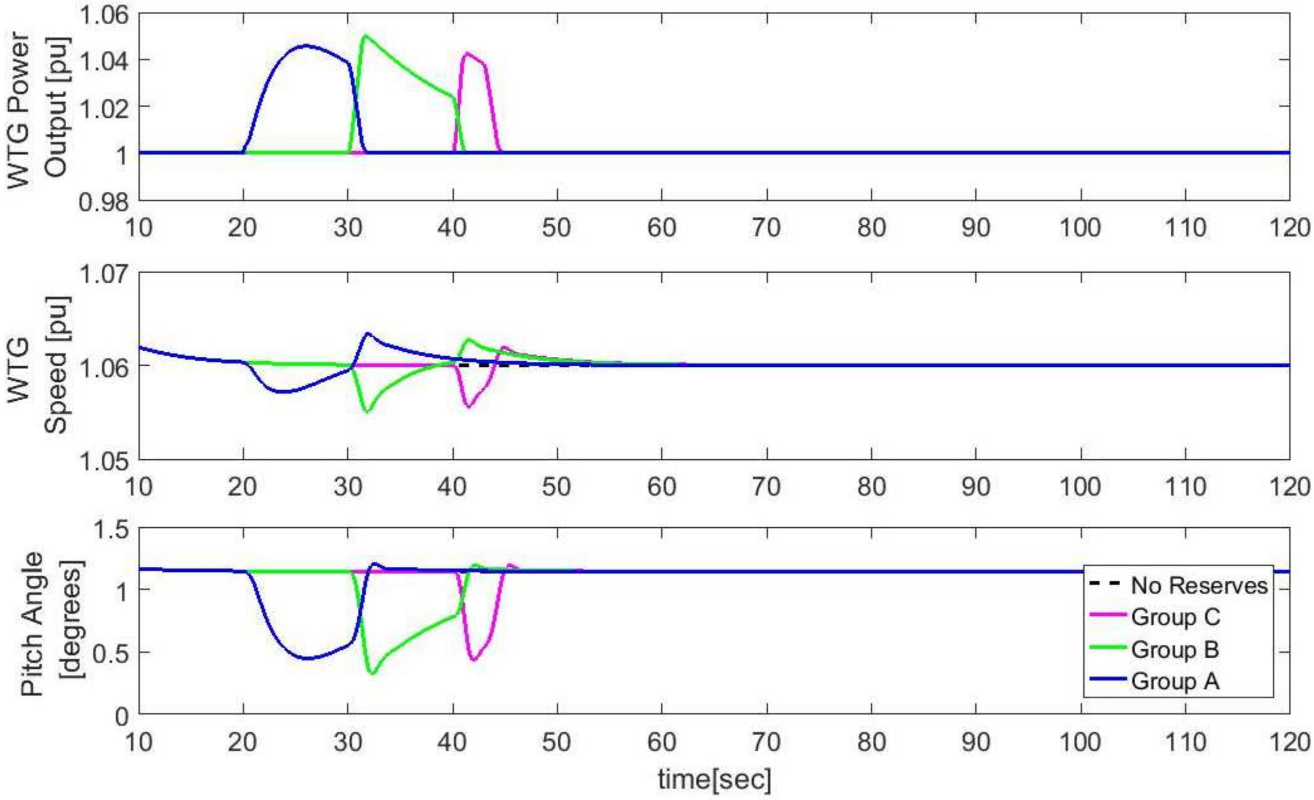

Figure 49: Wind Turbine Generator Active Speed and Power output and Pitch Angle of a single Wind Turbine of Groups A, B and C during a load increase of 5% of the base load, for K_{droop} equal to 0.5.

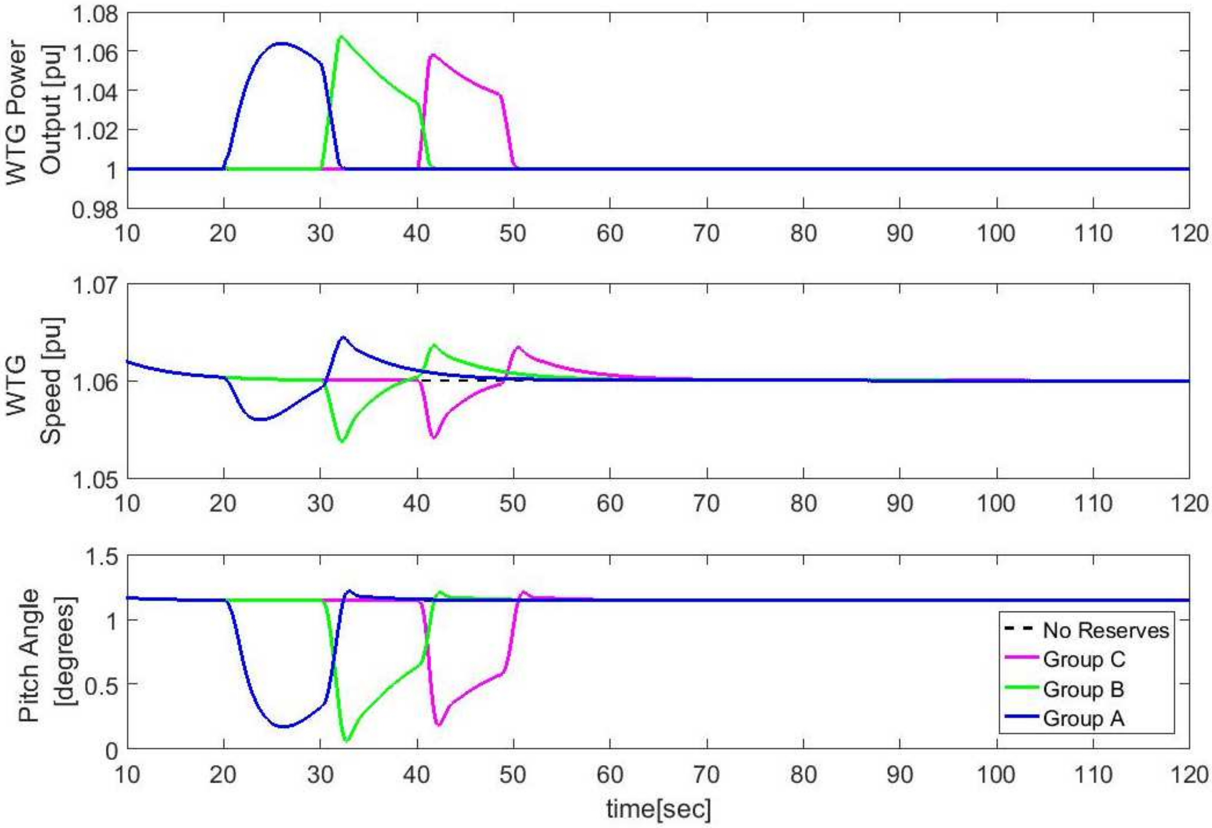

Figure 50: Wind Turbine Generator Speed and Active Power output and Pitch Angle of a single Wind Turbine of Groups A, B and C during a load increase of 7% of the base load, for K_{droop} equal to 0.5.

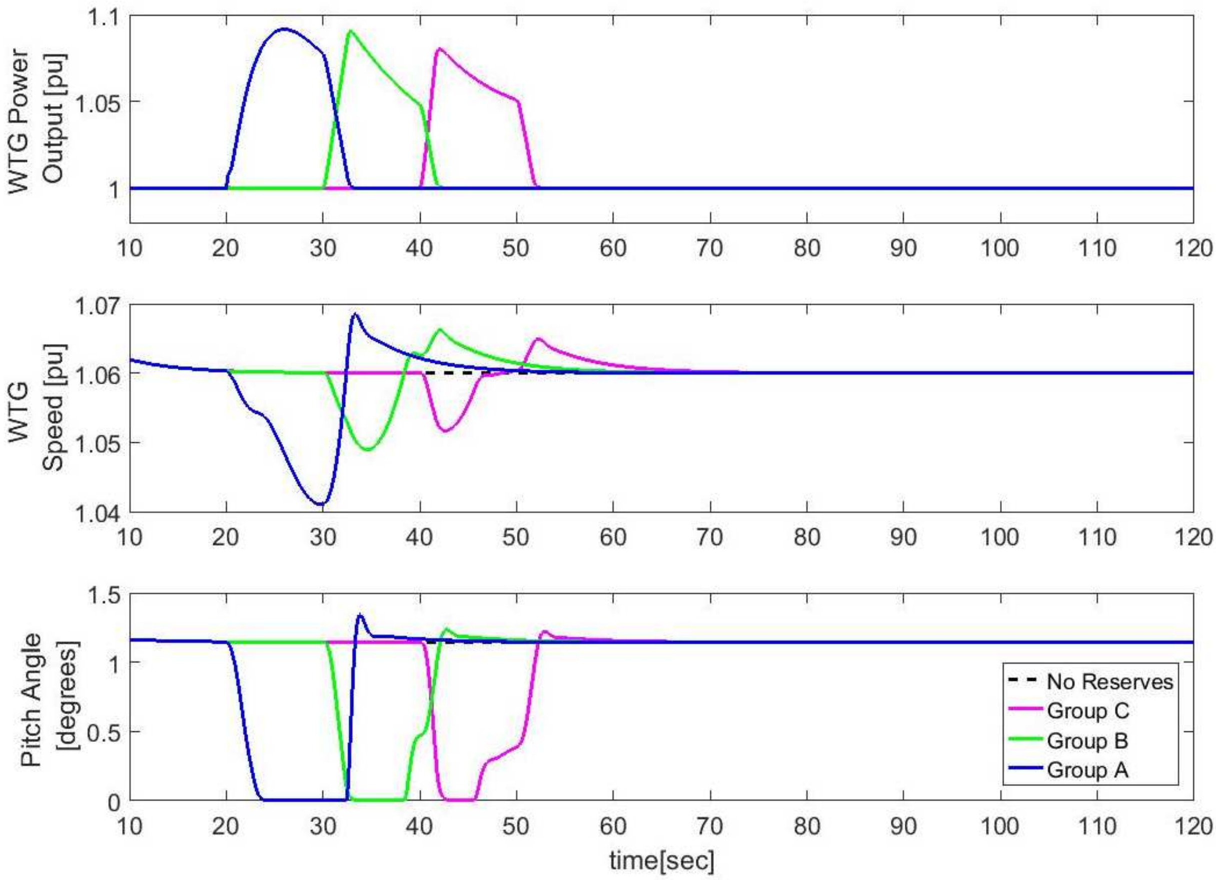

Figure 51: Wind Turbine Generator Speed and Active Power output and Pitch Angle of a single Wind Turbine of Groups A, B and C during a load increase of 10% of the base load, for K_{droop} equal to 0.5.

Comparison of different strategy scenarios

The same scenarios that have been compared for Case Study 1 are depicted in the following figure for above rated wind speed conditions to observe the benefits offered by the suggested strategy at this mode of operation. The chosen scenarios are:

- Base Scenario: No frequency response is provided by the wind farm.
- Scenario 1: All wind turbines are tuned in the same way with a gain droop constant equal to 0.25.
- Scenario 2: The wind turbines are arranged in 3 groups, with 60 wind turbines assigned to Group A, 40 to Group B and 20 to Group C. The gain droop constant obtains a value of 0.4 .

For the frequency deviation, the load is increased by 10% of the base load at $t_{dis} = 20\ sec$ in all cases. The time limit for reserves provision is set to 10 seconds.

The benefit of the frequency response for the defined scenarios as well as the effect of the recovery period on the grid frequency are depicted in Figure 52.

Even though for below rated wind speed conditions the two scenarios compared have similar results, with the improvement on the less severe second deep in the frequency caused during the rotor recovery being the only significant improvement offered by Scenario 2, under above rated wind speed conditions the offered advantages are much more important.

Since the limitation for providing positive reserves is a time limitation for the response provided by each wind turbine that allows for the maximum junction temperature of the converter components not to be exceeded, the reserves provided by the wind farm under Scenario 1 are reduced to zero after ten seconds of reserve provision. This causes a second deep in the frequency that is though less significant compared to the one observed under below rated wind speed conditions as no recovery is required. The higher the amount of reserves provided the moment that the allowed time frame is reached the more severe the effect on the frequency will be.

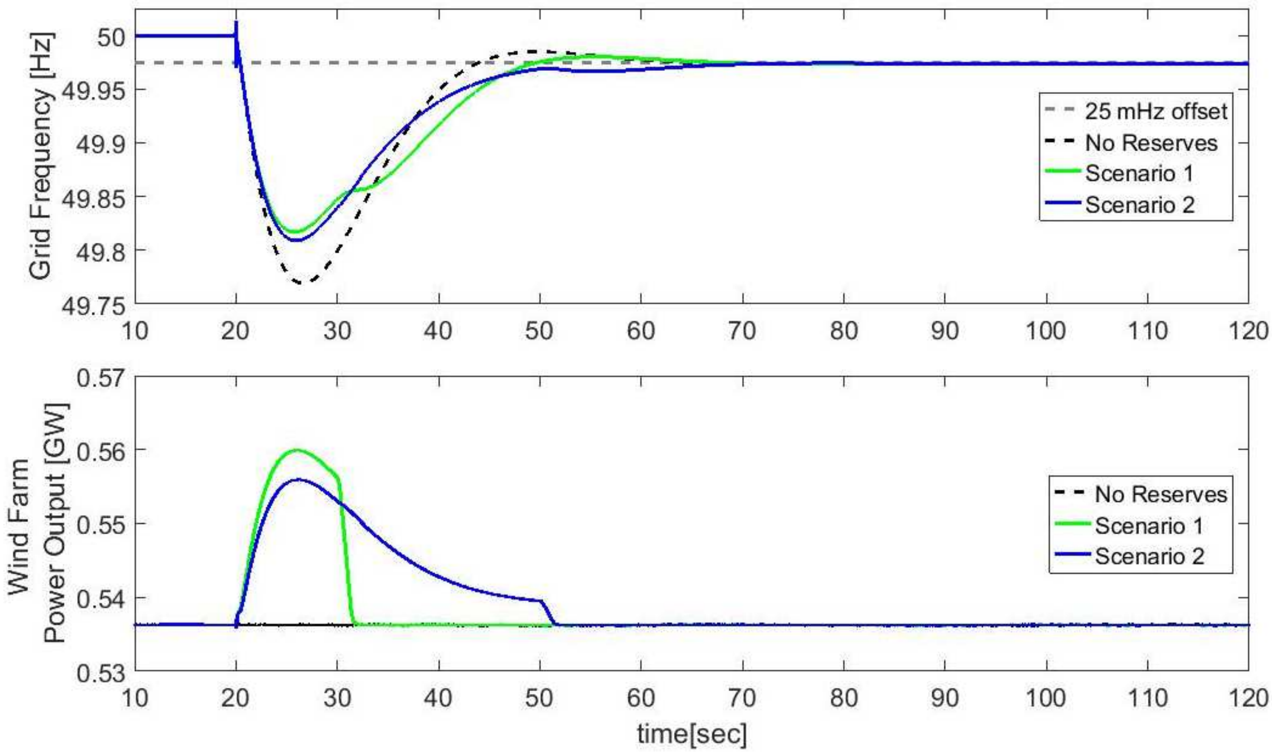

Figure 52: Comparison between the two different strategies.

Table 8: Performance Indicators for the comparison of the different control strategies.

Preformance Indicators	Investigated Scenarios		
	Base Scenario	Scenario 1	Scenario 2
Frequency Nadir [Hz]	49.769	49.817	49.809
Improvement in the Frequency Nadir [mHz]	-	48	40
FSO interrupted due to limitations	-	YES	YES
Duration of FSO [sec]	0	10	30
ROCOF [Hz/sec]	0.035	0.03	0.032
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	24 (4%)	20 (3.33%)

The impact on the grid frequency is not significant and it can be reduced by applying a smaller allowed rate of change in the power output of the wind turbine generator within the control design. However, this scenario results in a very short response, which constitutes a significant limitation regarding the type of product that can be offered to the Ancillary Service Market through this scenario. Thus, the most important disadvantage of Scenario 1 constitutes the fact that the total duration of frequency response that can be offered to the Ancillary Service Market is strictly limited to the time-period for which a converter can be overloaded, which in this study has been set to 10 seconds. However, through arranging the wind turbines in groups (Scenario 2) a more sustained response can be achieved under this mode of operation allowing for an active power product of 30 seconds to be offered to the market, if three groups are used.

For above rated wind speed conditions more sustained responses (e.g., of one or two minutes) can be achieved by increasing the number of groups. The same amount of total reserves can still be provided to the grid, since enough energy is available in the wind, while the kinetic energy stored in the rotating masses can also be used if required. Thus, even if the total number of wind turbines assigned to Group A is reduced, with a higher gain droop constant the total reserves provided can be maintained the same, or at least not significantly reduced.

On the other hand, for below rated wind speed conditions the total amount of kinetic energy available under certain wind speed conditions is the same, thus achieving a more sustained response would result in reduced total reserves provided. If though, sufficient reserves are provided during the first 30 seconds following a disturbance the grid frequency is usually sufficiently restored with only a small offset remaining that can be further reduced or eliminated by frequency containment and frequency restoration reserves. Thus, a product with a duration of 30 seconds is considered a more appropriate solution considering the limitations for the wind turbine technology.

6.3 Case Study 3: Over-frequency deviation under below rated wind speed conditions

An over-frequency deviation constitutes a much simpler situation for wind turbines, since their power output can be decreased as long as there is enough power generated. Thus, the required reserves are provided without restrictions by the first group in line, while the only interesting point to observe constitutes the recovery period of the rotor.

During the frequency supporting operation of the wind turbine under below rated wind speed conditions additional kinetic energy is stored in the rotating masses for the necessary negative active power reserves to be provided. The surplus kinetic energy needs to be afterwards released so that the wind turbines can restore the operational speed at its optimal value to operate according to the Maximum Power Point Tracking principle, when not supporting the grid frequency (normal operation). No time limitations exists in this case, therefore the rotor recovery will take place when the frequency is sufficiently restored close to its nominal value. Thus, no extreme frequency deviations are expected to occur due to the recovery period. Additionally, the recovery term can be reduced to achieve a smoother recovery without endangering the proper operation of the wind energy conversion system.

If it is desired the rest of the wind turbine groups could be used to achieve an even smoother power output of the wind farm through decreasing slightly the power output during the recovery period of the first group of wind turbines used to support the grid frequency. Even without such an action the second frequency deviation caused during the rotor recovery is quite smooth and occurs when the frequency deviation has been restored up to the offset of 25 mHz (as designed), thus such a control strategy is outside of the scope of this work as it is not considered a critical point.

In order to test the performance of the implemented controllers and to define the boundaries during negative reserve provision, a series of simulations have been run that include a sensitivity analysis for the severity of the frequency deviation, a sensitivity analysis for the aggressiveness of the rotor recovery and a gain droop constant sensitivity analysis.

Finally, the two possible strategies allowed through the wind farm controller for managing the available wind turbines are compared and the advantages and disadvantages of each one are discussed.

Sensitivity Analysis for the severity of the frequency deviation

A sensitivity analysis for the severity of the frequency deviation has been performed and is depicted in Figure 53, for different events (5%, 7% and 10% decrease of the load) at $t_{dis} = 20\ sec$ to test the response of the controller under the different events, the benefit on the grid frequency and the effect of the rotor recovery. During the rotor recovery the active power output of the wind turbine generator is set to be increased by 2% of the rated power.

In all cases, the controller has provided all reserves requested, while the frequency response of the wind farm only stopped when the frequency had sufficiently restored with only an offset of 25 mHz remaining according to the controller design. The peak in the grid frequency has been significantly decreased and held within the tolerable boundaries. The improvement on the frequency peak ranges from 24 to 51 mHz, while the maximum reserves provided range from 12 to 25 MW, for increased severity of the frequency deviation. The ROCOF has in all cases been improved.

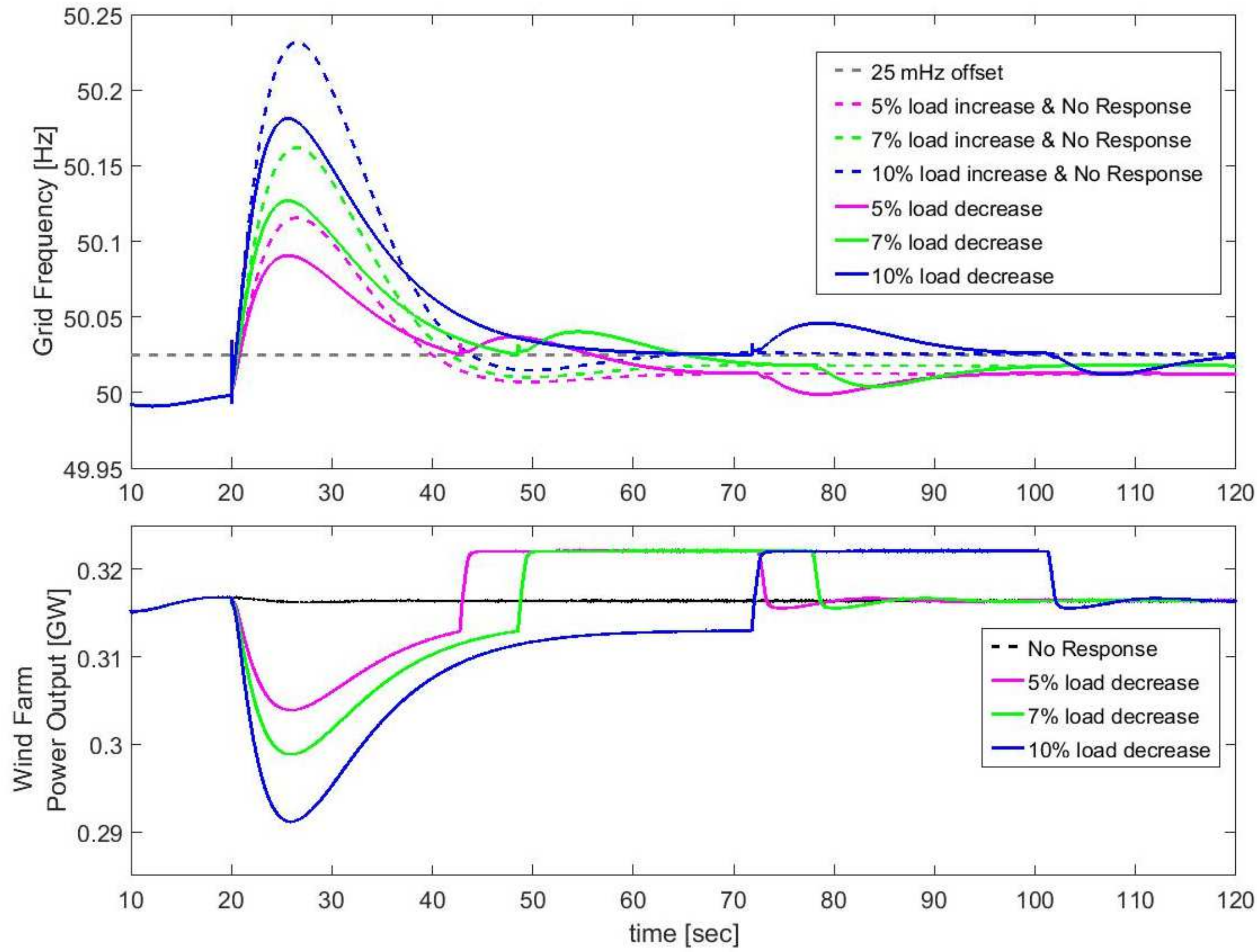

Figure 53: Sensitivity Analysis for severity of the frequency deviation sensed and the impact on the grid frequency as well as on the wind farm response.

The rotor recovery caused a much smaller and quite smooth second frequency deviation. The rotor recovery occurred right after the end of the frequency supporting operation, however in this mode of operation it can be delayed if required so that different groups of wind turbines recover at different time instants.

An important disadvantage in this case is that only the first group of wind turbines contributes to frequency support, since the provided response is not for any reason restricted and thus the rest of the groups are not activated. However, this is necessary for a sufficiently long response of around 30 seconds to become possible during an under-frequency deviation, as explained in the previous sections.

Table 9: Performance Indicators for the Sensitivity Analysis for severity of the frequency deviation.

Preformance Indicators	No Response from the Wind Farm ($K_{droop} = 0$)			With Frequency Support from Wind Farm ($K_{droop} = 0.5$)		
Load Decrease [%]	5%	7%	10%	5%	7%	10%
Frequency Peak [Hz]	50.115	50.162	50.232	50.091	50.127	50.181
Improvement in the Frequency Peak [mHz]	-	-	-	24	35	51

Duration of rotor recovery [sec]	-	-	-	30	30	30
Frequency Peak during the rotor recovery [Hz]	-	-	-	50.037	50.04	50.046
ROCOF [Hz/sec]	0.018	0.025	0.036	0.016	0.022	0.031
Maximum Reserves Provided by Wind Farm [MW]	-	-	-	12 (2%)	17 (2.83%)	25 (4.17%)

The wind turbine generator speed and power output as well as the pitch angle of a single wind turbine of each group for the different load events tested is depicted in Figure 54.

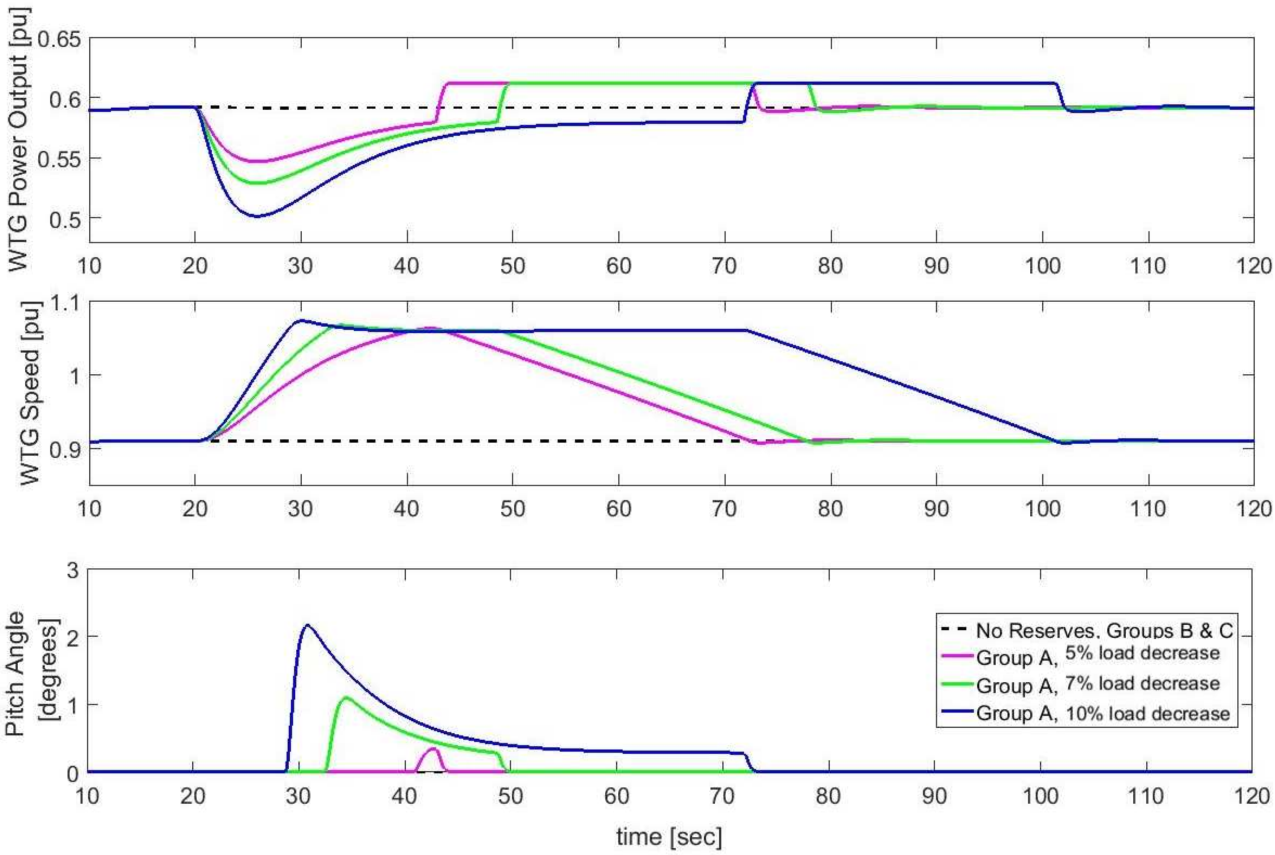

Figure 54: Sensitivity Analysis for severity of the frequency deviation sensed and the Wind Turbine Generator Speed and Power output, and on the Wind Turbine pitch angle, for one Wind Turbine of each group, with K_{droop} set to 0.5.

Only Group A is of interest in this case, as the rest of the groups are not participating in frequency support. It can be observed that the power output of the wind turbines is sufficiently reduced through storing kinetic energy in the rotating masses, thus resulting in an increase of the rotor speed. If the rotor speed increases above the activation point of pitch control pitch angle starts increasing to discard the surplus power produced and thus significant over-speeds are avoided. In all cases the rotor speed has been maintained below 1.1 pu and is afterwards restored by means of the normal pitch control.

After the required reserves have been provided, the kinetic energy stored in the rotating masses is released. Hence, the generator (and thus rotor) speed decreases back to its optimal value for the given wind speed conditions. The rotor recovery lasts substantially shorter (30 seconds) as a part of the negative reserves is provided through storing kinetic energy in the rotating masses and a part is provided through discarding the surplus power by means of pitch control. Only the amount of kinetic energy stored in the rotating masses needs to be afterwards released. The response of the wind turbines successfully follows the controller design and no limitations are violated.

Importance of managing the recovery period

A sensitivity analysis for the recovery term $\Delta P_{recovery_{max}}$ has been performed to show the impact of a smoother or more aggressive rotor recovery on the grid frequency. A load decrease of 10% of the base load has been imposed at $t_{dis} = 20\ sec$ to test the response of the controller under the different situations, the impact on the grid frequency, the effect of the rotor recovery. The results of the simulations are depicted in Figure 55. The gain droop constant is set to 0.5 for all cases.

In all cases the controller has provided all reserves requested, while the frequency supporting operation of the wind farm only stopped when the frequency had sufficiently restored with only an offset of 25 mHz remaining according to the controller design.

The second over-frequency event caused during the rotor recovery is less significant for decreasing values of $\Delta P_{recovery_{max}}$, however longer recovery periods are required for decreased $\Delta P_{recovery_{max}}$ values. Thus, a *trade-off* between the duration and the aggressiveness of the recovery period is observed.

It can be concluded from the simulation results that the rotor recovery after the provision of negative reserves is a much less critical situation compared to the case that follows positive reserve provision. The recovery can be achieved in such a smooth way that the effect on the grid frequency can be negligible. It is moreover possible to delay the rotor recovery until wind speed conditions decrease and use it to continue producing the same amount of power which will cause the rotor speed to gradually restore back to its optimal value. Alternatively, the stored kinetic energy can be used to later on provide positive reserves, if an under-frequency deviation occurs. What will happen first depends on the wind speed conditions and the deviations of the grid frequency. In both cases though, it can have a beneficial effect on the wind turbine operation and/or the total money that can be earned either through the electricity or through the reserves sold.

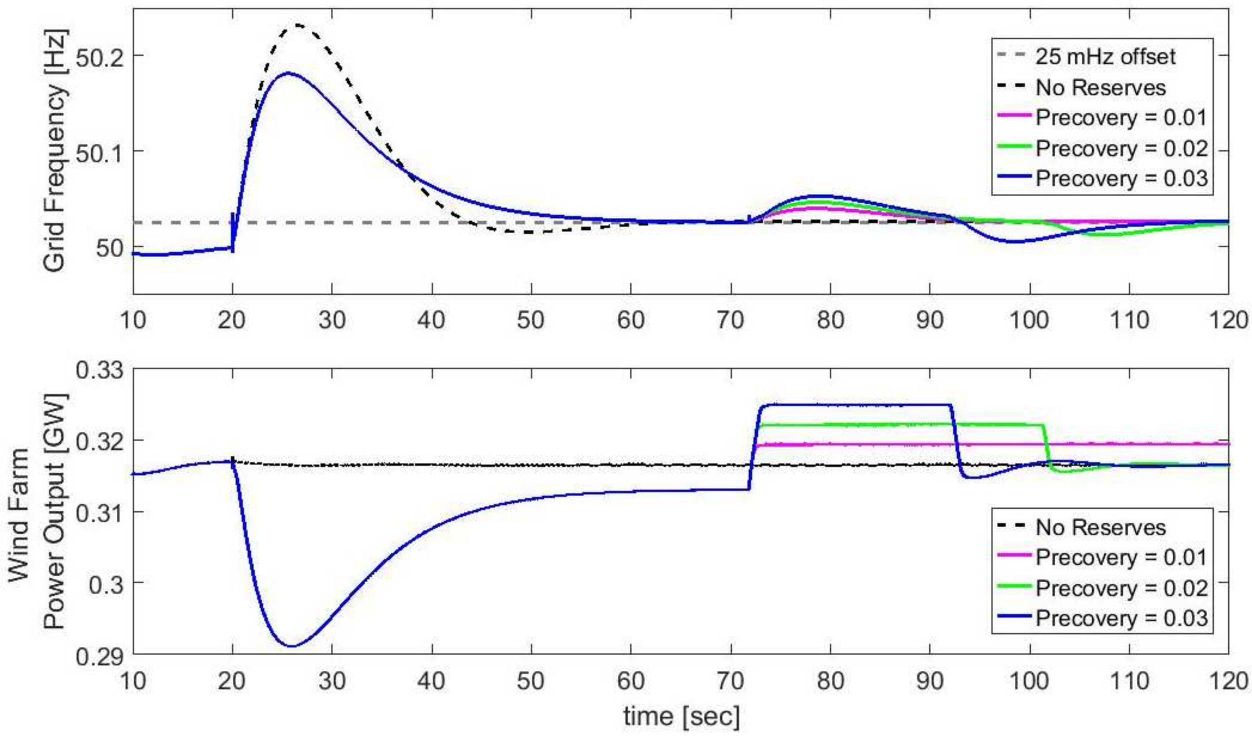

Figure 55: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load decrease of 10% of the base load, Sensitivity Analysis for $\Delta P_{recovery_{max}}$.

Sensitivity Analysis for the gain droop constant

A sensitivity analysis of the gain droop constant $\mathrm{K_{droop}}$ has been carried out during a 10% load decrease that occurs at $t_{dis} = 20\ sec$. During the rotor recovery the active power output of the wind turbine generator is set to be increased by 2% of the rated power.

The impact of the frequency response for different values of the gain droop constant as well as the effect of the recovery period on the grid frequency, are depicted in Figure 56.

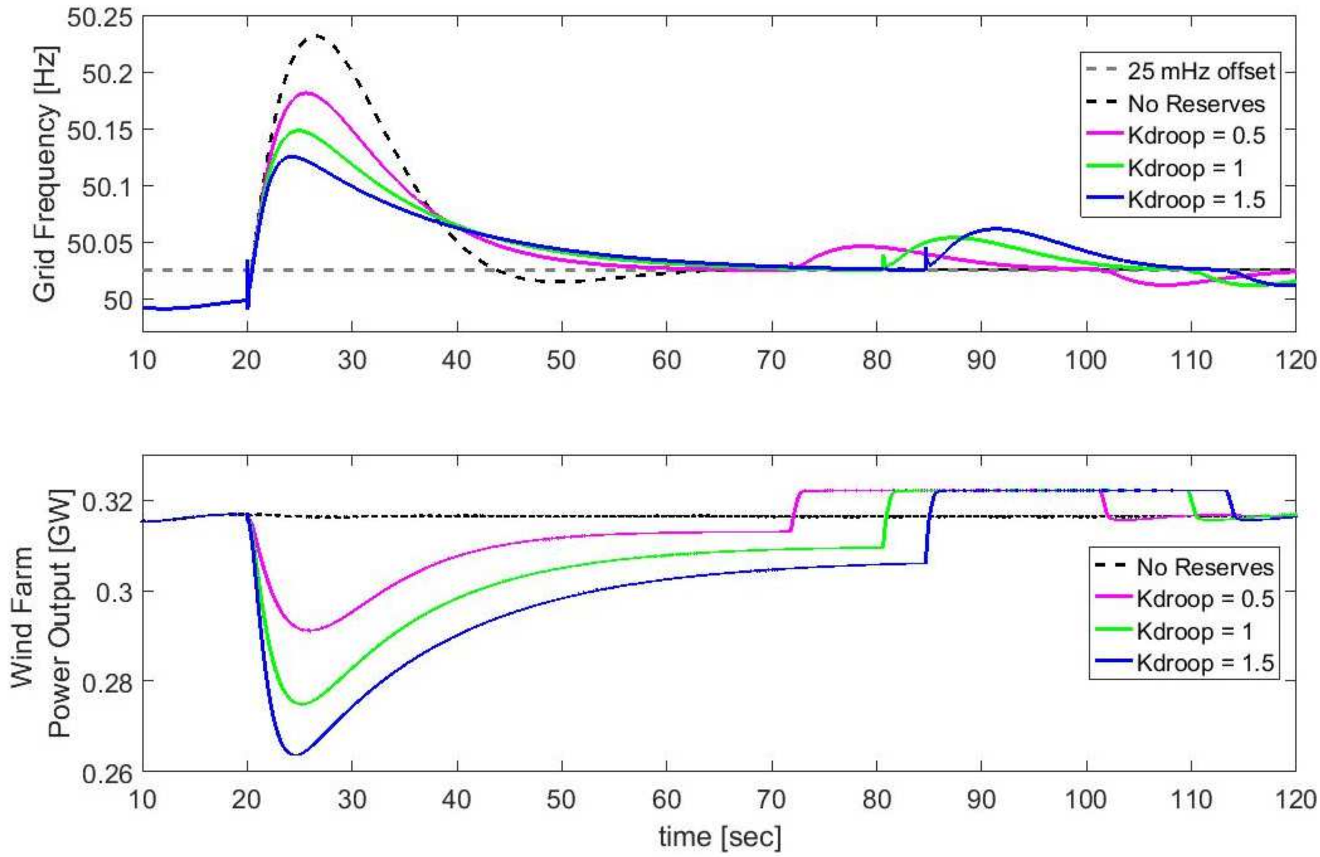

Figure 56: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load decrease of 10% of the base load, Sensitivity Analysis for K_{droop}.

The improvement on the frequency peak ranges from 49 mHz to 105 mHz, while the maximum reserves provided range from 25 to 52 MW for increasing values of the gain droop constant K_{droop} from 0.5 to 1.5. The response provided stops only when the frequency is sufficiently restored with only the offset of 25 mHz remaining.

The frequency peak is significantly improved however, the frequency event lasts significantly longer when the wind farm provides a frequency response. During the rotor recovery a second much less severe over-frequency deviation is caused. This is more significant for increased gain droop constant values. The improvement on the ROCOF increases with the gain droop constant.

Finally, when providing negative reserves it is always important to consider that they such a response will be accompanied by economic losses due to the amount of power that will not be produced and thus not sold as electricity to the grid during the over-frequency deviation. Hence, an important factor to consider is the price of the electricity in comparison with the price of the reserves provided and the frequency with which over-frequency events typically occur.

Table 10: Performance Indicators for the Sensitivity Analysis for the gain droop constant.

Preformance Indicators	Gain Droop Constant Values			
	$K_{droop} = 0$	$K_{droop} = 0.5$	$K_{droop} = 1$	$K_{droop} = 1.5$
Frequency Peak [Hz]	50.230	50.181	50.148	50.125
Improvement in the Frequency Peak [mHz]	-	49	82	105
FSO interrupted due to limitations	-	NO	NO	NO
Duration of rotor recovery [sec]	-	30	30	30
Frequency Peak during the rotor recovery [Hz]	-	50.045	50.054	50.063
ROCOF [Hz/sec]	0.036	0.031	0.025	0.021
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	25 (4.17%)	41 (6.83%)	52 (8.67%)

The wind turbine generator speed and power output as well as the pitch angle of a single wind turbine of each group, for the different load events tested is depicted in Figure 57.

Only Group A is of interest in this case as the rest of the groups are not participating in frequency support. It can be observed that the power output of the wind turbines is sufficiently reduced through storing kinetic energy in the rotating masses which results in an increase of the rotor, and thus generator, speed. If the rotor speed increases above the activation point of pitch control, pitch angle starts increasing to discard the surplus power.

For increased values of the gain droop constant the rotor speed has been increased up to around 1.1 pu before pitch control managed to sufficiently increase the pitch angle to maintain the rotor speed at its maximum allowed value. This is because pitch control is slow and it cannot instantly change the pitch angle a lot. Hence, steep decreases of the wind turbine power output should not be requested by pitch control, which means that high gain droop constant values above 1.5 should be avoided.

The rotor speed is restored back to its optimal value for the given wind speed conditions after the necessary reserves have been provided by means of the recovery controller that releases the kinetic energy that has been stored in the rotating masses during the frequency response. Normal pitch control also restored the pitch angle back to a zero value, after the necessary reserves have been provided and thus the rotor speed started to decrease below its maximum allowed value (activation point of pitch control).

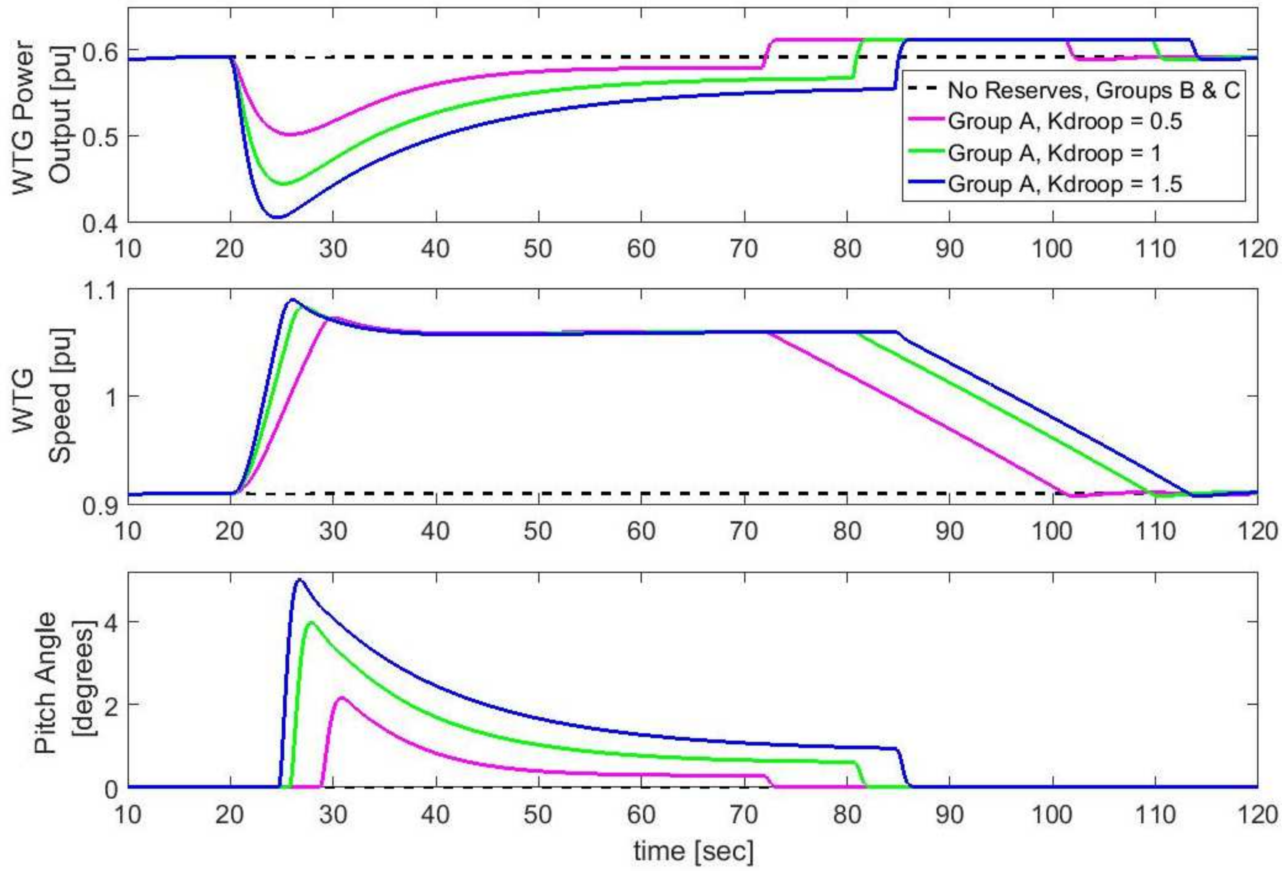

Figure 57: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load decrease of 10% of the base load, Sensitivity Analysis for K_{droop}.

Comparison of different strategy scenarios

With the implemented control design two ways to use the wind turbines available within the wind farm are possible. One is to tune them all in the same way so that they can simultaneously provide the necessary reserves according to the frequency deviation and the second is to arrange them in groups. The second strategy is basically beneficial for provision of positive reserves to achieve a more sustained response under various wind speed conditions. However, the duration of the frequency response provided is not a problem during the provision of negative reserves. Thus, it is important to compare these two strategies to see what we lose in terms of possible reserves that could be provided if we always arrange the wind turbines in groups. The depicted scenarios are:

- <u>Base Scenario:</u> No frequency response is provided by the wind farm.
- <u>Scenario 1:</u> All wind turbines are tuned in the same way.
- <u>Scenario 2:</u> The wind turbines are arranged in 3 groups, with 60 wind turbines assigned to Group A, 40 to Group B and 20 to Group C.

For the frequency deviation, the load is decreased by 10% of the base load at $t_{dis} = 20\ sec$ in all cases. The gain droop constant is set to one for both scenarios.

The benefit of the frequency response for the defined scenarios, as well as the effect of the recovery period on the grid frequency, are depicted in Figure 58.

As expected, in the case of negative reserve provision arranging the wind turbines in groups results in significant decrease of the reserves provided from 60 to 42 MW. This however can be easily solved by assigning increased gain droop constants (up to 1.5) for negative reserve provision. It is though important to observe that for increased gain droop constant values equal to 1, when the wind turbines are tuned in the same way, they also recover simultaneously thus causing a quite significant second over-frequency deviation comparable with the first one. This problem could however be resolved by arranging the wind turbines in groups that all obtain a *FLAG* parameter value equal to 1, with different delay times, that will cause the different groups to recover at different time points.

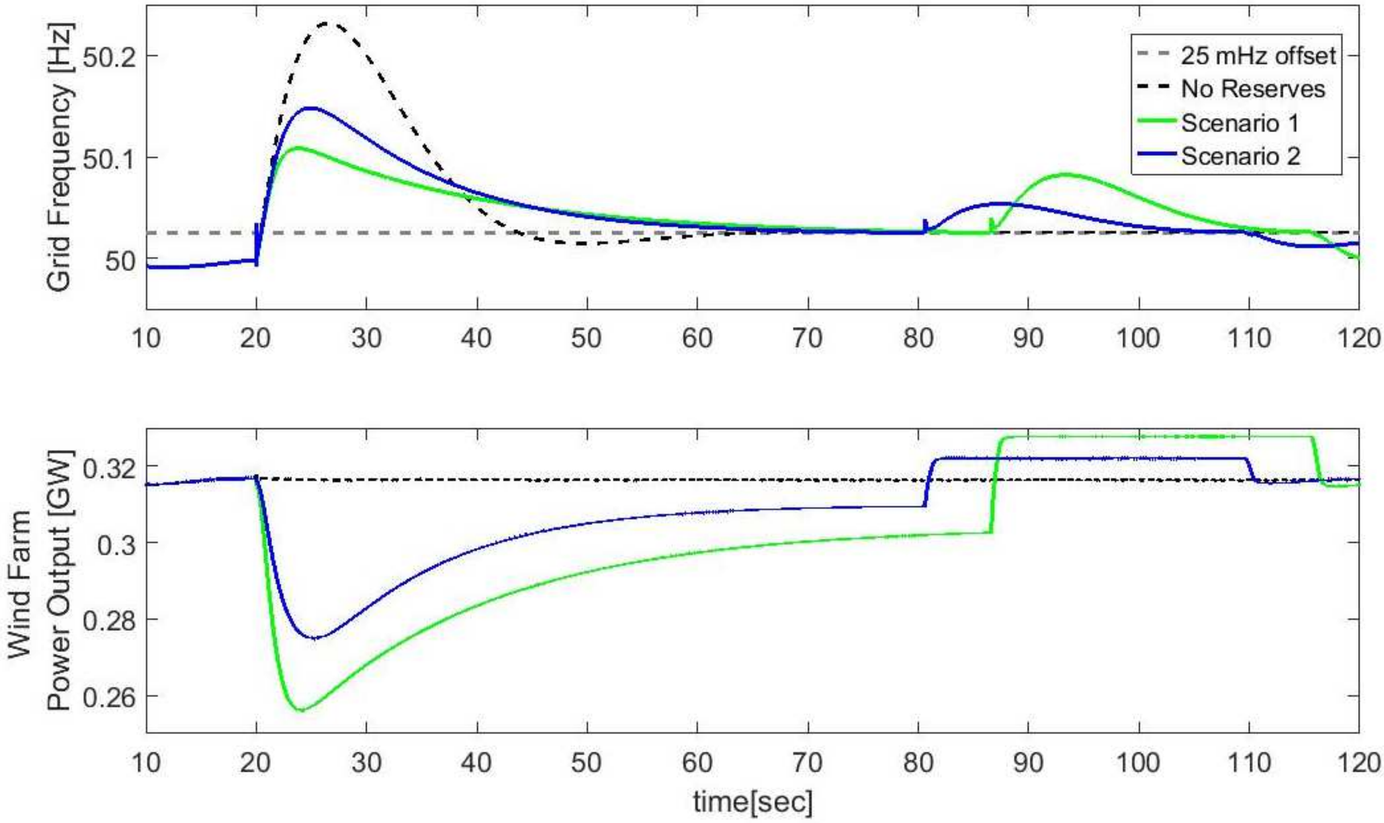

Figure 58: Comparison between the two different strategies

Alternatively, the kinetic energy stored in the rotating masses to provide the necessary negative active power reserves could be kept as reserves to support an under-frequency deviation that may follow. If increasing wind speed conditions occur before that, the surplus power will simply be discarded by means of the pitch control. Moreover, if the wind speed conditions decrease the surplus kinetic energy could also be used so that the wind turbine continues to provide the same amount of power (thus benefiting the amount of electricity sold to the grid), even though less energy is available in the wind. This would cause the rotor speed to start decreasing until it is restored to the optimal value for the sensed wind speed conditions. The normal control which follows the maximum power point tracking principle can then take over. This would however require a more sophisticated control design, which falls outside of the scope of this project.

Table 11: Performance Indicators for comparing the different control strategies.

Preformance Indicators	Investigated Scenarios		
	Base Scenario	Scenario 1	Scenario 2
Frequency Peak [Hz]	50.232	50.108	50.148
Improvement in the	-	124	84

Frequency Peak [mHz]			
FSO interrupted due to limitations	-	NO	NO
Duration of rotor recovery [sec]	-	29	29
Frequency Peak during the rotor recovery [Hz]	-	50.082	50.054
Duration of FSO [sec]	-	67	61
ROCOF [Hz/sec]	0.036	0.018	0.025
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	60 (10%)	42 (7%)

6.4 Case Study 4: Over-frequency deviation under above rated wind speed conditions

The support of an over-frequency deviation under high wind speed conditions can probably be considered the most straightforward situation. Not only no limitations exist in providing the necessary reserves in such a case, but also the recovery of the rotor (if required) is undertaken by normal pitch control and thus the power output of the wind turbine is not affected.

The only interesting point to discuss constitutes the slower action of pitch control which could temporarily result in over-speeds above 10% of the rated speed if a significant amount of reserves is suddenly requested that needs to be facilitated by means of pitch control. Such a situation though would only occur for increased gain droop constant values.

Thus, a sensitivity analysis for the severity of the frequency deviation and a gain droop constant sensitivity analysis have been performed to test the performance of the controller and to use the simulation results to specify the allowable range within which the gain droop constant parameter can be varied.

Sensitivity Analysis for the severity of the frequency deviation

A sensitivity analysis for the severity of the frequency deviation has been performed for different events (5%, 7% and 10% decrease of the load) at $t_{dis} = 20\ sec$ to test the response of the controller under the different events and to observe the benefit on the grid frequency. The simulation results are depicted in Figure 59.

In all cases, the controller has provided all reserves requested, while the frequency supporting operation of the wind farm only stopped when the frequency had sufficiently restored with only an offset of 25 mHz remaining according to the controller design.

The peak on the grid frequency has been significantly improved and held within the allowable boundaries. The improvement in the frequency peak ranges from 24 to 48 mHz and the total reserves provided range from 12 to 24

MW, with more reserves provided in more severe frequency deviations resulting in more significant improvements in the frequency peak. In all cases the ROCOF has also been smoothened.

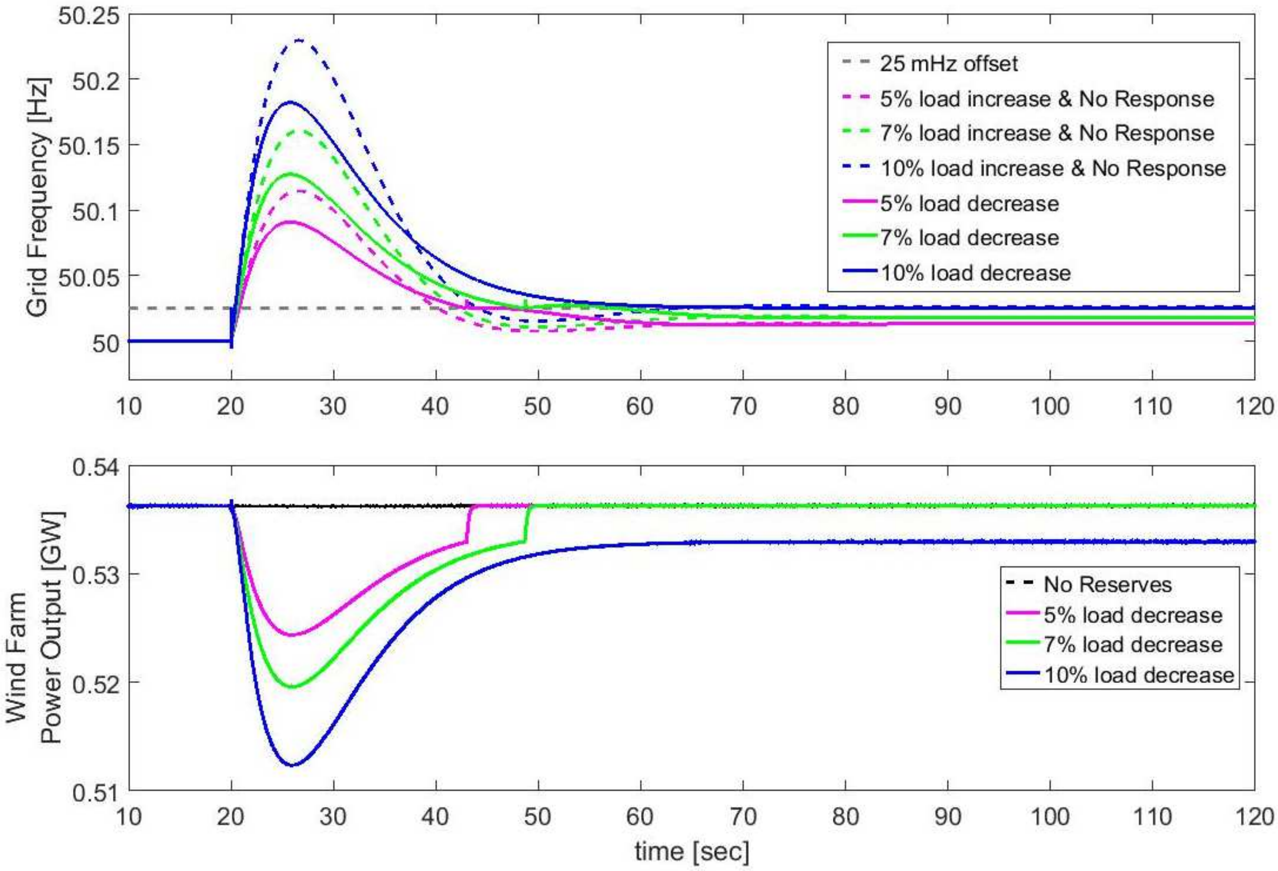

Figure 59: Sensitivity Analysis for severity of the frequency deviation sensed and the impact on the grid frequency as well as on the wind farm response.

Table 12: Performance Indicators for the severity of the frequency deviation.

Preformance Indicators	No Response from the Wind Farm ($K_{droop} = 0$)			With Frequency Support from Wind Farm ($K_{droop} = 0.5$)		
Load Decrease [%]	5%	7%	10%	5%	7%	10%
Frequency Peak [Hz]	50.114	50.161	50.230	50.091	50.127	50.182
Improvement in the Frequency Peak [mHz]	-	-	-	24	34	48
FSO interrupted due to limitations	-	-	-	NO	NO	NO
ROCOF	0.018	0.025	0.036	0.016	0.022	0.031
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity	-	-	-	12 (2%)	16 (2.67%)	24 (4%)

(600 MW)						

The wind turbine generator speed and power output as well as the pitch angle of a single wind turbine of each group, for the different load events tested is depicted in Figure 60.

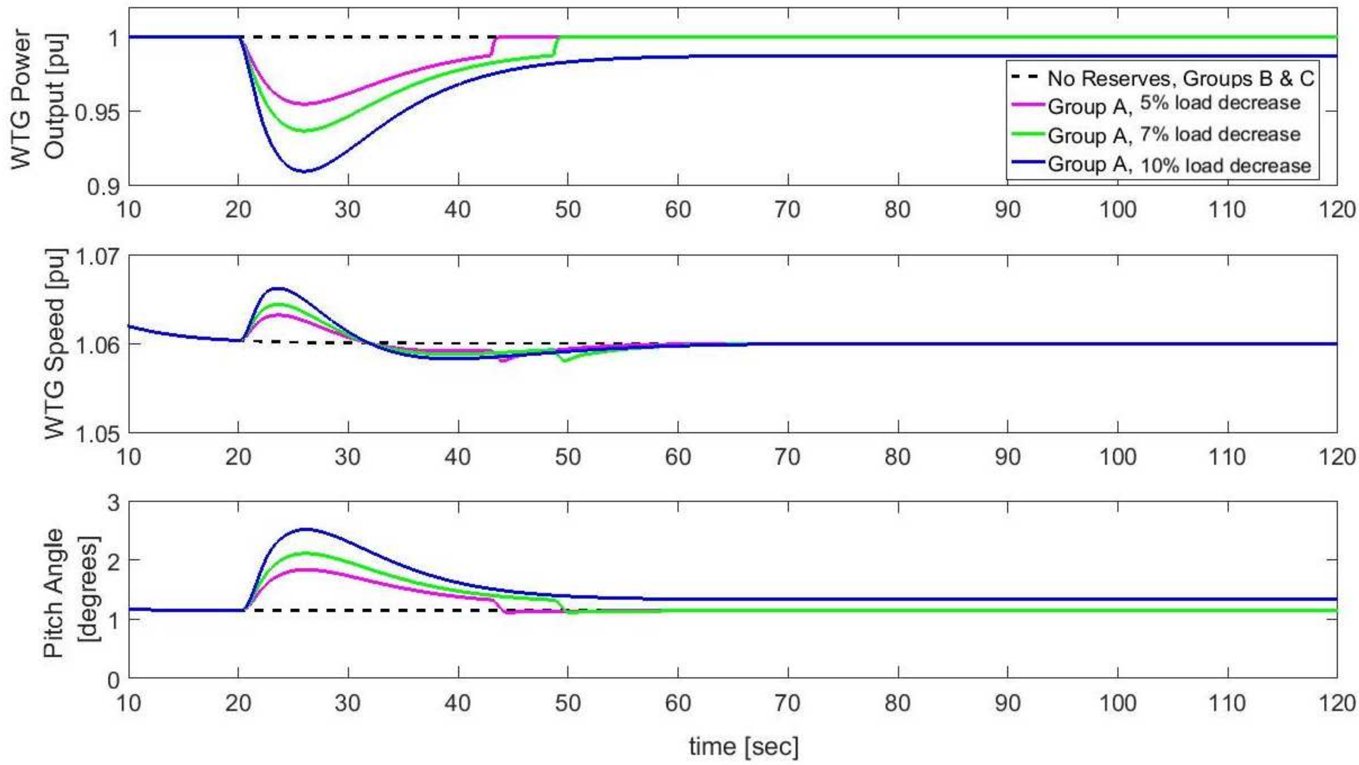

Figure 60: Sensitivity Analysis for severity of the frequency deviation sensed and the Wind Turbine Generator Speed and Power output, and on the Wind Turbine pitch angle, for one Wind Turbine of each group, with K_{droop} set to 0.5.

Only Group A is of interest in this case as the rest of the groups are not participating in frequency support. It can be observed that the power output of the wind turbines is sufficiently reduced through increasing the pitch angle, thus resulting in discarding the surplus power by means of pitch control.

An increase of the pitch angle of less than 2 degrees is in all cases sufficient for providing the requested reserves. The rotor speed is slightly increased before pitch angle obtains the required value because pitch control is mechanically activated and is thus slow. The rotor speed is restored back to its optimal value at the end of the frequency response by means of the normal pitch control. In all cases, the increase of the rotor speed was less than 0.01 pu.

Sensitivity Analysis for the gain droop constant

A sensitivity analysis of the gain droop constant $\mathrm{K_{droop}}$ has been carried out during a 10% load decrease that occurs at $t_{dis} = 20\ sec$. The impact of the frequency response for different values of the gain droop constant is depicted in Figure 61.

The improvement on the frequency peak ranges from 48 mHz to 103 mHz, while the maximum reserves provided range from 24 to 50 MW for increasing values of the gain droop constant K_{droop} from 0.5 to 1.5. The response provided stopped only when the frequency had been sufficiently restored with only the offset of 25 mHz remaining.

The frequency peak is significantly improved however, the frequency event lasts longer when the wind farm provides a frequency response. Moreover, for increased values of the gain droop constant a second (much less severe) over-frequency deviation occurs the moment that the wind farm stops providing reserves. The benefit on the ROCOF increases with the gain droop constant.

Finally, when providing negative reserves it is always important to consider that such a response is accompanied by economic losses due to the amount of power that will not be produced and thus not sold as electricity to the grid during the over-frequency deviation. Hence, an important factor to consider is the price of the electricity in comparison with the price of the reserves provided and the frequency with which over-frequency events typically occur.

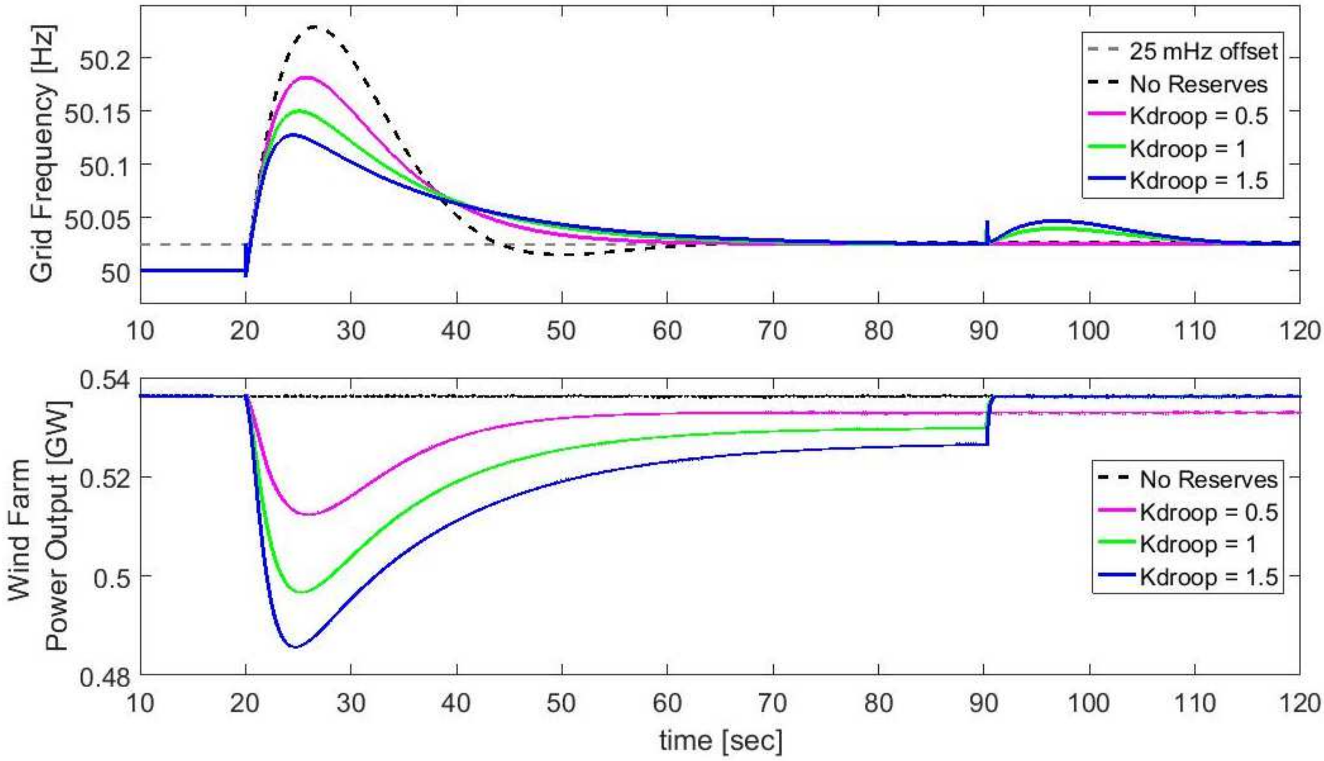

Figure 61: Grid Frequency and Wind Farm Active Power Injection at the Point of Common Coupling (PCC) during a load increase of 10% of the base load, Sensitivity Analysis for K_{droop}.

Table 13: Performance Indicators for comparing the different gain droop constant values.

Preformance Indicators	Gain Droop Constant Values			
	$K_{droop} = 0$	$K_{droop} = 0.5$	$K_{droop} = 1$	$K_{droop} = 1.5$
Frequency Peak [Hz]	50.230	50.182	50.150	50.127
Improvement in the Frequency Peak [mHz]	-	48	80	103
Duration of Frequency Deviation [sec]	24	56	62	68
FSO interrupted due to limitations	-	NO	NO	NO
ROCOF [Hz/sec]	0.036	0.031	0.025	0.022

Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	24 (4%)	39 (6.5%)	50 (8.33%)

The wind turbine generator speed and power output as well as the pitch angle of a single wind turbine of each group for the different load events tested is depicted in Figure 62.

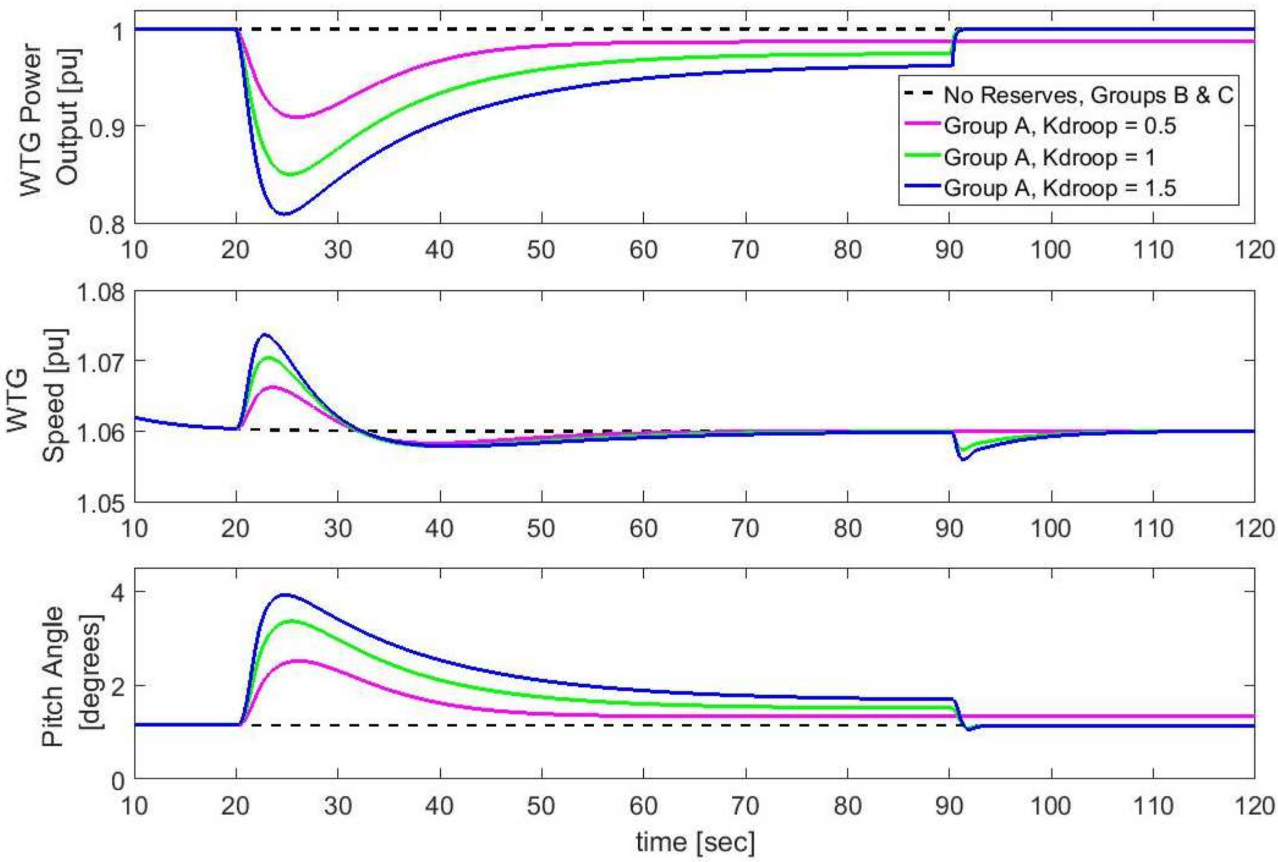

Figure 62: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load decrease of 10% of the base load, Sensitivity Analysis for K_{droop}.

Only Group A is of interest in this case as the rest of the groups are not participating in frequency support. It can be observed that the power output of the wind turbines is sufficiently reduced through increasing the pitch angle, thus resulting in discarding the surplus power by means of pitch control. A further increase of the pitch angle of less than 2 degrees is in all cases sufficient for providing the requested reserves.

The rotor speed is slightly increased before pitch angle obtains the required value because pitch control is mechanically activated, and is thus slow. The rotor speed is restored back to its optimal value at the end of the frequency response by means of the normal pitch control. For increased gain droop constant values the rotor speed deviates more from its normal value for the given wind speed conditions due to the slow action of pitch control and thus increased gain droop constant values should be avoided.

Comparison of different strategy scenarios

With the implemented control design two ways to use the wind turbines available within the wind farm are possible. One is to tune them all in the same way so that they can simultaneously provide the necessary reserves in proportion to the frequency deviation and the second is to arrange them in groups.

The second strategy is basically beneficial for provision of positive reserves as it achieves a more sustained response under various wind speed conditions. However, the duration of the frequency response provided is not a problem during the provision of negative reserves. Thus, it is important to compare these two strategies to see what we lose in terms of possible reserves that could have been provided if we always arrange the wind turbines in groups. The depicted scenarios are:

- Base Scenario: No frequency response is provided by the wind farm.
- Scenario 1: All wind turbines are tuned in the same way.
- Scenario 2: The wind turbines are arranged in 3 groups, with 60 wind turbines assigned to Group A, 40 to Group B and 20 to Group C.

For the frequency deviation the load is decreased by 10% of the base load at $t_{dis} = 20\,sec$ in all cases. The gain droop constant is set to one for both scenarios.

The impact of the frequency response for the defined scenarios as well as the effect of the recovery period on the grid frequency are depicted in Figure 63.

As expected, in the case of negative reserve provision arranging the wind turbines in groups results in significant decrease of the reserves provided from 58 to 39 MW. This however can be easily solved by assigning increased gain droop constants (up to 1.5) for negative reserve provision.

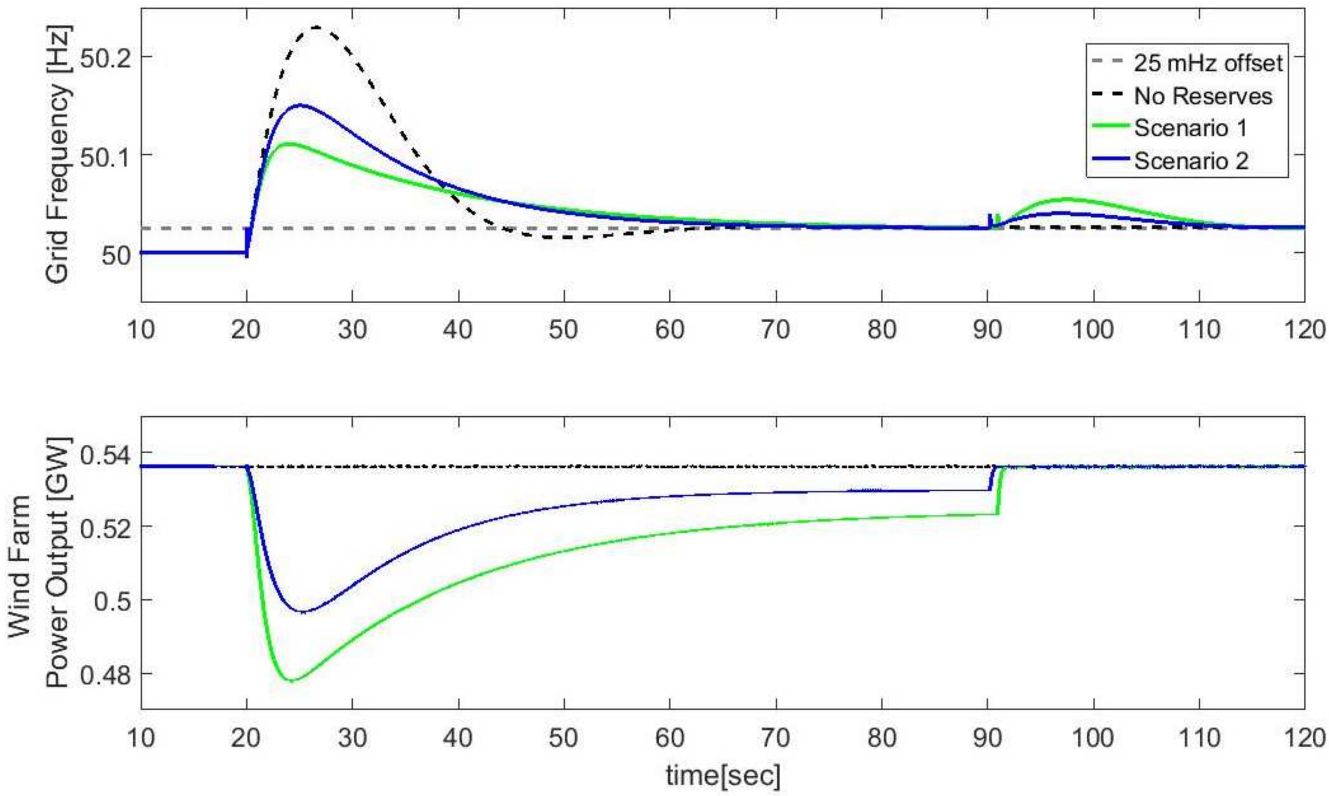

Figure 63: Comparison between the two different strategies.

Table 14: Performance Indicators for comparing the different control strategies.

Preformance Indicators	Investigated Scenarios		
	Base Scenario	Scenario 1	Scenario 2

Frequency Peak [Hz]	50.230	50.111	50.150
Improvement in the Frequency Peak [mHz]	-	119	80
FSO interrupted due to limitations	-	NO	NO
Duration of FSO [sec]	24	71	70
ROCOF [Hz/sec]	0.036	0.019	0.025
Maximum Reserves Provided by Wind Farm [MW] and in % of the total installed Wind Farm capacity (600 MW)	0	58 (9.67%)	39 (6.5%)

6.5 Lessons Learned

From the simulation results important lessons learned have been captured regarding the correct parameter settings in the implemented controller. These also provide meaningful information regarding the capabilities of the wind turbine technology in terms of frequency support, and are thus summarized in this section.

First of all, it is important to point out that the implemented controller has been designed with first priority to respect the identified limitations. No limit violations, such as aerodynamic stall or extreme overloading of the converter have occurred in any of the performed simulations. However, it is important to vary the wind farm controller parameters only within certain ranges. In this way, unwanted situation, such as very short responses from the wind farm due to limited kinetic energy available in the rotating masses or over-speeds due to steep decreases of the power output that need to be facilitated by means of pitch control, can be avoided.

To this end, the following guidelines are provided as *"lessons learned"* from the simulation results:

1. The *gain droop constant* $\boldsymbol{K_{droop}}$ $[\mathbf{1/Hz}]$ constitutes the parameter that controls the amount of reserves provided by a single wind turbines in the presence of a frequency deviation. The appropriate setting of this parameter value plays an important role, since it will determine the bid size offered to the market. Increased values of this parameter under low wind speed conditions may result in a frequency response shorter than desired.

   Typical values of this parameter range from 0 (no response) to 1.5, with different values leading to optimal results depending on the wind speed conditions and the type of frequency deviation (under-frequency or over-frequency event).

   More specifically, the higher values of this range are only suitable for negative reserve provision. The highest value of 1.5 is boundary, as it can already result in over-speeds as high as 10% above the nominal value. Thus, a value up to 1 is recommended for negative reserve provision, if de-coupled products are available in the market for positive and negative reserves. Only if positive and negative reserves are provided as different products is it possible to assign high gain droop constant values to the controller for negative reserves provision (such as 1). Such high gain droop constant values should not be used for positive reserve provision, since they may cause much shorter responses in the case that low wind speed conditions occur.

If positive and negative reserves need to be provided in one symmetric product, the choice of the gain droop constant should be determined according to the worst-case scenario. This is the provision of positive reserves under below rated wind speed conditions.

For low wind speed conditions, if all wind turbines are simultaneously used for reserve provision, a gain droop constant value around 0.25 or lower is recommended. If the wind turbines are arranged in three groups (as presented in the simulation results) a value of around 0.4 or lower is recommended to achieve a similar frequency nadir and a frequency response with duration of around 30 seconds.

Even though frequency deviations more severe than 200 mHz occur, the participation in the ancillary service market would require from the participant to be able to provide the active power product with the same duration under more severe frequency deviations as well. In such a case, the gain droop constant value needs to be further reduced, to a value around 0.25 for the case that the wind turbines are arranged in groups. The simulation results for this gain droop constant value resulted in a maximum of 14 MW provided as reserves to the load (after the losses in the transmission system). This corresponds to 2.33% of the total installed capacity, but considering the amount of power actually generated under this wind speed conditions, the amount of reserves provided corresponds to 4.43%.

For lower wind speed conditions below 9 m/s (for the used wind turbine design), reserves should not be provided, since the available kinetic energy is very limited. Thus, a second quite severe deep in the frequency may occur due to the very short response provided by the wind farm, that will cause the recovery period to take place before the frequency having sufficiently restored. For even lower wind speed values, very close to the cut-in wind speed value, that correspond to a wind turbine generator power output below 0.35 pu the controller already does not allow the provision of reserves, to avoid causing aerodynamic stall.

If higher wind speed conditions are expected, according to the mean wind speed value of a certain wind farm, and with relatively low turbulence values (for decreased risk of non-availability), then slightly increased gain droop constant values could be used. However, in such a case it becomes essential to arrange the wind turbines in groups, due to the time limitation that needs to be respected. In this way, even when the converter is over-loaded, the maximum junction temperature that the semiconductor devices can withstand is not exceeded.

In general, it can be concluded that the appropriate values of the gain droop constant should be decided according the wind speed conditions expected for a certain wind farm and the market design (symmetric or de-coupled products for positive and negative reserves, duration of response, availability requirements, etc.). Thus, general conclusions are difficult to be made.

2. The ***time period*** $\boldsymbol{\Delta t_{release}}$ $[\boldsymbol{sec}]$ *represents the time-period within which the kinetic energy of the rotor will be released*, in case that an under-frequency deviation occurs under low wind speed conditions. In such a case, the kinetic energy stored in the rotating masses is used as a mechanism to satisfy the necessary positive active power reserves. This parameter is basically used to calculate the limit that ensures that aerodynamic stall does not occur.

   Typical values for this parameter range from 2 to a few seconds. Small values will result in releasing an important part of the available kinetic energy that can be safely released fast and may cause short responses from a single wind turbine. However, if increased values are assigned to this parameter, the provided reserves will be restricted in order for the available kinetic energy to be steadily released.

It is considered more beneficial for the grid frequency to provide the necessary reserves during the first few seconds to improve the frequency nadir. Thus, it is recommended that this parameter is set to 2 seconds, as suggested also in [13]. A more sustained response can still be achieved by imposing decreased gain droop constant values or by arranging the wind turbines in groups.

3. The ***time limit*** $\boldsymbol{T_{FSO}}[\boldsymbol{sec}]$ represents the *time limit that needs to be imposed to the duration of the Frequency Supporting Operation (FSO) of the wind turbine, in case the active power injection of the wind turbine exceeds its rated power output.* In this way, overheating the semi-conductor components of the converter due to the increased currents flowing can be avoided.

   Typical values for this parameter range between 10 and 15 seconds, while increased values should in any case not be assigned in this control design. Increased time limit values without additional safety measures may result in overheating the converter components above the maximum junction temperature.

   For this study, a conservative time limit of 10 seconds has been imposed to ensure that the suggested design respects the maximum junction temperature limit that the semiconductor devices within the converters can withstand. However, due to the low gain droop constant values that can only be assigned to the controller for positive reserve provision, the converters are not overloaded more than 10% in any of the performed simulations. This limit is much lower than the 25% limit that has been imposed in the control design.

   Since the temperature increases with the power (and thus the current) that flows through the converters as well as with time, the temperatures are not expected to increase substantially. Hence, if accurate temperature measurements were available, it is expected that longer durations could be achieved for positive reserve provision above the rated power output of the wind turbine generator.

   If temperature measurements are available, then this limit could be replaced by a control design that would stop the provision of reserves when the measured temperature would approach close to the maximum junction temperature. However, in order to appropriately arrange the wind turbines in groups to achieve a response with the desired duration, it is important to be aware of the time period for which positive reserves can be provided under such conditions.

4. The ***delay time*** $\boldsymbol{T_{delay}}[\boldsymbol{sec}]$, which *represents the time-period for which the recovery of the rotor will be delayed*. The delay of the rotor recovery will only be successful if the rotor speed does not reach its minimum allowed value. In such a case, the recovery of the rotor will be forced to start to avoid aerodynamic stall.

   Typical values for this parameter range from 0 (no delay, immediate recovery) to several seconds. In general, the rotor recovery can be delayed as long as the rotor speed remains above its minimum allowed value. Increased values of this parameter will under no circumstances cause unwanted situations, such as aerodynamic stall, since the recovery of the rotor will in such a case be forced by a different part of the controller.

   It is important to keep in mind that imposing a delay time does not guarantee the delay of the rotor recovery after the provision of positive reserves.

5. The ***saturation limits of the recovery controller*** $\boldsymbol{\Delta P_{recovery_{max}}}[\boldsymbol{pu}]$ ***and*** $\boldsymbol{\Delta P_{recovery_{min}}}[\boldsymbol{pu}]$, obtain a value of a small percentage of the rated power of the wind turbine generator, *by which the active power output of the wind turbine will be increased/decreased during the rotor recovery*, when reserves are provided under low wind speed conditions.

   $\boldsymbol{\Delta P_{recovery_{max}}}[\boldsymbol{pu}]$ represents the power term by which the wind turbine generator power output will be increased during the recovery period of the rotor following an over-frequency deviation, thus when the surplus kinetic energy stored needs to be released.

Typical values for this parameter range from 0.005 to 0.03 pu (0.5 to 3% of the rated power). The low values in this range are beneficial for the grid frequency, since the impact of the recovery period will be negligible. They will however result in much longer recovery periods, for which the wind turbine will not be available to support the grid frequency if another event occurs. Therefore, it is suggested that a value around 0.01 or 0.02 pu (1% or 2% of the rated power) is used.

$\boldsymbol{\Delta P_{recovery_{min}}[pu]}$, represents the power term by which the wind turbine generator power output will be decreased during the recovery period of the rotor following an under-frequency deviation, thus when the kinetic energy that has been released needs to be restored.

Typical values for this parameter range from 0.015 to 0.03 pu (1.5 to 3% of the rated power). Lower values should in any case not be assigned to this parameter, as they may result in aerodynamic stall. The low values within the allowed range will result in a smoother but longer recovery period, while higher values will result in a shorter but more aggressive recovery period. Thus, it is suggested that a value of 0.02 pu (2% of the rated power) is used.

In general, a *trade-off between the aggressiveness and the duration of the recovery period* is observed. The overall goal constitutes to achieve a smoother recovery that can be more easily addressed by conventional generation, with a reasonable duration that is comparable to the duration of the frequency response provided.

Even though a wind turbine with a rated power of 5 MW has been used for the purposes of this project, the controllers are all designed in pu quantities which are afterwards converted to appropriate units. Thus, the control design is not affected by the size of the wind turbine, and could be easily integrated into a wind turbine model of the same type (Type 4) but of different size.

However, it may be the case that different wind turbine modelling principles are used for the controllers of a different wind turbine model. (e.g., maximum power point tracking principle, rotor speed controller, pitch angle controller). It is important to keep in mind that the proposed controller design is appropriate for a wind turbine model that follows the design presented in section 3.3.

Finally, the same frequency and wind farm controller could be used either for an onshore or an offshore application. An AC interconnection is considered in this project in order to account for the losses in the transmission network and to be able to observe the impact on the grid frequency. It is possible to use the implemented frequency controllers with an HVDC interconnection, however adjustments may be required in this case. These may include the frequency measurement that should be taken at the AC side of the network as well as adjustments in the control of the HVDC converters. It is important that the HVDC converter control does not counteract the frequency response provided by the wind farm. A more in depth analysis of the implications resulting from an HVDC interconnection fall outside of the scope of this work.

7. Recommendations at the Ancillary Service Market level

Considering the theoretical analysis and the simulations results, what recommendations can be made at the Ancillary Service Market level with respect to the provision of Ancillary Services by Wind Turbines and Wind Farms?

The fourth research question of this project requires making recommendations to the Ancillary Service Market that will reflect the capabilities of the wind turbine technology regarding frequency support. To this end, both the theoretical analysis conducted in chapters from 2 to 5 as well as the simulation results presented in chapter 6 are used as in input for this step. The active power product that can be provided by the wind turbine technology together with the important technical specifications are described, while important requirements that will encourage the participation of the wind turbine technology are explained.

From the literature review and the simulation results, sufficient evidence has been provided that the provision of frequency support from wind turbines and wind farms is both possible for all modes of operation as well as beneficial for the grid frequency. The benefit on the grid frequency becomes more clear if a scenario of increased wind penetration levels is considered, that would otherwise result in decreased system inertia and insufficient spinning reserves that can cause frequency deviations outside the allowable operation limits.

However, limitations do exist regarding the duration of the response as well as the amount of reserves that can be provided by the wind turbine technology. Moreover, it is not suggested that this technology is used to support the grid frequency at low wind speed conditions close to the cut-in wind speed, as the available kinetic energy stored in the rotating masses is extremely low under such conditions. This increases the possibility of aerodynamic stall or of very short responses, that may in the end not have a beneficial impact on the grid frequency.

The existing frequency control mechanisms in the German ancillary service market have been described in section 2.2, and are summarized here:

- Primary Control Reserve (Frequency Containment Reserve)
- Secondary Control Reserve (Frequency Restoration Reserve)
- Minute Reserve (Restoration Reserve)

Inertial Response is another frequency control mechanism provided by synchronous generators. However, such an option is not available in the German ancillary service market, as the European interconnected power system has sufficient amount of inertia at the moment. Nevertheless, requirements for inertia control by wind power plants have started to be implemented in Spain, Ireland and Denmark, where low inertia situations have already started to occur. Moreover, implementing the necessary control equipment in Wind Power Plants that will allow for provision of active power reserves in the presence of a frequency deviation is also recommended by ENTSO-E [35].

From the available frequency control mechanisms the ones of interest for wind power plants to participate are the ones that provide a fast frequency response, thus inertial response and frequency containment reserves. This is because wind turbines can only provide transient responses. The provision of more sustained responses, if possible in large wind farms with many wind turbines, will result in significantly decreased amount of reserves provided during the first few critical seconds following a frequency deviation.

However the Primary Control Reserve option currently available within the German Ancillary Service Market requires a duration of 15 minutes. Such a sustained response cannot be achieved by the wind turbine technology, unless high wind speed conditions are guaranteed, which is not possible.

The critical situation that may occur in the future regarding frequency control under increased renewable penetration levels, is a situation where the weather conditions at a certain point in time allow for RES to contribute to a substantial amount of the load. Thus, conventional generation will not be satisfying an important part of the load at that time. In case a frequency event occurs under such conditions, sufficient response from conventional power plants may not be available to maintain the frequency within the desirable boundaries. This may result in violation of the power system operational limits.

However, conventional generation can take over the support of frequency in time, and since it is considered a more economical way to provide ancillary services, especially for longer responses, there is no necessary for wind power plants to provide sustained responses. It is though important that the wind power plants satisfying the load the moment that an event occurs are enriched with the necessary controllers to be able to assist to frequency support during the first few critical seconds following a disturbance.

The options currently available in the Ancillary Service market do not however offer an appropriate “Fast Frequency Response” option for wind power plants to participate. Such increased RES penetration levels that would result in frequency stability issues are generally not encountered in the European interconnected network. Sufficient system inertia is currently available. Thus, the current options mostly represent the capabilities of conventional power plants, or other new technologies such as storage and not of wind power plants.

A significant change in the market design in terms of fast frequency response services is not expected earlier than 2050. However, incentives for provision of such services can be expected in the future [35]. A possible scheme could be similar to the one used for the provision of Frequency Containment Reserves (Primary Control Reserves for the German ancillary service market), with an activation time less than 30 seconds and increased flexibility.

Important suggestions at the Ancillary Service Market level, based on the simulation results and the theoretical analysis regarding the capabilities and limitations of the wind turbine technology, are presented in the following paragraphs.

Fast Frequency Response (FRR) option

In total, the most important restriction when it comes to reserves provision from the wind turbine technology, constitutes the duration of the response provided. A trade-off is observed between the *amount of reserves* that can be provided and the *duration* for which they can be maintained.

After a certain point, maintaining the response provided for a longer time-period (e.g., for a few minutes), will result in significant reduction of the amount of reserves that can be provided. This will also reduce the economic benefit that can be achieved for the wind power plants providing this service to the ancillary service market. Moreover, in an increased RES penetration level scenario, such as the one that is considered in this study, the critical situation will is the reduction of the frequency nadir that occurs. Afterwards other means of frequency support can take over which can provide a more sustained response but need more time to be activated.

The wind turbine technology can start providing the necessary reserves quite fast, within milliseconds, and thus it can assist to frequency support during the first few critical seconds that determine the severity of the disturbance. The option of Primary Control Reserve that is currently available within the German Ancillary Service Market entails an activation time of 30 seconds. Thus, it is logical that a Fast Frequency Response service or Inertial Response service required from the wind turbine technology will be required to last at least 30 seconds. Within these 30 seconds the primary control reserves will be fully activated, and will take over the frequency support. The activation time can be considered less than 1 second.

A duration of one or two minutes could possibly be achieved, however it would result in a significant decrease of the reserves provided, thus it is not suggested by this study. Moreover, the risk of non-availability would be higher in such a case, in case of decreasing wind speed conditions.

Another important point to discuss constitutes the way in which the rotor recovery will be handled. Considering the simulation results, it is recommended to allow 1-2 minute breaks in between the cycles of Fast Frequency Reserves provision. During these breaks the rotor recovery can take place, if necessary.

Additionally, the maximum allowed deviation from the normal power output during the recovery period needs to be specified to prevent a more severe frequency deviation during the rotor recovery. It is recommended that the power output of a single wind turbine generator is allowed to increase or decrease by 2% of its rated power output. This will allow for a quite smooth recovery with a duration that will not exceed 1 or 2 minutes maximum. A limit of the rate of change of the wind farm power output could also be provided as a technical specification of the offered options in the ancillary service market to avoid steep increases or decreases of the provided power term.

Moreover, it can be requested that the frequency controller within the wind turbines is able optimize the recovery period for smoother recoveries to be achieved, if possible. This is however dependent on the wind speed conditions and the severity of the frequency deviation that may vary and can thus not be controlled. Therefore, it is not realistic to further specify the product provided by wind power plants according to such a strict rule. It could however be included as a condition to which the market participants need to comply.

The described Fast Frequency Response service is depicted in Figure 64.

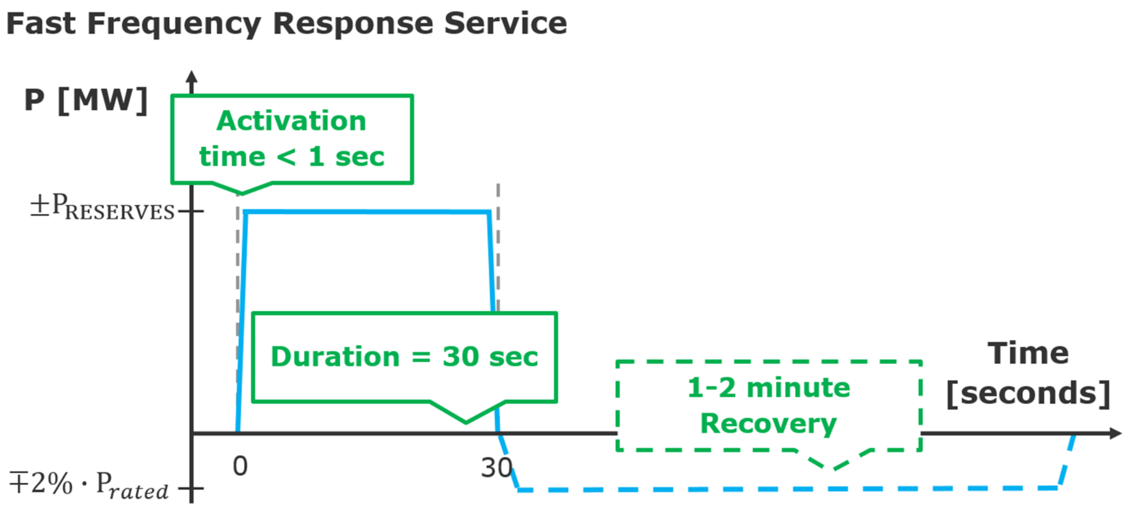

Figure 64: Fast Frequency Response service.

Daily tenders

Within the available options in the German ancillary service market, the ones that concern the provision of Frequency Containment and Frequency Restoration Reserves are provided in weekly tenders. Only the provision of Restoration Reserves is facilitated in daily tenders. However, RES highly depend on accurate weather predictions to more accurately specify the amount of reserves that they can provide. Therefore, daily tenders would allow them to participate in the ancillary service market without increased concern of strict fines in case of non-availability, due to unexpected change in the wind speed conditions. Thus, daily tenders are recommended for the proposed Fast Frequency Response service.

Less strict availability requirements & non-availability penalties

Within the German ancillary service market, 100% availability is required from the participants. This constitutes an important barrier for RES, due to their dependence on weather conditions. As a result, the participation of a wind power plant may be highly discouraged due to the high fines that the owner may be faced with in case of an unexpected change in the weather conditions.

On the other hand, it is important for the technical requirements of the ancillary service market options to ensure the proper operation of the power system in a way that its stability is not endangered. Hence, it is required that the participants are discouraged from frequently interrupting the provided services.

An alternative way for motivating the participants to choose an appropriate bid size that they can sustain for the required time period, could be to separately reward the provided reserves and the availability of the participant. Thus, in a case of interruption of the provided services, the participant would lose money from the payment, rather than being faced with strict penalties.

Finally, the reason behind an non-availability condition should be examined to ensure that all possible measures are taken from the participants to prevent such a situation.

De-coupled positive and negative active power reserve products

The capabilities of the wind turbine technology differ for providing a negative and a positive product to the market. Hence, even though the amount of negative active power reserves that can be potentially provided is generally higher, the amount of positive reserves is in any case limited by the worse-case scenario. This occurs at low wind speed conditions.

Thus, if two separate products are offered for positive and negative active power reserves, the interested participants could separately bid for each one of them with different bid sizes. A lack of sufficient participants for the provision of positive active power reserves, due to the complexity of the controller and the existing limitations, could however lead to increased prices for the positive reserve product in such a case.

8. Conclusions

To conclude, it is possible to use the wind turbine technology to support the grid frequency under all modes of operation (below and above rated wind speed) and for all types of frequency deviations (under-frequency and over-frequency events). Operating the wind turbines at de-loaded power output is not necessary to provide the required reserves. Thus, a frequency response does not have to be accompanied by economic losses due to low electricity generation efficiency.

However, limits of the electrical and mechanical components do exist for the response that can be provided. These need to be respected so that no unwanted situations occur. Overall, the frequency response that can be provided by a wind power plant is considered short. Nevertheless, it can have a positive impact on the frequency nadir and the ROCOF of a frequency deviation.

More detailed answers to the research questions of this project are briefly provided in the following paragraphs, with references to the appropriate chapters that include a more detailed analysis.

What are the required modifications at the Wind System level to enable the provision of Ancillary Services?

The necessary modifications at the wind system level that enable frequency support have been identified and are analytically explained in section 4.2. The key modifications required are in the power electronic converter control loops that allow for the active power reference signal to be appropriately adjusted according to the frequency deviation sensed. These has been successfully integrated within the initial model. The frequency controller design implementation is analytically presented in section 4.4.

In more details, the normal rotor speed controller has been replaced by the frequency controller, which other than the modified rotor speed controller, also includes a reserves and recovery controller. Even though pitch control is also used as a mechanism to provide reserves, modifications at the pitch angle controller are not required. The normal pitch controller will respond as desired when required to achieve the modified active power reference signal sent to the converters through the frequency controller.

Overall, all changes implemented are software oriented, thus no modifications in the hardware of the system are required.

What are the associated limitations for the provision of Ancillary Services by Wind Turbines?

The limitations for frequency support from the wind turbine technology have been elaborated and thoroughly discussed in section 4.3. These are briefly summarized as follows:

- The *power available in the wind*, which is highly dependent on the wind speed conditions.
- The *converter maximum power transfer capability*, which is translated into maximum junction temperature that the semiconductor devices can withstand.
- The *minimum rotor speed* limit, below which aerodynamic stall occurs.
- The *management of the recovery period*, that determines how the wind farm response provided will influence the grid frequency dynamics.
- *The pitch control*, which is considered slow because it is mechanically operated hence very steep decreases of the wind turbine power output should not be requested.
- The *stresses imposed to the mechanical components* due to the excessive use of pitch control for reserve provision or to the loads experienced, that may negatively affect the lifetime of mechanical components, as

well as the *impact on the lifetime of the electrical components*, such as the converters, from continuously overloading them.

- The *time limitation* on the frequency response provided, mostly to ensure that the temperature in the converter components will not in any case increase beyond its maximum allowed value.

From the identified limitations, the ones that could be addressed through the software and model used (minimum rotor speed, aggressiveness of rotor recovery, converter maximum power transfer capability, time limit), have all been considered in the controller design and are in all cases respected. Appropriate ranges of all control parameters are specified. If the settings provided to the controller follow the guidelines, no unwanted situations or limit violations occur (e.g., over-speeds or very short responses) through this control design, since priority is always placed on respecting the limits. For the limits that would require a different type of software (mechanical or thermal oriented) sufficient information has been provided to lay the foundation for future investigation.

What are the associated challenges and arising benefits by the simultaneous provision of Ancillary Services by multiple Wind Turbines in a Wind Farm?

A single wind turbine can only provide very limited reserves (especially when it comes to the positive active power reserves under low wind speed conditions). During a frequency deviation, the total response provided by a wind farm, however, can have a more substantial contribution to the grid frequency.

In order to reveal the potential benefits that arise from multiple wind turbines within a wind farm providing a frequency response as well as to identify the challenges that accompany such a combined response, a wind farm controller has been designed and several simulations have been performed. The wind farm controller and the wind farm topology used for this study are analytically explained in chapter 5. The simulation results performed are presented and discussed in chapter 6. The conclusions from these two chapters are summarized as follows.

The most important *benefits* offered by many wind turbines (more than three) within a wind farm used to support the grid frequency are summarized as follows:

- The *total reserves provided are higher* compared to the single wind turbine case, thus the contribution to the grid frequency can be significant (with appropriate management of the response time). Thus, a sufficient bid size can be achieved to be offered to the ancillary service market. The bid size increases with the installed capacity and the number of available wind turbines within the wind farm. Moreover, the height of the bid size varies according to the expected wind speed conditions (i.e., expected mean wind speed and turbulence within a certain wind farm). The higher the bid size, the more the economic benefits that can be achieved by the product offered to the market.
- A *more sustained response* can be achieved if sequential signals are sent to different wind turbine groups. This allows to deal with the existing limitations of the wind turbine technology. Thus, a more beneficial frequency response can be provided from a wind farm with many wind turbines. The implemented wind farm controller allows for the available wind turbines to be arranged in groups. Thus, a total response that can last 30 seconds becomes possible even under the most critical cases. However, the gain droop constant, and thus the bed size, need to be appropriately adjusted according to the expected wind speed conditions.

The most important *challenges* that are associated with the simultaneous provision of frequency supporting services by multiple wind turbines within a wind farm are summarized in the following:

- The *correct specification of the bid size* according to the worst-case scenario. In this way, a frequency response that cannot be maintained as long as desired due to the limited resources that can be provided as reserves under low wind speed conditions can be avoided.

  In general, the critical cases are the provision of positive active power reserves under below and above rated wind speed conditions.

For above rated wind speed conditions, the limitation constitutes a time limitation to avoid reaching the maximum junction temperature that the semiconductor devices within the converters can withstand. The time limit imposed in this study is 10 seconds, which is considered a conservative limit. If accurate temperature measurements are available, longer responses may be possible. The reason lies in the fact that the converter is usually not overloaded significantly, as the large frequency deviations do not occur often. In any case a frequency response of 30 seconds can be guaranteed with the use of 3 groups.

However, under below rated wind speed conditions, the provision of the necessary reserves entails more risks due to the high dependency on the wind speed conditions. Thus, accurate forecasts become essential, which together with the mean wind speed and the turbulence expected for a specific wind farm, should be used to determine the bid size in a way that the risk of non-availability is limited as much as possible.

- *Imposing the optimal combination of settings for the wind farm controller parameters* to achieve the most beneficial response, according to the option available within the Ancillary Service Market and the expected wind speed conditions.

  The wind farm controller comprises of a number of parameters, whose values can be varied within the specified ranges. Values outside of the allowed ranges may result in unwanted situations and should thus not be used. More details about the correct parameter settings are provided in section 6.5. If the parameter settings follow the specified ranges no unwanted situations will occur. Both the wind turbine as well as the wind farm controller have been designed with priority to respect the existing limitations.

- The choice of a *reasonable number of wind turbines for each group within the wind farm* that will allow for the desirable response from the wind farm in total to be achieved.

  The wind farm controller allows for the wind turbines to be arranged in more than one groups and to be used successively for reserve provision. The number of wind turbines that are assigned to each group can be varied. However, extreme situations where a very low number of wind turbines is assigned to a certain group may have unwanted results in terms of the amount of reserves provided or the duration of the response achieved. Hence, the available wind turbines should be carefully arranged in groups according to the discussion in section 5.2.

Considering the theoretical analysis and the simulation results, what recommendations can be made at the Ancillary Service Market level with respect to the provision of Ancillary Services by Wind Turbines and Wind Farms?

According to the theoretical analysis and the results of the simulations, a number of recommendations were made at the ancillary service market level. These are analytically discussed in chapter 7 and are briefly presented as follows:

- The most appropriate frequency supporting service option to be provided by the wind turbine technology constitutes a *"Fast Frequency Response"* or *"Inertial Response"* option, with a duration of 30 seconds. An activation time of less than one second can be considered.

  Breaks of 1 or 2 minutes should be allowed in between the cycles of reserve provision during which the wind turbines will be allowed to recover, if required. The allowed variance of a single wind turbine generator power output during the rotor recovery should not be more than 2-3% of its rated power, to avoid severe frequency deviations due to the rotor recovery.

  Finally, a limit of the rate of change of the wind farm power output could be provided as a technical specification of the offered options in the ancillary service market to avoid steep increases or decreases of the provided power term.

- *Daily tenders* are suggested, since wind power plants are highly dependent on accurate weather predictions to specify the appropriate bid size.
- *Less strict non-availability penalties* and/or replacement of non-availability penalties by availability payments.
- *De-coupled positive and negative reserve products*.

9. Suggestions for Future Work

The most important points that were considered outside of the scope of this project, but it would be beneficial to be studied by future work, are summarized in the following:

- Include a *wind speed estimator in the controller*. The wind speed constitutes an important parameter of the designed frequency controller, since it is used to calculate the optimal rotor speed value, which is used by the rotor speed controller, as well as for the limits that restrict the reserves provided to respect the identified limitations.

  However, it can be argued that accurate wind speed measurements in reality do not exist. The common practice under normal operating conditions is to use the generator speed measurement as the most accurate indication of the wind speed conditions. In this control design though the kinetic energy stored in the rotating masses is used as a mechanism to provide the necessary reserves to support the grid frequency under low wind speed conditions. Thus, the generator speed deviates from its optimal value. As a result, the measured generator speed is not sufficient to estimate the wind speed conditions. It is however possible to combine measurements of the generator speed, the pitch angle and the active power output of the wind turbine generator to estimate the wind speed conditions. Several wind speed estimators have been suggested by the literature. A wind speed estimator that is similar to the one suggested here is described in the "Wind Energy Handbook" [26].

- *Optimize the parametrization of the controllers* in the model. The PI controllers used in the model have the initial proportional and integral gains that were originally assigned in the initial model, designed by PSCAD. The use of these gains in no case causes the unstable operation of the system. However, certain over-shoots observed in the simulation results could be avoided if the tuning of the controllers is optimized. This may also allow for a smoother frequency response.

  Re-tuning the controllers was not a priority for this project, due to the time that it would require. Thus, it is suggested as future work.

- *Estimate the effect of such a control design on the lifetime of the mechanical (pitch controller) and electrical (converters) components.* Pitch control is mechanically operated, and thus its frequent use for reserve provision will cause changes in the mechanical structure (fatigue) that would reduce its lifetime. Pitch control is already considered a component that requires regular maintenance, especially if used very frequently.

  It is interesting to note that in certain wind turbine designs it is preferred to slightly over-load the generator and the converter through allowing slightly higher generator speed values. As a result the frequency of the pitch control activation can be reduced, which has a positive impact on its lifetime. Thus, for low wind speed variations, the generator speed is not allowed to change.

  When pitch control is used as a mechanism to provide the required reserves, the effect on its lifetime is proportional to the frequency of its usage for reserve provision. However, the balancing product is expected to be less frequent compared to the normal operation of pitch control. Thus, the effect on pitch control is expected to be negligible. Nevertheless, more thorough studies are required to prove this in practice. These are not possible with the software used in this project, and are thus suggested as future work.

  Moreover, more frequently overloading the converter will result in its components experiencing increased temperatures more often. This can also have a negative impact on the converters' lifetime. Thus, further studies are required to more accurately estimate the effect of the implemented controller on the converters' lifetime. This is also considered outside of the scope of this project, and is therefore suggested as future work.

- *More accurately estimate the duration for which the converters can be overloaded to provide positive active power reserves under high wind speed conditions*. In this study, this time limit (T_{FSO}) has been conservatively set to 10 seconds. In this way, it is ensured that temperatures above the maximum junction temperature allowed do not occur.

  Moreover, the converters are in general not overloaded more than 10% in any of the simulation results presented even though a higher limit (25%) has been assigned to the controller. This is not considered a significant increase as it may be even caused during normal operating conditions for certain wind system designs, in order e.g., to avoid frequent use of pitch control.

  The value of this parameter could be probably increased if more detailed studies or research is conducted on the temperatures developed within the converters due to the implemented control design, as well on the properties and technical characteristics of the semiconductor devices. It is possible that the results differ depending on the converters used. Such a study was also not possible with the software used, and is thus considered outside of the scope of this work.

- *Study different possible cooling mechanisms for the converters, following the provision of positive active power reserves under high wind speed conditions, as well as the duration required for sufficiently cooling the converters so that the same wind turbine can be re-used for the same response.*

  The duration required for cooling the converters is an important topic to study. This, together with the duration of the recovery period, determines the required duration of the breaks in between the cycles of reserves provision. If it is concluded that time periods longer than 1 or 2 minutes are required for sufficiently cooling the converters, this may result in long periods of non-availability of the wind turbine to support the grid frequency. The duration for cooling the converter will also depend on the temperatures reached during the period of reserves provision. Such a study was not possible with the software used and it is considered outside of the scope of this project.

- *Adjust the control design to test the response of the controller under real wind speed conditions.* For this project constant wind speed conditions have been considered, which is however not the case in reality. Thus, it would be very useful to study how such a control design would respond to varying wind speed conditions. This is not expected to require significant changes in the control design. Moreover, the control design can then be improved to appropriately manage the recovery period according to the wind speed conditions. Finally, the challenges associated with the rotor recovery under decreasing wind speed conditions can be investigated. It is important to ensure that aerodynamic stall does not occur.
- *Optimize the way in which wind turbines are arranged in groups to achieve a more sustained response.* Through this project, certain guidelines are given regarding some general rules according to which the wind turbines can be arranged in groups. However, it is not considered within the scope of this project to study different scenarios that consider different numbers of wind turbines assigned to different number of groups. Thus, the optimization of the number of wind turbines that should be assigned in each group is suggested as future work.
- *Perform a cost-benefit analysis*. The motivation for providing the necessary active power reserves to support the grid frequency constitutes the economic incentives that can be achieved from such a scheme through the participation in the ancillary service market. Thus, a cost-benefit analysis would be an important study that would determine whether the potential economic benefits are sufficient to overcome the additional

costs. The additional cost could for example include the costs required to enrich the wind systems with the required control design as well as the possibly increased maintenance costs.

Additionally, the results of the cost-benefit analysis could be compared with the results of a cost-benefit analysis for the provision of a "Fast Frequency Reserve" product to the Ancillary Service Market by the storage technology. Storage constitutes another technology used for supporting the grid frequency.

Finally, the combination of the wind turbine technology with storage could be studied to conclude to whether it is economically interesting to add storage to increase the product provided to the ancillary service market.

- *Study the effect of turbulence experienced within a wind farm on the performance of the controller.* Within this study, the wind speed conditions are considered constant. The effect of phenomena such as turbulence caused due to multiple wind turbines operating within a wind farm or due to obstacles are neglected.

  Such type of a study is in any case not possible with the software used and is thus suggested as future work. The wind speed conditions that actually occur within a wind farm constitute quite a complicated topic that deserves closer attention.

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Appendix I: Controller Parameters

Additional information about the design characteristics of the controllers of the implemented model are provided in this Appendix. First of all, all PI controllers used in the model are designed according to the following equation:

$$Output = Input \cdot (K_p + \frac{1}{s \cdot T_i})$$

The gains and limiters for the controllers used (and have not been specified in the previous chapters) are provided in the following table:

Table 15: Controller Parameter Values.

Parameter Values	Controller		
	Rotor Speed Controller	Recovery Controller	Pitch Angle Controller
Proportional Gain K_p	1	1	150
Integral Gain T_i [sec]	2	2	0.04
Maximum Limiter	1 pu	-	27 degrees
Minimum Limiter	0 pu	-	0 degrees
Rate of change limiter	-	0.03 pu	10 degrees

Other than the rate of change limiter imposed to the recovery controller, the rest of the values provided in this table were an input to this project. Thus, these are the values that were already available in the initial model that was used for the project. This model belongs to the library of models provided by PSCAD. The study of General Electric [29] was used as a basis for the design of this model.

Appendix II: Additional Simulation Results for Case Study 1

Sensitivity Analysis for the gain droop constant

The active power output and the speed of a Wind Turbine Generator from each one of the available groups and for the different gain droop constant values, are depicted in Figure 65 , Figure 66, Figure 67 and Figure 68. All the wind turbines that belong to the same group respond in the same way, thus the waveform for only one wind turbine of each group are provided. In all cases, the controller responded successfully and provided the requested reserves, until the moment when the rotor speed approached to its minimum allowed value. Thus, the rotor recovery was forced to avoid aerodynamic stall.

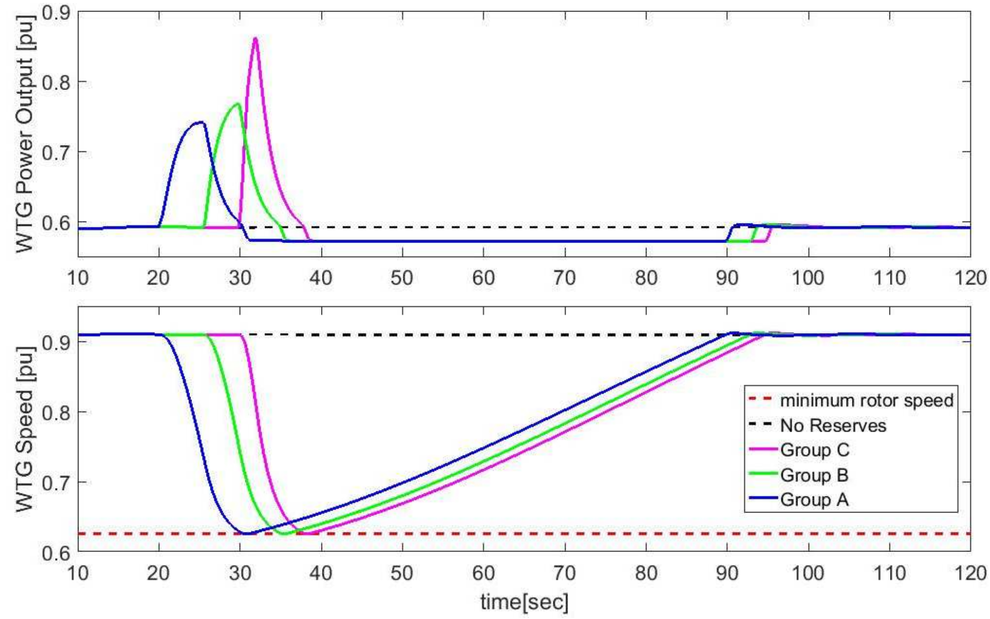

Figure 65: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 10% of the base load, for K_{droop} equal to 1

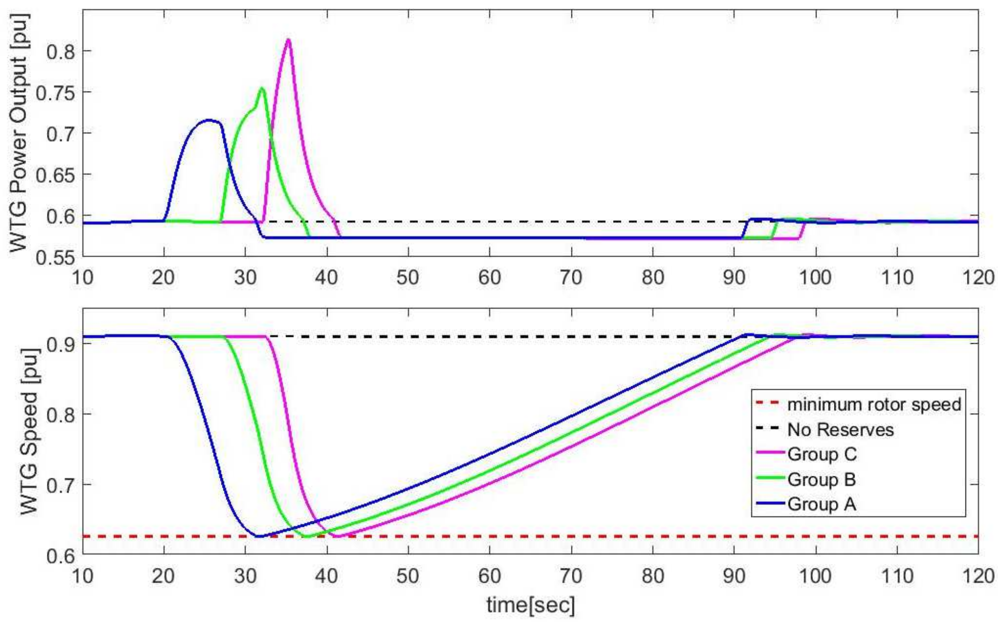

Figure 66: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 10% of the base load, for K_{droop} equal to 0.75.

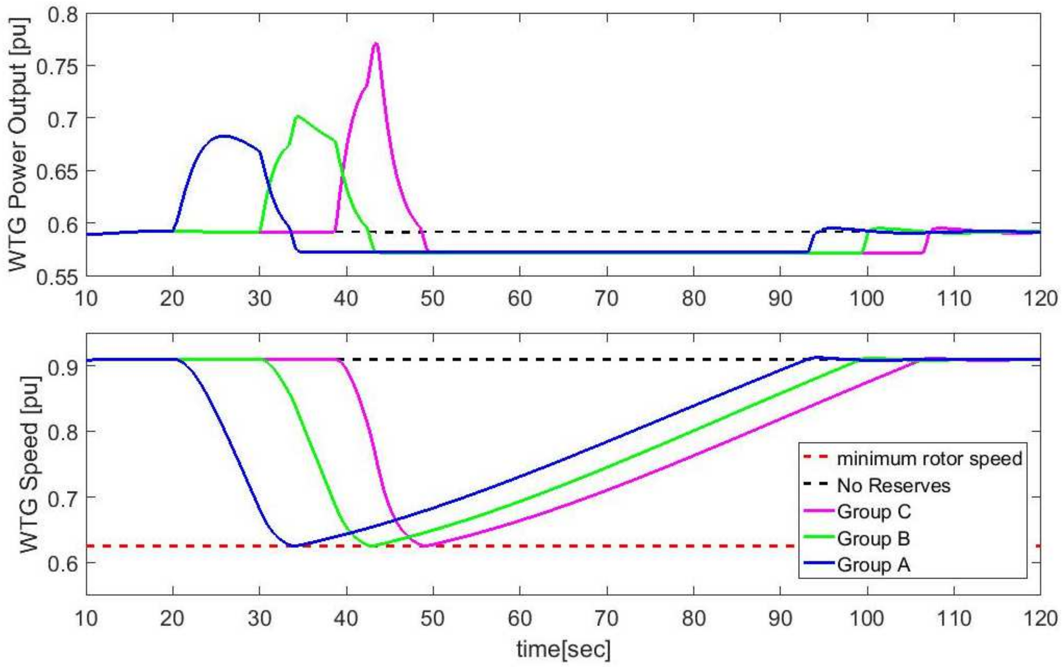

Figure 67: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 10% of the base load, for K_{droop} equal to 0.5.

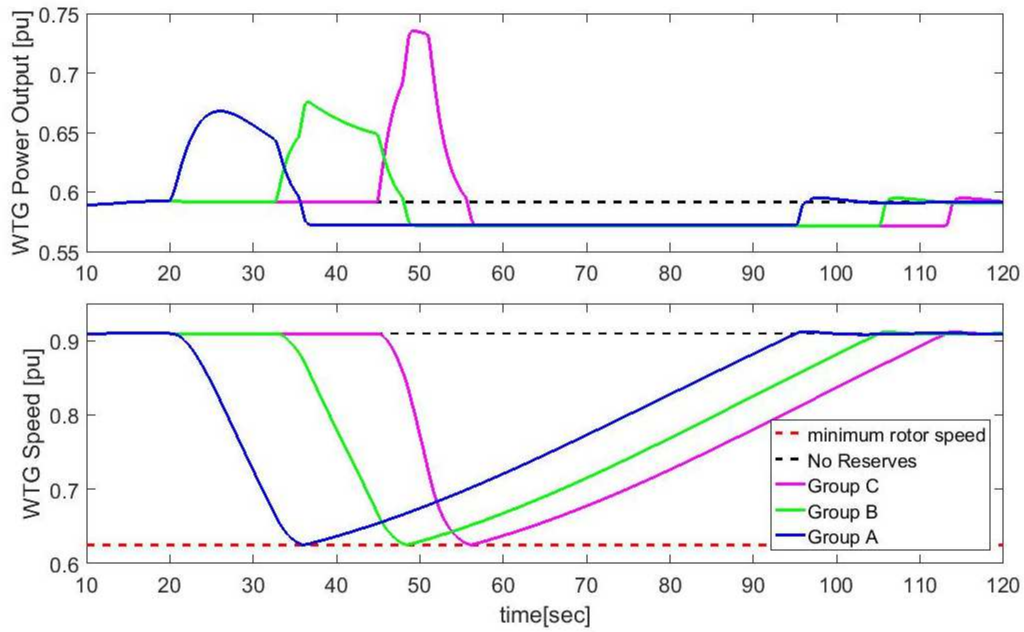

Figure 68: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 10% of the base load, for K_{droop} equal to 0.4.

Importance of managing the recovery period

The active power output and the speed of a Wind Turbine Generator of the wind turbines for the different $\Delta P_{recovery_{min}}$ values are depicted in Figure 69 ($\Delta P_{recovery_{min}} = 0.015\ pu$) and Figure 70 ($\Delta P_{recovery_{min}} = 0.03\ pu$).

It can be observed that the higher the value of $\Delta P_{recovery_{min}}$ the more steep the increase of the rotor speed during the recovery period and the more aggressive and faster the recovery is. For the lowest value of $\Delta P_{recovery_{min}}$ the recovery was not completed within the simulation time.

Values lower than 0.015 pu should in any case not be chosen, since they may result in aerodynamic stall, because not enough power is kept to stop the decrease of the rotor speed and divert it so that it slowly starts increasing. A value of 0.02 pu is suggested since it results in a recovery period of around 60-70 seconds that is smooth enough, without significant differences from the case of 0.015 pu.

The duration of the recovery period should be comparable to the duration of reserve provision (around 30 seconds). Longer recovery periods will result in the wind turbines (or wind farm) not being available to support another frequency deviation that may follow.

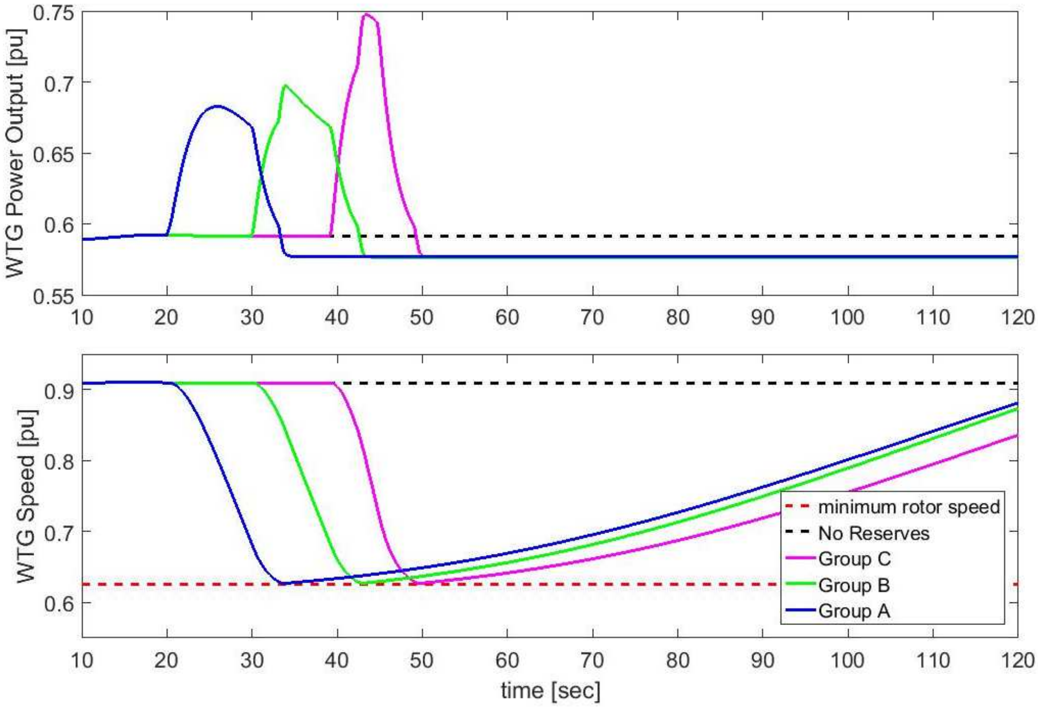

Figure 69: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 5% of the base load, for$\Delta P_{recovery_{min}}$ equal to 0.015.

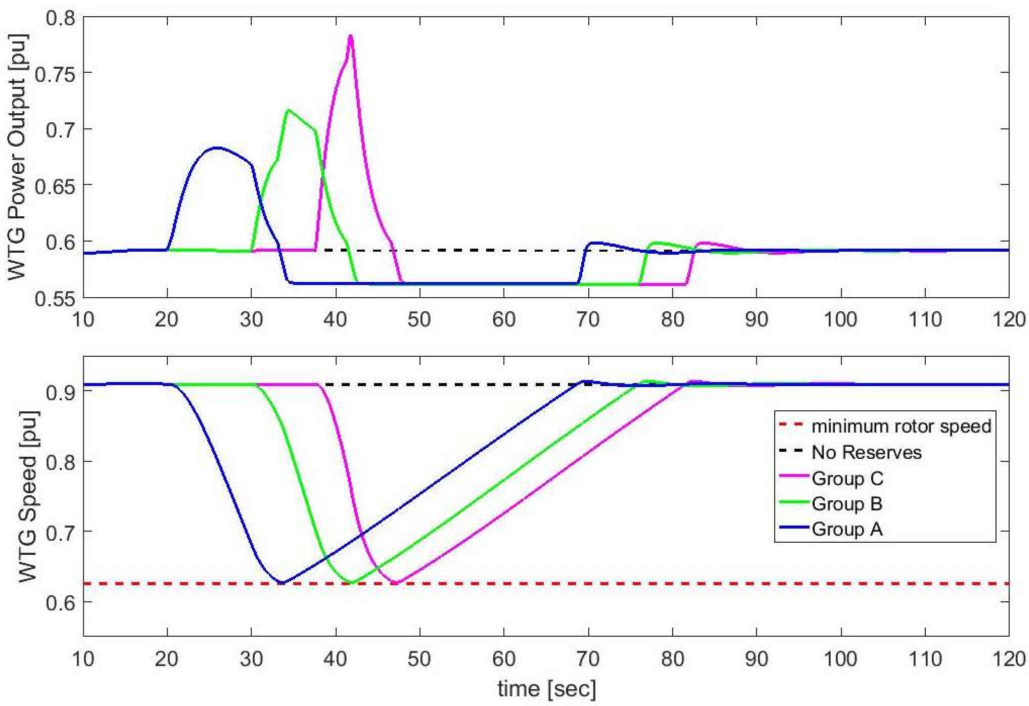

Figure 70: Active Power output and Speed of a single Wind Turbine Generator of Groups A, B and C during a load increase of 5% of the base load, for$\Delta P_{recovery_{min}}$ equal to 0.03.

Effect of Delay Time on the Wind Farm Frequency Response and on the grid frequency

The wind turbine generator power output and speed for one wind turbine of each groups (Groups A, B and C) both for the case where a zero delay time is imposed to all groups as well as for the case where a non-zero delay time is imposed in the different groups is depicted in Figure 71.

It can be observed that for Group A the controller ignores the imposed delay time and forces recovery as the rotor speed approached too close to its minimum allowed value. For Group B the recovery is successfully delayed, while during the delay period the wind turbines that belong to group B not only compensate for the power term required for the recovery of the wind turbines in group A, but also provide the very small amount of reserves still required to support the grid frequency, even though the frequency deviation sensed is less than 25 mHz. Hence, the controller successfully responds according to its design, and a more sustained response is achieved by the wind farm in total.

Alternatively, the controller could have been designed to provide zero reserves proportionally to the frequency deviation. In such a case, the wind turbines of group B would only be compensating for the recovery of the wind turbines in Group A. Finally, Group C is normally not activated to provide any reserves (under zero delay time settings), however if a delay time higher than the delay time imposed for the previous groups is imposed for Group C, as in this case, then the wind turbines that belong to Group C will be used to compensate for the recovery of the wind turbines in groups A and B, in order for the recovery period of the wind farm in total to be delayed for the maximum delayed time that is imposed to group C (7.5 seconds).

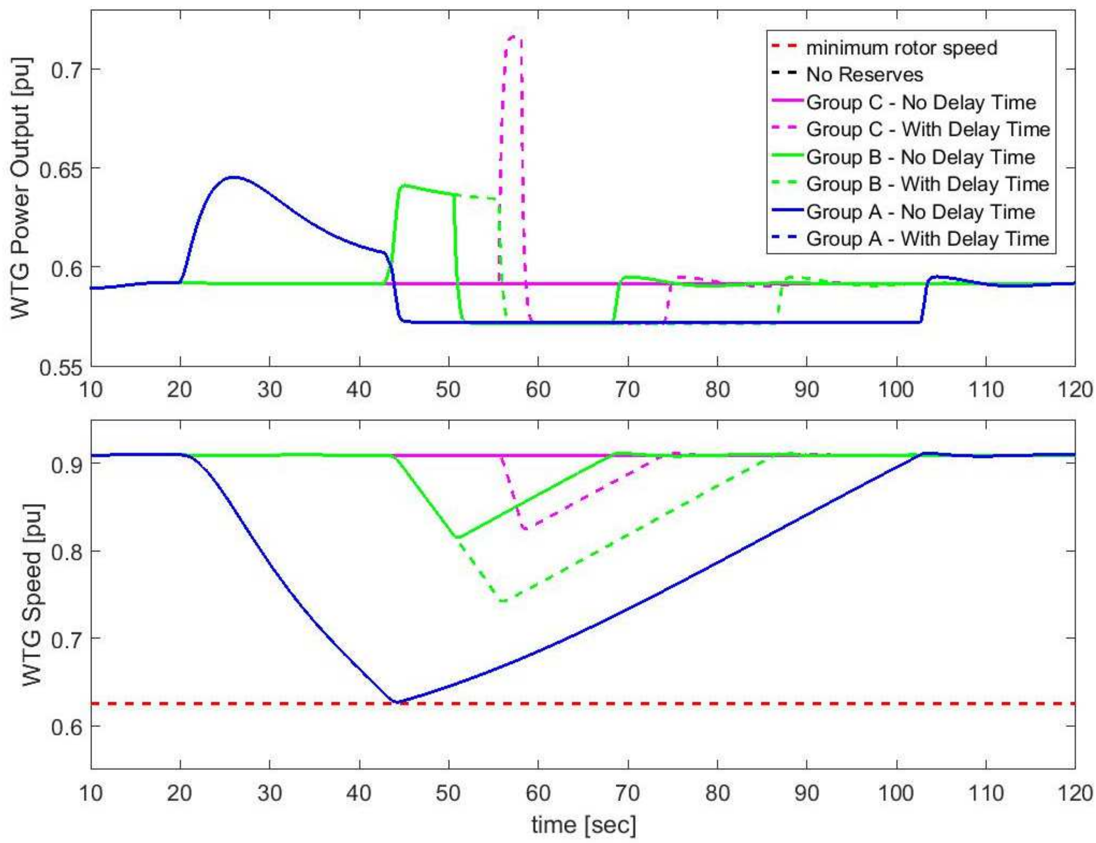

Figure 71: Active Power output and Speed of a single Wind Turbine Generator during a load increase of 7% of the base load, Effect of the delay time.

Sensitivity Analysis the gain droop constant if all wind turbines are tuned in the same way

The active power output and the speed of a Wind Turbine Generator of the wind turbines for the different gain droop constant values are depicted in Figure 72. All the wind turbines are tuned in the same way thus the waveform for only one wind turbine is provided. In all cases, the controller responded successfully and provided the requested reserves until the moment the rotor speed approached its minimum allowed value. Thus the rotor recovery was forced to avoid aerodynamic stall.

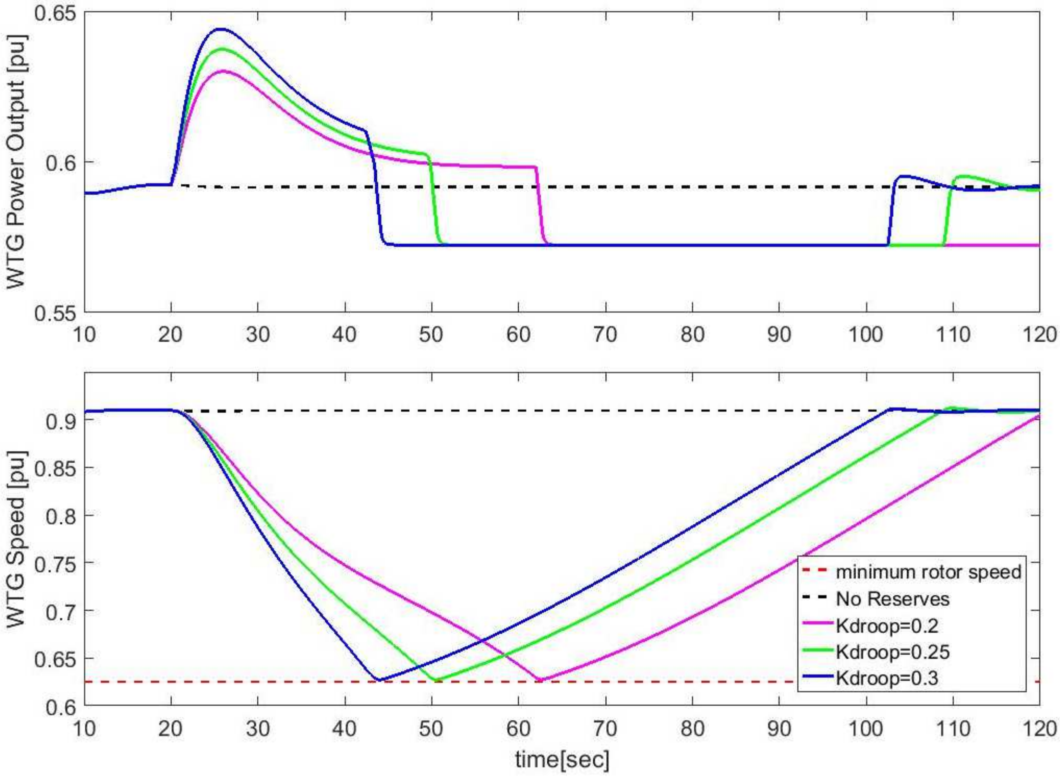

Figure 72: Active Power output and Speed of a single Wind Turbine Generator during a load increase of 10% of the base load, Sensitivity Analysis for K_{droop}.