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Control of Swedish wind power plants meeting future grid codes in a changing power market

Josefin Hedberg

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

Industrial Electrical Engineering and Automation

Abstract

Climate change is an issue that can no longer be ignored and actions are taken all over the world in order to prevent the effects from becoming too severe. The energy system is transitioning towards more renewable energy sources and wind power has an important role in this development. The penetration of wind power in a lot of countries all over the world has increased rapidly during the last decade, and the effects of this can be seen when looking at the balance of transmission systems. Wind power has traditionally been viewed as a marginal resource and has therefore experienced limited requirements when it comes to helping out with maintaining the system balanced. But now that wind power is increasing its share in the power system, WPPs (Wind Power Plants) also need to contribute to keeping the balance. Modern WPPs have a lot of abilities for active and reactive power control, but there are still questions to be answered when considering the best way to manage this control, and how the interaction of WPPs, grid owners and market shall occur.

This master thesis was performed on behalf of E.ON Wind Sweden AB in Malmö, and the division of Industrial Electrical Engineering and Automation at Lund University, Faculty of Engineering. The purpose of the thesis is to investigate how control of WPPs can be applied in order to meet future TSO (Transmission System Operator) requirements and a changing market, with an extra focus on the Swedish situation. Two main cases of control are studied: 1) the possibility of reactive power control contributing to the local voltage balance, and 2) how WTGs (Wind Turbine Generator) within a WPP can be coordinated during curtailment making the process more efficient considering wake effects. The cases are studied through simulations using the computer programs DIgSILENT PowerFactory, and MS Office Excel.

The first study concludes that modern WPPs are capable of providing reactive power, contributing to the local voltage balance. But this will occur within certain limits. The recommendation is that a reactive power service shall be sold to the grid owner, providing an extra income for the WPP owner and allowing the grid owner to use the WPP as a resource in the network. These kinds of services are also more likely to be seen in the future, when a new power system is developed which is able to adapt to an increased amount of renewable energy. This new power system needs to be smart and efficient, using all available assets in the best possible way. Being the first to introduce this service will result in a leading position within the market of such services.

The second study provides two main strategies for coordination of WTGs within a WPP during curtailment. Which strategy to choose depends on the wind speed. At lower wind speeds it is recommended to start by curtailing the first row of the WPP letting more wind pass through to the back rows with the main goal of avoiding unplanned turbine stoppages. At higher wind speeds the strategy is to curtail the WPP starting at the back row in order to avoid additional fatigue on the turbines caused by increased turbulence and to make the control as fast and as accurate as possible. This is a simplified way of describing the strategies; since they also depend on parameters such as the extent of the curtailment, the wind direction, and the amount of turbines available. If the curtailment reuired is extensive during high wind speeds, it is recommended to curtail the WPP equally in order to avoid pushing single turbines too much when stresses on the structure are already high. Such control can be implemented with current technology, but developing an algorithm which coordinates this specific process would improve the control. The coordination strategies can be used today, but they will prove even more useful for future large WPPs that will need to perform curtailment, either due to grid code requirements, or even more likely due to acting on the regulating power market.

Keywords: *wind power, WPP, WTG, control, coordination, reactive power, active power, ancillary service, grid code, transmission system, curtail, Sweden, Denmark, ENTSO-E, regulating power*

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Nomenclature and Abbreviations

C_P	Rotor power coefficient, definition of how large part of the power in the wind that is extracted by the rotor
C_T	Thrust coefficient, definition of how large part of the force hitting the turbine that is made up by the thrust force
DLR	Dynamic Line Rating
DSO	Distribution System Operator
ENDK	Energinet.dk, the Danish TSO
ENTSO-E	European Network of Transmission System Operators for Electricity, European joint committee for owners of electricity networks, European TSOs are members.
FSM	Frequency Sensitive Mode
GoO	Guarantees of Origin, type of green certificate
GSO	Generation System Operator, operates the WPP
HPPP	High Performance Park Pilot, Siemens overhead control system for WPPs
HVDC	High Voltage Direct Current
LVRT	Low Voltage Ride Through, a WTG function supporting the WTG during a sudden voltage dip
NC	Network Code, new European grid codes stated by ENTSO-E
OPC	Communication standard for computers. Allows communication between hardware and software
PCC	Point of Common Coupling, point in the grid where consumers are or can be connected, can be same as POC
P_n	Nominal power
POC	Point of Connection, the point in the public electricity supply network where the WPP is or can be connected. Grid codes apply in this point
PPC	Power Plant Controller, Vestas overhead control system for WPPs
pu	Per-unit, expression of system quantities as a fraction of a defined base unit quantity
RES	Renewable Energy Sources
RfG	Requirements for Generators, one of the NCs stated by ENTSO-E
SE4	Price area 4 in Sweden, the most southern price area in Sweden
STATCOM	Static Synchronous Compensator, based on power electronics, can work both as source and sink for reactive power
SVC	Static VAR Compensator, can work both as source and sink for reactive power
SvK	Svenska Kraftnät, the Swedish TSO
TSO	Transmission System Operator
U_c	Nominal production voltage, the WPP should be able to maintain nominal production at this voltage measured in the POC
U_{nom}	Nominal wind speed, the lowest wind speed at which the WTG reaches its nominal power output
VOB	VestasOnline Business, Vestas web based monitoring and control system for WPPs
VOC	VestasOnline Compact, Vestas web based monitoring and control system for smaller WPPs
WebWPS	Wind Power Supervisor, Siemens web based monitoring and control system for WPPs
WPP	Wind Power Plant
WTG	Wind Turbine Generator

Table of Contents

1 Introduction

1.1 Background

The impacts of climate change can no longer be denied. IPCC's (Intergovernmental Panel on Climate Change) latest report in 2014 concluded that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (IPCC 2013). Extremely likely defined by IPCC means 95 – 100 % probability, so there is little room left for doubts. There is an ongoing process of preventing climate change, and one very important step is a transition of the energy system. Looking at only the last 30 years, the energy system has gone through an extensive change, decreasing its oil dependency, especially considering the generation of electricity. Even though a substantial amount of this void has been filled with natural gas and nuclear power, the share of renewable energy sources has increased rapidly. In 2013 the renewables accounted for almost 22 % of the world's electricity production and in 2014 wind power contributed to almost 5% of the global electricity demand (International Energy Agency 2015; International Energy Agengy 2014; World Wind Energy Association 2015). According to a report published by IEA (the International Energy Agency) wind power can account for 18 % of the world's power production by 2050 (International Energy Agency 2013b).

The penetration of wind power in Sweden has increased rapidly during the last decade, with a yearly production of 0.9 TWh 2004 and 11.5 TWh 2014 (Svensk Energi 2015). The Swedish government has set a goal to install an additional 30 TWh wind power by 2020 compared to the levels of 2002 so there is a large increase in wind power penetration in Sweden to be expected within the coming years (Svensk Vindenergi 2014; Regeringskansliet 2015). Indeed, just next to Sweden in Denmark, the penetration of wind power has increased even more. With 39% of the energy production coming from wind power in 2014 this is a world record in percent of electricity originating from wind power. The goal is to reach 50% share of the electricity production coming from wind power by 2020 as a main step in becoming totally independent of fossil fuels (Energinet.dk 2015; ClimateProgress 2015).

The challenge with a large amount of wind power feeding into the system is that traditionally the WPPs have been unbound by requirements of supporting the extra power and voltage control that is necessary to stabilise the grid. The view has been to let the WPPs produce as much as they can when the wind is blowing, and rely on hydropower and conventional power plants (that is using some kind of fuel) in order to provide this control. Figure 1.1 shows how an increased amount of wind power is directly connected to problems in maintaining the normal frequency. The left y-axis shows the amount of MW wind power installed in Sweden between 2001 and 2014, and the right y-axis shows the amount of minutes per week that the frequency deviated from its approved interval during the same time period.

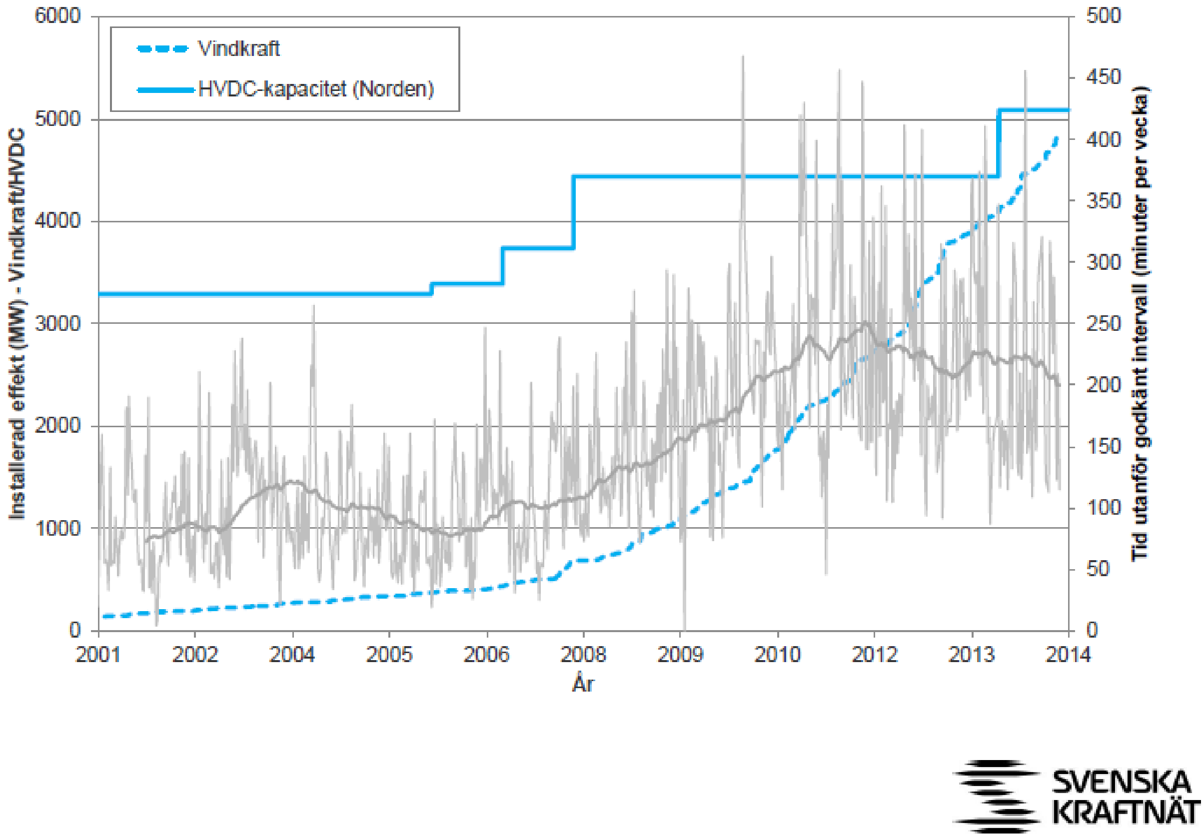


Figure 1.1. The amount of MW wind power in Sweden and the amount of minutes per week that the frequency deviated from its pre-approved interval during the period of 2001 – 2014 (Svenska Kraftnät 2015).

But now that the times are changing, with an increased penetration of wind power into the system, also WPPs need to provide these services. Some WPPs already have the ability to supply active and reactive power control to stabilise the grid and are doing so in order to comply with demands from TSOs or because they receive a constraint payment. For example these demands are a reality in Denmark right now due to their large penetration of wind power. If Sweden also continues to increase the penetration of wind power, it is only a question of time before Sweden experience similar demands from the TSO as the Danish WPPs are experiencing right now.

The wind power business is starting to recognize the demand for more control, and development of more advanced turbines is ongoing. Some technologies are already available, but they need to be used in an efficient way considering both the best operating strategies for different wind power technologies and the different parameters that cooperating with the grid entails. This way of considering the system as a whole is a key factor in order for the best result possible to be achieved.

1.2 Purpose

This master thesis will evaluate the demand of increased control of WPPs in Sweden, and investigate ways of improving the control considering both the external grid and internal WPP strategies. The aim will be to investigate how WPPs can contribute to keep the active and reactive power balance in the network helping to maintain the local voltage balance, and how the WTGs within a WPP can be coordinated during curtailment making the process more efficient considering wake effects.

1.2.1 Research questions

- Which demands concerning curtailment of active power and requirements of reactive power control can Swedish WPPs expect in the future?

- How can the WTGs within a WPP be coordinated during curtailment of active power making the process more efficient considering wake effects?
- How can control of reactive power within a WPP contribute to maintaining local voltage balance?
- What are the possibilities for Swedish wind power entering the balancing market?
- What are the possibilities of selling a service to the DSO (Distribution System Operator) helping out with keeping local voltage balance through reactive power control?

1.3 Method

1.3.1 Literature study

In order to gain information about the future control needs for large Swedish WPPs, current Swedish requirements stated by grid codes were studied. Analysing also the Danish and European grid codes also gives an insight to changes relating to future Swedish requirements. These requirements in conjunction with a study of the market are the incentive for more advanced control of large Swedish WPPs.

1.3.2 Analysis of control systems

When the increased requirements are identified, a technical analysis investigates which control actions can be carried out by the control systems. Two technical systems are studied, the Siemens HPPP (High Performance Park Pilot) and the Vestas PPC (Power Plant Controller). Features of modern Siemens and Vestas WTGs are presented in order to find reference parameters for the simulations. Some ways of performing the control at some of E.ONs WPPs are presented.

1.3.3 Simulations

The simulations are based on actions that can be carried out by the systems mentioned above, and using WTG features taken from modern Siemens and Vestas WTGs used in current projects. There are two chapters concerning simulations. The first one is about how control of reactive power within a WPP can contribute in maintaining the local voltage balance and the second one is about how WTGs within a WPP can be coordinated during curtailment of active power making the process more efficient considering wake effects.

1.3.4 Economic analysis

The economic analysis presents how WPPs can be economically compensated during curtailment, and analyses the possibilities of wind power entering the Swedish balancing market. The possibility of selling a service to the DSO/TSO assisting in keeping the local voltage balance is analysed, and a short discussion considering a future ancillary service and capacity market is also presented.

1.4 Limitations

When investigating a subject it is tempting to involve all possible aspects, but in this case this was not possible to accomplish within the timeframe allocated for a master thesis, therefore some limitations had to be made.

The grid codes that are of highest interest for this subject are the Danish, Swedish and European grid codes. The Swedish grid codes are interesting since this thesis is focusing on Swedish WPPs. Denmark is a country close to Sweden that has a lot of wind power, so studying the requirements stated in Denmark gives a hint of how the Swedish requirement might change with a higher penetration of wind power. European grid codes are also interesting, since they will affect most of the countries in Europe. These three sets of grid codes are presented further in chapter 3.

Considering the European grid codes, provided by ENTSO-E, there are actually ten different sets of grid codes covering different part of the transmission system. However analysing all of those grid codes would not have been possible within the limits of this thesis, therefore the one that is most relevant for the subject was chosen.

The only control systems and turbines studied are from Vestas and Siemens. These manufacturers are both among the world's biggest WTG manufacturers, and they are commonly used by E.ON.

The original plan for the simulations using DIgSILENT PowerFactory was to not only perform load-flow simulations but also dynamic simulations. However, for different reasons the program was not available for use until the end of the working process. The obtained results of the load-flow simulations are still useful, but more value would have been added to the results if dynamic simulations could have been performed as well.

Other limitations concerning the simulations made using DIgSILENT PowerFactory relate to the network model. The model is provided by ENDK (Energinet.dk, the Danish TSO) and created for research and educational purposes, meaning that the simulations are not based on a real network. However, the model has valid parameters mimicking a real network and it is sufficient for testing the theories stated in this thesis.

When performing the calculations considering coordination of WTGs within a WPP, different equations were used in order to find the wake effects, the C_p and the C_T of the turbines. Real values collected from turbine specifications where used to the largest extent possible, but some simplifications had to be made. Since C_T curves for different pitch angles could not be located within the timeframe of the thesis, more simplified equations was used instead. These equations do however provide results that are sufficient for testing the theories stated in this thesis.

1.5 Outline of the report

Chapter 2

This chapter describes an overview of the control of WPPs. A summary of the importance of grid codes and a changing energy market will be presented, followed by an overview of a WPP, describing different parts and its functions. Then some ancillary services that WPPs can provide will be presented, and after that an overview of the simulations.

Chapter 3

This chapter presents an overview of requirements made by TSOs in Sweden, Denmark and Europe regarding WPPs, and the current market outline.

Chapter 4

This chapter describes the Siemens and Vestas control systems, and the features of some of their modern WTGs are summarised. There is also a short description of how these control systems are used by E.ON today.

Chapter 5

This chapter investigates how control of active and reactive power within a WPP can contribute to keeping balance in the network, emphasising the WPP capacities of performing reactive power control and how it affects the local voltage balance. Simulations will be performed using DIgSILENT PowerFactory, and a network model supplied by ENDK that is used for research and study purposes.

Chapter 6

This chapter investigates how the WTGs within a WPP can be coordinated during curtailment of active power making the process more efficient considering wake effects. Models and different cases are defined, and basic simulations are performed using Excel. The results are presented using graphs.

Chapter 7

This chapter describes an economic analysis discussing the economic gain of performing the different types of control investigated in this thesis. The economic reasons for coordination of the WTGs within a WPP during curtailment will be discussed, together with the possibilities of wind power entering the regulating power market. The possibilities of selling a service to the DSO/TSO to assist with maintaining local voltage balance through reactive power control will be discussed, and a short analysis of a future ancillary service and capacity market will also be presented.

2 Control of WPPs – overview

2.1 Grid codes and changing market

Every country has their own grid codes that all parties affecting the transmission system network has to comply with, including all power plants connected to the network. These grid codes include keeping the voltage within predefined limits, not exceeding a predefined active power production limits, keeping the frequency within certain limits, etc. As mentioned above, WPPs have traditionally experienced requirements that are a bit less strict compared to traditional power plants, letting the other power plants in the system compensate for e.g. the WPPs varying active power output. Now that the penetration of WPPs in the network is increasing, also the WPPs need stricter requirements in order to help keep the balance in the network. In order to investigate which future demands Swedish WPPs can expect, this thesis is focusing on the Danish, Swedish and European grid codes.

Another part of the energy system affecting the control of WPPs is the power market. It plays an important role since the price of electricity decides how profitable it will be for a certain power plant to produce electricity. Today, the market is also to some extent affected by different supporting systems for renewable energy, which creates a difference in profitability for producing renewable energy between countries. Systems for providing economical compensation for WPPs during curtailment already exist in some countries e.g. Denmark, and most likely these systems will also be introduced in other countries in the near future.

When the requirements due to changing grid codes are getting stricter, and the rules of the market are changing, the WPPs need to prepare to adapt to these changes, so that they are considered when building new WPPs, or if possible implemented in existing WPPs. Investigating these incitements for an increased control will therefore have its own chapter in this thesis (chapter 3), before proceeding by presenting how the WPPs can meet these control requirements.

2.2 The WPP structure

The WTGs of a WPP are interacting with the grid both electrically and digitally, producing electricity and exchanging information and control signals. Figure 2.1 displays the structure of the WPP and how it is connected to the gird. The different parts of the WPP will be further described below.

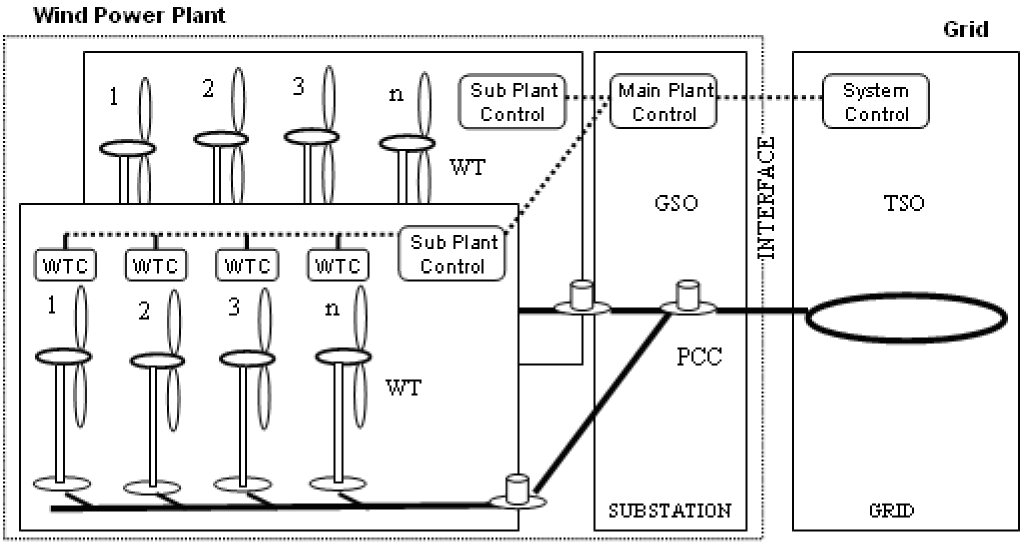


Figure 2.1. WPP structure and grid interaction (Lindgren et al. 2012).

2.2.1 Wind turbines

The amount of WTGs within the WPP can vary heavily, ranging from just a few to several hundreds of WTGs considering the largest WPPs. The trend is that the WTGs are getting larger, meaning that the number of WTGs needed in a WPP to produce a certain amount of power is decreasing. Especially the development for offshore WPPs points towards larger parks with larger turbines. The WPPs operating today have WTGs with a power production in the range of 2 – 6 MW, but the largest turbine that is built for testing and is expected to be released on the market this year is an 8 MW turbine for offshore usage (Wind Power Monthly n.d.).

The technology of the WTG differs a bit between different turbine manufacturers, and is also changing when newer models are being developed. There are pros and cons of using different types of turbine drive train technologies with either asynchronous or synchronous generators, and with or without a gearbox, but a common denominator is the development towards using full-scale converters, since they allow a much more advanced control of the WTG. The full-scale converter decouples the frequency of the generator from the grid frequency, allowing a more flexible control of the rotor speed and active power production of the turbine. This technology also provides an extensive reactive power exchange allowing the WTGs to inject/ extract reactive power to the grid when needed, and this can be done also when the WTG is not producing active power.

2.2.2 Internal collection network

The internal collection network consists of cables connecting the WTGs with each other, and finally with a substation. The structure of the network can differ, but usually the WTGs are connected in parallel along rows, with the turbine closest to the substation connected to the substation. If the WPP consists of more than a few turbines, the cable size will also differ within the WPP. The size depends on the current and power transferred, since the cables going through the turbines at the end of the row which is closest to the substation will need to have the ability to tolerate higher currents. The reason for this is that the voltage level throughout the WPP is the same, and these cables are also transferring power generated by turbines further out in the rows, increasing the current when closing in on the substation. The cables normally also carry the communication lines used for the WTGs to communicate with the main plant control. Today the internal transmission network of the WPPs is based on AC, but there is a lot of research going on concerning how to switching to a DC based network instead.

2.2.3 Substation

The cables transferring the power from the WTGs are collected in the substation, and the voltage is raised in order to minimise losses when the power is transferred further away from the WPP and connected to the main grid, usually using one single cable. Common plant voltages are 22 or 33 kV, and depending on the voltage at the POC (Point of Connection)/ PCC (Point of Common Coupling) where the WPP is connected to the main grid, the voltage might be raised to e.g. 130 kV. The connection between the substation and the main grid can be either AC or DC. If the WPP is large, it might be desirable to have several substations.

2.2.4 Main grid

The WPP can be connected to a main grid of different voltage levels, e.g. the regional or national transmission network, depending on the size of the WPP, or to HVDC (High Voltage Direct Current) systems. The main grid is controlled by the DSO or TSO depending on which voltage level that is considered, and an agreement between the GSO (Generation System Operator) and the DSO or TSO determines the conditions and possible ancillary services for the WPP operation. These conditions apply in the POC (Point of Connection)/ PCC (Point of Common Coupling) where the WPP is connected to the main grid.

2.2.5 Control systems

All WTGs have a local controller that controls the power production according to the wind conditions, and also controls the turbines according to signals received from the main plant control. The main plant control can be located at the substation, but it can be controlled from any location using digital signals. The main plant control has different functions, controlling the WPP in order to achieve as high production as possible, and making sure that the WPP is complying with local grid codes and TSO demands. Therefore, the main plant control can receive signals both from the GSO and from the TSO. This controller is seen as one unit from the grid side by the external control, but it can also control all turbines of the WPP individually or via a sub plant control. The external system control is operated by the TSO. Today parts of the control are set to operate automatically, but some parts of the communication between the GSO and TSO are still done manually via email or phone calls. In other words, there is still room for improvements considering the communication, since using only digital signals would be a better way of conducting the control.

2.3 Challenges of grid and WPP interaction

The changing grid codes and power market mentioned above creates a need for ancillary services provided by WPPs. These services can be defined as all additional services that WPPs provide in addition to the main service i.e. the active power production. These services can either be required by grid codes, or traded separately. Most of the services include controlling the active and reactive power in some way. As mentioned above in the introduction, the power system has traditionally relied on conventional power plants and hydropower to provide these ancillary services, such as keeping the system balance considering, for example, active power flows and maintaining frequency and voltage levels. Now that the penetration of wind power in the system is increasing, the need for such ancillary services also from WPPs is increasing.

Modern WTGs with full-scale converters have a lot of abilities to provide different ancillary services. An example is frequency control. Grid codes define certain frequency ranges and time spans where the WPP needs to be able to stay connected and operate. The WPP control systems can usually run in two different frequency control modes, one simple mode only responding to increased frequencies and one more advanced mode also responding to decreased frequencies. When using the more advanced mode the WPP needs to run in a curtailed mode, which causes loss of revenues. This implies that the service can be traded on an ancillary service market. Another example of an ancillary service that modern WPPs can perform is LVRT (Low Voltage Ride Through). Grid codes specify the extent of the voltage range which the WPP needs to be able to tolerate. Different WTGs have different LVRT capabilities, which are specified for each turbine.

This thesis will specialise in two different types of control. The first one is control of the reactive power output of WPPs contributing to maintaining the local voltage balance, which is a type of ancillary service. This ancillary service may be required by grid codes in the future, or traded separately on an ancillary service market. The reactive power capability of modern WTGs is extensive. The current requirements stated by the Swedish TSO include maintaining the reactive power exchange in the POC at 0 MVar. The Danish grid code allow the power factor to be set within the range of 0.95 capacitive to 0.95 inductive. When the voltage deviates in the system, the Swedish DSO handles this through connecting or disconnecting capacitors/ reactors. The reactive power study will look further into how WPPs could participate in this control, helping the DSO to maintain the local voltage stability in the grid through injecting/ extracting reactive power. This kind of service can be used today, but the need for such a service will be even stronger with an increased penetration of wind power in the system.

The second type of control that is analysed in this thesis is coordination of WTGs within a WPP during curtailment. This is a special function that should be used when the WPP is curtailed, which is an ancillary service that is already used, and will be needed even more in the future. WPPs are curtailed today for different reasons. The grid might be overloaded, or the prices too low to make production profitable. When WPPs are curtailed for some reason, the common way to perform the curtailment is to give the WPP a new active power setpoint, and let the main plant control curtail the available turbines without considering how the turbines affect each other within the WPP. If the WTGs within the WPP would be coordinated considering parameters such as their position, the wind direction and speed, the curtailment could be performed in a more optimised way. This thesis will investigate the options for this coordination.

The two studies will be performed using simulations. Figure 2.2 displays a simple block model of the system that will be simulated. The model will be used a bit differently for active and reactive power simulations. In the case of active power, the focus will be on the two blocks to the right, the “coordination” and the “WPP” blocks. The aim of the active power control will be to find the best way to coordinate the WTGs within the WPP during curtailment, the procedure for this will be described in detail in chapter 6.

In the reactive power case, the different loads and production from other power plants included in the grid model will cause fluctuations in voltage and generate a need for an injection or extraction of reactive power in order to maintain the balance. The WPP will accommodate the need for reactive power, as long as this need is within the limits of its capability. Considering the simulations of reactive power, which will be described more in detail in chapter 5, the entire system displayed in figure 2.2 will be needed.

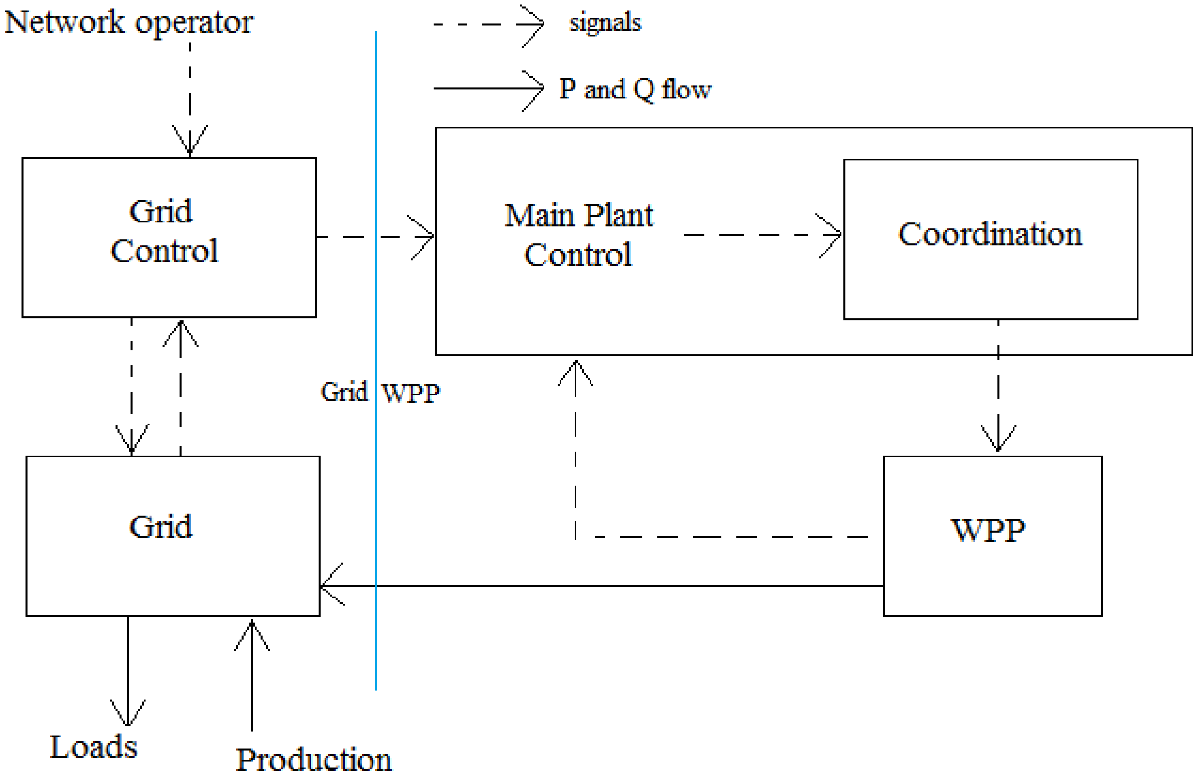


Figure 2.2. Simple block model of the system used in the different studies.

3 TSO requirement and market overview

The main part of this chapter will describe some of the Swedish, Danish and European grid codes that affect power plants. All grid codes apply in the POC, which is the interface between the grid and the WPP, see the blue line in figure 2.2. The second part of this chapter will provide a short market overview.

3.1 European Network Codes

The European grid codes are called Network Codes (NC), and they are stated by ENTSO-E (European Network of Transmission System Operators for Electricity) which is an association consisting of 41 TSOs from 34 European countries. The main objective of ENTSO-E is to achieve a sustainable energy system with a high integration of renewable energy sources, and to obtain a European internal energy market meeting the energy policy objectives of the European Union of affordability, sustainability and security of supply (ENTSO-E 2014b). The NCs stated by ENTSO-E are rules in the process of becoming laws (ENTSO-E 2014a). When a NC is implemented on a national level, a three year transition period is expected before it will enter into force (ENTSO-E 2013b).

ENTSO-E is currently working on ten different NCs representing different sections of the European transmission system and electricity market. The main sections are connection codes stating requirements physically affecting the transmission system, operational codes concerning how the system should operate, and market codes stating the requirements for the market. The NC that is of highest interest for this thesis is the code concerning Requirements for Generators (RfG) (ENTSO-E n.d.). The summary of requirements that follows in the rest of this chapter originates from that NC. The NC RfG has entered Comitology, which means that it is in the process of becoming law (ENTSO-E 2014a).

Some requirements stated in the NC RfG differ depending on synchronous area. This thesis focuses on the Nordic synchronous area. Different requirements apply to power generating modules (including power park modules, in this case WPPs) of different sizes divided into categories defined by ENTSO-E. The categories are:

Type A: A power generating module with a power output of 0.8 kW or more and a connection point of below 110 kV

Type B: A power generating module with a power output shown in table 3.1 and a connection point of below 110 kV

Type C: A power generating module with a power output shown in table 3.1 and a connection point of below 110 kV

Type D: A power generating module with a power output shown in table 3.1 and a connection point at 110 kV or more. This type can also be a synchronous power generating module or power park module with a connection point of below 110 kV and a power output at or above a level predefined by the relevant TSO. This level cannot be higher than the level in table 3.1 (ENTSO-E 2013a).

Table 3.1. Definitions of the different categories defined by ENTSO-E for different synchronous areas (ENTSO-E 2013a).

Synchronous Area	**Minimum capacity for type B**	**Minimum capacity for type C**	**Minimum capacity for type D**
Continental Europe	1 MW	50 MW	75 MW
Nordic	1.5 MW	10 MW	30 MW
Great Britain	1 MW	10 MW	30 MW
Ireland	0.1 MW	5 MW	10 MW
Baltic	0.5 MW	10 MW	15 MW

3.1.1 Tolerance of frequency and voltage deviations

A power generating module of type A, B, C or D in the Nordic synchronous area has to be able to withstand the frequency variations specified in table 3.2 without disconnecting from the network. Exceptions can be made when agreed upon by the relevant TSO, network operator and the power generating facility owner if it is economically and technically feasible. A power generating module shall have the ability to automatically disconnect at specified frequencies if required by the relevant network operator. A power generating module shall also be able to stay connected and operate when the frequency is changing, according to a rate of change defined by the relevant TSO (ENTSO-E 2013a).

Table 3.2. Minimum time periods for which a power generating module located in the Nordic synchronous area should be able to stay connected to the grid and operate when the frequency deviates from 50 Hz (ENTSO-E 2013a).

Frequency range [Hz]	Time period for operation
47.50 – 48.50	30 minutes
48.50 – 49.00	To be defined by each TSO, but not less than 30 minutes
49.00 – 51.00	Unlimited
51.00 – 51.50	30 minutes

The NC RfG also specifies additional requirements for withstanding of faults, reconnection, robustness, system management etc. for type B, C and D. For power generating modules of type C and D, the TSO and the network operator have the right to specify at which voltages at the POC the power generating module needs to be able to disconnect automatically. A power generating module of type D in the Nordic synchronous area needs to be able to stay connected to the network and operate within the voltage ranges specified in table 3.3. The voltage is expressed in per unit, relating the voltage at the connection point to the nominal voltage (ENTSO-E 2013a).

Table 3.3. Minimum times for operation at different voltage ranges for a power generating module of type D in the Nordic synchronous area (ENTSO-E 2013a).

Voltage Range [pu]	Time period for operation
0.90 – 1.05	Unlimited
1.05 – 1.10	60 minutes

Wider voltage ranges or longer minimum time periods can be agreed upon by the relevant TSO, network operator and the power generating facility owner if it is considered to be technically and economically feasible (ENTSO-E 2013a).

3.1.2 Tolerance to voltage dips

Power park modules of type B, C and D shall be able to stay connected to the grid and operate during a voltage dip caused by a fault. The requirements for voltage levels and time parameters during voltage dips shall be specified by each TSO according to the ranges specified in table 3.4, table 3.5 and figure 3.1. The TSOs shall also specify conditions for calculations resulting in conditions to be considered for the fault-ride-through capability of the power generating module. These conditions apply in each POC and shall be provided to the power plant owner by the network operator (ENTSO-E 2013a). The conditions are regarding:

- pre-fault minimum short circuit capacity [MVA]
- pre-fault operating point of the power generating module expressed in voltage and active and reactive power output
- post-fault minimum short circuit capacity [MVA]

Table 3.4. Voltage and time parameters associated with figure 3.1 for fault-ride-through capability of a power park module of type B and C (ENTSO-E 2013a).

Voltage parameters [pu]		**Time parameters [seconds]**	
U_{ret}	0.05 – 0.15	t_{clear}	0.14 – 0.25
U_{clear}	U_{ret} – 0.15	t_{rec1}	t_{clear}
U_{rec1}	U_{clear}	t_{rec2}	t_{rec1}
U_{rec2}	0.85	t_{rec3}	1.5 – 3.0

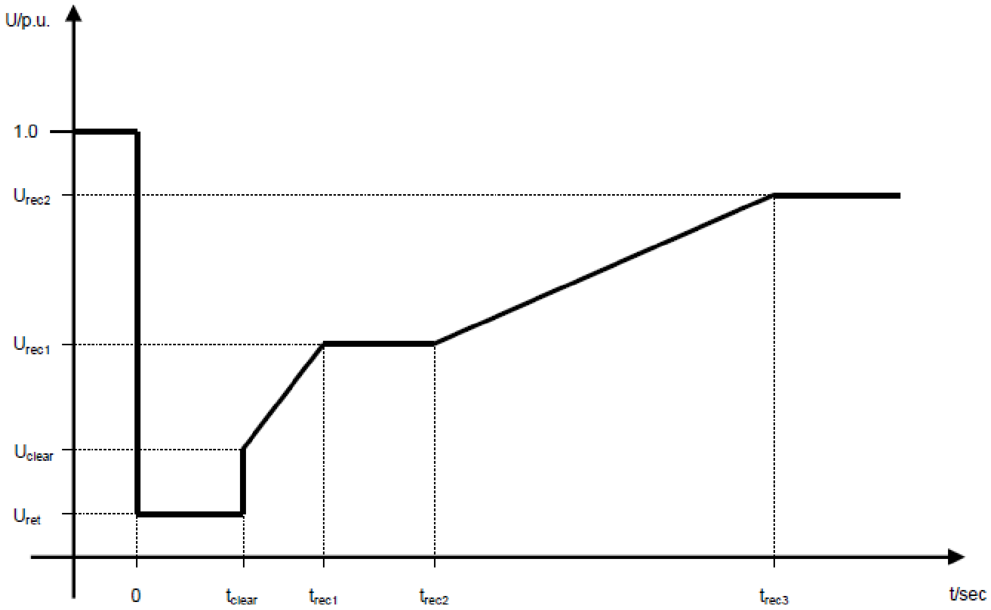


Figure 3.1. Fault-ride-through profile. The voltage is defined as the ratio of its actual value and its nominal value in per unit. U_{ret} is the retained voltage, and U_{rec} is the recovered voltage (ENTSO-E 2013a).

Table 3.5. Voltage and time parameters associated with figure 3.1 for fault-ride-through capability of a power park module of type D (ENTSO-E 2013a).

Voltage parameters [pu]		**Time parameters [seconds]**	
U_{ret}	0	t_{clear}	0.14 – 0.25
U_{clear}	U_{ret}	t_{rec1}	t_{clear}
U_{rec1}	U_{clear}	t_{rec2}	t_{rec1}
U_{rec2}	0.85	t_{rec3}	1.5 – 3.0

The relevant network operator shall have the right to define the capability of power park modules of type B, C and D to provide reactive power. The network operator and the TSO shall furthermore have the right to require additional fast acting reactive current injections in the POC in case of three-phase symmetrical faults. This can be done in two ways, either ensuring additional reactive current in the POC, or at the terminals of the individual units of the power park module. The amount of reactive current supply should be specified by the relevant TSO and network operator, and at least 2/3 of the additional reactive current shall be provided in less than 10 milliseconds. The target value shall be reached with an accuracy of 10 % within 60 milliseconds from the occurrence of the voltage deviation. In total, the reactive current contribution shall not exceed 1 pu of the short term dynamic current rating (covering up to 0.4 seconds) of the total power park module or the individual units of the power park module. The relevant network operator and the TSO can also require additional asymmetrical current injection during asymmetrical faults (ENTSO-E 2013a).

3.1.3 Control requirements

The following section will give a summary of control requirements stated by the NC RfG.

Frequency stability

All types of power generating modules need to be able to activate an active power frequency response decreasing the active power when the frequency exceeds a limit predefined by the relevant TSO. The limit should be in the range of 50.20 to 50.50 Hz with a droop range of 2 - 12 %. If the response time is greater than 2 seconds, this needs to be justified by the power generating facility owner to the TSO. The active power production should be maintained stabile during the frequency response (ENTSO-E 2013a).

Power generating modules of type C and D should also be able to handle frequency drops, increasing the active power. The frequency limit for this frequency response should be defined by the relevant TSO. The limit should be in the range of 49.80 to 49.50 Hz with a droop range of 2 – 12 %. The ability for increasing the power is dependent on a number of factors such as the maximum capacity of the power generating module, the operating and ambient conditions and available primary energy sources. If the response time is greater than 2 seconds, this needs to be justified by the power generating facility owner to the TSO. The active power production should be maintained stabile during the frequency response (ENTSO-E 2013a).

Power generating modules of type C and D should also be able to operate in Frequency Sensitive Mode (FSM). This means that the power generating module reacts to over/ underfrequencies by reducing/ increasing the active power output according to the predefined ranges specified in figure 3.2 and table 3.6. When the frequency is high, the response is limited by the minimum regulatory level, and when the frequency is low, the response is limited by the maximum capacity, the operating and ambient conditions, and the available energy primary sources (ENTSO-E 2013a).

Table 3.6. Parameters for active power frequency response for power generating modules of type C and D (ENTSO-E 2013a).

Parameters		**Ranges**
Active power range related to maximum capacity $\frac{\lvert\Delta P_1\rvert}{P_{max}}$		1.5 – 10 %
Frequency response intensity	$\lvert\Delta f_i\rvert$	10 – 30 mHz
	$\frac{\lvert\Delta f_i\rvert}{f_n}$	0.02 – 0.06 %
Frequency response deadband		0 – 500 mHz
Droop s_1		2 – 12 %

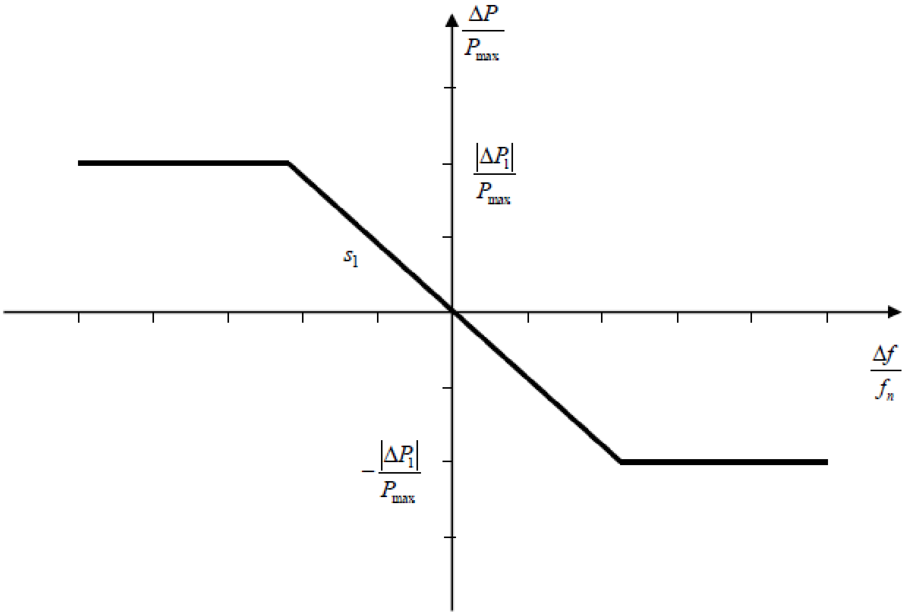


Figure 3.2. Example of graph for active power frequency response for power generating modules of type C and D. The case shown in the figure has zero deadband (ENTSO-E 2013a).

The exact parameters of figure 3.2 and table 3.6 are selected by the relevant TSO. If the power generating module is a technology with inertia, the response needs to be activated within 2 seconds receiving a signal of activation, unless justified otherwise. If the power generation module is a technology without inertia (e.g. wind power), the time lag for the response shall be specified by the TSO. The response should be fully activated after 30 seconds, unless the TSO has admitted longer activation times motivated by network stability. The power generating module should be able to provide the frequency response during a time specified by the TSO, in the range of 15 to 30 minutes, considering the active power available. The frequency response parameters should be available for the relevant network operator and/or TSO at all times using an on-line transfer (ENTSO-E 2013a).

If power parks of type C or D do not have an inherent inertia damping frequency oscillations, and if they are larger than a MW size predetermined by the relevant TSO, they shall be required to install control functions that can provide additional active power (acting as a synthetic inertia) (ENTSO-E 2013a).

Voltage stability and reactive power capability (concerning power park modules type C and D)

If there is a very long line or cable from a power park module of type C or D to the POC, the relevant network operator may require additional reactive power from the owner of the line or cable to compensate for the reactive power demand of the line or cable (ENTSO-E 2013a).

The relevant TSO and network operator shall define the reactive power capability for the power park for two different cases; at maximum capacity and below maximum capacity. For the first case (at maximum capacity) the requirements are defined using a U-Q/P_{max} – profile (see figure 3.3) and for the second case (below maximum capacity) the requirements are defined using a P-Q/P_{max} – profile (see figure 3.4). All requirements apply at the POC (ENTSO-E 2013a).

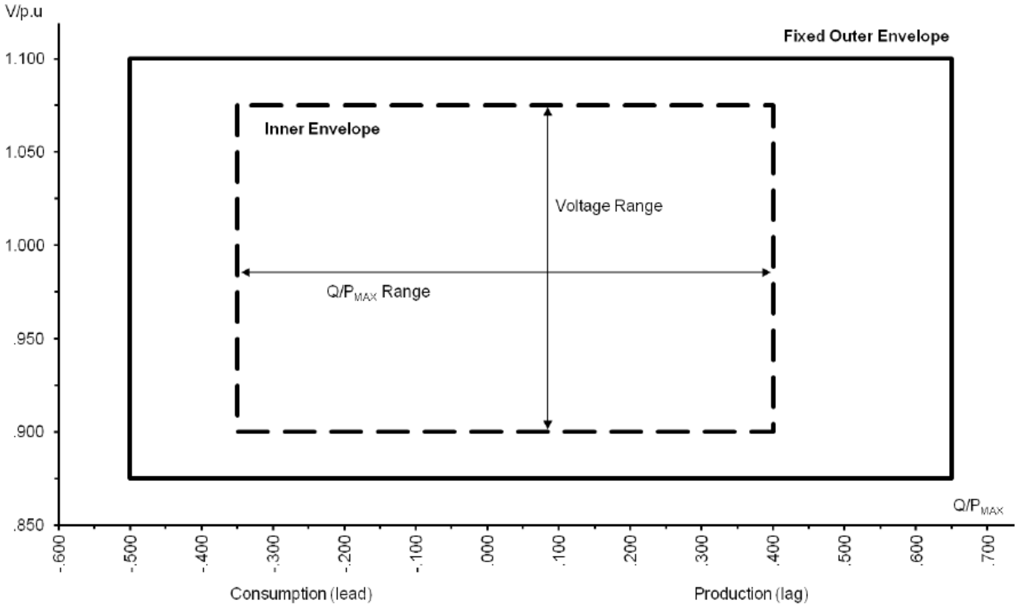


Figure 3.3. Boundaries of U-Q/P_{max} – profile displaying an example of how the requirements for reactive power capability at maximum capacity can be illustrated. V is the ratio of the actual voltage and the nominal voltage in the POC in pu. Q is the reactive power and P_{max} is the maximum capacity (ENTSO-E 2013a).

The profile can have any shape and needs to be within the inner envelope, which does not need to be rectangular, but it needs to be within the limits of the outer envelope (ENTSO-E 2013a). Table 3.7 displays the parameters for the inner envelope.

Table 3.7 Parameters for the inner envelope in figure 3.3 for different synchronous areas (ENTSO-E 2013a).

Synchronous area	Maximum range of Q/P_{max}	Maximum range of steady state voltage level [pu]
Continental Europe	0.75	0.225
Nordic	0.95	0.150
Great Britain	0.66	0.100
Ireland	0.66	0.218
Baltic States	0.80	0.220

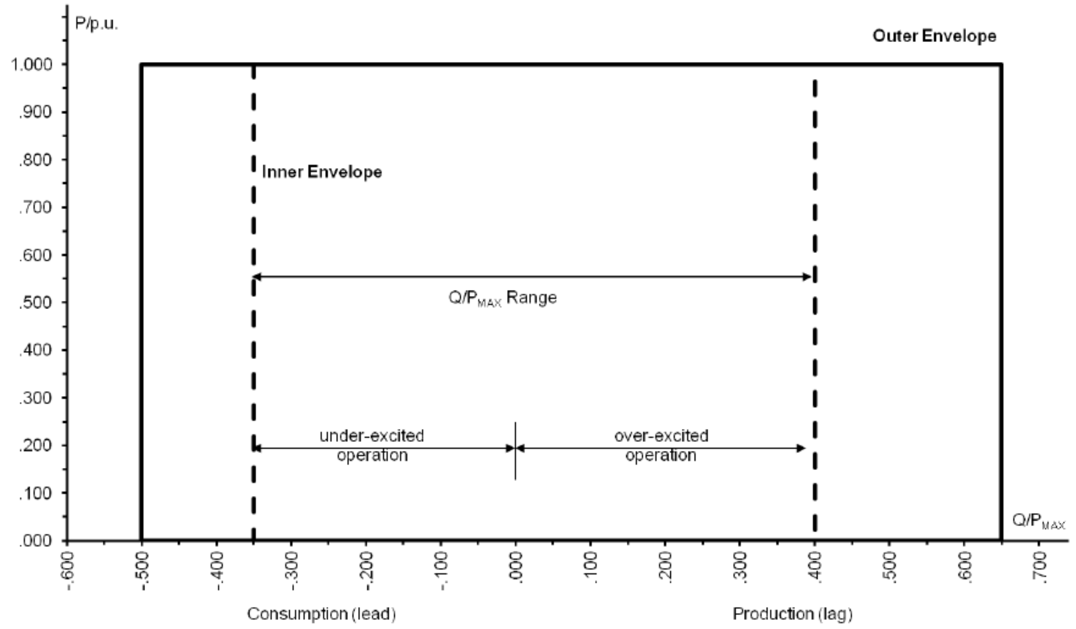


Figure 3.4. Boundaries of P-Q/P_{max} – profile displaying an example of how the requirements for reactive power capability below maximum capacity can be illustrated. P is the ratio of the actual active power and the maximum capacity in pu. Q is the reactive power and P_{max} is the maximum capacity (ENTSO-E 2013a).

The P-Q/P_{max} – profile needs to be within the inner envelope, which needs to be within the limits of the outer envelope. For the Nordic synchronous area the maximum range of Q/P_{max} is 0.95 pu and the active power range is 1 pu. The profile can have any shape and it shall include conditions for reactive power at zero active power. The power park module does not need to comply with the profile if all units are not technically available (ENTSO-E 2013a).

Automatic reactive power control can be performed using three different modes, voltage control mode, reactive power control mode and power factor control mode.

If the voltage control mode is used, a voltage setpoint is specified in the POC. The setpoint needs to be in the range of at least 0.95 to 1.05 pu with steps no greater than 0.01 pu, with a slope with a range of at least 2 - 7 % with steps of no less than 0.5 %. When the network voltage equals the setpoint voltage, the reactive output shall be zero. If a deadband is used, it shall be in the range of ± 0.5 % of the nominal voltage with steps no greater than 0.5 %. The relevant network operator shall specify the time that may pass before the change in reactive power output has reached 90 % following a step change in voltage, which should be in the range of 1 – 5 seconds following the gradient and settle within 5 – 60 seconds. At steady state, the reactive tolerance should be no greater than 5 % of the maximum reactive power (ENTSO-E 2013a).

If reactive power mode is used, the reactive power setpoint at the POC shall be within the range defined in figure 3.3 with steps and accuracy within ± 5 MVar or ± 5 % of full reactive power (the smallest option is to be chosen) (ENTSO-E 2013a).

If power factor control mode is used, the power factor at the POC shall be within the range defined in figure 3.3 with steps no greater than 0.01. The target power factor value shall be specified by the relevant network operator (ENTSO-E 2013a).

The relevant TSO shall specify if the power park module needs to contribute to damping of power oscillations. The TSO also specifies if active or reactive power contribution is prioritised during a fault when fault-ride-through capabilities are needed. If the active power contribution is prioritised, the response shall not take longer than 150 milliseconds (ENTSO-E 2013a).

3.1.4 Other requirements

Power generating modules of type A and B shall be able to cease its active power output in the course of 5 seconds after receiving a stop signal. Power generating modules of type A, B and C shall be able to connect automatically to the network according to an agreement with the relevant TSO. The agreement include conditions for frequency ranges and maximum admissible gradient of increase of active power output (ENTSO-E 2013a).

Power generating modules of type B shall be able to reduce the active power output as instructed by the relevant TSO and/ or network operator. Power generating modules of type C and D shall have the ability to adjust an active power setpoint following an instruction by the relevant TSO or network operator. This setpoint shall be possible to adjust manually, in case of problems with control devices. The network operator shall in cooperation with the TSO state the ramping limits, i.e. the maximum and minimum rates of change of active power (ENTSO-E 2013a).

The owner of power generating modules of type B, C and D should agree with the relevant TSO and network operator on settings and schemes concerning control that is relevant for stability, protection of the network and enabling emergency actions. Changes of such settings and schemes shall be coordinated between the three parties (ENTSO-E 2013a).

According to the NC RfG, the order of priority for different protection and control devices for power generating modules of type B, C and D should be as follows:

- Network system and power generating protection
- Synthetic inertia, if applicable
- Frequency control (active power adjustment)
- Power restriction
- Power gradient constraint

Power generating modules of type B, C and D shall have the ability to exchange information with the relevant TSO and/or network operator. The frequency of the information shall be within time intervals stated by the relevant TSO and/or network operator (ENTSO-E 2013a).

3.2 Danish grid codes

The Danish TSO ENDK has stated special requirements for wind power concerning WPPs larger than 11 kW. In order to be approved for access to the grid, these requirements must be met. In Denmark WPPs are divided into four different categories depending on size, with larger WPPs experiencing stronger demands. The four categories are:

A: WPPs with a power output range of 11 kW to 50 kW

B: WPPs with a power output range of 50 kW to 1.5 MW

C: WPPs with a power output range of 1.5 MW to 25 MW

D: WPPs with a power output greater than 25 MW

3.2.1 Tolerance to frequency and voltage deviations

All Danish WPPs need to be able to handle variations in voltage and frequency without a major change in production. The owner of the local grid states the normal operating voltage for the Point of Connection (POC) for the WPP, and the WPP should be able to operate within a range of ±10% of the operating voltage. The voltage can differ from location to location, but depending on the prevailing voltage level (extra high, high, medium or low), the voltage needs to stay within certain levels stated by ENDK. The normal operating frequency area is 49.50 to 50.20 Hz. Further frequency demands are stated in table 3.8 (Energinet.dk 2014c).

Table 3.8. Frequency requirements for different production modes and different categories of WPPs (Energinet.dk 2014c).

Category **Demands**	**A**	**B**	**C**	**D**
Frequency [Hz]				
Normal production	49.50 – 50.20	49.00 – 51.00	49.00 – 51.00	49.00 – 51.00
Normal production if possible	47.00 – 49.50	-	-	-
Normal production for minimum 30 min	-	47.50 – 49.00 and 51.00 – 51.50	47.50 – 49.00 and 51.00 – 51.50	47.50 – 49.00 and 51.00 – 51.50
Normal production for minimum 30 sec	-	47.00 – 47.50 and 51.50 – 52.00	47.00 – 47.50 and 51.50 – 52.00	47.00 – 47.50 and 51.50 – 52.00

For all frequency deviations, the permitted voltage deviation is ± 10 % of normal operating voltage.

3.2.2 Tolerance to phase jumps and voltage dips

WPPs of category C and D must be able to withstand a sudden (80-100 ms) phase jump of 20° without disconnecting or reducing the output. After a phase jump or voltage dip within the acceptable limits, the WPP must return to normal production within 5 seconds after the event. Figure 3.5 displays the requirements for tolerance of voltage dips for WPPs of category C and D (Energinet.dk 2014c).

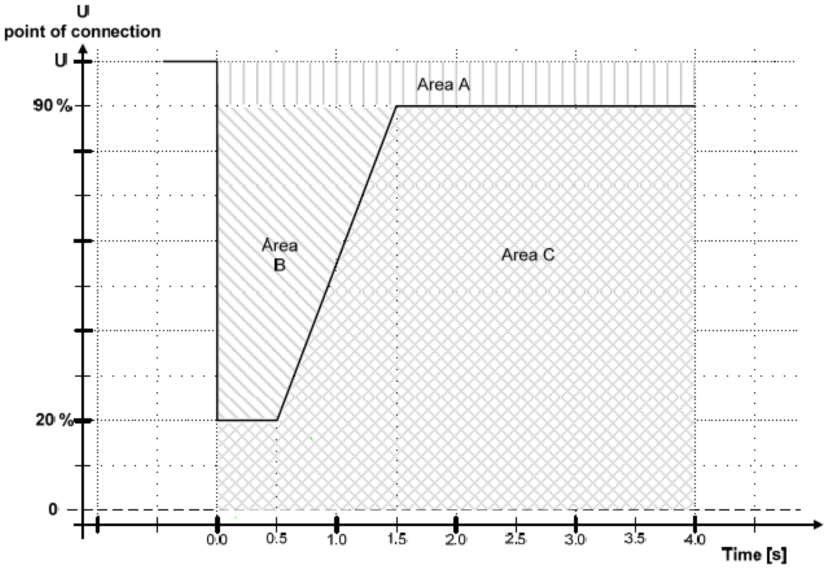


Figure 3.5. Requirements of voltage dip tolerance for category C and D WPPs (Energinet.dk 2010).

At area A, normal operation is required, and at area C disconnection is allowed. At area B the priority is to provide reactive power in order to help stabilize the voltage level. Figure 3.6 shows the requirements of reactive power supply during a voltage dip for the different areas (Energinet.dk 2014c).

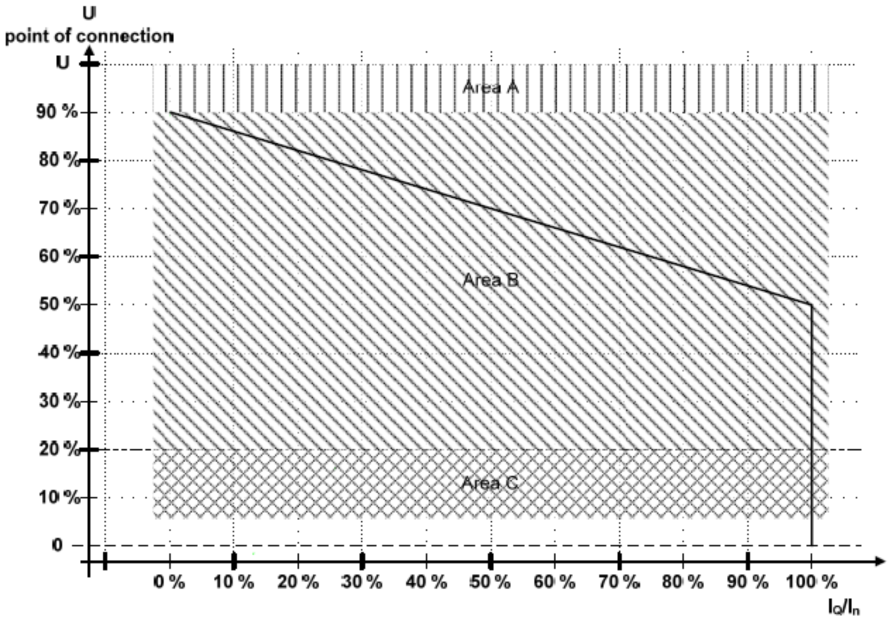


Figure 3.6. Requirements for reactive power supply during a voltage dip for category C and D (Energinet.dk 2010).

ENDK also specifies requirements for withstanding of faults, and limit values for different disturbances. The WPP should be able to withstand all fault types for a period of 150 ms, with additional requirements of tolerance to fault reoccurrence depending on the fault type. The defined disturbances are DC-content (max 0,5 % of nominal current), asymmetry between phases (no larger than 16 A), rapid voltage changes (4 % of U_n if $U_n \leq 35$ kV and 3 % of U_n if $U_n \geq 35$ kV), flicker, harmonic disturbances, inter-harmonic disturbances and frequency disturbances between 2 and 9 kHz (Energinet.dk 2014c).

3.2.3 Control requirements

The following section will give a summary of the control requirements that Danish WPPs are experiencing.

Table 3.9. Control requirements for WPPs of the four different categories (Energinet.dk 2014c).

Category **Control function**	**A**	**B**	**C**	**D**
Frequency response	X	X	X	X
Frequency control	-	-	-	X
Absolute production constraint	-	X	X	X
Delta production constraint	-	-	-	X
Power gradient constraint	-	-	X	X
Q control	X	X	X	X
Power factor control	X	X	X	X
Voltage control	-	-	-	X
System protection	-	-	X	X

Frequency response means that when the net frequency exceeds a predefined limit between 50.00 and 52.00 Hz, the WPP should automatically curtail the active power in order to contribute to the network stability. For the response to be efficient, the control needs to be quick, operating between 2 and 15 seconds after the disturbance, with an accuracy of 10 mHz. The TSO decides on a maximum frequency that will provide a limit indicating when control is required. A common frequency limit is 50,20 Hz (Energinet.dk 2014c).

Frequency control is more detailed than the frequency response, with the possibility to set the frequency points f_1 to f_7, f_{min} and f_{max} to any value in the area of 47.00 to 52.00 Hz with an accuracy of 10 mHz, see figure 3.7. The control shall act within 2 seconds after a change in frequency has been observed, and be completely carried out after 15 seconds (Energinet.dk 2014c).

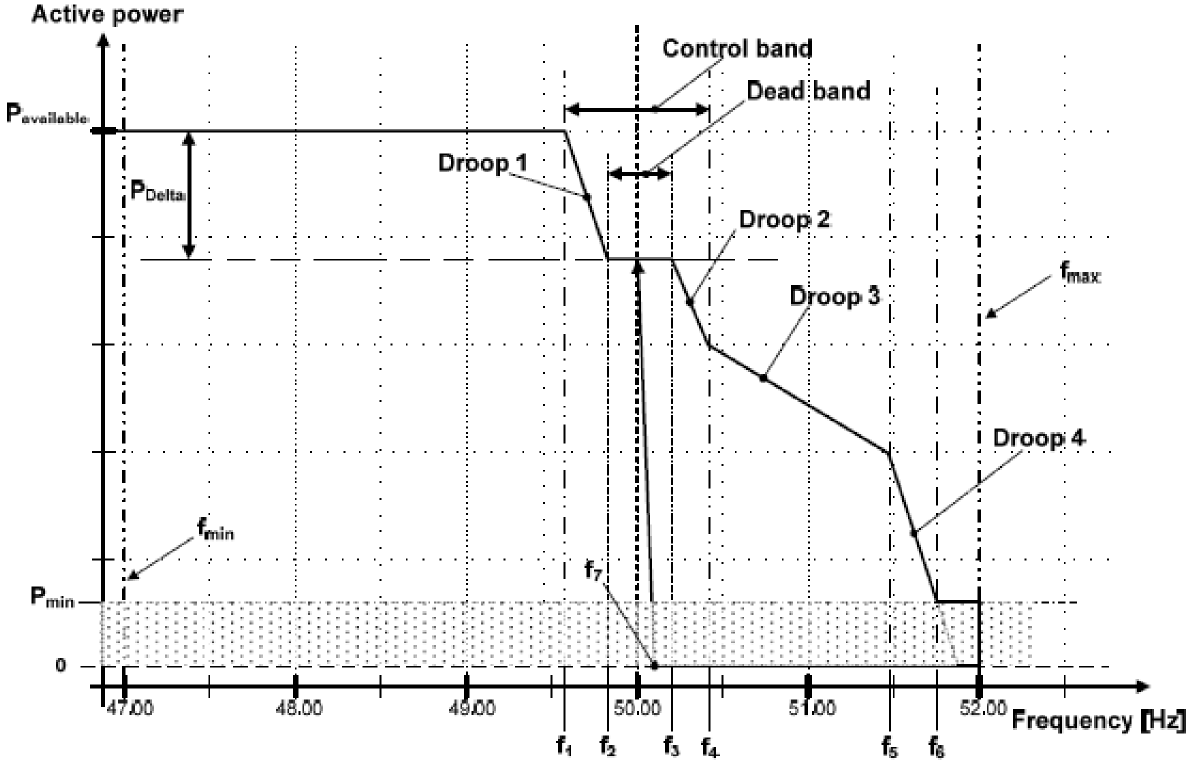


Figure 3.7. An example of how the frequency control function can look like (Energinet.dk, 2010).

The frequency points f_1 to f_4 form a control band and a dead band for the primary control. If the net frequency exceeds f_5, the upwards regulation cannot start until the net frequency is below f_7. The P_{Delta} is the power reserve kept in order to regulate the production upwards in case of a grid frequency drop (Energinet.dk 2014c).

Absolute production constraints are set in the POC in order to protect the network, it is a predefined maximum value for the active power delivered in that point. The control should act within 2 seconds after receiving a signal for a new set point, and be completely carried out after 10 seconds (Energinet.dk 2014c).

The *delta production constraint* is used for restraining the active power in relation to the possible power so that there is room for upwards regulation. The control should act within 2 seconds after receiving a signal for a new set point, and be completely carried out after 10 seconds (Energinet.dk 2014c).

The *power gradient constraint* is used to limit the maximal speed of which the active power production can change due to changes in wind speed or new set points for the active power. This limit will prevent fast changes that could cause instability in the network. The control should act within 2 seconds after receiving a signal for a new set point, and be completely carried out after 10 seconds (Energinet.dk 2014c).

The following paragraphs presents control concerning reactive power and voltage. All control concerning voltage and reactive power are mutually exclusive, meaning that only one of them can be activated at a time. It shall be possible to tune in a gradient for reactive power control using set points, the standard value for the gradient is 10 MVar/sec (Energinet.dk 2014c).

Q control is a type of reactive power control that regulates the reactive power in the POC independently of the active power. The reactive power is set to a fixed value that does not change when the active power changes. The WPP should be able to receive a Q set point with an accuracy of 1 kVar. The control should act within 2 seconds after receiving a signal for a new set point, and be completely carried out after 30 seconds (Energinet.dk 2014c).

Power factor control is a function controlling the reactive power proportionally to the active power in the POC. The WPP should be able to receive a power factor set point with an accuracy of 0,01. The control should act within 2 seconds after receiving a signal for a new set point, and be completely carried out after 30 seconds (Energinet.dk 2014c).

Voltage control is a function used to stabilize the voltage level in the voltage reference point, which is located either at the POC, the PCC or at a point in between. A particular WPP will have a particular dynamic area for the voltage control within the limits of maximal and minimal voltage and reactive power for that WPP. The droop (voltage change caused by change in reactive power) for the control must be set inside these limits. This control function is not the first priority for the WPP, and might not be carried out due to priority of other control functions. The superior coordination of the voltage control is performed by the grid owner in collaboration with the TSO. The control should act within 2 seconds after receiving a signal for a new set point, and be completely carried out after 10 seconds (Energinet.dk 2014c).

System protection is a type of control which can perform a fast downwards regulation of the active power to one or several predefined set points when an order of such a regulation is received. The grid owner predefines the set point when the WPP is put into service, and there should be at least five predefined set points. The control should act within 1 second after receiving a signal for a new set point, and be completely carried out after 10 seconds (Energinet.dk 2014c).

Additional requirements for WPPs of category A

The WPP should be designed to maintain the power factor interval 0,95 – 1,0 when the production is larger than 20 % of the rated power (Energinet.dk 2014c).

Additional requirements for WPPs of category B

The WPP should be designed so that the reactive power in relation to the active power at all times is operating in the marked area in figure 3.8. When the WPP is disconnected or not producing active power, no reactive power compensation is demanded (Energinet.dk 2014c).

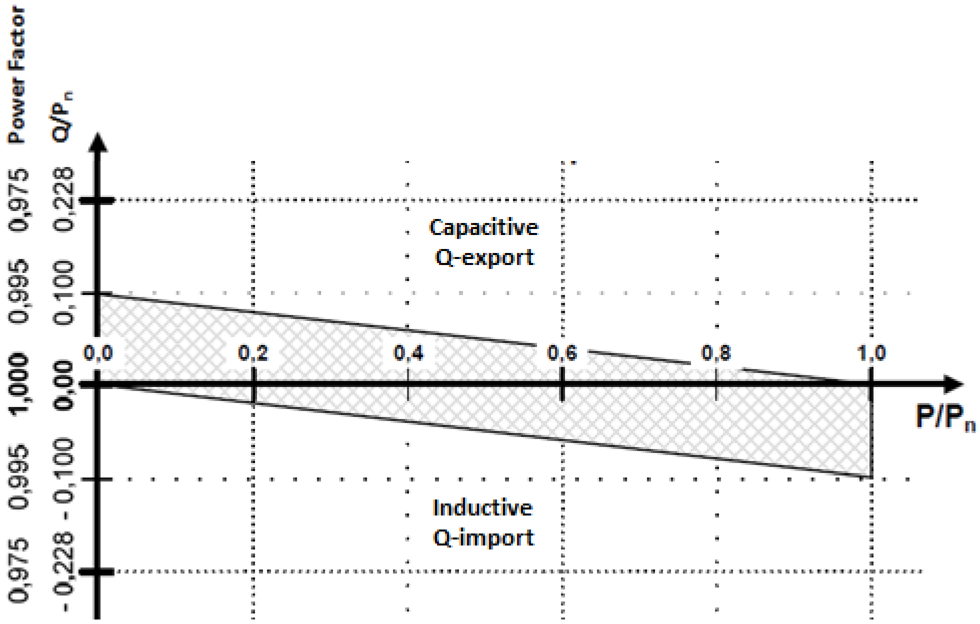


Figure 3.8. Requirements for reactive power production in relation to active power production for WPPs of category B (Energinet.dk 2014c).

Additional requirements for WPPs of category C

The WPP should as a minimum be able to curtail its active power continuously to an arbitrary value within the range of 100 – 40% of the rated power. There should also be a function curtailing the active power during high winds close to the cut-out speed, so that the WPP does not come to an immediate stop when the cut out speed is reached. This regulating function should be possible to activate/ deactivate if such a command is received. The curtailment can be continuous or discrete, and if it is discrete, the steps should not be smaller than 25 % of rated power. More detailed curtailing parameters are agreed on with the grid owner when the WPP is put into service (Energinet.dk 2014c).

The WPP should be designed so that the reactive power in relation to the active power at all times is operating in the marked area in figure 3.9. When the WPP is disconnected or not producing active power, it is the plant owner’s responsibility to compensate for the reactive power of the WPP. This reactive power can be delivered from the grid if there is an agreement with the grid owner. The voltage range for reactive power delivery is also defined, see figure 3.10 (Energinet.dk 2014c).

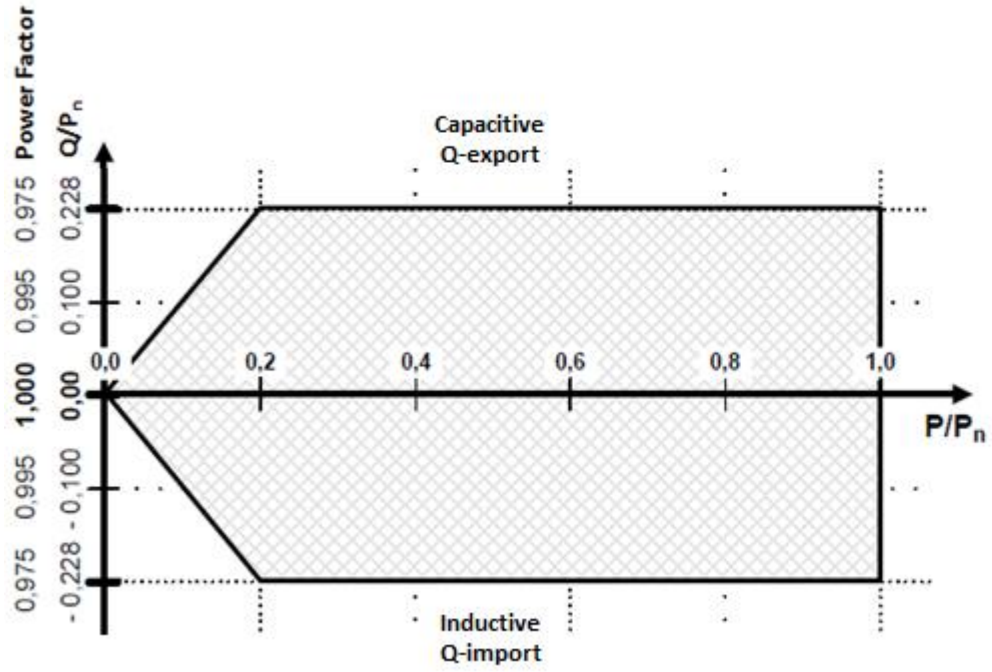


Figure 3.9. Requirements for reactive power production in relation to active power production for WPPs of category C (Energinet.dk 2014c).

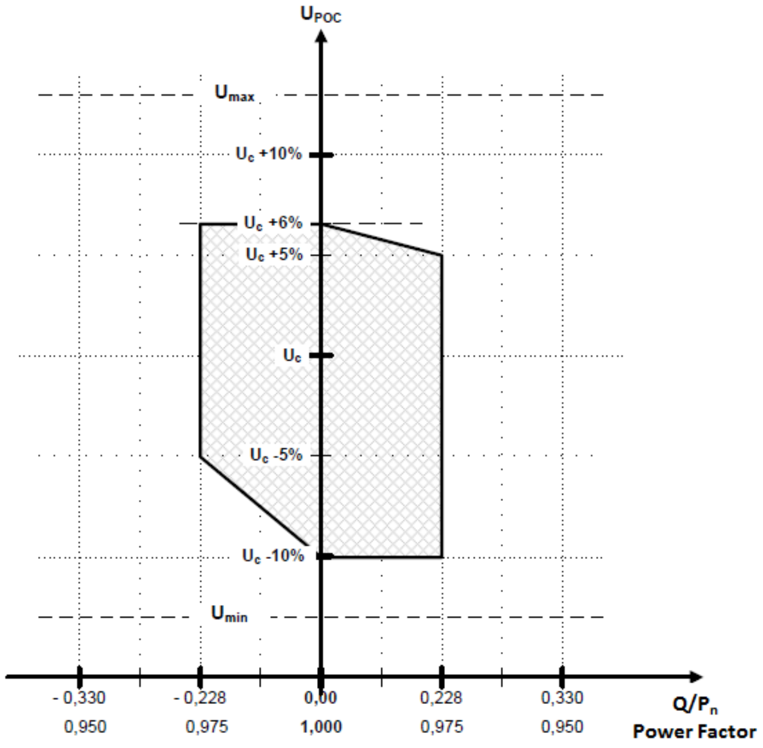


Figure 3.10. Requirements for voltage control range for WPPs of category C (Energinet.dk 2014c).

Additional requirements for WPPs of category D

The demands specified for category C also applies to category D. An additional demand is that the WPP should as a minimum be able to curtail its active power continuously to an arbitrary value within the range of 100 – 20% of the rated power (Energinet.dk 2014c).

The WPP should be designed so that the reactive power in relation to the active power at all times is operating in the marked area in figure 3.11. When the WPP is disconnected or not producing active power, it is the plant owner's responsibility to compensate for the reactive power of the WPP. This reactive power can be delivered from the grid if there is an agreement with the grid owner. The voltage range for reactive power delivery is also defined, see figure 3.12 (Energinet.dk 2014c).

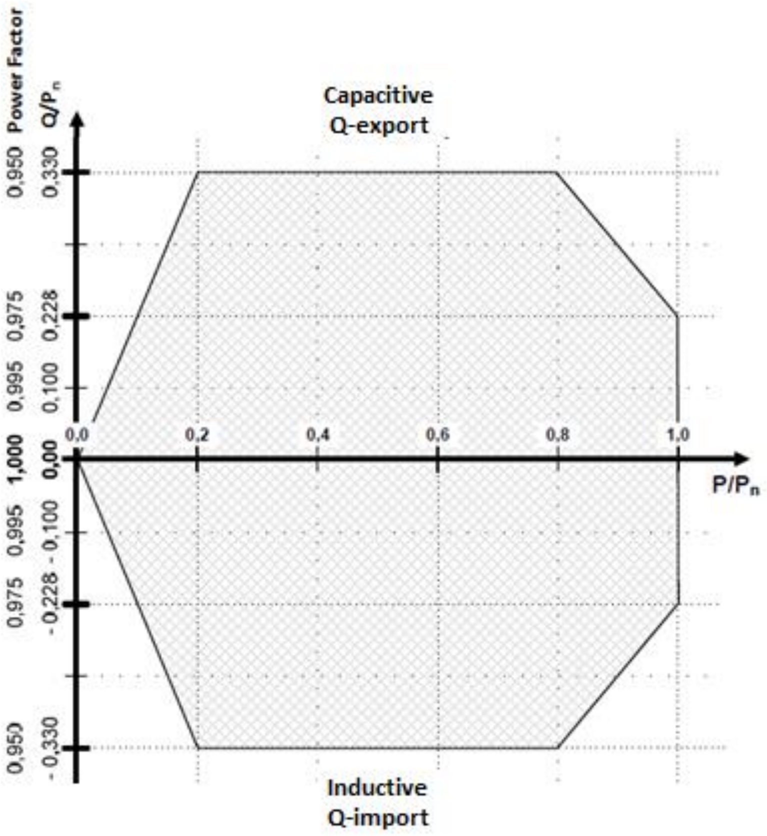


Figure 3.11. Requirements for reactive power production in relation to active power production for WPPs of category D (Energinet.dk 2014c).

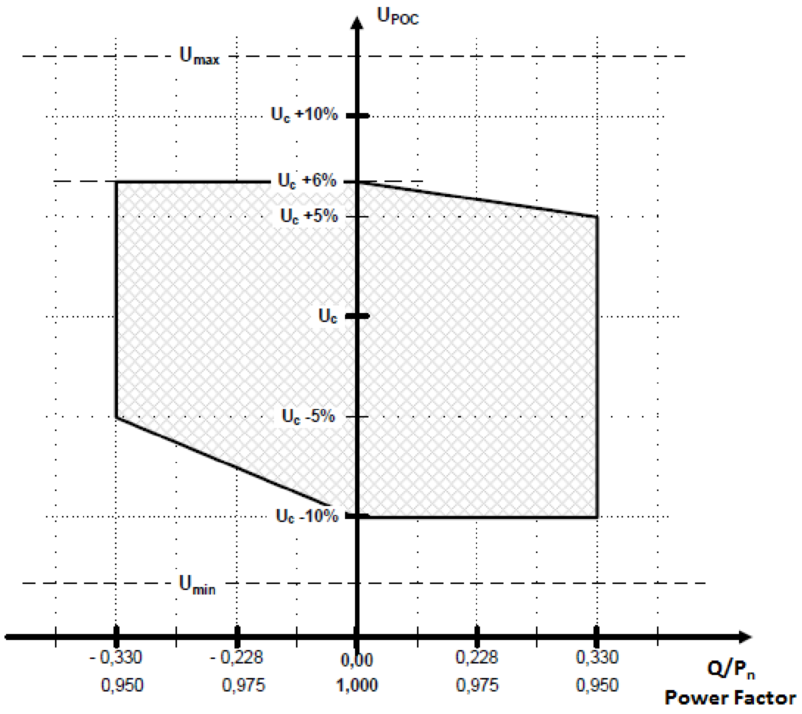


Figure 3.12. Requirements for voltage control range for WPPs of category D (Energinet.dk 2014c).

3.2.4 Constraint payments for Danish WPPs

In Denmark, offshore WPPs constructed following a call for tenders, can be ordered by Energinet.dk to curtail its active power. The reason for curtailment can be faults or maintenance in the transmission network or the landing facilities that bring the electricity ashore, or the grid might be overloaded. The WPP owner is compensated according to a predefined economic model in case of curtailment. This system forces Energinet.dk to obtain an economical optimum between paying WPP owners for curtailment, or invest in reinforcements of the transmission grid, and to act accordingly (Energinet.dk 2014a). The economic model for calculating the constraint payments will be further analysed in section 7.

3.3 Swedish grid codes

The Swedish TSO SvK (Svenska Kraftnät) requires WPPs to comply with certain regulations in order to maintain a reliable national power system. In Sweden WPPs are divided into different categories depending on size, with larger WPPs experiencing stronger demands (Svenska Kraftnät 2005). The three categories are:

Small WPPs: WTGs with a power output greater than 1.5 MW
WPPs with a power output range of 1.5 MW to 25 MW

Mid-sized WPPs: WPPs with a power output range of 25 MW to 100 MW

Large WPPs: WPPs with a power output greater than 100 MW

3.3.1 Tolerance to frequency and voltage deviations

The frequency and active power requirements for a small WPP are specified in table 3.10.

Table 3.10. Frequency and active power output requirements for a small WPP (Svenska Kraftnät 2005).

Frequency [Hz]	Power output	Operation time
47.50 – 49.00	< 5 % reduction	> 30 min
49.00 – 51.00	maintained	continuous
51.00 – 52.00	reduced	> 30 min

The frequency, voltage and active power requirements for mid-sized and large WPPs are specified in table 3.11. The voltage is related to nominal voltage for a WTG recalculated to the WPP's largest voltage considering the voltage drop during maximal active power.

Table 3.11. Frequency, voltage and active power requirements for mid-sized and large WPPs (Svenska Kraftnät 2005).

Frequency [Hz]	Voltage [% of total]	Power output	Operation time	Others
47.50 – 49.70	90 - 110	-	10 min	These requirements only need to be manageable a few times
47.50 – 49.00	95 - 105	< 5 % reduction	> 30 min	-
49.00 – 49.70	90 - 105	maintained	continuous	-
49.70 – 51.00	90 - 105	maintained	continuous	-
	105 - 110	< 10 % reduction	> 1 hour	-
51.00 – 52.00	95 - 105	Reduced	> 30 min	Return to normal production within 1 min when f < 50,1 Hz

3.3.2 Tolerance to voltage dips

The requirements for tolerance of voltage dips for small and mid-sized WPPs are displayed in figure 3.13.

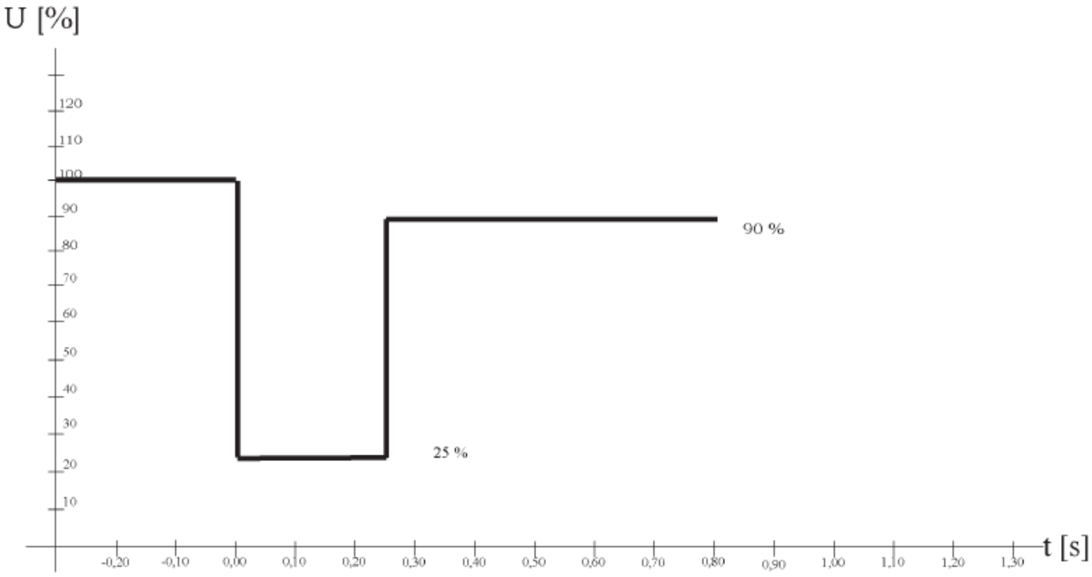


Figure 3.13. Requirements for tolerance of voltage dips for small and mid-sized WPPs (Svenska Kraftnät 2005).

The requirements for tolerance of voltage dips for large WPPs are displayed in figure 3.14.

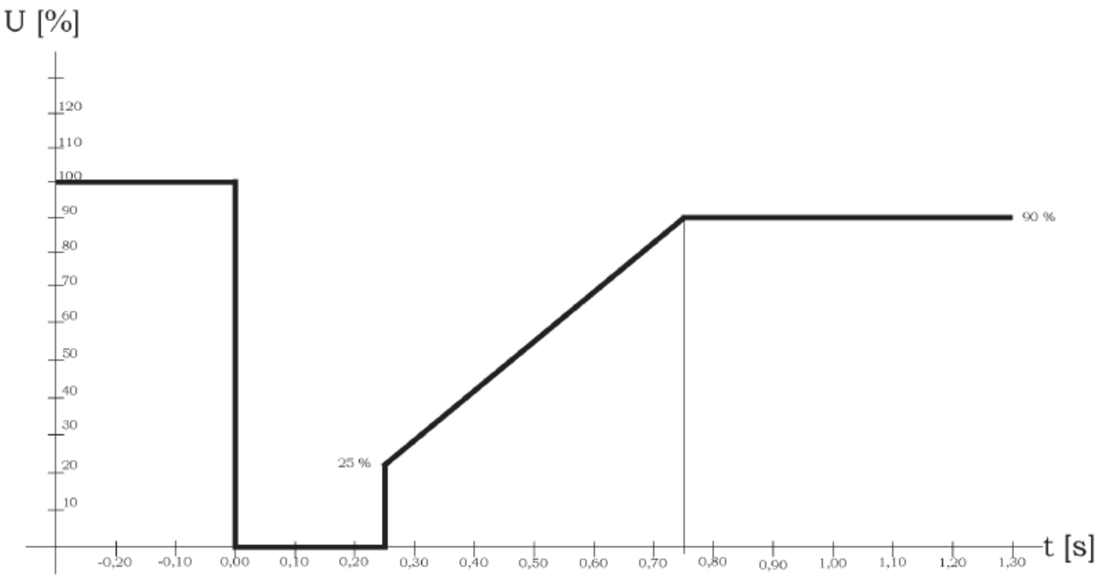


Figure 3.14 Requirements for tolerance of voltage dips for large WPPs (Svenska Kraftnät 2005).

SvK also states that all WPPs should be able to handle the variations in voltage for one or more phases that may occur due to momentary faults without losing contact with the grid. All WPPs should also be able to handle short variations in voltage that may occur due to common events such as faults caused by thunder or connection problems without losing contact with the grid (Svenska Kraftnät 2005).

3.3.3 Control requirements

Small WPPs (excluding the ones with directly connected asynchronous generators) shall be equipped with automatic voltage control in order to contribute to voltage stabilisation in case of voltage instability in the grid. Mid-sized and large WPPs shall be equipped with automatic voltage control, adjustable in the range of ± 5 % of nominal voltage. The voltage regulation unit is MVar/kV. All WPPs should be designed so that the reactive power exchange can be set to zero. (Svenska Kraftnät 2005). This need to be fulfilled also when the WTG is energized (connected). It is possible to seek for exception up to 5 WTG or 10 MW (Kursumovic 2015). Other power plants (excluding WPPs) have stricter requirements considering the ability to produce and consume reactive power (Svenska Kraftnät 2005).

Single WTGs that are part of a WPP should be able to have individual settings regarding the circumstances that will cause a stop in production. If the WTGs are stopping, they are not allowed to stop all at the same time, a maximum of 30 MW/ min is permitted to be disconnected. It shall be possible to control the power production of a WPP so that it does not exceed a predefined power level. This power level shall be possible to control when receiving a signal, and the control algorithm should be changeable. It shall be possible to control the production level to below 20% of maximum power within 5 seconds (Svenska Kraftnät 2005).

Mid-sized and large WPPs should be equipped with control functions so that it is possible to control them manually within 15 minutes after a disturbance in operation. The control functions shall include connection and disconnection to the grid, and control of active and reactive power (Svenska Kraftnät 2005).

3.4 Analysis of grid code differences

The three sets of grid codes are quite similar, but there is a small but consistent difference in the level of the requirements. The trend is that the European NC (NC RfG) and the Danish grid code include stronger demands than the Swedish grid code, especially when it comes to control requirements. The following section will display some examples of this. The comparison between the grid codes is based mainly on the larger categories of WPPs.

When comparing the tolerance of frequency deviations, the NC RfG and Danish grid code have slightly stronger demands, especially in the lower frequency range. If table 3.2, 3.8 and 3.10 are compared, it can be seen e.g. that the lowest frequency under which the WPPs are required to operate normally for a minimum of 30 minutes is 47.50 Hz for all analysed grid codes, but in the Swedish example, a 5% power reduction is allowed, resulting in a requirement that is a bit milder for the Swedish case. The Danish grid codes also include stronger demands concerning tolerable voltage deviations related to the frequency deviations.

All the analysed grid codes have defined voltage profiles displaying to what extent a voltage dip is allowed. When comparing these profiles (see figure 3.1 and 3.14) it can be seen that both the Swedish and the European codes requires a tolerance of a voltage dip to zero. In both cases the WPP should be able to stay connected to the grid and operate during a maximum of 0.25 sec with zero voltage, before they are allowed to disconnect. The NC RfG is a bit stricter in the sense that the WPPs should be able to endure a longer time compared to the Swedish case before the voltage level is recovered, and the recovered voltage level is allowed to be lower for the European case compared to the Swedish case.

When it comes to the Danish grid code, the requirements are a bit different. Danish WPPs still need to be able to withstand faults, but the defined voltage profile displaying the requirements for tolerance to voltage dips is a bit different, since it does not require the WPP to stay connected and operate during a voltage dip down to zero, but they do however have specified requirements considering the support of reactive current to the network in order to help stabilise the voltage level, see figure 3.5 and 3.6. The NC RfG also has some requirements for additional reactive current injections (see section 3.1.2) but the limits for these requirements are to some extent left to be decided by the relevant TSO.

The requirements for the supply of reactive power during normal operating conditions also differ between the different grid codes. The NC RfG and the Danish grid code have specified requirements concerning the WPPs ability to provide reactive power to the grid. These requirements are depending on the WPP size and in the NC RfG case also synchronous area. The Swedish grid code requires the WPPs to have the possibility to adjust the voltage level, but the only existing requirement of reactive power exchange is that it should be possible to be set to zero.

Considering control requirements in general, the NC RfG and the Danish grid code have very specified requirements compared to the Swedish grid code. These Danish and European control requirements give a hint of what the future Swedish requirements might look like.

3.4.1 Requirements to be further analysed

The possible frequency response modes that the studied turbine control systems can provide will be presented, but these frequency response modes will not be further tested during simulations. Similarly the capabilities of tolerating voltage dips will be presented, but not further investigated. If dynamic simulations had been made, these requirements could have been tested as well.

The control requirements considering reactive power capabilities during normal operating conditions specified by the Danish grid code will however be tested during simulations. The NC RfG and the Danish grid code have more specified requirements then the Swedish ones stating reactive power limits depending on active power production and voltage level. The NC RfG concerning WPPs in the Nordic synchronous area define a range for which the WPP should be able to operate, by stating operational envelopes with maximum operational ranges and limits for the WPP. The relevant national TSOs are to state the exact shape of the operational envelopes within the limits stated by ENTSO-E. Considering this, testing the WPP for grid code compliance is more relevant for the Danish grid code than according to the NC RfG. These tests are performed in chapter 5.

All grid codes contain requirements considering curtailment of active power, and chapter 6 is dedicated to investigate different coordination strategies in order to make the curtailment more efficient. The possible speed of controlling active and reactive power for the investigated turbines is also presented.

3.5 Market overview

The Nordic power market, Nord Pool Spot, controls the price of electricity and regulating power in Sweden, Denmark, Norway, Finland, Estonia, Latvia and Lithuania. Every day, there is a bidding going on deciding the price of electricity for the next day, and this price is based on the expected supply and demand, which controls the required production and consumption. This day-ahead market is called Elspot, it sets the price of electricity production for every hour during the next day, and it closes every day at 12.00 CET. There is also an intra-day market called Elbas, as a supplement to the Elspot market, in order to adjust the power supply more accurately and make sure that the right amount of power is being produced. Trading at Elbas takes place every hour around the clock until one hour before the power is being delivered. There is also a regulating market at Nord Pool spot, trading extra power reserved for keeping the balance in the network (Nord Pool Spot 2015d). The regulating power is defined as a decrease or increase in power production, which can be activated within 15 minutes, and the market is open until 45 before the operation hour. The prices emanates from the spot price during the specific hour, with increased prices for up-regulation and decreased prices for down-regulation (Bang et al. 2012). If for example 100 MW is sold on the day ahead market for the spot price, and 40 of these 100 MW is sold on the regulating power market on the day of operation, the price received for the 40 MW will be the difference between the spot price and the regulating power price. However since the 40 MW was already sold on the day ahead market for the spot price, the power plant owner will in the end receive both the spot price and the regulating power price for the 40 MW sold on the regulating power market.

With an increased penetration of wind power in the system, and increased possible controllability of the WPPs, it will be more profitable to use wind power as regulating power. E.ON Wind is considering this possibility, and evaluating the best way of doing this. When considering wind power as regulating power, only down-regulation is considered, since WPPs usually do not have any room for upwards regulation, if they are not curtailed to begin with. The motivation for introducing wind power on the regulating market is the regulating prices, which needs to pass a certain level in order to make the action profitable. Since wind power receives not only the spot price but also revenues from subsidy systems for renewable energy, the regulation prices need to differ a lot from the spot price for the curtailment of WPPs to be profitable. The subsidy systems for renewable energy differ between countries, and the Danish and Swedish system will be described below.

3.5.1 Subsidy systems for renewable energy in Sweden and Denmark

The subsidy systems are related to the spot price. An average of the spot price during the last 14 years is EUR 34 per MWh for the entire Nord Pool system (Nord Pool Spot 2015b). The prices have changed quite a bit from year to year and also in between countries within the system, but the average price presented here is for the sake of comparison with the revenue prices presented in the following section.

The green certificate system in Sweden

The largest part of the Swedish subsidy system for renewable energy is based on electricity certificates. Renewable energy producers receive one electricity certificate for every MWh produced electricity. The electricity certificates are then sold on a market where supply and demand determines the price. The buyers are electricity supply companies, who have to buy electricity certificates according to a certain quota (Energimyndigheten 2015b). The price of the electricity certificates is therefore affected by two factors, the amount of electricity certificated available on the market, i.e. the amount of renewable electricity being produced, and the quota that the electricity supply companies need to meet. The system is introduced by the Swedish government, and by controlling the quotas, the Swedish government can also control how effective the system will be. There is also another type of green certificates called GoO (Guarantees of Origin) which works similarly to the electricity certificate system, but the GoO can be given to any type of electricity production, simply stating the origin of the electricity production. One GoO is given for every MWh produced, and they are traded on an open market where the actors are electricity producers and electricity supply companies (Energimyndigheten n.d.; SKM - Svensk Kraftmäkling n.d.). GoO are not only used in Sweden, but also other countries is Europe. Since the prices of GoO are very low compared to the prices of electricity certificates, the GoO are not included in the following discussion.

The electricity certificate system was introduced in Sweden in 2003, and in 2012 Norway also joined the system. The mutual goal is to increase the renewable electricity production in Sweden and Norway with 26.4 TWh during the period 2012 – 2020. During 2012 – 2014 an additional 10.3 TWh was built, of which 8.6 TWh was supplied by Sweden. During 2014, 64 % of the added renewable electricity production came from wind power, and it is likely that wind power will continue to be a main player in the expansion of the renewable energy production (Energimyndigheten 2015a).

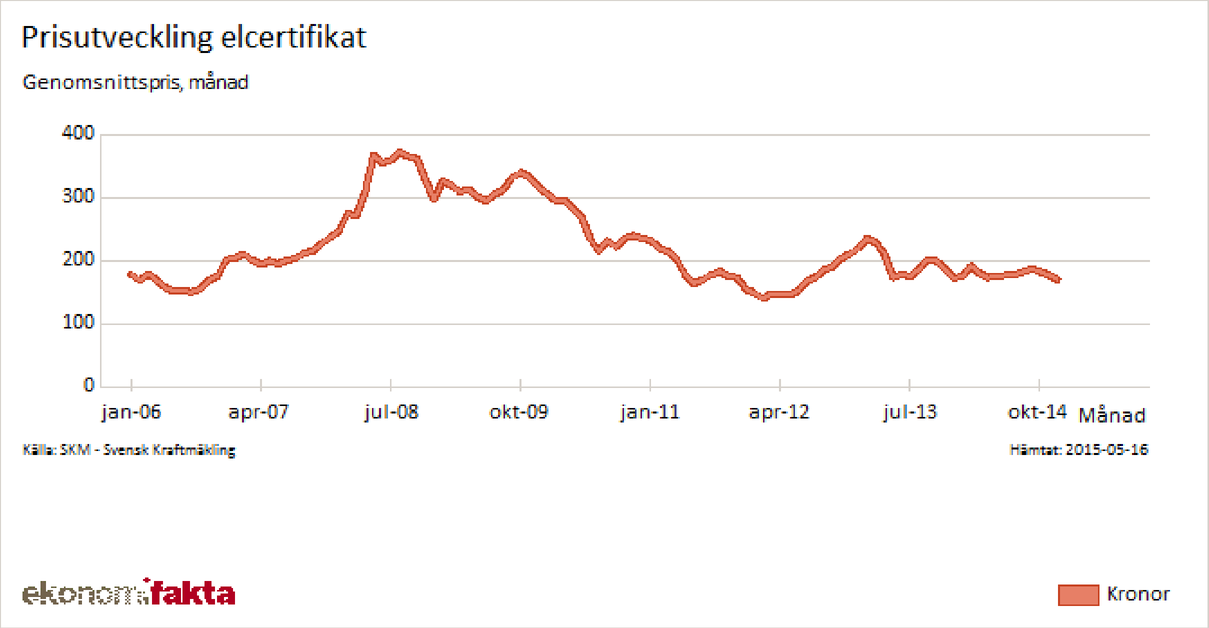


Figure 3.15. The price development of electricity certificates in SEK during the period 2006 – 2014 (Ekonomifakta 2015).

As figure 3.15 shows, the prices of electricity certificates have differed quite a lot during the period of 2006 – 2014. The average price during the period is about SEK 230 (EUR 25, assuming that EUR 1 equals SEK 9.3). Looking at the average price so far during 2015, it is now down to SEK 150 (EUR 16) (SKM - Svensk Kraftmäkling 2015).

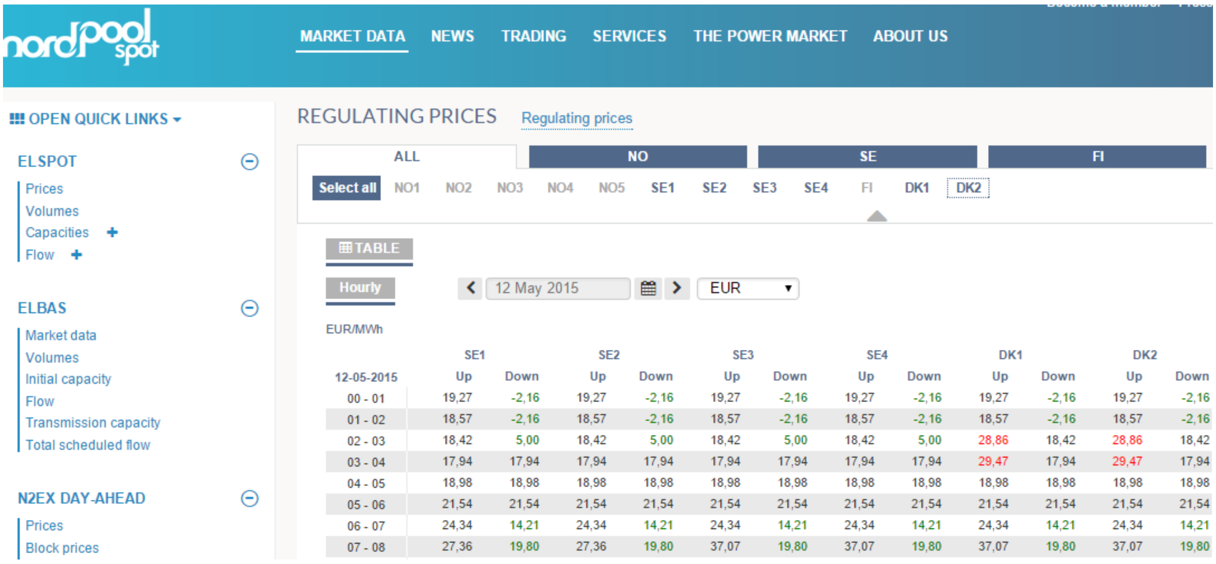
The feed-in tariff system in Denmark

For onshore wind power, an additional DKK 0.25/kWh (EUR 33/MWh, EUR 1 equals DKK 7.5) is added to the spot price for the first 22 000 hours of full production (peak-load hours). This system is valid for wind power connected 21 February 2008 or later. For offshore wind power installed following a tender, the feed-in tariffs differ in price. When it is decided that a site is suitable for offshore wind power, the companies that wants to build a WPP at that site will offer bids of how much the feed-in tariff needs to be in order for them to build the WPP and profit from the project in the long run. The lowest bid wins, e.g. for the Horns Rev 2 WPP the price is DKK 0.518/kWh (EUR 69/MWh), and for the Rödsand 2 WPP the price is DKK 0.629/kWh (EUR 84/MWh) (these prices are the total price received, independent of the spot price). Also the Anholt WPP receives this feed-in tariff with a price of DKK 1.051/kWh (EUR 140/MWh). For offshore WPPs, the feed-in tariff applies for the first 50 000 peak load hours, during a maximum of 20 years. There is also an extra premium for covering feeding fees related to supply electricity to the grid, and the TSO pays for e.g. additional substations and landing cables needed etc. (International Energy Agency 2013a; Danish Energy Agency n.d.). The first WPPs to enter the feed-in tariff program that are a result of a tender process was Horns Rev 2 and Rödsand 2, with a tender process starting in 2004 (Danish Energy Authority 2005). Older WPPs receive different feed-in tariffs that are not always as profitable as the newer ones. Some of these older WPPs are participating in the regulating power market when the prices become low enough. For new WPPs like Kriegers Flak and Horns Rev 3 the feed-in tariff has changed again, not providing any price supplement during negative spot prices (Danish Energy Agency 2014). This change is made to adapt to a system with a higher penetration of wind power providing an incitement for wind power to participate on the regulating power market. The feed-in tariffs following a tender process is very important for the possibility to build new WPPs in Denmark since they provide a secure income for a substantial part of the WPP lifetime, making the investment more secure then if the WPP for example would be built in Sweden where the income is more dependent on the spot price.

3.5.2 Analysis of the possibilities of wind power entering the regulating power market

Comparing the two subsidy systems described in this chapter, it is clear that the Danish system is more beneficial for the expansion of the wind power business, since it provides better incitements for building new WPPs. The differences also result in different conditions considering wind power on the regulating power market, as mentioned above. Since some Danish offshore WPPs are not affected by the spot prices as long as their feed-in tariffs are valid, the regulating power price would need to differ very much from the spot price for curtailment to be beneficial for these Danish WPPs. Swedish WPPs are overall more sensitive to the spot price, since the only guarantied revenue they are getting apart from the spot price is the revenue from selling electricity certificates and GoO, and as seen above the prices of electricity certificates are quite low compared to the revenues that Danish WPPs are receiving. That is the present state of the market, but since the prices are constantly changing, these conditions will also change following a change in the market situation.

The possibility of introducing wind power to the regulating power market in Sweden requires a spot price that passes the point where curtailing the WPP would generate a higher revenue then the electricity certificates, also taking other parameters into consideration such as risks of curtailing, etc. The probability of such low prices is increasing with the present increase in amount of RES (Renewable Energy Sources) in the system. This phenomena is especially clear in SE4 (Swedish price area 4) and Denmark where there is a limited access to hydropower that is the cheapest source of regulating power. Other power sources like natural gas, biomass, coal etc. can also be used as regulating power. In countries like Sweden and Norway with access to a lot of hydropower, it is more common to use hydro power as regulating power. There have even been some cases where the regulating prices have been negative (see figure 3.16), and during the summer of 2014 SvK requested more control objects in SE4 since there was a high probability of network congestion in the system. In the case of figure 3.16, all price areas in Sweden and Denmark experienced negative regulating prices during the first two hours of 12th of May 2015. Some main reasons for the negative prices were that the wind power production was high, 6 nuclear power reactors in Sweden were on maintenance. Also since the hydropower was preparing for the spring flood, the hydropower needed to keep letting water out of the dams and was therefore not used as regulating power to its normal extent. Negative electricity spot prices are also starting to become more common with the increased penetration of RES in the system. This can be seen in Denmark and Germany who both have a high and increasing share of RES in their systems. These countries are also well connected to SE4, and therefore the prices in SE4 are affected by the system balance in Denmark and Germany.



EUR/MWh

	SE1		SE2		SE3		SE4		DK1		DK2	
12-05-2015	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
00 - 01	19,27	-2,16	19,27	-2,16	19,27	-2,16	19,27	-2,16	19,27	-2,16	19,27	-2,16
01 - 02	18,57	-2,16	18,57	-2,16	18,57	-2,16	18,57	-2,16	18,57	-2,16	18,57	-2,16
02 - 03	18,42	5,00	18,42	5,00	18,42	5,00	18,42	5,00	28,86	18,42	28,86	18,42
03 - 04	17,94	17,94	17,94	17,94	17,94	17,94	17,94	17,94	29,47	17,94	29,47	17,94
04 - 05	18,98	18,98	18,98	18,98	18,98	18,98	18,98	18,98	18,98	18,98	18,98	18,98
05 - 06	21,54	21,54	21,54	21,54	21,54	21,54	21,54	21,54	21,54	21,54	21,54	21,54
06 - 07	24,34	14,21	24,34	14,21	24,34	14,21	24,34	14,21	24,34	14,21	24,34	14,21
07 - 08	27,36	19,80	27,36	19,80	37,07	19,80	37,07	19,80	37,07	19,80	37,07	19,80

Figure 3.16. Market data from the web page of Nord Pool spot showing the regulating power prices of SE4 on the 12th of May 2015. Note that the prices are negative during the first two hours of the day (Nord Pool Spot 2015c).

When a WPP is producing more power than predicted, and the prices are low, the WPP could benefit from curtailment. If for example a WPP is forecasted to produce 100 MW during a certain hour and has sold these 100 MWh on the day ahead market, but the actual production is 110 MWh at the same time as there is overproduction in the system (the area is being curtailed) then the WPP owner need to pay a balancing cost to SvK for the extra 10 MWh produced. If the regulating prices at the same time are low or even negative, the WPP owner would benefit from curtailing the WPP instead and selling these 10 MWh as a manual regulation bid on the regulating power market.

The reasoning described above could apply both in Sweden and Denmark, but since the subsidy systems differ between the countries the rules for wind power at the regulating market would also need to differ in order for all WPPs to benefit on the regulating market also in Denmark. If Danish WPPs like Rödsand 2 that always receives its feed-in tariff should enter the regulating power market, the revenue for curtailing needs to be not only the price on the regulating power market but also a compensation for the loss of subsidies. Even though this would mean an additional cost for ENDK, they would still benefit from this in the end, since making it possible for all larger Danish WPPs to act actively on the regulating power market to help the balance of the power system will result in lot of positive effects on the system. If for example the winds are strong in Denmark and all WPPs are at full production during a time with low consumption, the system will be overloaded, the regulating prices will dive, and ENDK will have problems adjusting the balance. Considering this, there is a strong incitement for introducing all larger WPPs in Denmark on the regulating power market, but when this is done, there needs to be an agreement with ENDK considering compensation for lost subsidies. The new feed-in tariffs that will apply for Kriegers Flak and Horns Rev 3 are already adopting to this, as mentioned above, but it would be desirable to also make it beneficial for large WPPs receiving the old feed-in tariff to act actively on the regulating power market and help the system balance.

A further analysis considering wind power entering the regulating power market can be found in chapter 7.

4 Control systems – properties and functions

This chapter will present a summary of Siemens and Vestas control systems. In the end of the chapter, a short description of control systems used on some of E.ONs WPPs will be described.

4.1 Control systems

The Siemens WPPs are monitored and controlled using system called WebWPS (Wind Power Supervisor, a web based SCADA-system). There are different systems available to combine with the WebWPS controlling the turbines on a detailed level, but the one that is most up to date is the HPPP (High Performance Park Pilot). The system can be pre-programmed to control the output power to any level allowed by the wind (Skov Nielsen 2014; Siemens 2014). For Vestas turbines, the Vestas online control system is called VOB (VestasOnline Business) or VOC (VestasOnline Compact). The VOC is for smaller WPPs consisting of up to 10 turbines, and the VOB is for larger WPPs or customers who want more advanced functions. The VOB can be combined with a PPC (Power Plant Controller) for more advanced control on turbine level, and the PPC has similar functions compared to the Siemens HPPP (Vestas Wind Systems A/S 2015). The PPC output is generated by different sources such as grid measurements, local grid codes, plant reference set points from the VOB server or from external operators (Vestas Wind Systems A/S 2011). The following section will include a short summary of the key functions supported by the control systems.

If the Siemens WebWPS is used, the active and reactive power output can be scheduled for every hour during a week, allowing e.g. automatic curtailment according to the level submitted during trading. The values need to be entered manually. The different modes for setting the active and reactive power are scheduled values for predefined hour, day or week, or different interfaces such as OPC, hardware, governor (only active power, this option is used in the case of several HPPP and can set one of the parks as the reference for active power control) and production dependent (only reactive power, the reactive power is set as a function of production). There are a large number of different overhead settings that can be used, ranging from parameters such as choice of grid code depending on geographic location, to control loop parameters specified for e.g. active power or voltage control (Siemens 2014). The Vestas PPC also have similar functions, depending on the functions needed for the site (Vestas Wind Systems A/S 2011).

4.1.1 Fast control of power output (MW control)

When the WPP receives a signal not to deliver any power, the reference “0” is sent to the HPPP. In this mode the rotors are still spinning but not producing, and the grid inverter is active. When power production is once again requested, the turbines can start to produce immediately without needing to accelerate the rotor and activating the inverter. Another way of doing this is to send an idle command to the turbine. The rotor will keep rotating close to the working rpm, but the inverter will need to be disconnected from the grid. When the turbines are not producing, they need additional power from the grid. This can however be managed by the HPPP, trying to match internal power consumption with exact production, as long as the wind allows (Skov Nielsen 2014). The Vestas PPC also have a fast control of power output feature, which is called fast run-back. This feature is set do decrease the active power output at a speed specified by the relevant grid code (Vestas Wind Systems A/S 2012).

4.1.2 Ramp control

Both the Vestas and the Siemens control system have a ramp control function. The power output can be regulated from 100% - 0% in the course of a few seconds. The mechanical structure of the turbines decides how fast the regulation can be, typically around 20 % of installed capacity per second. The ramp function ensures that the change in power occurs with an acceptable speed, protecting the network from quick changes that could cause oscillations in frequency. The ramp rate can be set according to national grid codes (Skov Nielsen 2014; Vestas Wind Systems A/S 2012).

4.1.3 Frequency response

There are different modes for the frequency response, which are available both by the Vestas and the Siemens systems. The limited frequency response mode only responds to over-frequencies with a fast power reduction, which means that this response does not cause a large loss of production. The sensitive frequency response mode responds to both over- and under-frequencies. To utilize this mode, the turbines need to operate in delta control mode, creating room for an increase in power when the frequency drops. A typical dead band setting for the sensitive mode is ±0,015 Hz for 50 Hz system, but it can also be adjusted. An option is to only use upwards regulation when the plant is already curtailed, so that it does not have to run with reduced output when it is not necessary. The frequency response can be activated and de-activated during operation (Skov Nielsen 2014).

4.1.4 Inertial response (transient under frequency response)

This feature allows the turbine to extract extra energy (about 5 - 15 % of total) from the rotor during a short period of time (0 - 30 sec) as a response to a frequency drop. The ramp up/ down rate for this response can be set to 1 - 1000% of rated power per minute (Siemens 2014). This feature may slow the rotor's rpm if the wind range is low, and when the magnitude of the extra power extraction is specified, this slowdown slightly reducing total output should be considered. This feature is extra useful for weak grids with low inertia. This function is located partly at the HPPP and partly at the turbine controller (Skov Nielsen 2014).

4.1.5 Power boost

This feature allows the turbine to increase its nominal power output during special pre-specified conditions. The power boost is performed by increasing the rotational speed of the rotor proportionally to the power increase. This functionality is a turbine control feature (Skov Nielsen 2014).

4.1.6 High Wind Ride Through (HWRT)

This feature ramps down the production when the mechanical loads increase during high wind conditions, in order to avoid tripping of plants or the need to stop entire plants at once. During this process the WTGs can increase or decrease the power output depending on the wind conditions, making them very flexible. Another advantage with this feature is that if WPPs are ramped down due to too high winds, this gives other conventional plants more time to ramp up their production when they need to take over, compared to if the WPP would go from full production to a direct stop. This functionality is a turbine control feature currently not supported by the WPS software (Skov Nielsen 2014).

4.1.7 Park High Wind Function

This function is a centrally controlled ramp down function that is supported by some versions of WPS and HPPP. If the local wind conditions are high enough, the HPPP will ramp down the power level of a predefined number of turbines, to a level at which the grid owner can manage an instantaneous trip. When the wind speed decreases, the power level will be ramped up again (Skov Nielsen 2014).

The Vestas PPC has a similar function, ramping down the power output proportionally across the turbines when the wind is high and close to cut-out speed.

4.1.8 Voltage control

Both the Vestas and the Siemens systems have voltage control functions, including the possibility to use power factor control modes, reactive power control modes, and voltage control modes. The systems are similar, and the Siemens control system is described more in detail in this section.

The FSFC (Full Scale Frequency Converter) and HPPP work together when voltage control is performed. There are two types of voltage control. One fast, local, located in the wind turbine controller, and one slow central voltage controller in the HPPP transmitting reference signals to the fast system every 150 ms. The values of the reference signals are calculated based on a number of factors such as the central voltage reference, the measured voltage, the number of turbines available, and the reactive power exchange at the WPP central control and measurement point (Skov Nielsen 2014).

The features of the voltage control are low-voltage ride-through (LVRT), central and local control, and the most optimised control is achieved if all of these features are used. When a change in voltage is observed, the fast control located at turbine level respond by adjusting the voltage level. The central control adjusts the references transmitted to the turbines, so that the fast control performed by the turbines will have a short reaction time with minimal overshoot (Skov Nielsen 2014).

The system controls the reactive power production/ absorption in order to handle the voltage deviations. Sometimes it is necessary to add constrains to the reactive power production, when the active power production is low in order to avoid sudden spikes in the reactive power flow. This is done either according to absolute limits of the reactive power or using power factor constraints. The WPP can contribute to voltage control also when there is no wind if a special function is used. It is possible to choose if reactive power control mode or power factor mode is to be used. It is also possible to set predefined values for the reactive power reference, which will be executed automatically (Skov Nielsen 2014). The system can be controlled using an open or closed loop, and the different parameters for this control can be changed (Skov Nielsen 2014).

4.1.9 Fault Ride-Through (FRT)

The low-voltage ride-through (LVRT) operates at turbine level, and the purpose of the function is to maintain production during sudden voltage dips. It is a complex function, triggered by a dip in voltage below a predefined level, causing the converter to quickly provide reactive voltage support, and also using pitch operations to maintain the power production. The possible extent of the voltage dip is decided by the capabilities of the different turbines (Skov Nielsen 2014; Vestas Wind Systems A/S 2012).

4.1.10 Control on turbine level

The controllability of active power is as mentioned above very high, but when receiving a new setpoint for active power, the turbines have a limit for how low this setpoint can be. The limits differ, but for the most recent technology, the lowest setpoint possible is usually 10 – 20 % of nominal power, in order to protect the turbine.

A typical example of the reactive power capability of a modern turbine is controlling the reactive power output in the power factor range of 0.9 capacitive to 0.9 inductive. However, this range is specified at turbine level, not including any cables. Therefore reactive power capabilities for a WPP have to be specified for all parks separately in the POC, including cables. Also the capabilities of reactive current injections during voltage dips are specified on turbine level.

For the cause of the simulations, an arbitrary WTG is specified based on the relevant turbine models from Vestas and Siemens that are planned to be used in wind power projects that are currently being processed, see table 4.1, figure 4.1 and figure 4.2.

Table 4.1. Specification of parameters for the WTG used in simulations.

Parameter	Property/ unit	Value
Active power (nominal)	MW	3.3
Reactive power capability (at 0-1.5 MW)	MVar	-2.2 to +2.2
Power factor available in WTG	cos(φ)	0.863 capacitive to 0.933 inductive
Maximum curtailment	% of active power	10
Cut in wind speed	m/s	3
Cut out wind speed	m/s	22.5

The possible active power output at different winds (power curve) is displayed in figure 4.1.

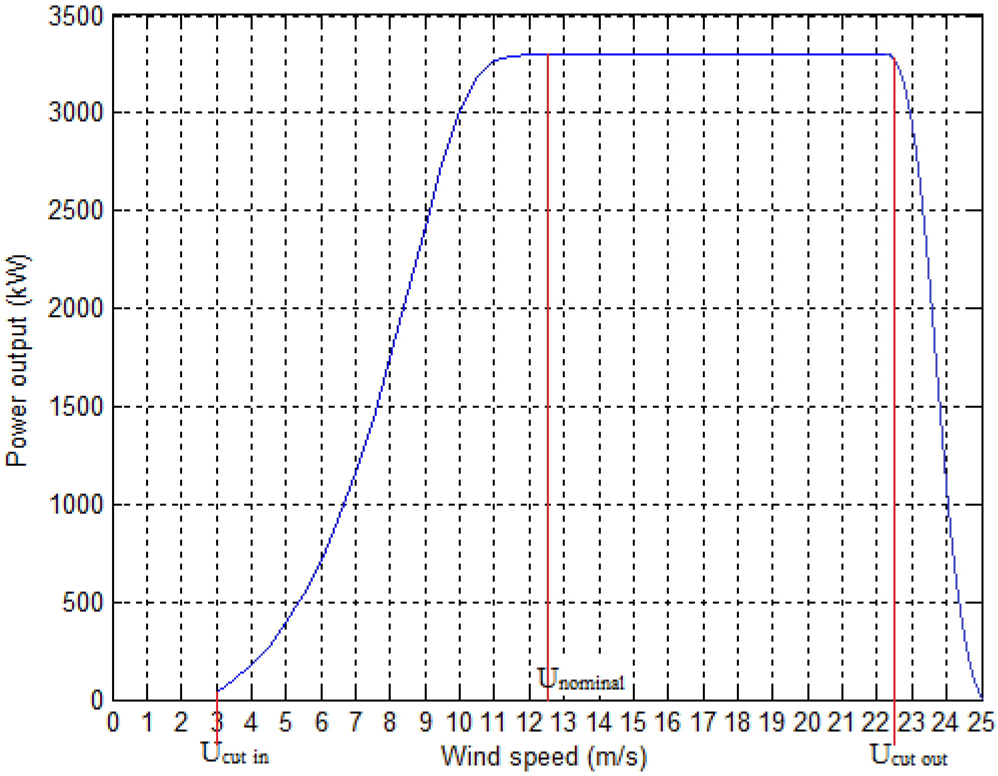


Figure 4.1. Power curve for the WTG used in simulations.

The reactive power capability depending on active power output is displayed in figure 4.2.

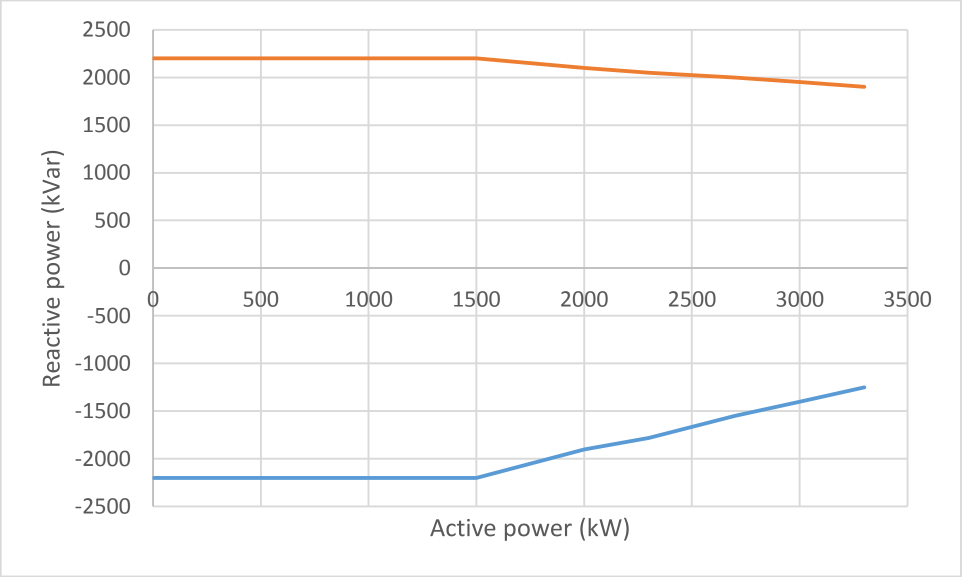


Figure 4.2. Reactive power capability at different active power outputs.

4.2 Control systems in Sweden

Curtailment of Swedish WPPs is quite rare today compared to e.g. the situation in the UK and Denmark, but as new WPPs are getting larger and larger, it is only a question of time before similar control is necessary also in Sweden. When curtailment is performed in Sweden today, the main reason is protection of the grid. The Kårehamn WPP outside of the north eastern part of Öland is an example of this. During a hot summer day, the overhead lines at Öland will not be able to handle maximum output from the WPP, since the heat will make them stretch, decreasing the distance to the ground to an unacceptable level. In order to avoid this situation, a protective system called DLR (Dynamic Line Rating) has been installed. This system sends a curtailment signal to the WPP overhead control system, which reduces the WPP output to the desired value. When the active power output is to be reduced, the control system distributes the order between the turbines so that all turbines will receive the same setpoint. Other parameters such as wake effects and wind direction etc. are not considered.

The reactive power control available in modern WPPs is used to keep the reactive power exchange in the POC to zero. Sometimes, depending on the size of the WPP, compensation devices like STATCOM are used, but when using turbines equipped with the latest technology, such devices should not be needed.

5 Simulations using DIgSILENT PowerFactory

In this chapter, simulations using DIgSILENT PowerFactory will be presented using the models and WPP features specified in previous chapters in order to investigate the active and reactive power capabilities of a corresponding WPP. A network model received from ENDK will be used. In order to investigate how the WPP can adopt to changes in the system, the network properties will be changed, for example by changing the load or the production levels from external sources in the grid. The goal of the simulations is to investigate how the active and reactive power output of the WPP can be controlled contributing to the network balance.

5.1 Network model

The network model used has been developed by ENDK for research and education (Akhmatov et al. 2006). The model is displayed in figure 5.1.

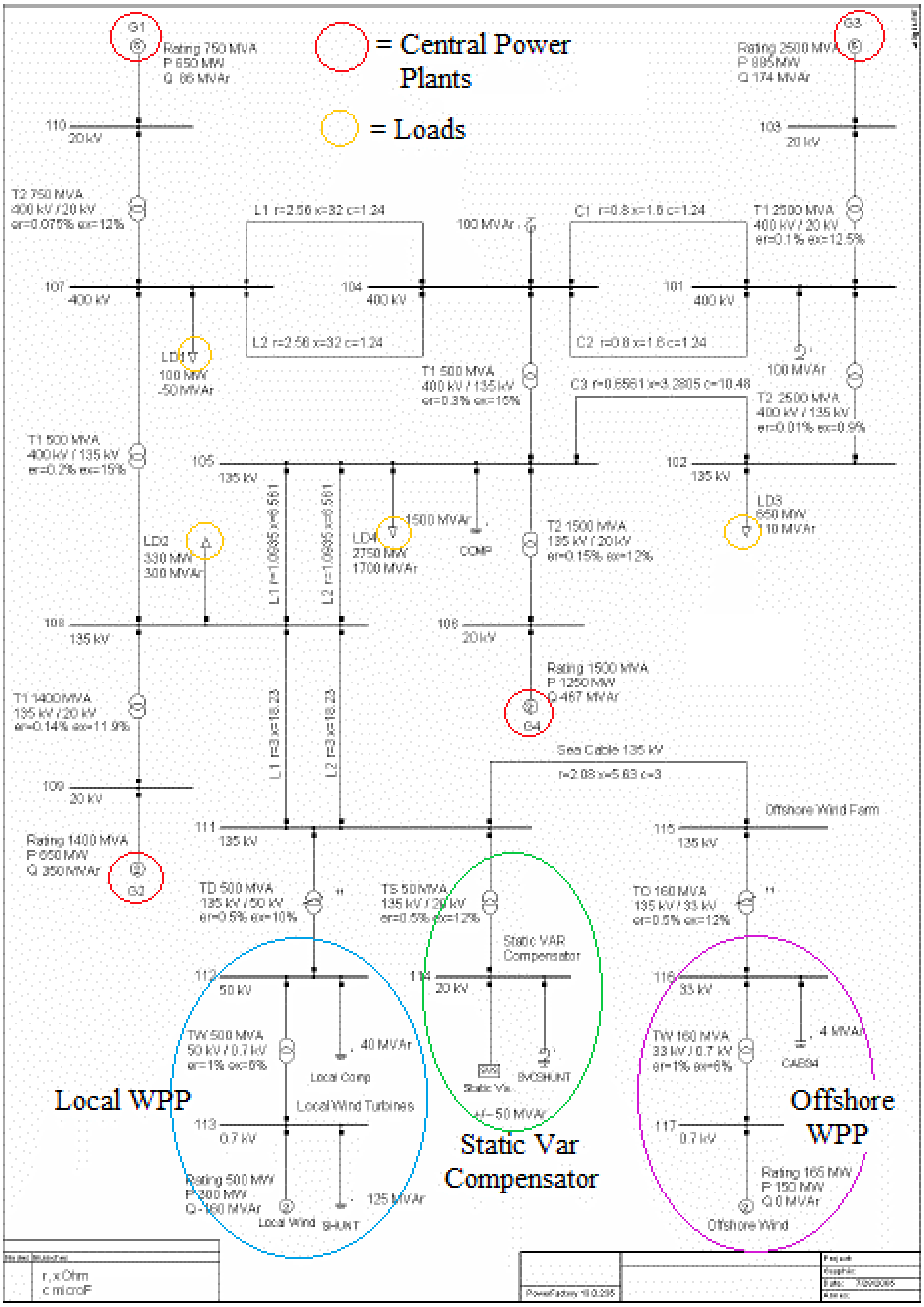


Figure 5.1. Network model provided by ENDK (Akhmatov et al. 2006).

The model is developed with the aim to represent a real grid, with several generators (power plants), loads (sources of consumption), capacitors and inductors. The four generators are labelled G1 – G4 and are equipped with synchronous generators with wound rotors. They have an active power production in the range of 650 to 1250 MW and are equipped with excitation and governor control. The 17 buses of the system range between 0.7 to 400 kV. There is also a local WPP connected to the system, represented by a lumped equivalent of fixed-speed turbines, meaning that the WPP is represented by one single asynchronous generator. The rated power of the local WPP is 500 MW, but it is set to run at 300 MW. A large offshore WPP is also connected to the system. The offshore WPP is also represented by one asynchronous generator, simulating fixed-speed and active stall controlled turbines. The offshore WPP is rated at 165 MW and running at 150 MW. The offshore WPP is connected to bus 111 via a 50 km long cable. A SVC (Static VAR Compensator) is also connected at bus 111 along with the onshore and offshore WPPs in order to improve the voltage profile in the bus (Akhmatov et al. 2006).

The starting point of the simulations will be to run a load flow for the system without making any changes in order to receive reference values for the settings of the system. Figures 5.2 – 5.4 show the system with the initial values.

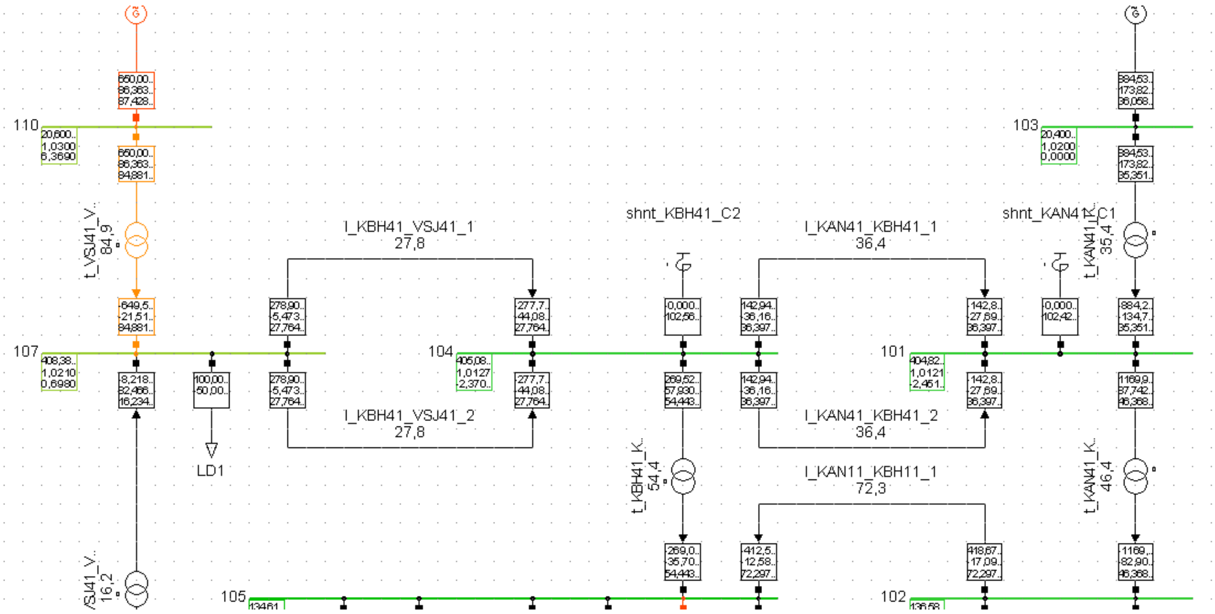


Figure 5.2. Result of a load-flow simulation with the original settings of the system, the top part of the network model is displayed in this figure.

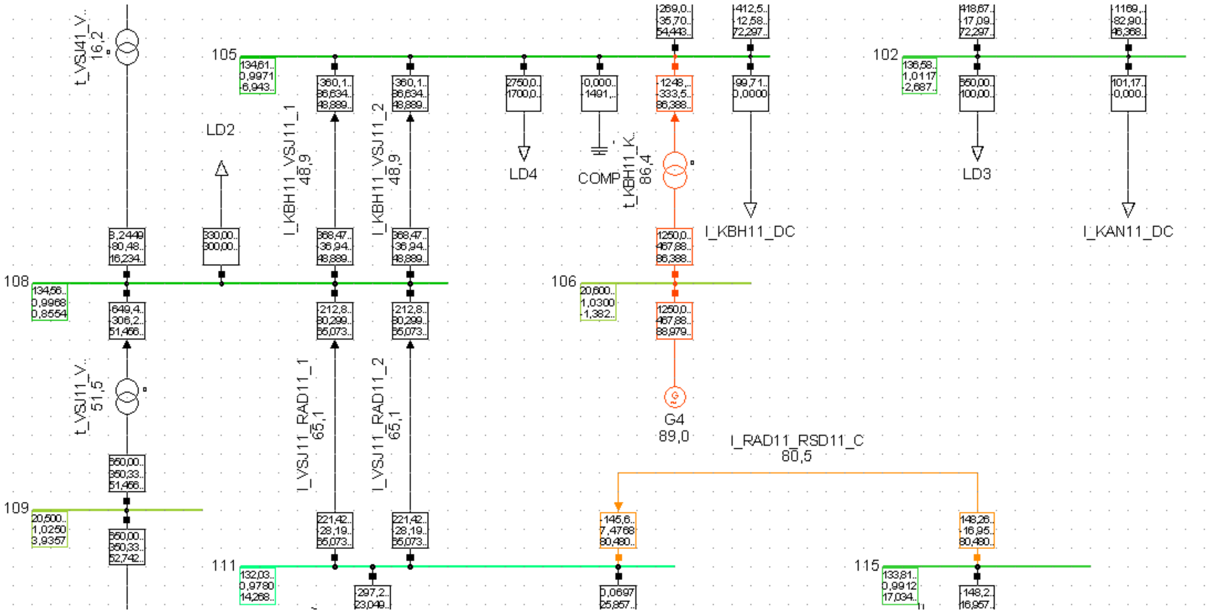


Figure 5.3. Result of a load-flow simulation with the original settings of the system, the middle part of the network model is displayed in this figure.

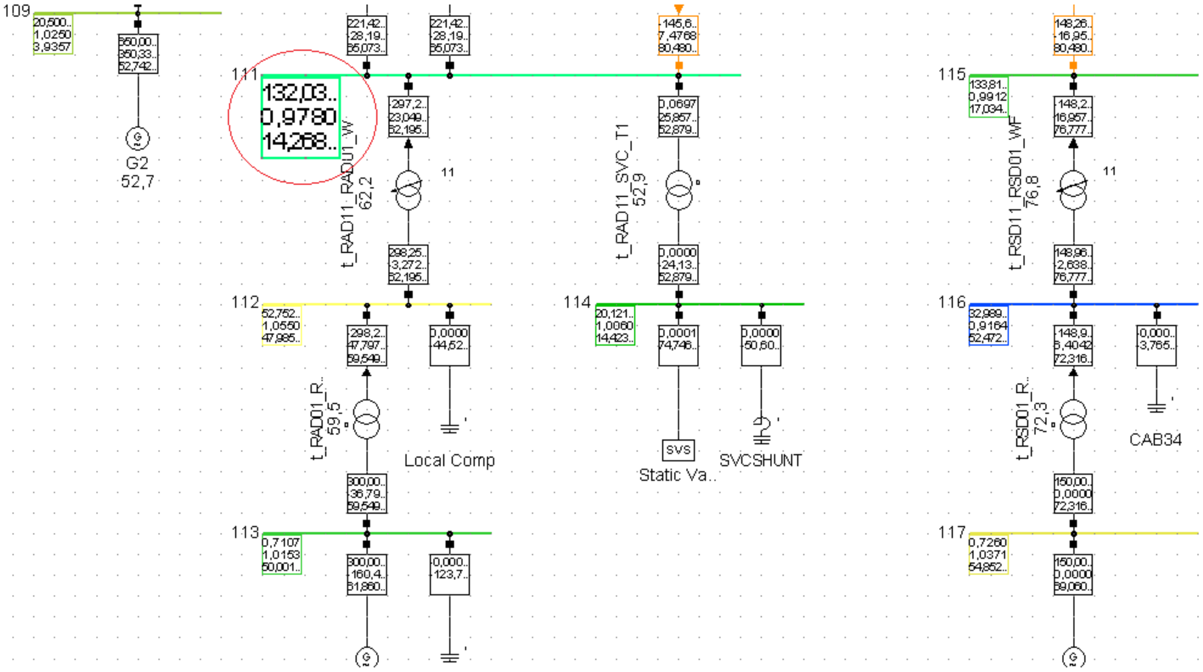


Figure 5.4. Result of a load-flow simulation with the original settings of the system, the bottom part of the network model is displayed in this figure. The output indicator at bus 111 is magnified.

The boxes with numbers in the figures are indicators of the system output after a load-flow simulation has been performed. The boxes that are located at the bottom left end of the buses show the state of the relevant bus. In figure 5.4 this output indicator is magnified, and the top row within the box shows the local voltage in kV, the middle row shows the local voltage in pu and the bottom row shows the angle between the current and the voltage in degrees. Figure 5.5 displays a further explanation of the output indicators in the system. The boxes located at the different lines and cables also have three rows. The top row shows the active power (MW), the middle row shows the reactive power (MVar), and the bottom row shows the loading (%). The minus signs indicate the direction of a certain flow (active or reactive power). For example a minus sign in front of the active power flow for an output box located next to a bus means that the active power is going into the bus, as is shown in figure 5.5.

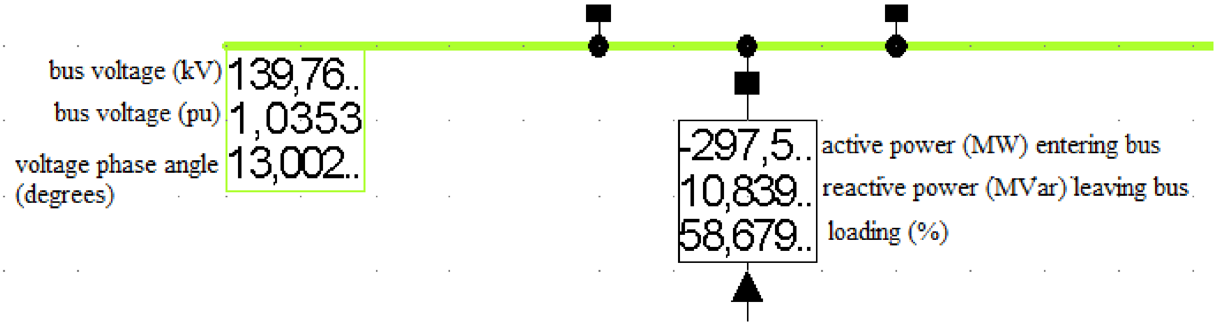


Figure 5.5. Explanation of the output indicators in the system.

In order to perform simulations with modern wind turbines with full-scale converters, the offshore WPP in the model is disconnected from bus 116 and replaced by new WTG models available in the DIgSILENT library. The capacitor connected at bus 116 is also disconnected. In order to create a WPP that can produce at least the same amount of active power as the original offshore WPP, 5 turbines with an output of 6 MW is used, and every turbine is set to correspond to 6 parallel machines, resulting in a WPP of 30 turbines with a possible active power output of 180 MW. The start-up setting of the WPP will however be to produce 150 MW, which is the same as the original offshore WPP. The power curve and the reactive power capabilities shown in figures 4.1 and 4.2 are scaled up to fit the larger turbine and implemented in the WTG models, see figures 5.6 and 5.7. Figure 5.8 shows the bottom part of the network with the new turbines connected instead of the offshore WPP.

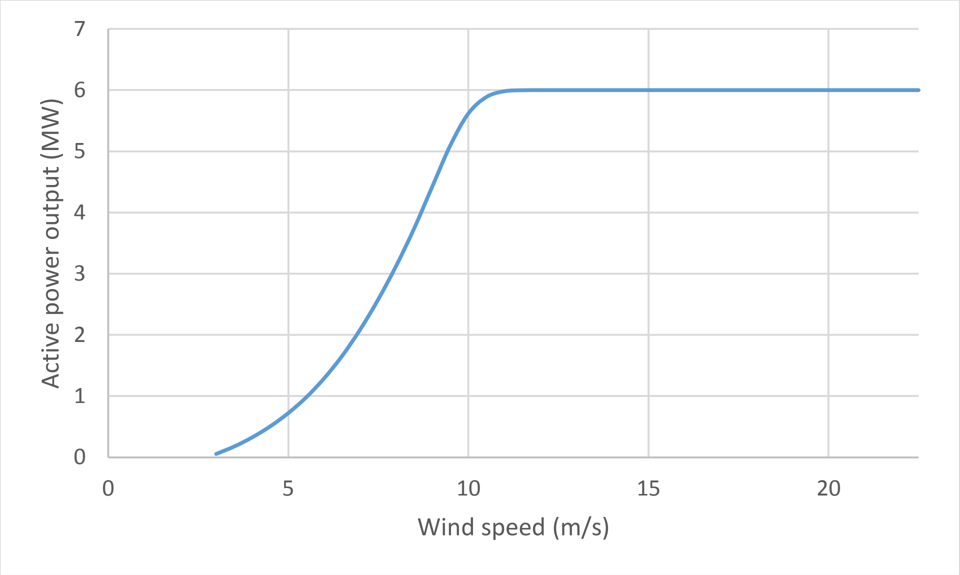


Figure 5.6. Power curve of the 6 MW WTGs used in the simulations, based on values from real turbines.

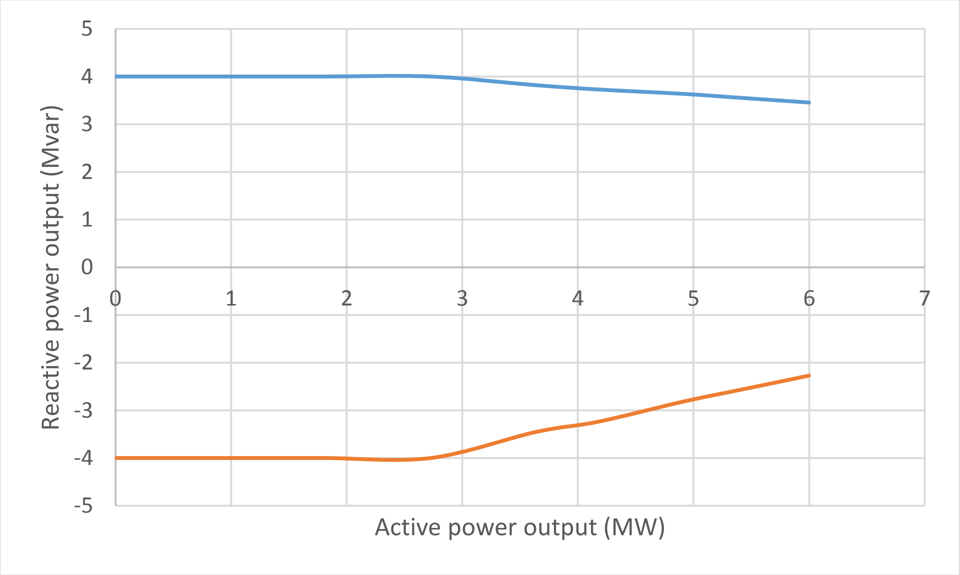


Figure 5.7. Reactive power capability for the WTGs used in the simulations, based on values from real turbines.

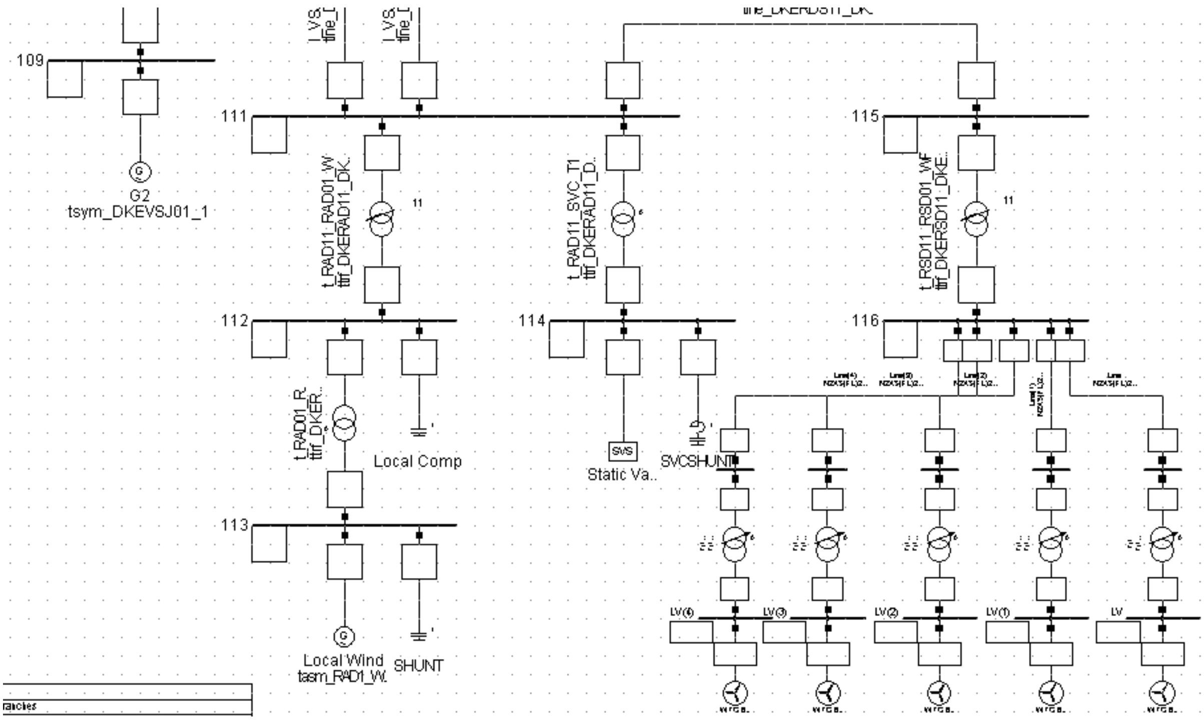


Figure 5.8. The bottom part of the network model with the offshore WPP disconnected and 5 turbines with an output of 6 MW set to correspond to 6 parallel machines for each turbine resulting in a WPP of 30 turbines connected instead.

5.2 Reactive power output from WPP replacing SVC

In order to see if the reactive power output of the new WPP can replace the SVC, a series of load flow simulations are run. The original setting of the SVC is maintaining a voltage level of 0.978 pu at bus 111 in order to keep the voltage level at bus 112 from being overloaded. First a simulation of the network with the old settings and the offshore WPP connected, but the SVC disconnected, is run. These results are compared with the results of the first simulation, where no settings have been changed. Figure 5.9 shows these two cases with the offshore WPP connected, the left side of the figure shows with SVC and the right side shows without SVC and the output indicators at bus 111 are magnified.

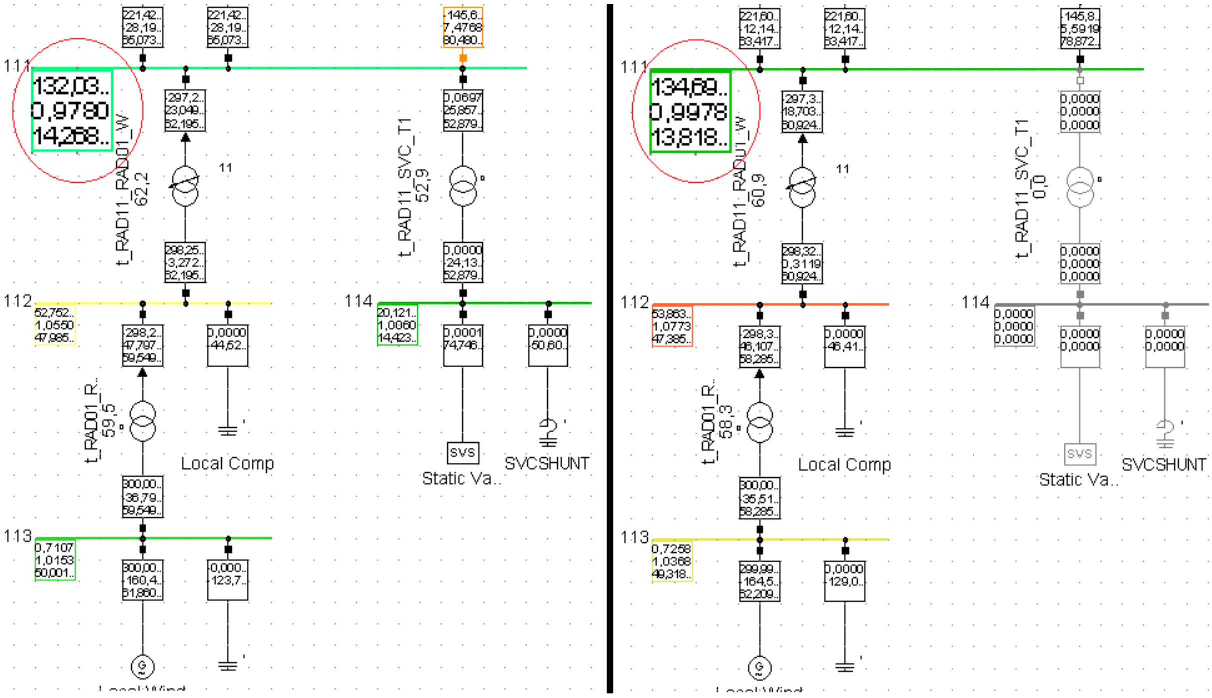


Figure 5.9. Load-flow simulation of the system, the bottom left side of the network is displayed, sowing the local WPP and the SVC. On the left side of the figure the settings are unchanged, and on the right side the SVC is disconnected. The output indicators at bus 111 are magnified.

Figure 5.9 shows that without the SVC connected to the system the voltage level of bus 111 is no longer maintained at 0.978 pu, and bus 112 becomes overloaded, as can be seen either by comparing the voltage levels with and without SVC (1.055 pu with and 1.077 pu without) or by looking at the red colour of the bus bar, indicating that it is overloaded.

The offshore WPP is disconnected and replaced by the new WPP described in the end of section 5.1. The new WPP is set to produce 150 MW in total, i.e. 5 MW per WTG. When the reactive power output is set to -0.591 MVar/WTG, i.e. -17.73 MVar for the entire WPP, the voltage level of bus 111 is kept at 0.978 pu maintaining the voltage level of bus 112 at 1.055 pu, see figure 5.10.

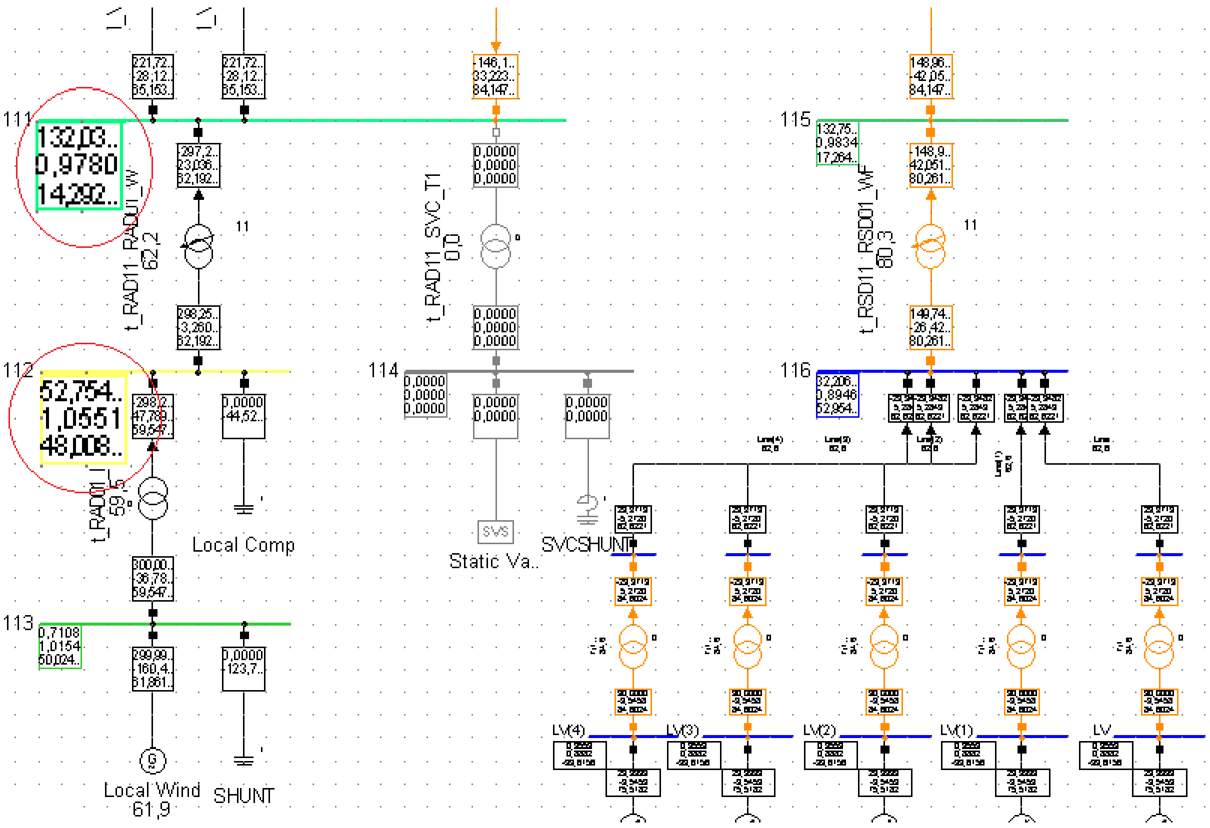


Figure 5.10. Load-flow simulation of the system with the new WPP connected. The SVC is disconnected and the new WPP is compensating the system with reactive power instead. The output indicators at bus 111 and 112 are magnified.

Since the SVC is no longer needed in the system, it will continue to be disconnected for all following simulations.

5.3 Grid code compliance

The grid codes always apply in the POC, which in this case is bus 111. As mentioned in chapter 3, the reactive power requirements differ between different countries. In Sweden the requirement is that the WPP should have the possibility to adjust the voltage level, and the reactive power exchange should be possible to be set to zero. The NC RfG (stated by ENTSO-E) and the Danish grid code have more specified requirements stating reactive power limits depending on active power production and voltage level. The NC RfG concerning WPPs in the Nordic synchronous area define a range for which the WPP should be able to operate, by stating operational envelopes with maximum operational ranges and limits for the WPP. The relevant national TSOs are to state the exact shape of the operational envelopes within the limits stated by ENTSO-E. Considering this, testing the WPP for grid code compliance is more relevant for the Danish grid code than according to the NC RfG.

The Danish grid code state that large WPPs (category D) should be able to operate within certain limits, see figures 3.11 and 3.12. When no active power is produced, the WPP owner still has a responsibility to compensate for the reactive power of the WPP. This can be done either by using reactive power provided by the grid according to an agreement with the grid owner which will be an additional cost for the WPP, or the WPP can provide the reactive power needed for compensation itself. Simulations will be made testing if the WPP can operate within the limits specified by figure 3.11.

The goal of the first simulation is to test the requirement 0 MVar at 0 MW in the POC. In order to achieve this, the WTGs reactive power output is set to -0.5699 MVar/WTG (-17.097 MVar for the entire WPP). The main reason for this need of reactive power extraction is the properties of the landing cable, which will be discussed in the end of this section. The result of the simulation is shown in figure 5.11.

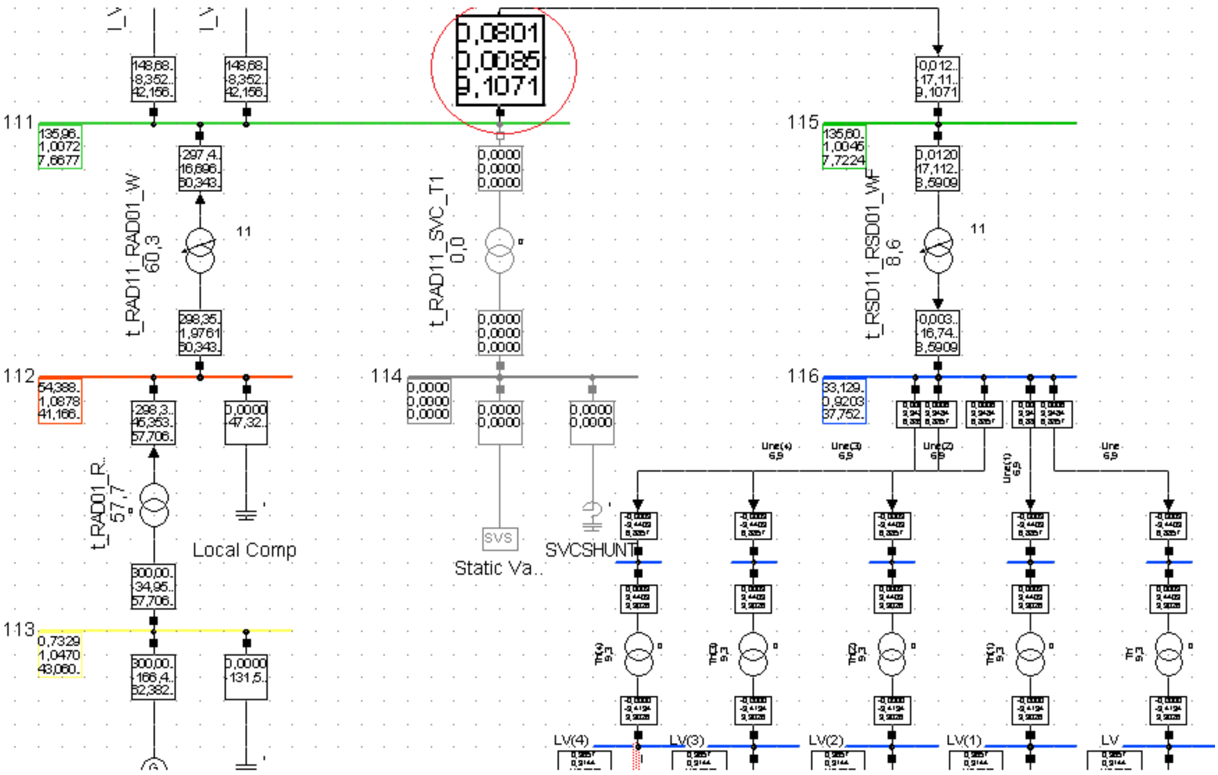


Figure 5.11. Load-flow simulation displaying the bottom part of the system when the active power output of the WPP is 0 MW and the reactive power output in the POC (bus 111) is approximately 0 MVar. The output indicator at the end of the landing cable (at the POC) is magnified.

The next step is to test the WPP at $P/P_n = 0.2$, which means that the active power output shall be 1.2 MW/WTG (36 MW for the entire WPP). According to figure 3.11, the reactive power output in the POC at this active power production shall be within the limits of $Q/P_n = \pm 0.33$, which in this case equals a reactive power output of ± 1.98 MVar/WTG (± 59.5 MVar for the entire WPP). These limits will be tested by simulations. In order to maintain a production of 36 MW in the POC, the active power production is set to 1.22 MW/WTG for the capacitive case and 1.23 MW for the inductive case. The reactive power output needed to maintain ± 59.5 MVar in the POC is 1.47 MVar/WTG for the capacitive case and -2.197 MVar/WTG for the inductive case. The results are displayed in figure 5.12.

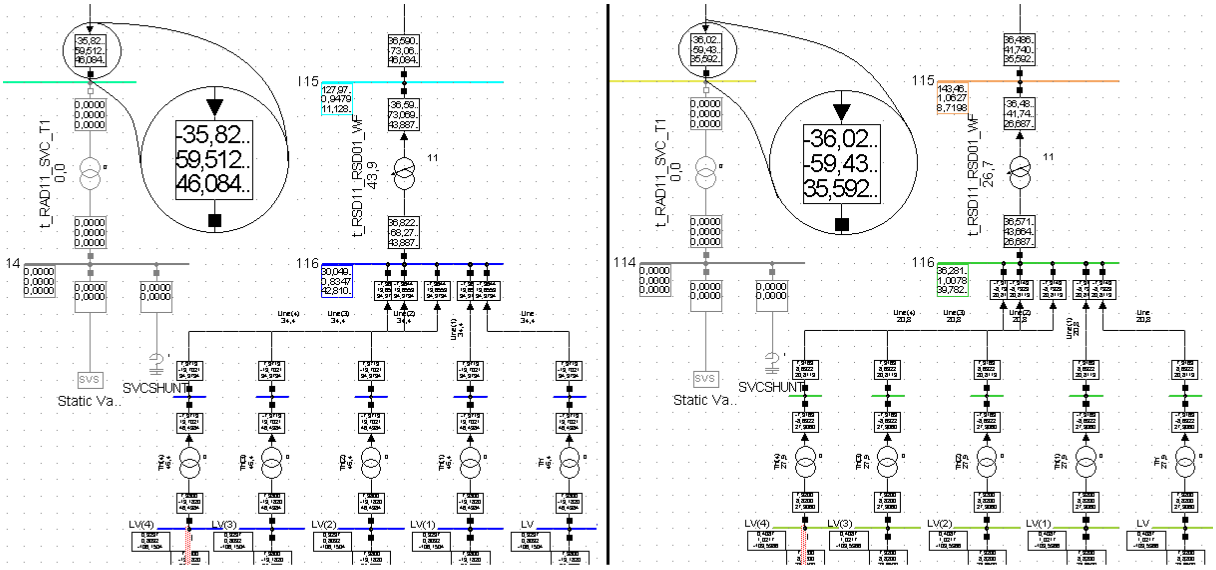


Figure 5.12. Load-flow simulation displaying the bottom part of the system when the active power output of the WPP is 36 MW and the reactive power output in the POC (bus 111) is approximately ± 59.5 MVar. The left side of the figure shows the inductive case and the right side shows the capacitive case.

The next point to be tested is when $P/P_n = 0.8$, i.e. the active power output is 4.8 MW/WTG (144 MW for the entire WPP). At this point the required reactive power limits are still ± 1.98 MVar/WTG (± 59.5 MVar for the entire WPP). The simulations show that these requirements are met when the active power production is 4.92 MW/WTG for the capacitive case and 4.94 MW/WTG for the inductive case. The reactive power output needed to maintain ± 59.5 MVar in the POC is 2.25 MVar/WTG for the capacitive case and -1.285 MVar/WTG for the inductive case. The results are displayed in figure 5.13.

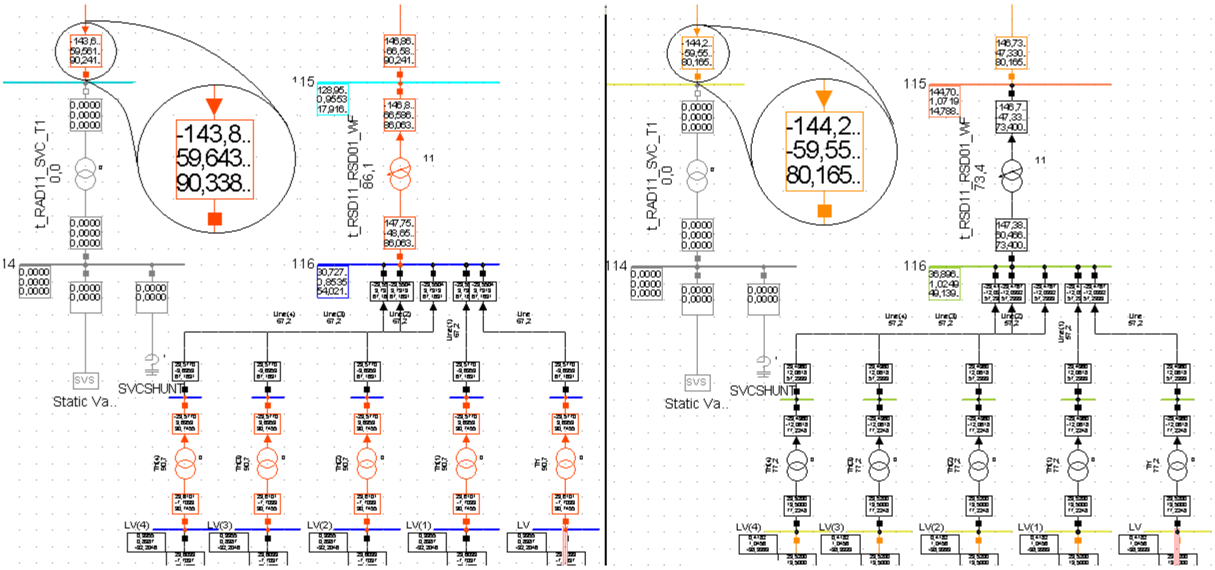


Figure 5.13. Load-flow simulation displaying the bottom part of the system when the active power output of the WPP is 114 MW and the reactive power output in the POC (bus 111) is approximately ± 59.5 MVar. The left side of the figure shows the inductive case and the right side shows the capacitive case.

The last point to be tested is when $P/P_n = 1$, i.e. the active power output is 6 MW/WTG (180 MW for the entire WPP). At this point the required reactive power limits are $Q/P_n = \pm 0.228$, which equals ± 1.368 MVar/WTG for the WPP used in simulations (± 41.04 MVar for the entire WPP). The simulations show that it is not possible to maintain an active power output of 180 MW in the POC in this case, since the maximum output of the WTGs is 6 MW and there are losses on the way to the POC. The reactive power output needed to maintain ± 41.04 MVar in the POC at full active power production is 2.03

MVar/WTG for the capacitive case and - 0.347 MVar/WTG for the inductive case. The results are displayed in figure 5.14.

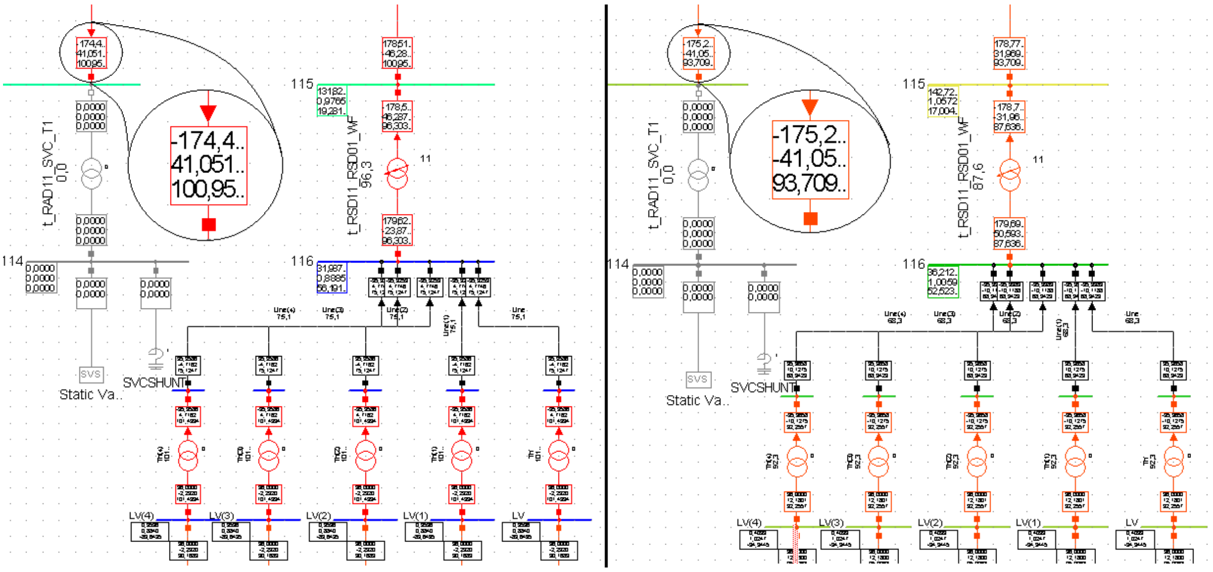


Figure 5.14. Load-flow simulation displaying the bottom part of the system when the WPP is producing maximum active power and the reactive power output in the POC (bus 111) is approximately ± 40.04 MVar. The left side of the figure shows the inductive case and the right side shows the capacitive case.

If the reactive output of the different cases is compared, the effect of the landing cable impedance can be studied at different active power outputs. Figure 5.15 shows the active and reactive power outputs in the POC and at WTG level.

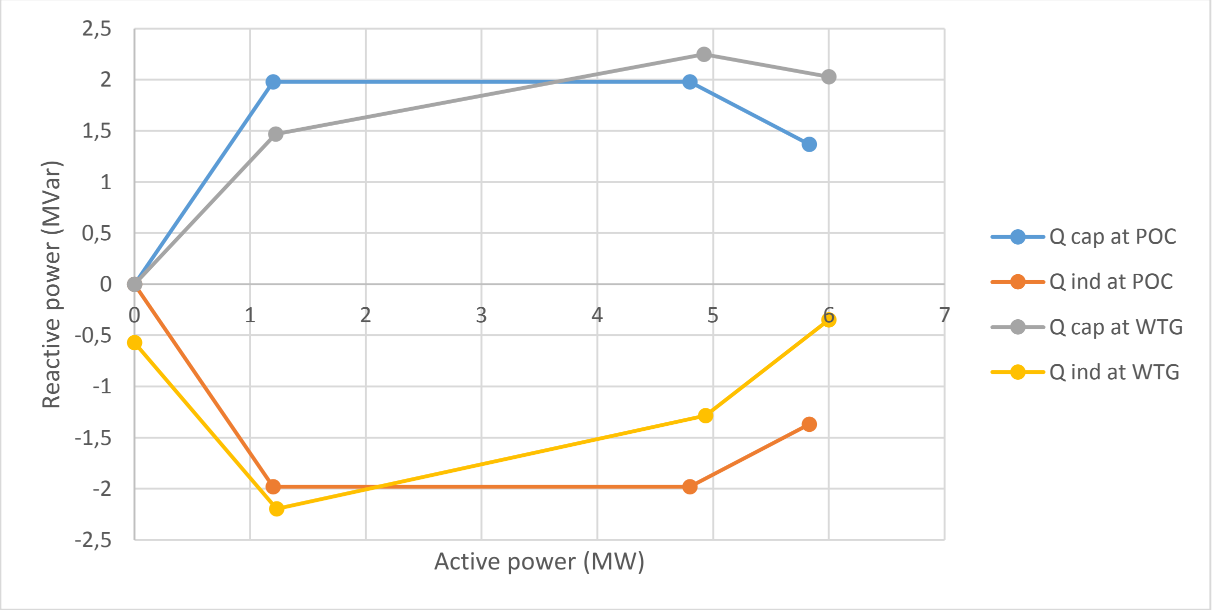


Figure 5.15. The active and reactive power at the POC and at WTG level.

At low active power flows the landing cable is more capacitive, requiring the WPP to compensate more on the negative side in order to obtain the desired values. At higher power flows on the other hand the landing cable becomes more inductive, requiring the WPP to compensate more on the positive side in order to obtain the desired values at the POC. When the WPP is performing this compensation, it manages to reach the target values.

5.4 Maximising capacitive/inductive reactive power output

In order to investigate how the system responds to large changes in reactive power generated by the WPP, the maximum capacitive/inductive (injecting/extracting) reactive power production available by the WPP is tested in two different simulation cases. Since the values from the reactive power capability curve shown in figure 5.7 are used, the maximum reactive power will be ± 4 MVar at a maximum of 2.73 MW. In both of the cases (max capacitive/inductive reactive power output), the entire system is affected, especially the bottom part of the system, since it is closest to the WPP. The results are displayed in figures 5.16 – 5.21. When the reactive power production is at its maximum capacitive level, the voltage levels become very high, and at the buses close to the WPP the voltage levels pass the steady state voltage limits, which are set to 0.95 – 1.05. At the other extreme, when the reactive power output is at its maximum inductive level, the voltage levels of the buses in the bottom of the system decreases below their steady state voltage levels, see figures 5.18 and 5.21.

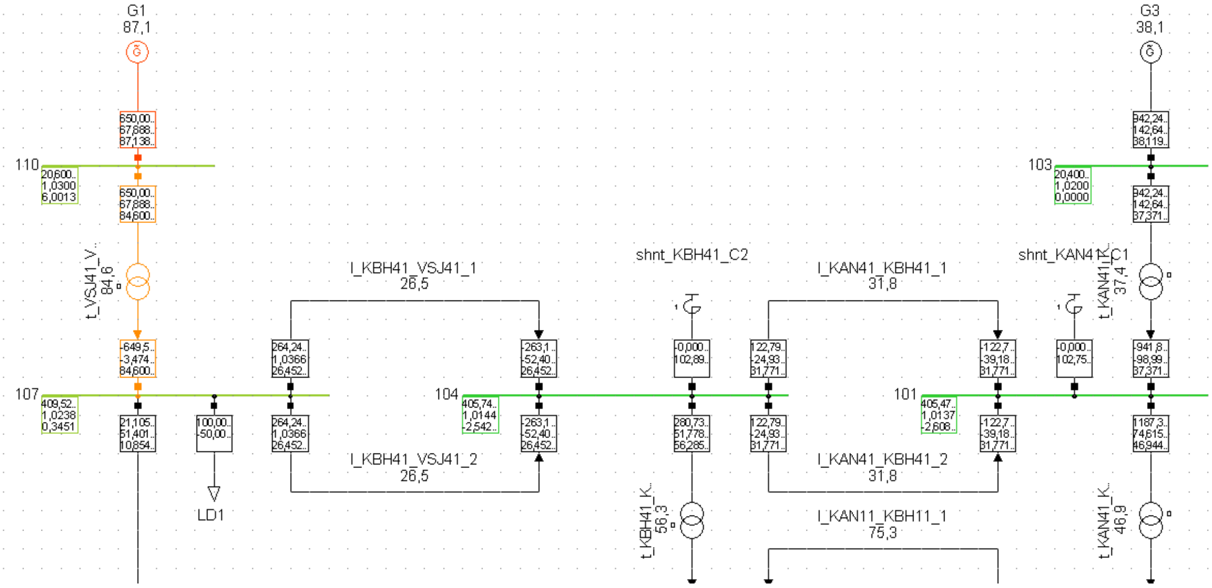


Figure 5.16. Load-flow simulation of the top part of the system when the reactive power of the WPP is at its maximum capacitive level.

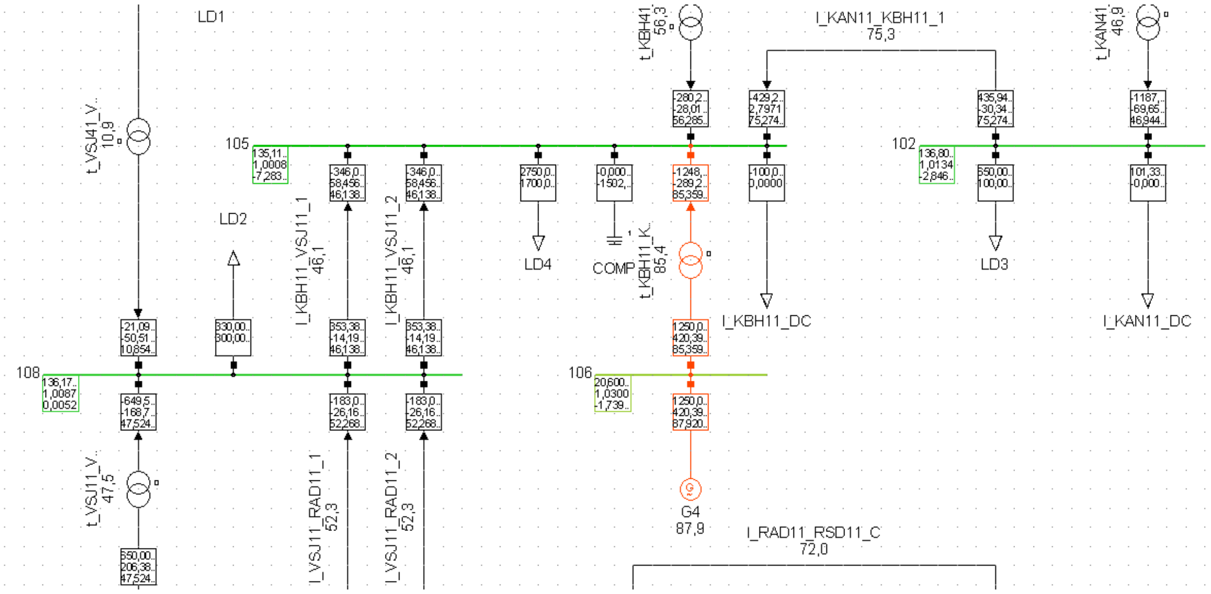


Figure 5.17. Load-flow simulation of the middle part of the system when the reactive power of the WPP is at its maximum capacitive level.

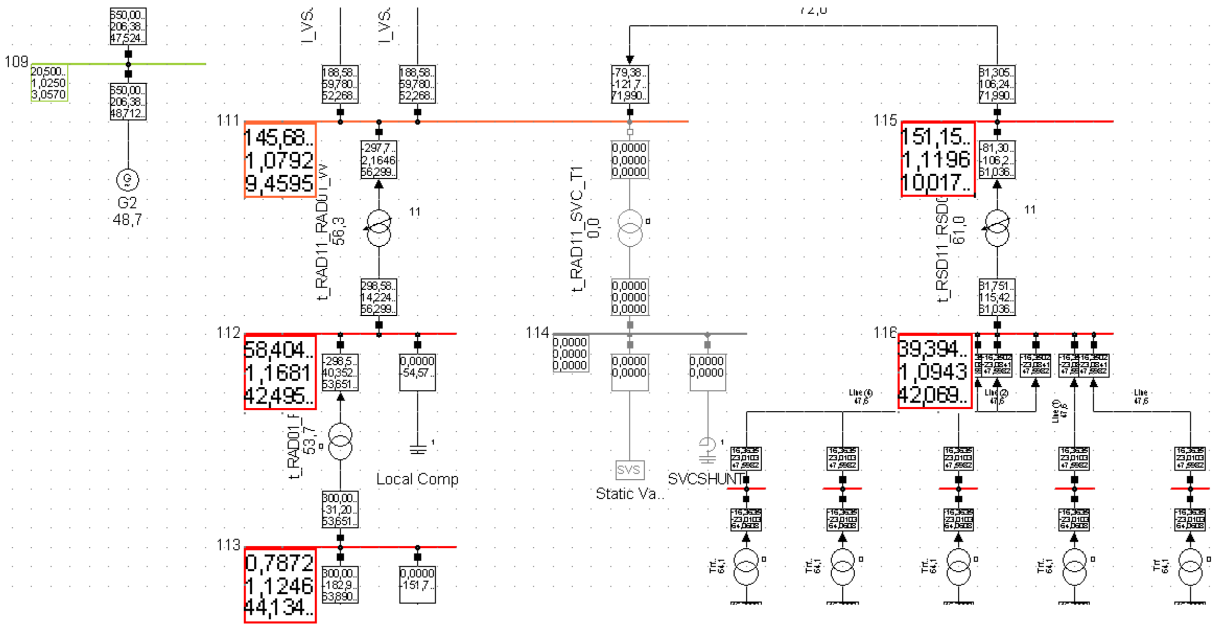


Figure 5.18. Load-flow simulation of the bottom part of the system when the reactive power of the WPP is at its maximum capacitive level. The output indicators at bus 111 – 113 and 115 - 116 are magnified.

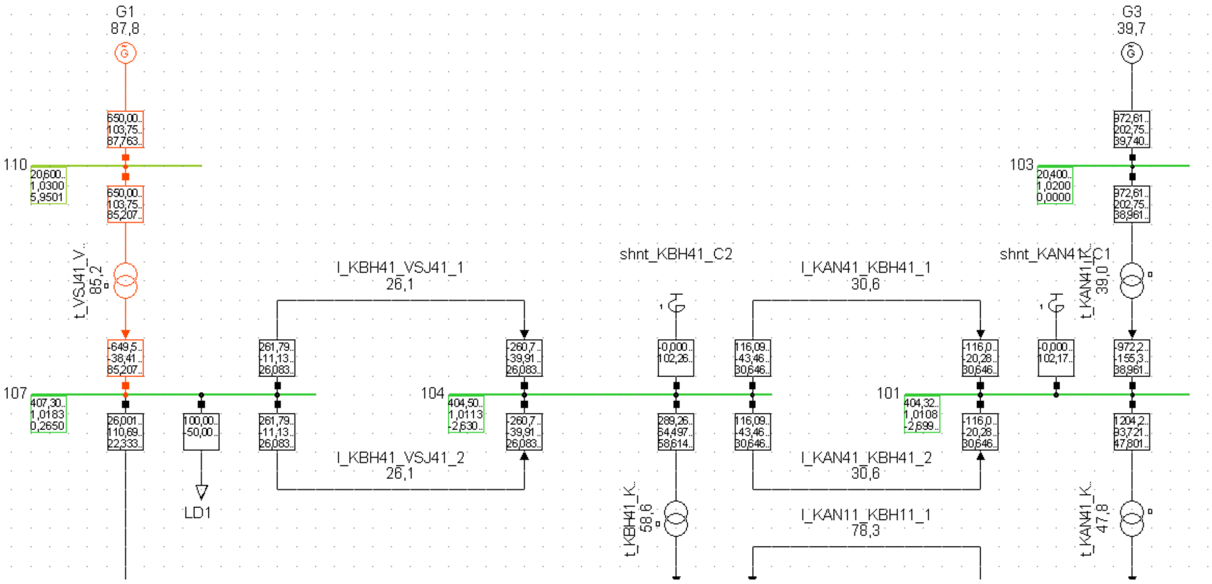


Figure 5.19. Load-flow simulation of the top part of the system when the reactive power of the WPP is at its maximum inductive level.

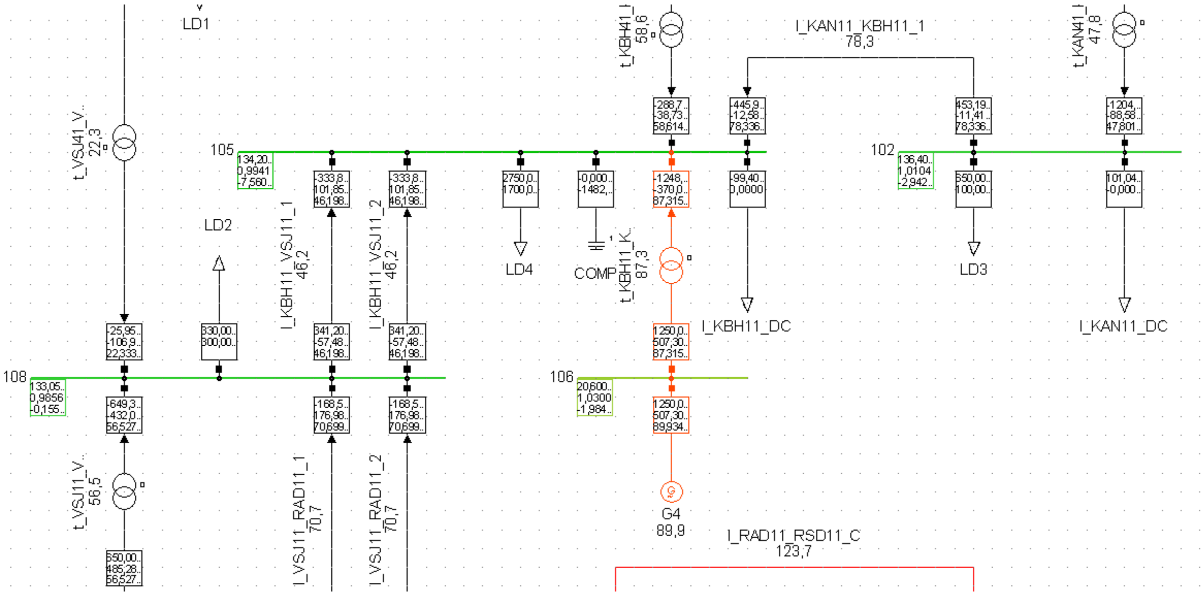


Figure 5.20. Load-flow simulation of the middle part of the system when the reactive power of the WPP is at its maximum inductive level.

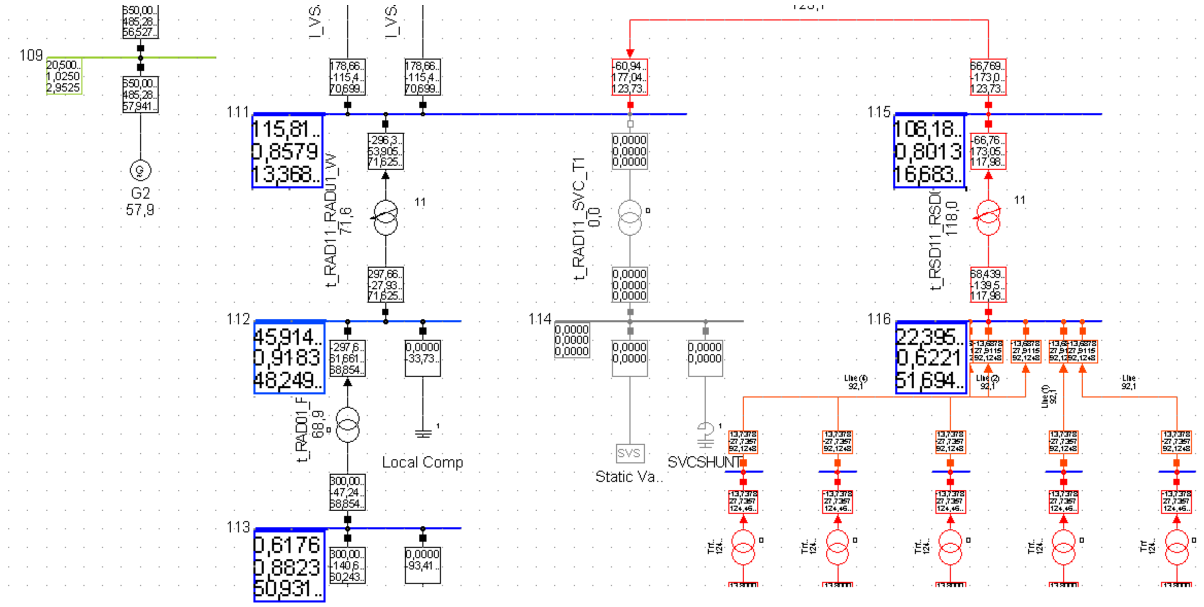


Figure 5.21. Load-flow simulation of the bottom part of the system when the reactive power of the WPP is at its maximum inductive level. The output indicators at bus 111 – 113 and 115 - 116 are magnified.

In the maximum inductive case, the transformers and the landing cable within the WPP cannot handle – 4 MVar at 2.73 MW since the voltage levels become too low. The power output needs to be decreased to 2.3 MW in order for the WPP to tolerate – 4 MVar. In reality the transformers and landing cable would be designed to handle the reactive power output desired.

5.5 Active power response

When simulating the active power response, the output of the power plant G2 is reduced from 650 MW to 625 MW. The power output of the WPP is increased in order to see how the WPP can balance the active power flow in the system. When performing this simulation, the main bus to consider is bus 105, since it is in the centre of the network, so the goal is to obtain the same active power balance in that bus as was found in its original state. When the active power output of the WPP is adjusted to 5.91 MW/WTG, i.e. a total output of 117.3 MW, then the active power balance of bus 105 is restored, see figure 5.22.

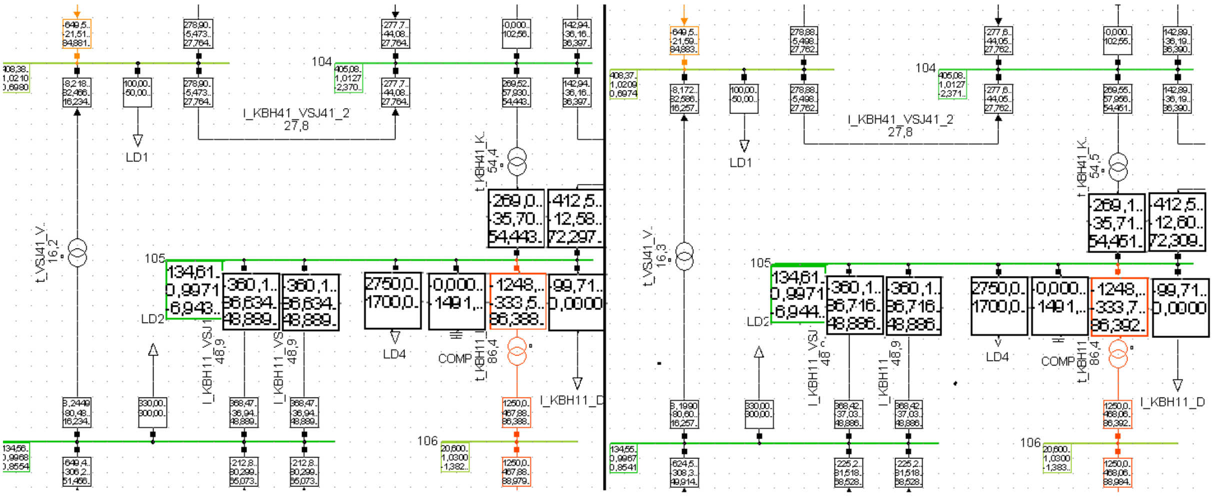


Figure 5.22. Load-flow simulation of the mid left part of the system. The left side of the figure shows the original settings, and the right side shows the system with the new WPP connected and the active power output of G2 reduced. The output indicators surrounding bus 105 are magnified.

In figure 5.22, the amount of active power entering and leaving bus 105 is approximately the same in both cases, meaning that the WPP is compensating for the reduced active power output of G2.

5.6 Control of active and reactive power simultaneously

In this section, both the active and reactive power will be adjusted in order to study how the WPP can balance the system both considering active and reactive power. This is done by increasing the active power output of the local WPP to 400 MW, which also changes the voltage levels in the surrounding buses. Two types of simulations are performed for this case. First, the active power of the main WPP is kept at 150 MW, only adjusting the reactive power. When this simulation is performed, the target voltage in bus 111 of 0.978 pu is obtained when the WPP is set to produce 1.54 MVar/ WTG i.e. 46.2 MVar for the entire WPP, see figure 5.23.

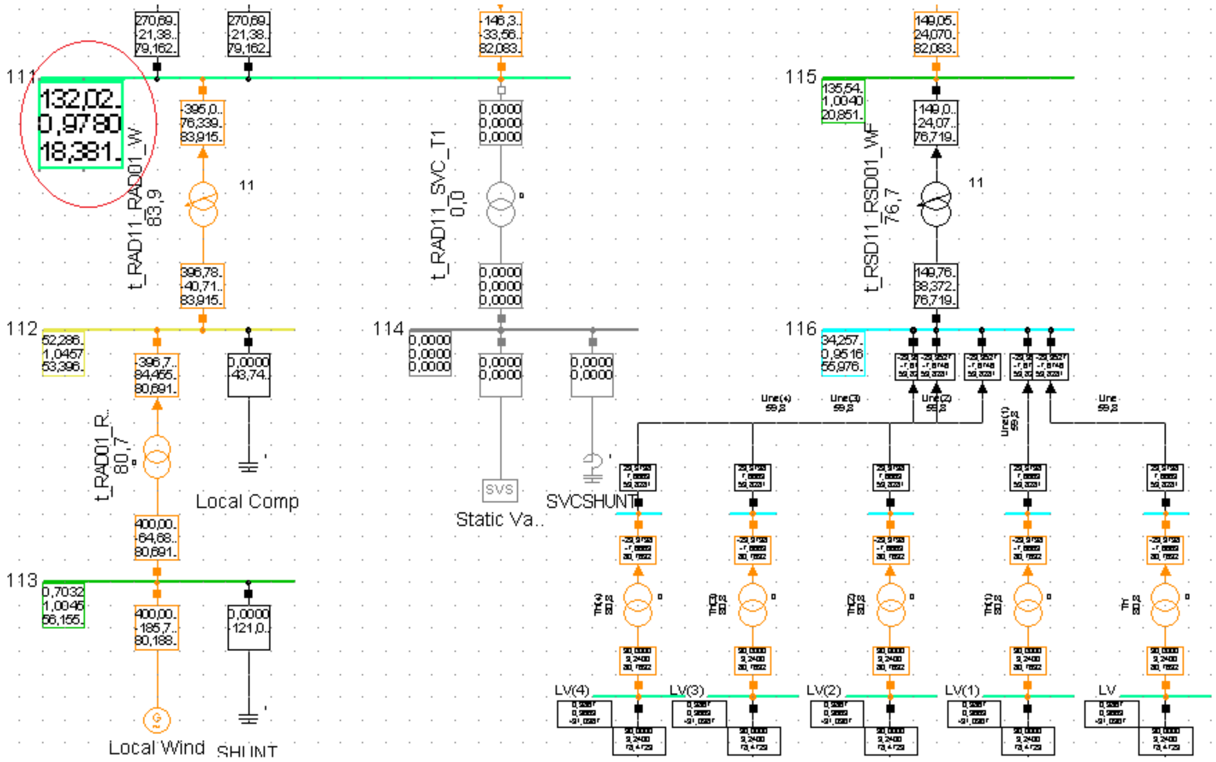


Figure 5.23. Load-flow simulation of the system with an increased power output of the local WPP to 400 MW the WPP balancing the voltage level in bus 111 through an increase in reactive power production. The output indicator at bus 111 is magnified.

In the second part of this simulation case, also the active power output is adjusted so that the active power balance of the system is the same as in the original case. The amount of active power transported from bus 111 to the rest of the system should then be the same as it was with the original settings. This results in an active power output of 1.61 MW/ WTG (48.3 MW for the entire WPP) and a reactive power output of 0.215 MVar/WTG (6.45 MVar for the entire WPP) see figure 5.24.

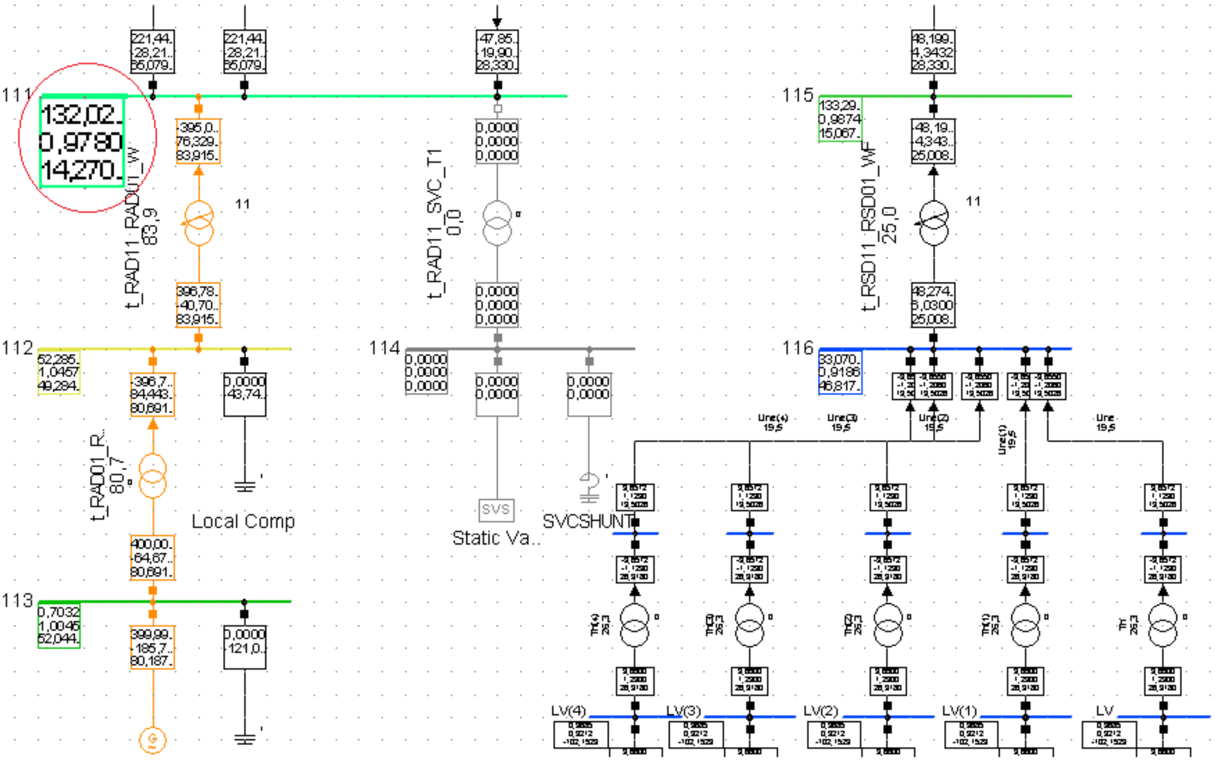


Figure 5.24. Load-flow simulation of the system with an increased power output of the local WPP to 400 MW and the new WPP balancing the voltage level in bus 111 and the active power level so that the system beyond bus 111 has the same values as in the original case. The output indicator at bus 111 is magnified.

5.7 Simulation analysis

The simulations show that the WPP is capable of keeping both the active and reactive power balance in the network, changing the production of active and/or reactive power when needed. As mentioned above, the power curve and reactive power capabilities of real turbines used in modern WPPs were implemented in the WTG models. However the control during the simulations is performed by manually adjusting the values of the active and reactive power and not by receiving a signal as would be done in reality. However this does not affect the result of the simulations, since the goal was to show what the WPP can do, and as presented in chapter 4, modern control systems have the ability to handle this type of control.

DIgSILENT PowerFactory also provides the possibility simulate the dynamic response of the system, which in these cases would have been interesting to study, but due to dynamic differences in the different models used which could not be solved within the timeframe of this thesis, dynamic simulations could not be performed. The maximum active and reactive power ramp rates for external control of the studied turbines are 0.1 pu/sec for active power and 20 pu/sec for reactive power. In the case of the 6 MW WTGs used in the simulations, that would mean 600 kW/sec and 120 MVar/sec, so the system response can be very fast. Usually this response speed is limited by grid codes, and therefore more moderate ramp rates are applied, the Swedish limit for active power is 30 MW/min. When the frequency response mode of the turbines is used, this power control acts faster, since it is an automatic response to a deviation in frequency.

Another factor that is important to consider is the type and length of the cables used within the WPP, and from the WPP substation to the network connection point. The location of the POC can differ depending on national grid codes, and this location is determined through an agreement between the TSO and the WPP owner. In Sweden for example the WPP owner is responsible for compensating for the reactive power losses of the cable between the substation and the connection point in the network, which is the POC, where the agreements are valid. During the simulations the cable connecting the WPP with the grid was kept from the original model. This cable is designed to tolerate the active power production of the original offshore WPP, which is similar to the new WPP, but the reactive power exchange differs. The reactive power flow of the old offshore WPP is compensated by a capacitor of 4 MVar and the SVC. The SVC is not located within the WPP, meaning that the reactive power compensation in the original case mainly does not go through the landing cable of the WPP. The cable is kept in the new model in order to change as little as possible between the models, and the only time where there is a problem with the cable during the simulations is when the reactive power of the WPP is at its maximum inductive production. In reality a different landing cable can be chosen. The cables within the WPP are chosen according to the voltage levels needed and kept short so that they will not have a major impact on the simulations. These simplifications are made in order to illustrate the WPP capabilities in a simple way that can be applicable to different cases, since the geography and topology of the site is not included.

Depending on the active power load and the type of cables, the amount of reactive power delivered to the system from the WPP will differ. When there is a high active power flow in the system, the voltage level drops and additional reactive power is needed. On the other hand when the flow of active power in the system is low, the voltage level increases, and reactive power needs to be extracted. This phenomenon can also be seen in figure 5.15, where there is a higher need of extraction of reactive power at low active power levels, and a higher need of injection of reactive power at higher active power levels. As seen in the simulations the WPP can do both these things, but it is important to consider the active power flow of the entire system.

When active and reactive power is transported through transformers, there are losses that need to be considered when adjusting the reactive power level. If additional reactive power is needed at some point in the system, there will be losses on the way, and these losses need to be compensated for in order to achieve the desired reactive power level at the desired point in the system. If on the other hand reactive power needs to be extracted from the system, the extraction does not need to be as extensive as corresponding injection, since there are losses on the way. As mentioned above the capacitive/inductive properties of the cables in the system also need to be considered, since they can be either net capacitive or net inductive, depending on their properties and the active power flow.

5.8 Additional strategies for future research

5.8.1 Coordination of WTGs during reactive power control

Another parameter that can be considered when meeting a demand of reactive power is the coordination of the reactive power response within the WPP. In order to make the reactive power response more efficient and minimise cable losses, the WTGs within the WPP can be coordinated depending on the amount of reactive power requested and the WTG location relative to the POC. For example, if only a small amount of reactive power is desired, using the WTGs that are closest to the POC will be a good strategy, since this will minimise cable losses. If on the other hand a large amount of reactive power is requested, using a larger group or all WTGs will be the best option.

Another factor that can be considered as a coordination parameter is the wake effect of the WTGs within the WPP (see 6.3 for more detailed description of wake effects). The WTGs that are furthest away from the wind (if the wind is coming from the north the WTGs that are furthest away from the wind are those at the very south end of the WPP) will be most affected by wake effects and therefore have the smallest active power output. If the WPP is producing a lot of active power so that there is little room for reactive power production, these WTGs that are furthest away from the wind might be more suitable for reactive power production than other WTGs with a higher active power production.

When developing an algorithm for coordination, it is important to also consider the fact that if the entire WPP is producing active power and only a few WTGs are delivering reactive power, the net reactive power delivery in the POC will also be affected by the other WTGs within the WPP. It is also important to consider the reactive power capability curve of the entire WPP in the POC recalculated including transformer and cable losses. When the WPP is at maximum active power production, it cannot deliver the maximum amount of reactive power at the same time. If the reactive power delivered can be sold as a service to the TSO/DSO, the active/reactive power production can be prioritised according to the revenue received for the relevant type of power production.

6 Coordination of the WTGs within a WPP during curtailment of active power

In this chapter, a way to consider the coordination of WTGs within a WPP will be studied using the models and features specified in above chapters. A part of the block model presented in figure 2.2 is developed into a more detailed model in order to illustrate how the control signals are distributed, see figure 6.1. The number of WTGs in the model is just an example, since the figure is meant to be descriptive. A more detailed model will be described focusing only on the WPP, and different simulation cases will be defined and tested using Excel.

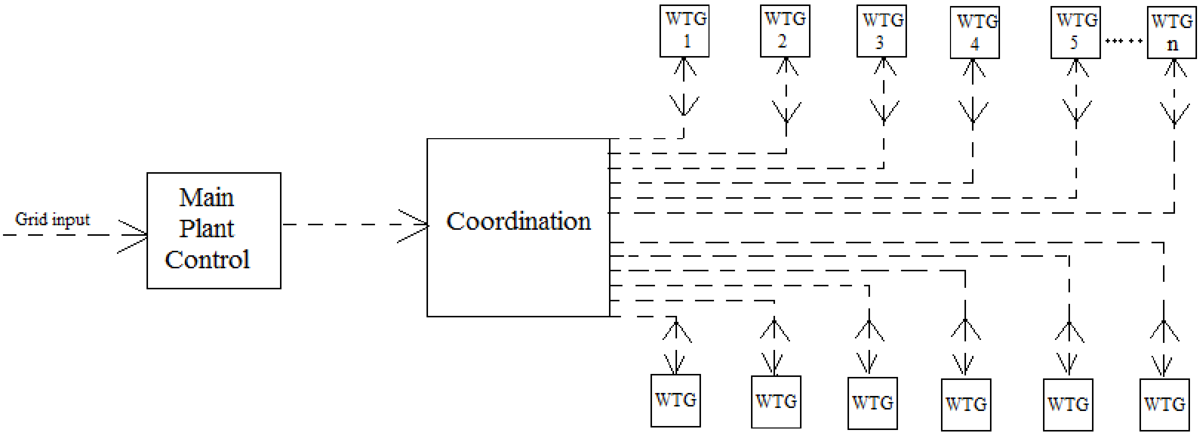


Figure 6.1. Block model of a WPP displaying the signals coming from the grid control, through the main plant control, and finally being distributed through coordination block.

6.1 Curtailment requirements and procedure

The grid codes described in chapter 3 state that they require WPPs to be able to curtail the park. The NC RfG states regarding power generating modules of type C and D that "the Power Generating Module control system shall be capable of adjusting an Active Power Setpoint as instructed by the Relevant Network Operator or the Relevant TSO" (ENTSO-E 2013, page 25). The Danish grid code state the following regarding WPPs of category D; "A WPP of this category shall be able to continuously control its active power output to an arbitrary value within the range of 100 to 20% of the rated power" (Energinet.dk 2014, page 57). The Swedish grid code states "It shall be possible to control the power production of a WPP so that it does not exceed a predefined power limit (MW). This power level shall be possible to control when receiving a signal, and the control algorithm should be changeable. It shall be possible to control the production level to below 20% of maximum power output within 5 seconds" (Svenska Kraftnät 2005, page 11). In other countries like Denmark and the UK, there are also frameworks for how WPP owners are economically compensated if curtailment is necessary, and this type of constraint payments are likely to be seen in other countries in the future as well (Renewable Energy Foundation n.d.; Energinet.dk 2014a). Considering these facts, curtailment of WPPs is something that is already done today, but in order to perform this curtailment in a more efficient way, the WTGs within the WPP needs to be coordinated considering how they affect each other.

When WPPs are curtailed, the common procedure is that all WTGs are curtailed equally, or the signal is distributed depending on the available active power in each WTG in order to make sure that the desired curtailment is achieved even though different WTGs might have different abilities for curtailment due to its output and some might be stopped for service, etc. This way of controlling the WPP considers some basic parameters in order to achieve the desired curtailment in a simple way. But since the WTGs position in relation to each other is not considered, this simple way of controlling the WPP might result in that WTGs are stopping, or increased turbulence for the WTGs in the back rows. These problems can be solved using coordination of the WTGs, taking into account how they affect each other.

6.2 Coordination model

In order to simulate how the coordination of the WTGs can affect the WPP, a model of 16 WTGs placed in a square will be used. The model is presented in figure 6.2.

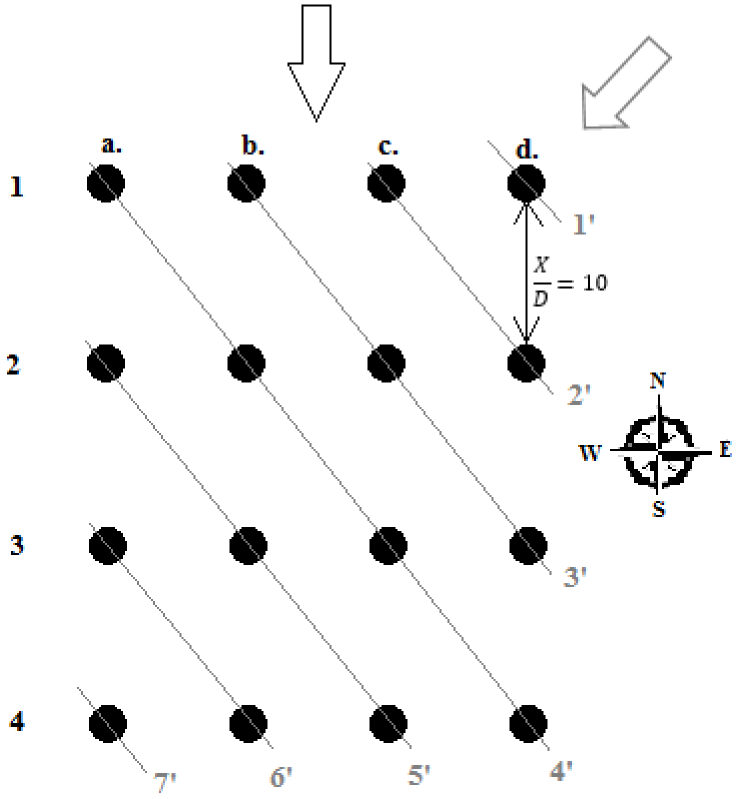


Figure 6.2. Model of a WPP with 16 WTGs. The prevailing wind direction is displayed by the black arrow, and the WTG rows are numbered from row 1 closest to the wind to row 4 furthest away from the wind. The columns are labelled from a) to d). The grey lines show what the new row definition would be if the wind came from north-east instead of north, resulting in rows 1' – 7'. X/D is the distance between the rows when the wind comes from the north.

Due to limited time and space, the prevailing wind direction, which is north in figure 6.2 above, is the only wind direction that will be studied in this thesis. When a WPP is designed, the prevailing wind direction for the site is considered, and the WTGs are placed so that the impacts of the wake effects on the other WTGs in the WPP will be as small as possible. Since the prevailing wind direction is the most likely wind direction, this assumption is a fair simplification. In reality it is however important to consider the wind direction, and if a real WPP is studied, the wind direction needs to be included in the algorithm. For example if the wind direction would be north-east instead of north, which is displayed with the grey arrow in figure 6.2, the WPP would then have seven rows (1' – 7' in the figure), and these rows need to be coordinated during curtailment. The strategy for coordination that is presented later in this chapter can still be applied also in reality, but the wind direction should be included in the model. The distance between the rows is labelled X/D in the figure, and this parameter will be described further below. If the wind came from north-east instead, X/D would change.

Different cases will be studied depending on wind speed and amount of power requested for curtailment. The wind speed will be divided into four categories, very low, low, medium and high speed. The categories are chosen depending on the turbine output at different wind speeds, see figure 6.3.

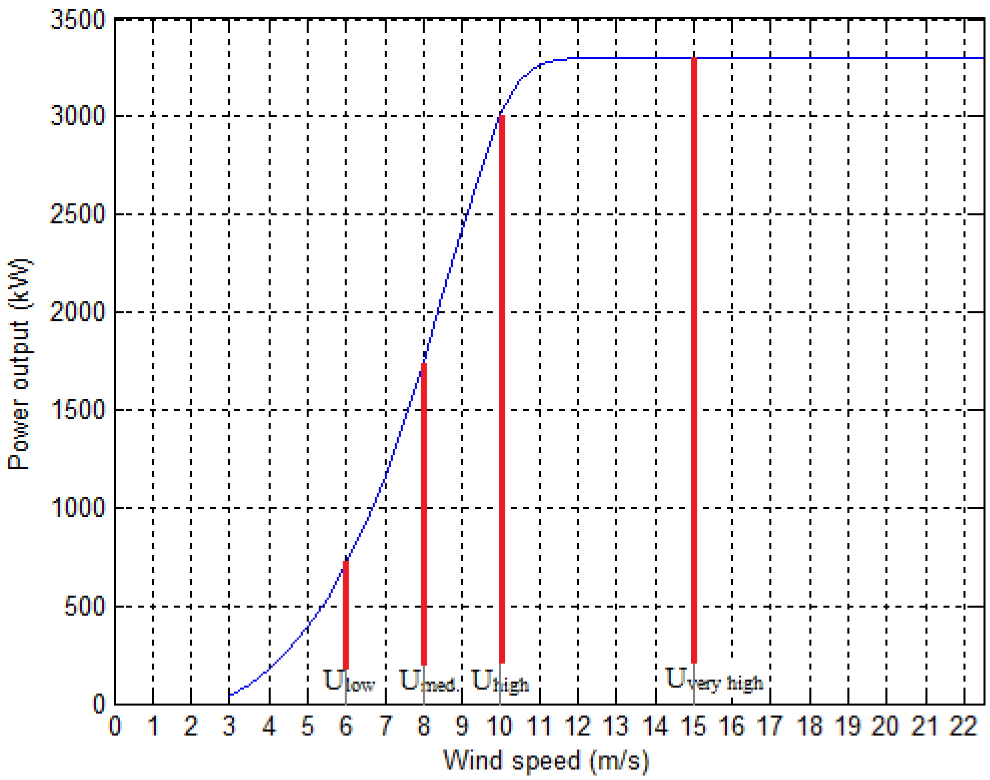


Figure 6.3. Power curve for the WTG used in the simulations with the different wind speed categories that will be tested marked in the figure.

The values used to generate the power curve in figure 6.3 are taken from a turbine specification (see chapter 4.1.10), and used as input values in Matlab in order to plot the power curve, for code see appendix 11.1.1.

6.3 Wake effects

The basic energy balance of wind turbines shows that when the wind passes through the turbine rotor plane, it slows down and expands, and energy is transferred to the turbine causing it to rotate. This causes a “wake” behind the turbine with reduced wind speed and more turbulent wind, affecting other turbines in the WPP. If for example the WPP and the wind conditions are as specified in figure 6.2, the turbines in row 2 will be affected by the wake caused by the turbines in row 1, reducing the wind speed approaching the turbines in row 2. In order to calculate the different wind speeds and power outputs for the different rows of the WPP, Katics wake model is used, see equation 1 and figure 6.4 (Manwell et al. 2009).

$$1-\frac{U_x}{U_0}=\frac{1-\sqrt{1-C_T}}{\left(1+2k\frac{X}{D}\right)^2} \qquad \text{eq. 1}$$

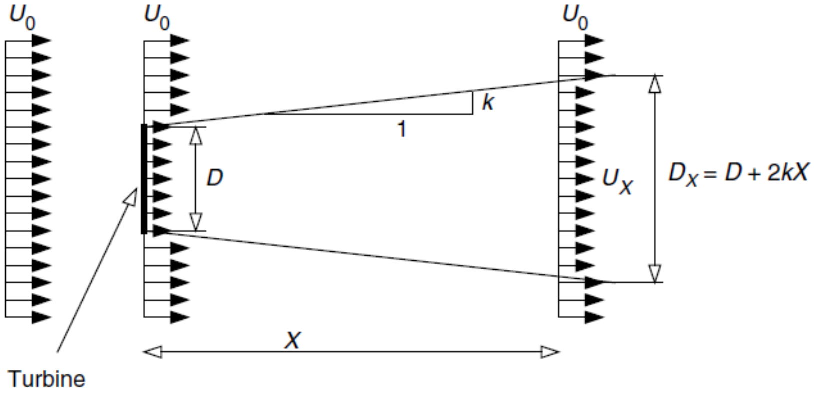


Figure 6.4. Schematic description showing the parameters used in Katics wake model (Manwell et al. 2009).

U_x is the wind speed approaching the next row, U_0 is the free wind speed before hitting the WPP, C_T is the thrust coefficient which varies with the tip speed ratio and the pitch angle, k is the wake decay constant and X/D is the distance between the WTGs divided by the rotor diameter, i.e. the quotient can be interpreted as "amount of rotor diameters". The k-value is assumed to be 0.04 for offshore and 0.075 for onshore WPPs (Sørensen & Thøgersen 2008; DTU Wind Energy n.d.) Originally the aim was to perform calculations for onshore WPPs, therefore the k-value 0.075 is used in calculations. However the strategies can be applied for both offshore and onshore WPPs, with a change in k-value for more accurate results. Praxis for X/D is 8 - 10 rotor diameters, in this case it will be set to 10, see figure 6.2 (Manwell et al. 2009).

In order to obtain values for C_T, equation 2 will be used to first find a C_P for each wind speed and power output, then a combination of equations 3 and 4 will be used to calculate C_T (Manwell et al. 2009).

$$P = \frac{1}{2}\rho A C_P U^3 \eta \qquad \text{eq. 2}$$

$$C_P = 4a(1-a)^2 \qquad \text{eq. 3}$$

$$C_T = 4a(1-a) \qquad \text{eq. 4}$$

In equation 2, the air density (ρ) is assumed to be 1.225 kg/m^3, which is the standard value often used in calculations (air density at 15°C and sea level) (Manwell et al. 2009). The area is taken from the WTG specification, and the efficiency (η) is assumed to be 1, meaning that losses are neglected. If the models are applied in reality the efficiency has to be included in the calculations, but since this thesis mainly aims to investigate strategies for coordination, some simplifications can be made. In order to calculate the power output for all rows taking wake effects into account, equation 1 will be used to gain a new U_x approaching each row, and this new U_x will be used to find a new power output at the new wind speed. The new power output for the new wind speed U_x will be collected from figure 6.3, using the Matlab zoom function.

When the WPP is curtailed, this result in new C_p and C_T values for the different rows. If for example the front row is curtailed, a new C_p value will be calculated using equation 2 with the new curtailed power output but the original wind speed. When this C_p value is obtained, a C_T value can be found using equations 3 and 4 or figure 6.5, see appendix 11.1.2 for Matlab code.

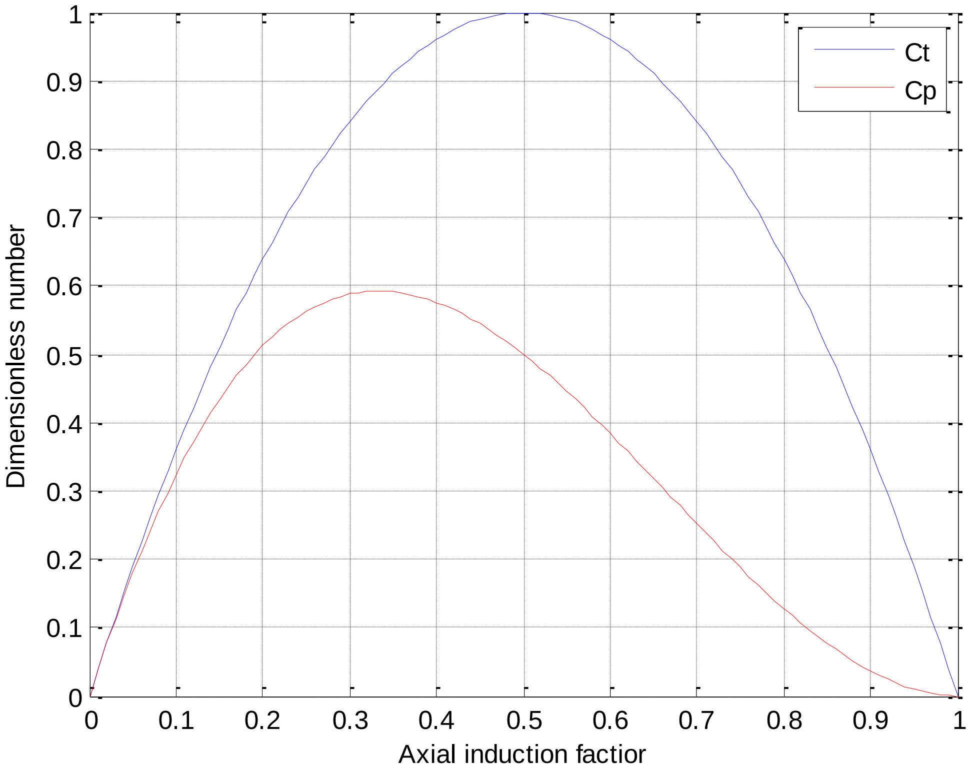


Figure 6.5. C_T and C_p curves plotted using equations 3 and 4. The axial induction factor is a quota describing how much the wind speed decreases when it reaches the turbine, i.e. it can be used as a measurement of how large part of the wind that is used to produce energy. The equations are valid for $a \leq 0.5$.

There are other ways to find C_T values that are specified for each turbine using C_T curves. Figure 6.6 shows the C_T curve for one of the studied turbines with the corresponding C_p curve plotted in the same figure (see appendix 11.1.2 for Matlab code). When using these curves, the C_p value for a certain curtailed row is calculated using the method described above, but using figure 6.6 to find a new C_T value instead. When calculating the new C_p value for the curtailed row at wind speeds below 8 m/s this C_p value will be lower than the original value, resulting in a higher corresponding C_T value. When calculating the new wind speed for the row behind the curtailed row using this new C_T, the new wind speed will be lower than without the curtailment, since higher C_T values give lower wind speeds, see equation 1. The problem is that the equations do not consider the pitch angle. In order to use this method, different C_T curves for different pitch angles would be necessary. These could not be located within the timeframe of the thesis, therefore the equations specified above are used instead.

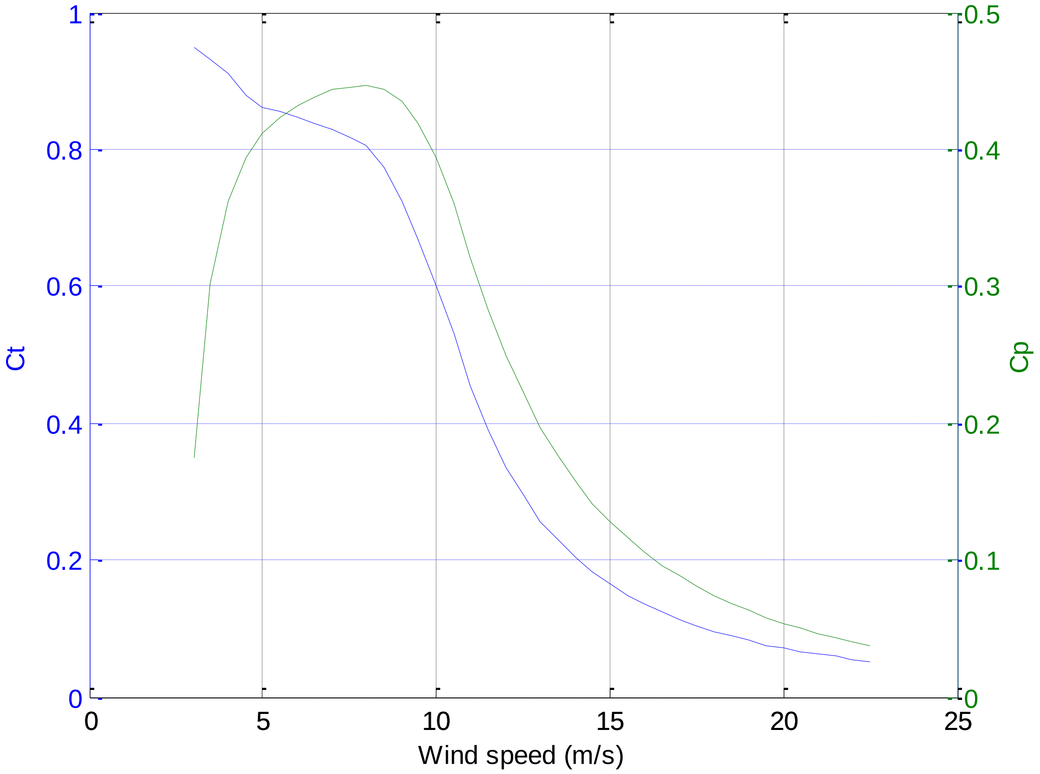


Figure 6.6. Typical C_T and C_p curves, the values are collected from a specification for one of the studied turbines.

6.4 Definition of wind speed categories

When the WPP is operating at nominal power, the total output is 52.8 MW. The wind speed categories are defined considering the power curve of the WPP, see figure 6.3. Low wind speed corresponds to 50 % of U_{nom}, (6 m/s), medium wind speed is the wind speed where the WTG reaches its maximum calculated C_p value (the rotor power coefficient), (8 m/s), high wind speed is 80 % of U_{nom} (10 m/s) and very high wind speed is 125 % of U_{nom} (15 m/s). The main parameter that is considered when choosing the wind speed categories is that they should illustrate how the wake effects are affecting the different rows of the WPP when coordinated in different ways during curtailment.

Table 6.1. Power output from the WTGs of the different rows at low wind speed.

Low wind speed U_0 = 6 m/s		
Row	**Approaching wind speed (m/s)**	**Power/WTG (MW)**
1	6.00	0.712
2	5.72	0.614
3	5.45	0.523
4	5.19	0.448
Total power output for WPP:		7.39

Table 6.2. Power output from the WTGs of the different rows at medium wind speed.

Medium wind speed U_0 = 8 m/s		
Row	**Approaching wind speed (m/s)**	**Power/WTG (MW)**
1	8.00	1.75
2	7.60	1.48
3	7.21	1.28
4	6.85	1.09
Total power output for WPP:		22.4

Table 6.3. Power output from the WTGs of the different rows at high wind speed.

High wind speed U_0 = 10 m/s		
Row	**Approaching wind speed (m/s)**	**Power/WTG (MW)**
1	10.0	3.01
2	9.58	2.78
3	9.18	2.54
4	8.80	2.29
Total power output for WPP:		42.5

Table 6.4. Power output from the WTGs of the different rows at very high wind speed.

Very high wind speed U_0 = 15 m/s		
Row	**Approaching wind speed (m/s)**	**Power/WTG (MW)**
1	15.0	3.30
2	14.5	3.30
3	14.7	3.30
4	14.5	3.30
Total power output for WPP:		52.8

When the wind decreases after passing a row due to the wake effect, the power output will decrease following the power curve of the turbine, see figure 6.3. At low and medium wind speeds, the slope of the power curve is increasing with increasing wind speeds, but when the wind reaches 8 m/s, the slope of the graph should start to decrease with increased wind speeds, since the maximum calculated value of C_p is reached, see figure 6.7 (the Matlab code is found in appendix 11.1.2).

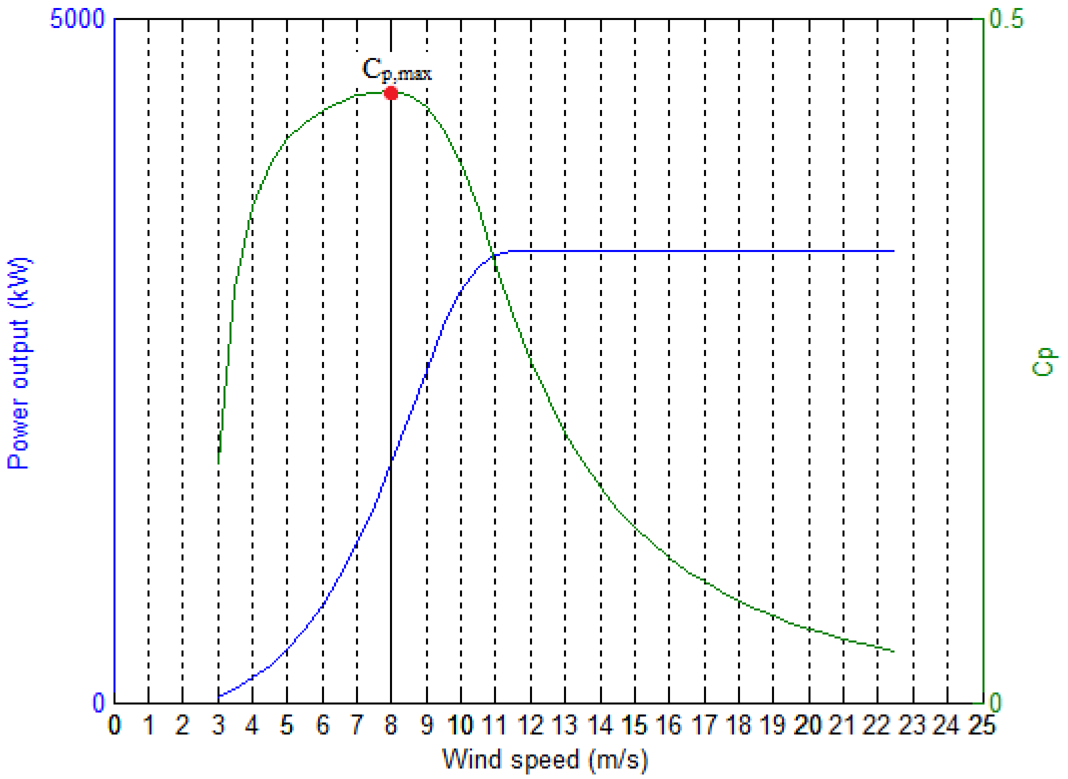


Figure 6.7. Power curve and C_p curve for the WTG used in simulations at different wind speeds.

This means that the power output during medium wind speeds will be more affected by wakes compared to the power output at low wind speeds. At high wind speeds the wake effect should have less impact since this wind speed range is defined at 10 m/s, and at this point the maximum value of C_p has been passed, meaning that the power curve should start to level out. However as mentioned above C_p is calculated using equation 2, and in order to do this, some assumptions need to be made. The values of the power output and the wind speed are taken from the turbine specification, which are the same values that are used to generate the power cure. But the assumption that the efficiency is 1, i.e. there are no losses, affects the location of the calculated maximum C_p value. In reality the maximum C_p value is reached at a wind speed between 8 and 9 m/s, meaning that the power curve does not start to level out at 8 m/s, but at a slightly higher wind speed. At very high wind speeds the wake effect has no impact on the power output, since the wind speed is higher than 12.5 m/s at all times, resulting in maximum power output. Figure 6.8 shows how the power output is affected by the wake effect at low, medium, high and very high wind speeds.

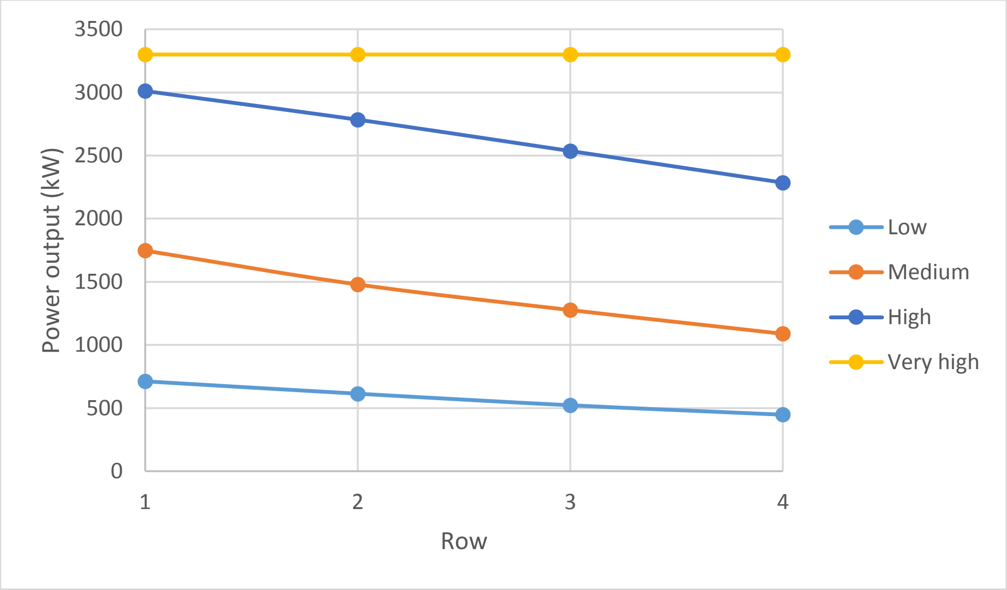


Figure 6.8. Power decrease between rows caused by the wake effect at different wind speeds.

If the medium wind speed category would be defined for the real maximum C_p value, the graph showing the power output of the different rows for the medium wind speed category would be steeper. The wind speed categories as defined above do however work for showing the effect of applying different coordination strategies.

6.5 Strategy all winds

The decision strategy for curtailment during all wind speeds can be described according to the state chart shown in figure 6.9.

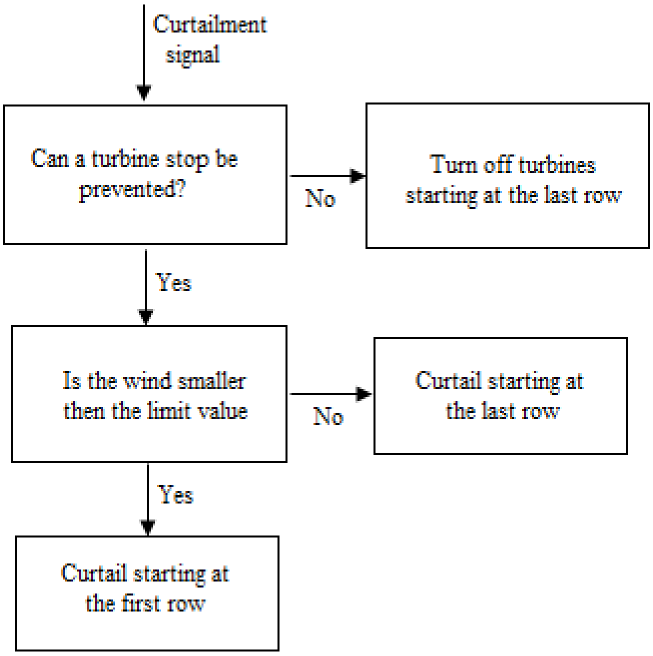


Figure 6.9. State chart describing an overview of the decision strategy during curtailment.

The first priority during curtailment is to avoid unplanned turbine stoppage. This might happen if a WTG is curtailed close to its maximum curtailment limit. The loss of revenue depends on how long the stoppage lasts, but since this is likely to happen during the night as is explained more in detail in section

7.1.1, the stoppage is likely to last for several hours. If the WPP is located offshore it might take days before a crew of technicians can reach the site to fix the problem if the weather is bad. On top of the loss of revenues there will also be a cost of sending technicians to the site. Adding up these factors the conclusion is that an unplanned turbine stoppage is a very unwanted event for WPP owners. Considering this, the first box in figure 6.9 with the statement "Can a turbine stop be prevented?" is very important. In order to decide this, an algorithm considering the wake effects of all turbines in the WPP need to be considered. In order to avoid a turbine stoppage, the strategy is to curtail the entire WPP, but curtailing the front rows a bit more than the back rows, since this will provide more wind for the back rows due to reduced wake effects caused by the front rows, and also the front rows have a larger room for curtailment to begin with since they are not effected by any wake effects. This strategy does not apply at very high wind speeds, since no rows are affected by wake effects. At very high wind speeds, the WPP should instead be curtailed equally.

If a turbine stoppage can be avoided, the next question is; will the turbines benefit from curtailment starting at the first or the last row of the WPP? The theory is that if the wind speed is smaller than a certain limit value (e.g. 8 m/s), the WPP will benefit from starting the curtailment at the first row, letting more wind pass through the WPP. On the other hand, if the wind speed is larger than this limit value, the impact of letting more wind through the WPP will decrease, and the impact of increased turbulence from starting the curtailment at the first row will be stronger than the benefits, resulting in increased fatigue on the turbines. The increased turbulence will also obstruct the control process since it will take longer time for the turbine output to stabilise allowing the control algorithm to calculate a new output considering the curtailment.

6.6 Definition of simulation cases

6.6.1 Low wind

Table 6.5. Example of different ways to curtail the WPP during low wind speeds and a curtailment of 12.5% to be tested during simulations.

a.	**WPP curtailed 12.5 %, i.e. 1.15 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail only row 1 (40.3 %)	0.287	Rows 2 - 4 will get more wind, small turbulence increase
2.	Curtail only row 4 (64.1 %)	0.287	Row 4 will stop
3.	Curtail row 1 and 2 equally	0.143	Rows 3 - 4 will get more wind, small turbulence increase
4.	Curtail row 3 and 4 equally	0.144	Row 4 will stop
5.	Curtail entire WPP equally	0.072	Rows 2 - 4 will get more wind, small turbulence increase

Table 6.6. Example of different ways to curtail the WPP during low wind speeds and a curtailment of 25% to be tested during simulations.

b.	**WPP curtailed 25 %, i.e. 2.30 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail only row 1 (80.6 %)	0.574	Row 1 will stop, rows 2 – 4 will get more wind
2.	Curtail row 1 50% and 2 and 3 equally	Row 1: 0.356 Row 2 and 3: 0.109	Rows 2 – 4 will get a bit more wind, small turbulence increase
3.	Curtail row 3 and 4 equally	0.287	Row 3 and 4 will stop, row 4 will get more wind
4.	Curtail entire WPP equally	0.144	Row 4 will stop, rows 2 - 4 will get more wind

6.6.2 Medium wind

Table 6.7. Example of different ways to curtail the WPP during medium wind speeds and a curtailment of 12.5% to be tested during simulations.

a.	**WPP curtailed 12.5 %, i.e. 2.80 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail only row 1 (40.0 %)	0.699	Rows 2 - 4 will get more wind, small turbulence increase
2.	Curtail only row 4 (64.2 %)	0.699	No impact
3.	Curtail row 1 and 2 equally	0.349	Rows 2 - 4 will get more wind, small turbulence increase
4.	Curtail row 3 and 4 equally	0.349	Row 4 will get more wind, small turbulence increase
5.	Curtail entire WPP equally	0.175	Rows 2 – 4 will get more wind, small turbulence increase

Table 6.8. Example of different ways to curtail the WPP during medium wind speeds and a curtailment of 25% to be tested during simulations.

b.	**WPP curtailed 25 %, i.e. 5.59 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail only row 1 (80.0 %)	1.40	Rows 2 – 4 will get more wind, small turbulence increase
2.	Curtail row 1 and 2 equally	0.699	Rows 3 – 4 will get a bit more wind, small turbulence increase
3.	Curtail row 3 and 4 equally	0.699	Row 4 will get more wind, small turbulence increase
4.	Curtail entire WPP equally	0.349	Rows 2 – 4 will get more wind, small turbulence increase

6.6.3 High wind

Table 6.9. Example of different ways to curtail the WPP during high wind speeds and a curtailment of 12.5% to be tested during simulations.

a.	**WPP curtailed 12.5 %, i.e. 5.31 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail only row 1 (44.1 %)	1.33	Rows 2 - 4 will get more wind, turbulence increase
2.	Curtail only row 4 (58.1 %)	1.33	No impact
3.	Curtail row 1 and 2 equally	0.664	Rows 2 - 4 will get more wind, turbulence increase
4.	Curtail row 3 and 4 equally	0.664	Row 4 will get more wind, turbulence increase
5.	Curtail entire WPP equally	0.332	Rows 2 - 4 will get more wind, turbulence increase

Table 6.10. Example of different ways to curtail the WPP during high wind speeds and a curtailment of 25% to be tested during simulations.

b.	**WPP curtailed 25 %, i.e. 10.6 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail row 1 86.7% and row 2 1.5%	Row 1: 2.61 Row 2: 0.0431	Rows 2 - 4 will get more wind, turbulence increase
2.	Curtail row 3 30.3% and row 4 82.0%	Row 3: 0.769 Row 4: 1.89	Row 4 will get more wind, turbulence increase
3.	Curtail row 1 and 2 equally	1.33	Rows 2 – 4 will get more wind, turbulence increase
4.	Curtail row 3 and 4 equally	1.33	Row 4 will get more wind, turbulence increase
5.	Curtail entire WPP equally	0.664	Rows 2 - 4 will get more wind, turbulence increase

6.6.4 Very high wind

Table 6.11. Example of different ways to curtail the WPP during very high wind speeds and a curtailment of 12.5% to be tested during simulations.

a.	**WPP curtailed 12.5 %, i.e. 6.60 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail only row 1 (50.0 %)	1.65	Rows 2 - 4 will get more wind, turbulence increase
2.	Curtail only row 4 (50.0 %)	1.65	No impact
3.	Curtail row 1 and 2 equally	0.825	Rows 3 - 4 will get more wind, turbulence increase
4.	Curtail row 3 and 4 equally	0.825	Row 4 will get more wind, turbulence increase
5.	Curtail entire WPP equally	0.413	Rows 2 – 4 will get more wind, turbulence increase

Table 6.12. Example of different ways to curtail the WPP during very high wind speeds and a curtailment of 25% to be tested during simulations.

b.	**WPP curtailed 25 %, i.e. 13.2 MW**		
	Action	**Power reduced / WTG (MW)**	**Expected additional impact on WPP**
1.	Curtail row 2 and 3 25.0% each, and row 4 50.0%	Row 2 and 3: 0.825 Row 4: 1.65	Rows 3 – 4 will get more wind, turbulence increase
2.	Curtail row 1 and 2 equally	1.65	Rows 3 – 4 will get more wind, turbulence increase
3.	Curtail row 3 and 4 equally	1.65	Row 4 will get more wind, turbulence increase
4.	Curtail entire WPP equally	0.825	Rows 2 – 4 will get more wind, turbulence increase

Table 6.13. Example of how the WPP can be curtailed during very high wind speed and 85 % curtailment to be tested during simulations.

Extra curtailment	**Action**	**Power reduced / WTG (MW)**
	Curtail entire WPP equally	2.81

6.7 Case analysis

6.7.1 Low and medium wind speed

When the WPP is curtailed during low wind speed, there is a risk that some WTGs will stop. This is an unwanted situation, since a WTG shutdown is a large risk that can result in costs due to loss of production, and if the WTG fails to start, an additional cost for sending technicians to fix the problem will occur. If the stop occurs during the night or at an offshore WPP during bad weather conditions, there will be an additional cost from loss of production since it will take some time before any technicians can reach the WTG. This is a main reason why WPP owners want to avoid curtailing their WPPs.

When curtailment is performed on for example row 1, which is closest to the wind, the wake effect from the turbines of row 1 will be lower than without curtailment, resulting in a higher wind speed approaching row 2. Curtailment will also result in more turbulence due to pitching of the blades, but at low or medium wind speeds this effect is expected to be low. Therefore, as mentioned in figure 6.9, a useful strategy might be to start by curtailing row 1, in order to let more wind pass through to the other WTGs. This strategy also decreases the risk of turbines stopping.

When WTGs in the front rows are curtailed letting more wind pass through the WPP and increasing the output of the back rows (if these WTGs are not already at maximum production) the WTGs of the back rows need to have a power output limit during the curtailment so that they will not increase their production. The power output limit for the non-curtailed rows will be set to the power output that they had before the curtailment when the simulation of the cases is performed.

The reason for letting more wind pass through the WPP during curtailment instead of curtailing the back rows is, as mentioned before, that a main goal of the control is to avoid a turbine shutdown. Since the WPP is curtailed, allowing an increase in production for the back rows would mean a more complicated control algorithm, curtailing the front rows even more in order to handle the production increase from the back rows. This method will be tested for two special cases at low wind speeds, since curtailment during these wind speeds results in the highest risk of a row stopping. The idea with these special cases is to try the different types of control also taking the additional output caused by reduced wakes into account.

6.7.2 High and very high wind speed

When a WPP is curtailed during high or very high wind speeds, the forces acting on the turbines are higher than during lower wind speeds. The turbulence caused by pitching of the blades of the WTGs in the front rows will have a higher impact on the back rows, compared to the cases with lower wind speed. Turbulence causes fatigue on the turbines, which result in higher risk of turbine failures and reduced turbine lifetime. Therefore it is important to use a control strategy that minimises the fatigue caused by increased turbulence at higher wind speeds. The strategy used to accomplish this is to curtail the back row (row 4) primarily (see figure 6.9), since the wake of the back row does not affect any other WTGs.

Another problem with turbulence caused by curtailment is that the control will take longer time, and it will be harder to achieve an accurate control. If row 1 is curtailed, the wind speed approaching the turbines in row 2 will increase, as mentioned above. It will take some time before the turbines have adjusted to the new wind speed and the new wind speed will result in a new output, which needs to be considered when the curtailment for that specific row is calculated, if the turbine output is allowed to increase. When curtailing a WPP during low or medium winds, starting the curtailment at row 1 makes sense since the main priority is to avoid a turbine shutdown, but when curtailing during high winds, this is not a great issue, if the curtailment is not very extensive. Then the main priorities becomes being able to perform a fast and accurate control and reducing the fatigue on the turbines, and during higher wind speeds the strategy to accomplish this will be to start the curtailment at the back rows.

6.8 Simulation results

The figures 6.10 – 6.26 displays the power output when curtailment is simulated for the different cases. In figures 6.10 – 6.23, the total used power output during curtailment is limited, meaning that the power output for the back rows is not allowed to increase. The graphs labelled “used” show the power output that will correspond to either the original power output before curtailment, or if that specific row is curtailed, the limited power output caused by the curtailment will be displayed. The graphs labelled “available” show the new available power output, which can be either the original power output if no rows in front of the examined row are curtailed, or the new available output that is obtained during some wind speeds due to decreased wake effects from curtailed rows in front of the examined row. This available power output is not used during the curtailment in figures 6.10 – 6.23. For calculations used to obtain the graphs, see appendix 11.2.

6.8.1 Low wind speeds

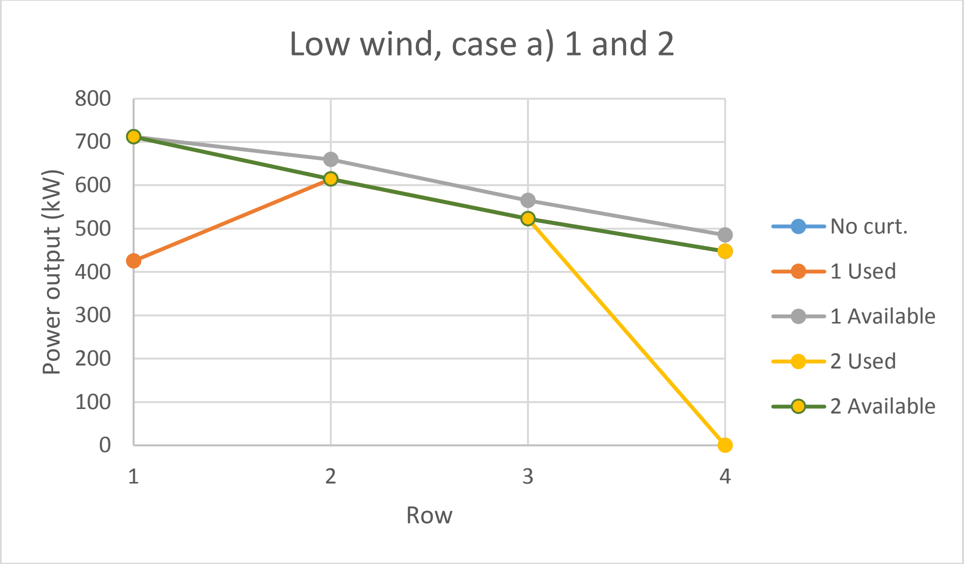


Figure 6.10. Power output during simulation of case a) 1 and 2 for low wind speed, 12.5% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.14. Actions displayed in figure 6.10.

a.	**WPP curtailed 12.5 %, i.e. 1.15 MW**
	Action
1.	Curtail only row 1 (40.3 %)
2.	Curtail only row 4 (64.1 %)

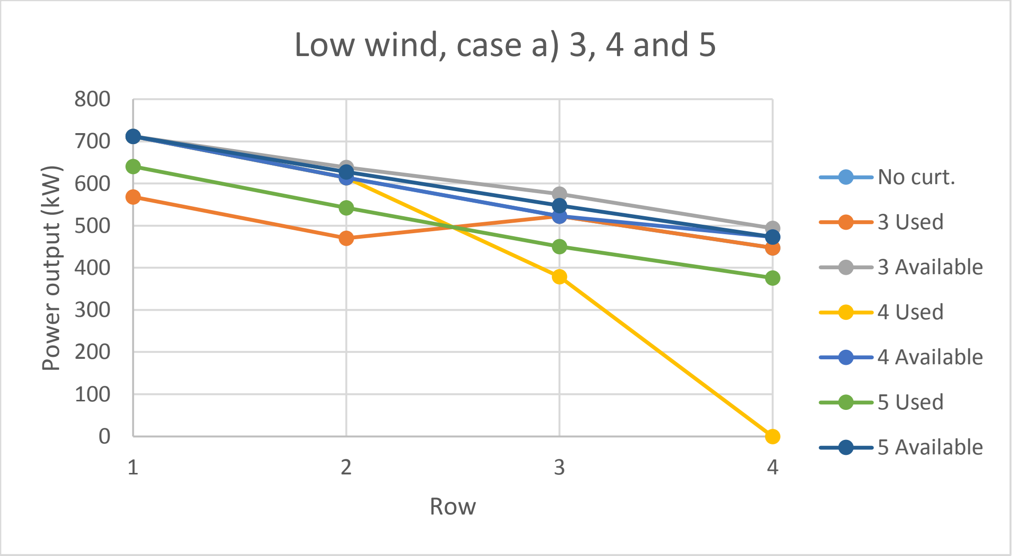


Figure 6.11. Power output during simulation of case a) 3, 4 and 5 for low wind speed, 12.5% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.15. Actions displayed in figure 6.11.

a.	**WPP curtailed 12.5 %, i.e. 1.15 MW**
	Action
3.	Curtail row 1 and 2 equally
4.	Curtail row 3 and 4 equally
5.	Curtail entire WPP equally

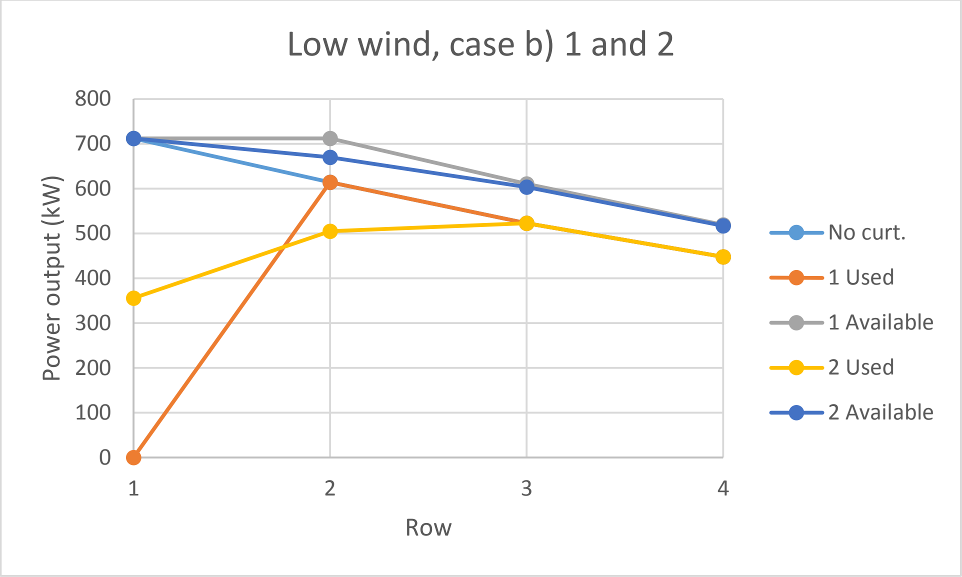


Figure 6.12. Power output during simulation of case b) 1 and 2 for low wind speed, 25% curtailment. The used, the available, and the non-curtailed power output is displayed.

Table 6.16. Actions displayed in figure 6.12.

b.	**WPP curtailed 25 %, i.e. 2.30 MW**
	Action
1.	Curtail only row 1 (80.6 %)
2.	Curtail row 1 50% and 2 and 3 equally

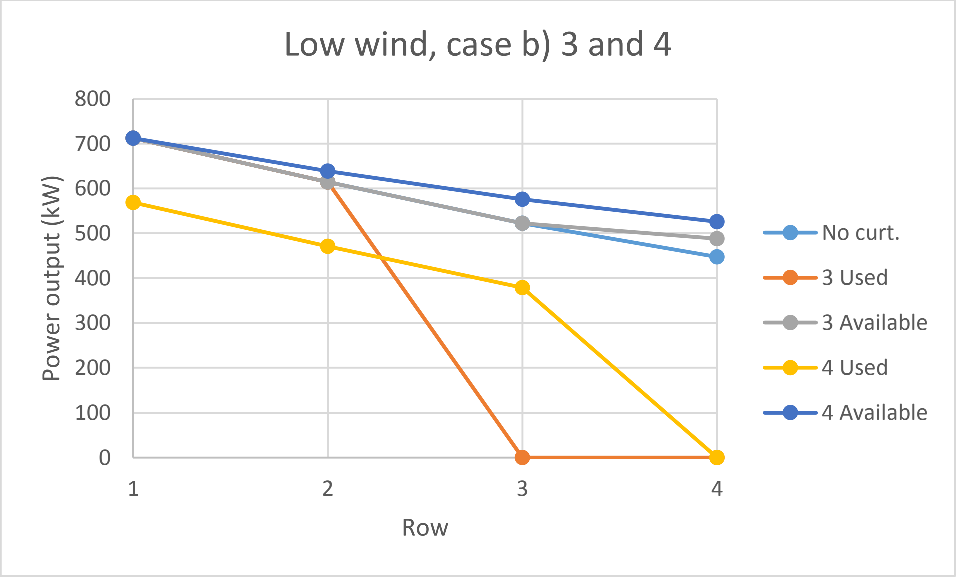


Figure 6.13. Power output during simulation of case b) 3 and 4 for low wind speed, 25% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.17. Actions displayed in figure 6.13.

b.	**WPP curtailed 25 %, i.e. 2.30 MW**
	Action
3.	Curtail row 3 and 4 equally
4.	Curtail entire WPP equally

Figures 6.10 – 6.13 show that curtailing the front rows result in a larger available power output for the back rows, confirming the hypothesis. Figure 6.10 shows the extreme case, where either only row 1 or only row 4 is curtailed. It is clear when row 1 is curtailed that the available power output for the other rows increases, whereas when row 4 is curtailed the available power output of the other rows is not affected and row 4 will stop.

As mentioned before, the risk of turbines stopping is largest when the wind is low. This becomes extra clear when looking at figures 6.12 and 6.13, displaying the larger curtailment of 25%. In those cases there are a lot of examples of rows stopping due to the curtailment. The only subcase where no row is stopping is the customised case b) 2, where row 1 takes care of half of the curtailment and rows 2 and 3 shares the other half.

If it is not possible to avoid that a row will stop, the best strategy is to stop the last row, in order to affect the rest of the WPP as little as possible.

6.8.2 Medium wind speeds

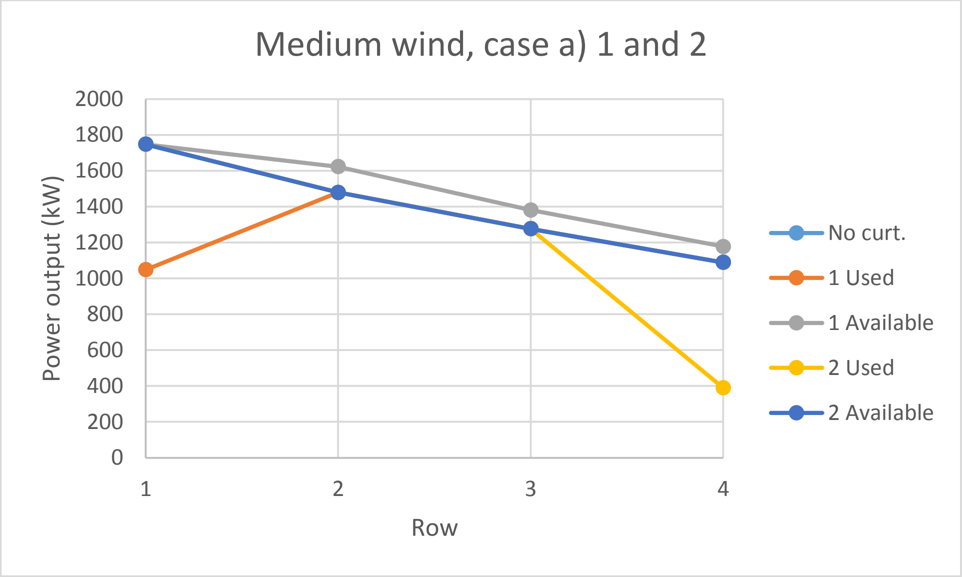


Figure 6.14. Power output during simulation of case a) 1 and 2 for medium wind speed, 12.5% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.18. Actions described in figure 6.14.

a.	**WPP curtailed 12.5 %, i.e. 2.80 MW**
	Action
1.	Curtail only row 1 (40.0 %)
2.	Curtail only row 4 (64.2 %)

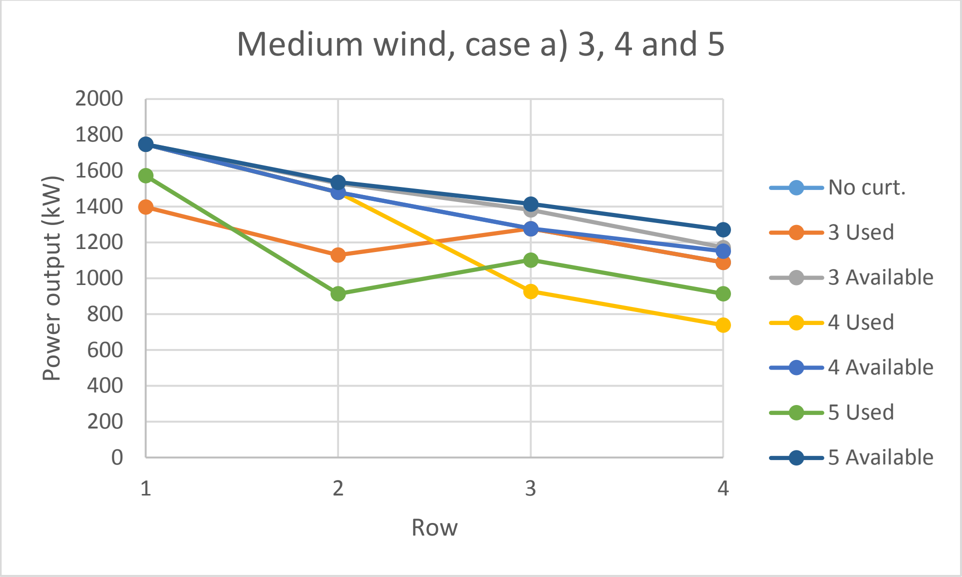


Figure 6.15. Power output during simulation of case a) 3, 4 and 5 for medium wind speed, 12.5% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.19. Actions described in figure 6.15.

a.	**WPP curtailed 12.5 %, i.e. 2.80 MW**
	Action
3.	Curtail row 1 and 2 equally
4.	Curtail row 3 and 4 equally
5.	Curtail entire WPP equally

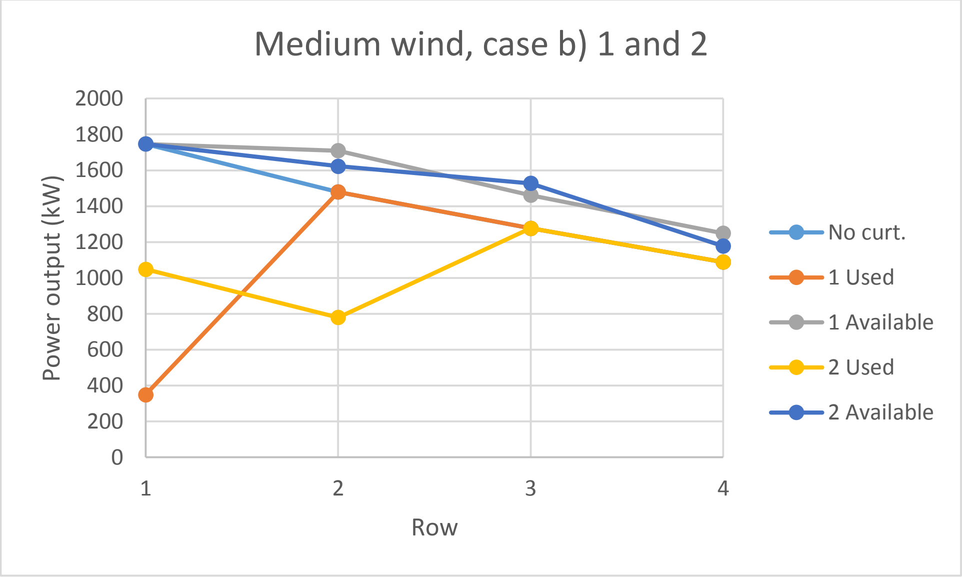


Figure 6.16. Power output during simulation of case b) 1 and 2 for medium wind speed, 25% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.20. Actions described in figure 6.16.

b.	**WPP curtailed 25 %, i.e. 5.59 MW**
	Action
1.	Curtail only row 1 (80.0 %)
2.	Curtail row 1 and 2 equally

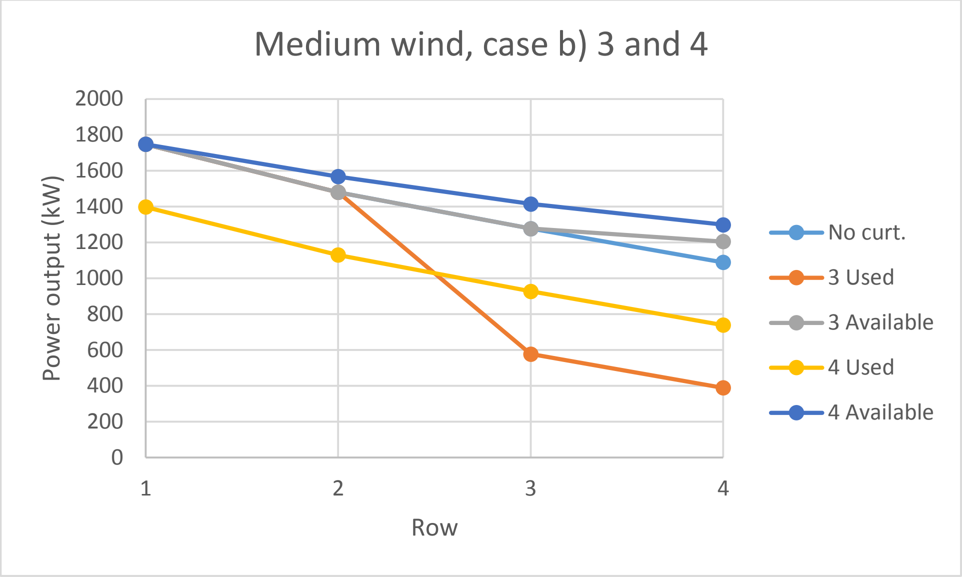


Figure 6.17. Power output during simulation of case b) 3 and 4 for medium wind speed, 25% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.21. Actions described in figure 6.17.

b.	**WPP curtailed 25 %, i.e. 5.59 MW**
	Action
3.	Curtail row 3 and 4 equally
4.	Curtail entire WPP equally

The same phenomena as described for low wind speeds in section 6.8.1 above can be seen for medium wind speeds, but in this case the effect is even larger, since the original wind speed hitting row 1 is 8 m/s, which is the wind speed where the maximum C_p of the turbine is reached and the power curve (figure 6.7) has its steepest slope, as discussed in section 6.4. Changed wind speeds at this point will therefore have a larger impact on the available power output compared to the other cases.

When curtailing a row, the effect of the wake decrease is strongest for the row directly following the curtailed row, which can be seen in figure 6.16. In case b) 1, only row 1 is curtailed, resulting in a higher wind speed approaching row 2 (compared to if row 1 would not have been curtailed) and therefore an increase in available power output for row 2. The wind increase also affects row 3, resulting in a larger available power output. The power output increase for row 3 is however even larger for case b) 2, when row 2 is also curtailed, since row 2 is no longer stopping the wind as much as it did when it was not curtailed. This shows that the effect of the wake decrease resulting in larger wind speeds passing through the WPP has the strongest effect on the rows directly behind the curtailed row.

6.8.3 High wind speeds

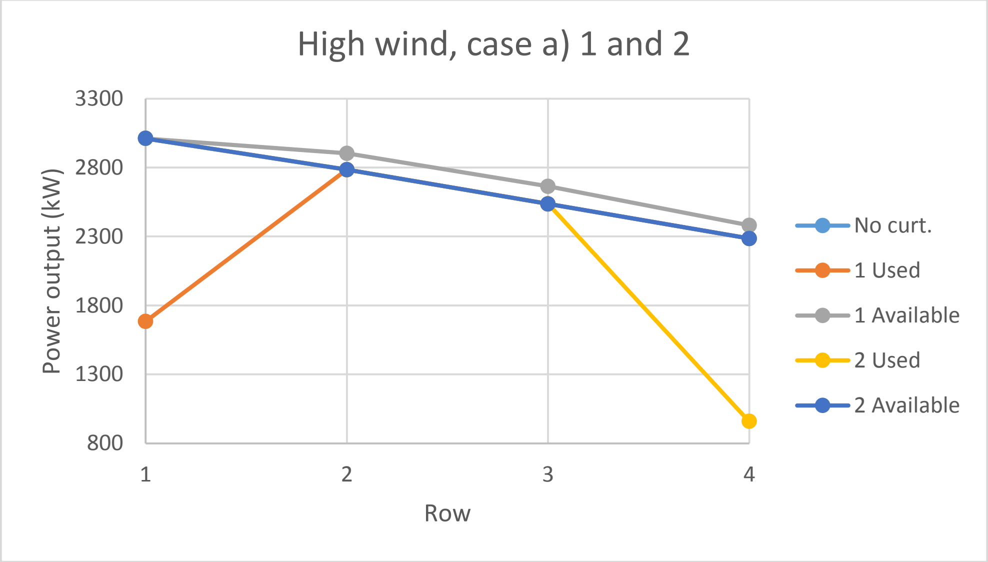


Figure 6.18. Power output during simulation of case a) 1 and 2 for high wind speed, 12.5% curtailment. The used, the available, and the non-curtailed power output are displayed. Note that the scale of the y-axis does not start on 0.

Table 6.22. Actions displayed in figure 6.18.

a.	**WPP curtailed 12.5 %, i.e. 5.31 MW**
	Action
1.	Curtail only row 1 (44.1 %)
2.	Curtail only row 4 (58.1 %)

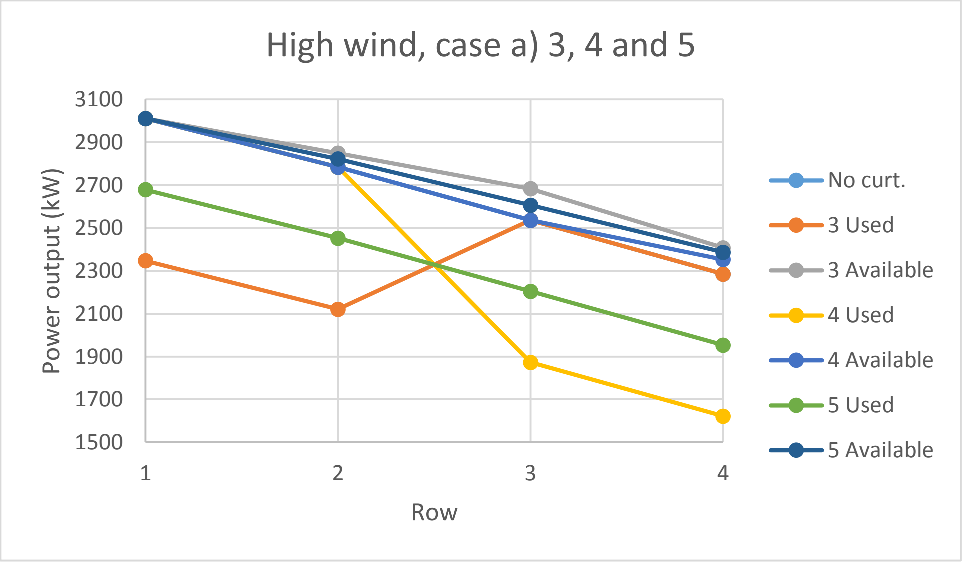


Figure 6.19. Power output during simulation of case a) 3, 4 and 5 for high wind speed, 12.5% curtailment. The used, the available, and the non-curtailed power output are displayed. Note that the scale of the y-axis does not start on 0.

Table 6.23. Actions displayed in figure 6.19.

a.	**WPP curtailed 12.5 %, i.e. 5.31 MW**
	Action
3.	Curtail row 1 and 2 equally
4.	Curtail row 3 and 4 equally
5.	Curtail entire WPP equally

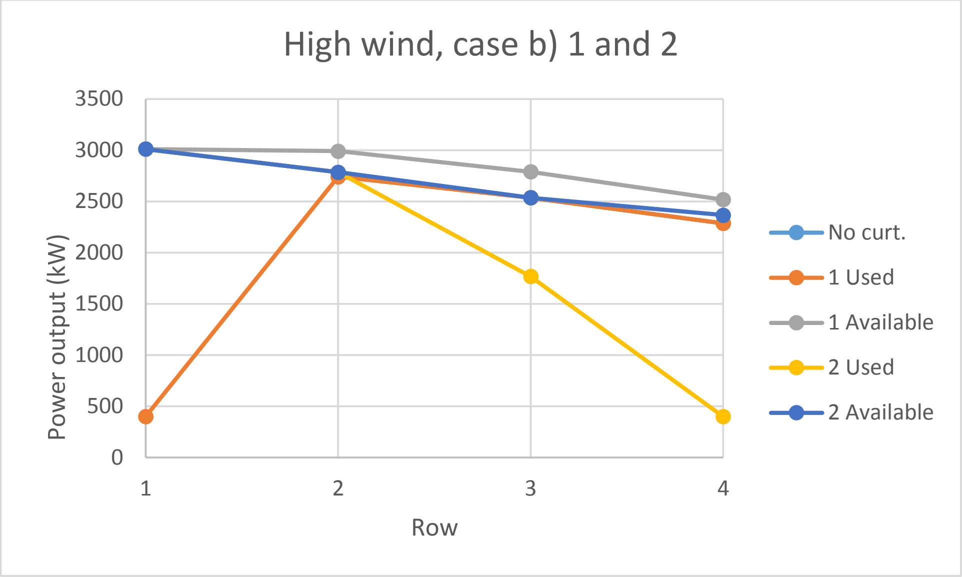


Figure 6.20. Power output during simulation of case b) 1 and 2 for high wind speed, 25% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.24. Actions displayed in figure 6.20.

b.	**WPP curtailed 25 %, i.e. 10.6 MW**
	Action
1.	Curtail row 1 86.7% and row 2 1.5%
2.	Curtail row 3 30.3% and row 4 82.0%

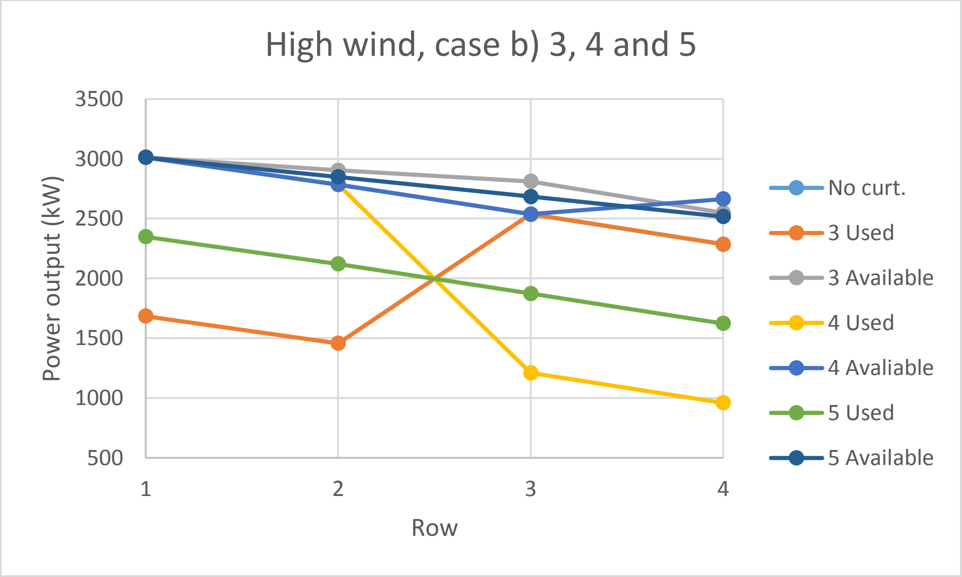


Figure 6.21. Power output during simulation of case b) 3, 4 and 5 for high wind speed, 25% curtailment. The used, the available, and the non-curtailed power output are displayed. Note that the scale of the y-axis does not start on 0.

Table 6.25. Actions described in figure 6.21.

b.	**WPP curtailed 25 %, i.e. 10.6 MW**
	Action
3.	Curtail row 1 and 2 equally
4.	Curtail row 3 and 4 equally
5.	Curtail entire WPP equally

For high wind speeds, curtailment of the front rows letting more wind through the WPP result in a higher available power output for the back row, similarly to the cases with low and medium wind speeds. The question is however if this is a desirable strategy for high wind speeds, since the forces acting on the WPP at these wind speeds are very high, and the increased turbulence caused by pitching the blades of the turbines in the front rows might cause problems. These problems will affect the WPP more than the possible benefit of letting more wind through the WPP will gain. Calculating the effect that pitching of the blades has on turbulence can be hard, since the wind itself is varying all the time, and it can be hard to distinguish the difference between turbulence caused by pitching and natural turbulence caused by the intermittency of the wind.

At these wind speeds the risk of unplanned turbine stoppages is not as significant as for lower wind speeds, so starting the curtailment from the back rows instead of the front rows in order to avoid too much turbulence might be a more profitable strategy. When designing a control algorithm for the coordination, it is important to consider where the limit is between when it is better to start the curtailment from the front rows or if it should be started from the back rows. The parameters that need to be considered are how much there is to gain by letting more wind pass though the WPP versus the damage caused by increased turbulence hitting the back rows.

For some of the figures showing the results of the high wind speeds case, the y-axis is shortened in order to better see the different graphs. This also makes the graphs more comparable with the low and medium wind speed cases, since the y-axis of the figures displaying the result of those cases originally has a smaller scale.

6.8.4 Very high wind speeds

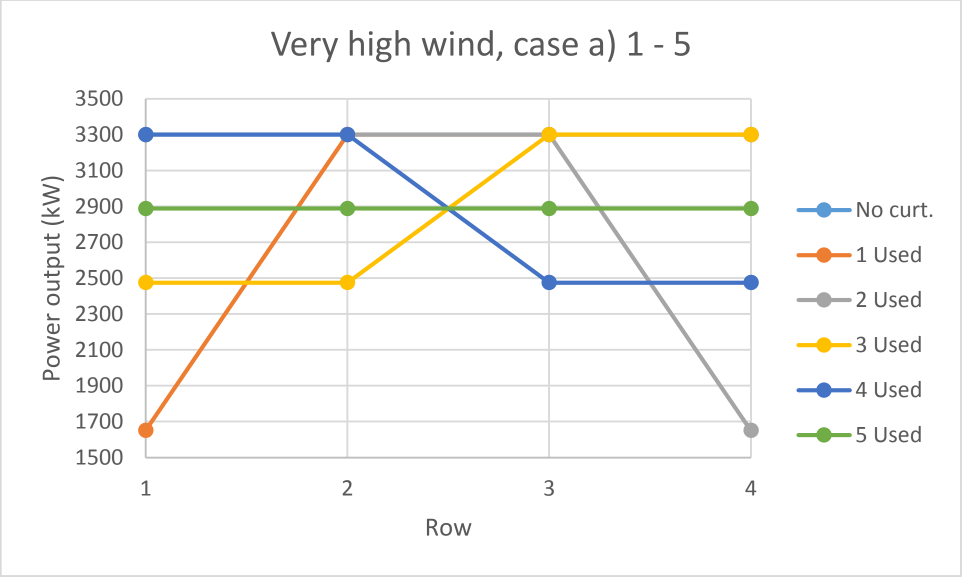


Figure 6.22. Power output during simulation of case a) 1 – 5 for very high wind speed, 12.5% curtailment. Only the used and the non-curtailed power output are displayed. Note that the scale of the y-axis does not start on 0.

Table 6.26. Actions displayed in figure 6.22.

a.	**WPP curtailed 12.5 %, i.e. 6.60 MW**
	Action
1.	Curtail only row 1 (50.0 %)
2.	Curtail only row 4 (50.0 %)
3.	Curtail row 1 and 2 equally
4.	Curtail row 3 and 4 equally
5.	Curtail entire WPP equally

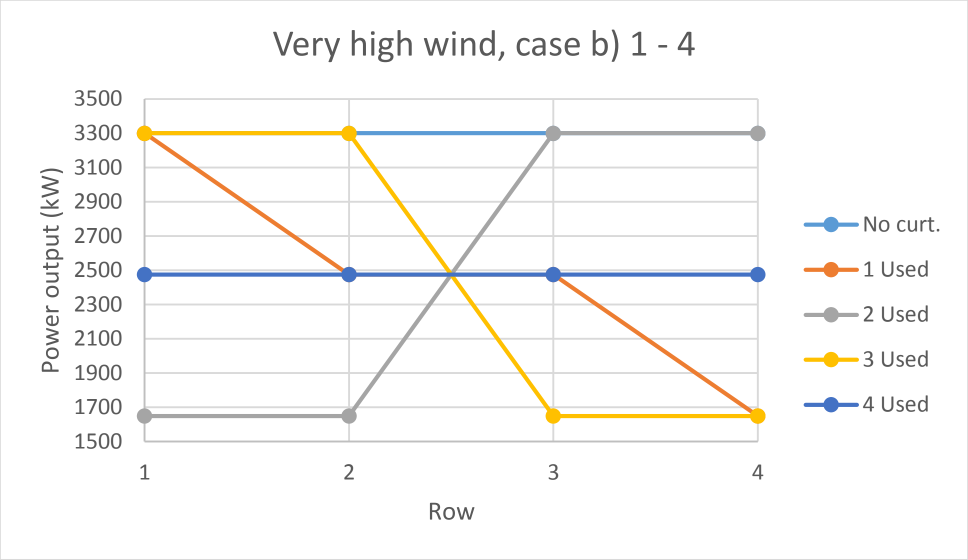


Figure 6.23. Power output during simulation of case b) 1 – 5 for very high wind speed, 25% curtailment. Only the used and the non-curtailed power output are displayed. Note that the scale of the y-axis does not start on 0.

Table 6.27. Actions displayed in figure 6.23.

b.	**WPP curtailed 25 %, i.e. 13.2 MW**
	Action
1.	Curtail row 2 and 3 25% each, and row 4 50%
2.	Curtail row 1 and 2 equally
3.	Curtail row 3 and 4 equally
4.	Curtail entire WPP equally

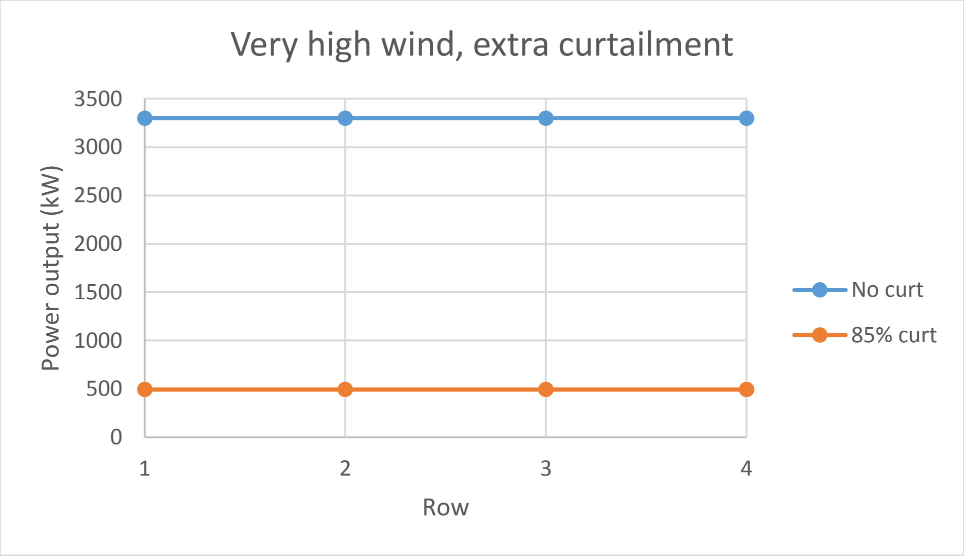


Figure 6.24. Power output during simulations of the case with extra curtailment during very high wind speeds. Only the used and the non-curtailed power output are displayed.

Table 6.28. Actions displayed in figure 6.24.

Extra curtailment	**Action**	**Power reduced / WTG (MW)**
	Curtail entire WPP equally	2.81

For the very high wind speeds cases, the available output is not shown in the figures, since it is the same as the power output with no curtailment. Since the wind speed is constantly higher than 12.5 m/s in these cases, the available power output will be 3300 kW at all times, which is the maximum power output. Since there is no increase in available power output, the strategy of curtailing the front rows and letting more wind pass through the WPP is not preferable in these cases. The most noticeable effect of using this strategy in these cases will be increased turbulence. In other words, the results show that a better strategy for these wind speeds is to start the curtailment at the back rows, as expected.

Figure 6.24 displays a case with extra curtailment (85%). When the curtailment is this extensive it is preferable to curtail the WPP equally, since curtailing only one, two or three rows would result in turbines stopping. A strategy curtailing all rows but the back rows a little bit more than the front rows in order to avoid extra turbulence can be considered, but at such high wind speeds and extensive curtailment, it is not recommended to curtail the WTGs too close to the limit of shutdown, since the risks in this case might be larger than the gains of such control. With a very extensive curtailment, a more desirable strategy is to curtail the entire WPP equally.

6.8.5 Special cases (low wind speed)

The first special case is based on case a) 5, which is 12.5% curtailment during low wind speed, curtailing the entire WPP, see figure 6.25. The curtailment of the first row equals one fourth of the total intended curtailment, since case a) 5 for low wind speed is based on curtailing the entire WPP equally. A new power output for row 2 is calculated, and row 1 is curtailed again, taking care of the extra power output from row 2. A new power output is calculated for row 2 taking the changed wind speed after row 1 into account, and when row 2 is curtailed, any additional power output from row 2 is taken care of by that curtailment. Then a new power output for row 3 is calculated, and the process continues in the same way through the WPP.

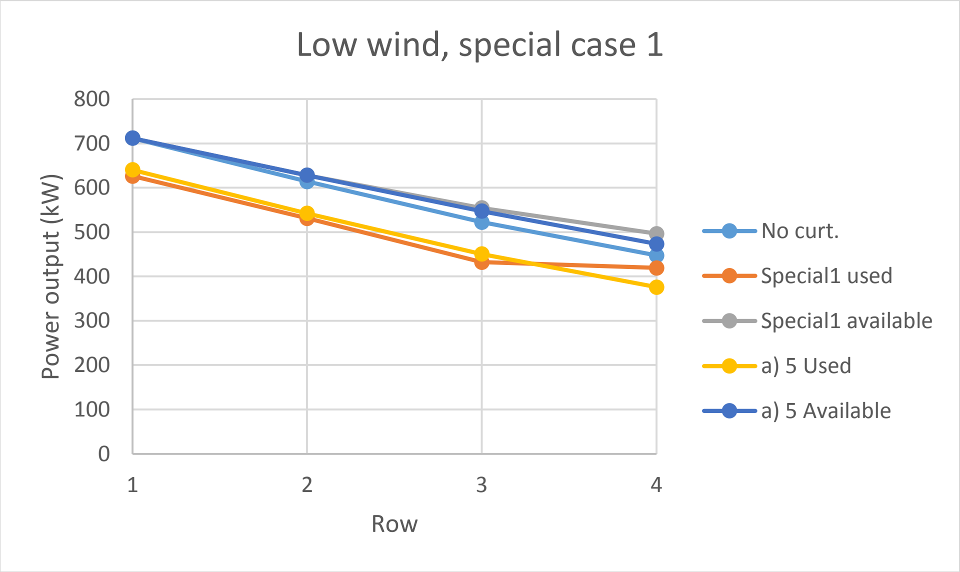


Figure 6.25. Power output during simulation of a special case for low wind speed, 12.5% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.29. Actions displayed in figure 6.25.

	WPP curtailed 12.5%
	Action
Special 1	Curtail entire WPP equally, let front rows take care of extra available power output
a) 5	Curtail entire WPP equally

Figure 6.25 shows that when the extra available power output from the back rows are taken care of by the first three rows, the last row does not need to be curtailed as much as in the case where the additional available output is not considered. This strategy could result in avoiding a turbine shutdown if the last row is close to the shutdown limit.

The second special case is based on case b) 4, which is 25% curtailment during low wind speed, curtailing the entire WPP, see figure 6.26. In this case, the aim of the curtailment is to keep the power output through the WPP on a more constant level, letting the first rows take care of the main part of the curtailment and only curtailing the back rows slightly. All of the extra available power output is not used in this case. This type of curtailment resembles a curtailment strategy that is used to some extent today, where all turbines are set to have the same output during the curtailment. If that strategy is used, it can be improved by taking the wake effects into account, as is done in the calculations for this second special case. To make this method workable, the control also needs to be designed in a special manner; curtailing the front rows first, letting more wind through the WPP before the back rows are curtailed as well. If the control is not performed in this way, the new power output setpoint might be too low for some of the turbines in the back row, and they will shut down.

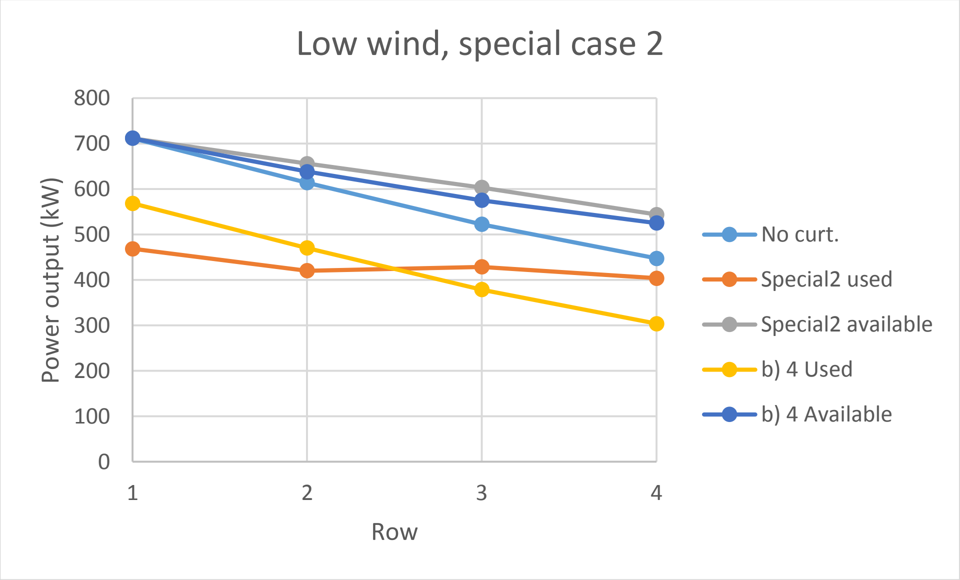


Figure 6.26. Power output during simulation of a second special case for low wind speed, 25% curtailment. The used, the available, and the non-curtailed power output are displayed.

Table 6.30. Actions displayed in figure 6.26.

	WPP curtailed 25 %
	Action
Special 2	Curtail front rows more and back rows less, use extra available output if necessary
b) 4	Curtail entire WPP equally

Comparing the graphs “Special2 used” and “b) 4 Used” in figure 6.26, shows that when this method is used, a turbine shutdown can be avoided. The “b) 4 Used” graph ends at 304 kW, which is lower than the minimum curtailment limit at 330 kW, meaning that the turbines in row 4 will shut down. In the special2 case, the power output is above 330 kW for all rows.

6.9 Additional strategies for future research

In the cases presented, all turbines are operating when no curtailment is performed. If the wind is even lower then specified in the cases, some of the back rows might not be operating due to the wake effects. When the curtailment starts and more wind passes through the WPP, the back rows will start operating if the wind increases enough. The question if the turbines should be allowed to start depends on the duration of the curtailment, since starting the turbines and letting them operate for just a short period before the wind is captured by turbines at the front rows again will not result in much production compared to the fatigue caused by the start. However every time the turbines are operating they are generating revenues, and therefore the turbines should be allowed to start if the curtailment will be ongoing for a while. If they are allowed to start, the increase in total power output for the WPP needs to be considered so that the curtailment is performed as intended.

A method that can be used during low wind speeds is to let the rotor speed increase instead of decrease during curtailment. This is also a way to consume power, resulting in a net curtailment. If this method is used, the process of getting back to normal production after a period of curtailment will be faster, since the rotor is already rotating at a speed close to the desired speed. This method also reduces the fatigue on the pitch equipment, since the blades are not pitched when the rotor speed is increased. Another advantage is that the risk of a turbine shutdown is reduced. Controlling the WPP according to the method described here also provides the ability to help the network during a frequency drop since the power output can be increased fast as a response to the drop in frequency.

7 Economic analysis

This chapter describes an economic analysis discussing the economic gain of performing the different types of control investigated in this thesis. The section covering the active power market will discuss the economic reasons for performing the coordination of the WTGs within a WPP during curtailment, together with the possibilities for economic compensation during curtailment. The section covering the reactive power market will discuss the possibilities of selling a service to the DSO/TSO helping out with keeping local voltage balance through reactive power control, and the possibilities of a future power and ancillary service market will also be discussed.

7.1 Active power market

7.1.1 Constraints payments and wind power entering the regulating power market

In order to estimate the limit for when it is profitable for a WPP to be curtailed and used as regulating power, a number of factors need to be considered. A main factor is of course the production loss, but also the loss of revenues from environmental subsidies, and the risk of curtailing the WPP need to be considered. In Denmark, curtailed offshore WPPs receive economic compensation for their loss of production, as mentioned in section 3.2.4. The compensation model is based on two different scenarios; either the curtailment order is issued before 11.00 on the day before the day of operation, or the curtailment order is issued after 11.00 on the day before the day of operation. If the order is issued before 11.00 on the day before the day of operation, the compensation will be as follows (Energinet.dk 2014b):

$$\boxed{compensation = (calculated\ production - actual\ production) * (spot\ price + price\ subsidy)} \qquad \text{eq. 5}$$

If the order is issued after 11.00 on the day before the day of operation, the compensation will be as follows (Energinet.dk 2014b):

$$\boxed{compensation = (calculated\ production - actual\ production) * (regulating\ power\ price + price\ subsidy)} \qquad \text{eq. 6}$$

The price subsidy is the difference between the feed-in tariff and the spot price, and any additional price subsidy that the WPP has. ENDK specifies how the non-supplied generation shall be calculated, using continuous wind measurement taking into account wake losses, offline turbines etc. and these values are logged every 5 minutes to be sent to ENDK at least once a day (Energinet.dk 2014b).

These simple models are created to make sure that WPP owner does not lose any money when they receive a curtailment order. Something to emphasise here is that these Danish WPPs do not choose to curtail their power output, they are ordered to do so by ENDK. It is however an example that can be used when further analysing the factors that need to be considered when estimating the price needed for curtailment of a WPP to be beneficial, and this model could also be used in Sweden if the Swedish system changes so that SvK can order curtailment of Swedish WPPs as well.

The other main factors are the risk that comes with the curtailment, and a profit margin. It is hard to put an exact price on the risk, since it includes a lot of different factors that also differ from site to site. For example, if curtailment takes place during low winds, there is a risk of turbines stopping, which causes losses in revenues and possible costs for sending technicians to the site if needed. However the curtailment will most likely happen during higher wind speeds, since the prices are usually lower during high winds and at times with low consumption, and the price will need to pass below a certain level in order to make it more profitable to sell the regulating capacity then to continue to produce. There are still risks of curtailing during high winds, especially if the curtailment is extensive. The fatigue on the turbines will also increase due to the curtailment reducing the turbine lifetime. In order to calculate the exact cost caused by the extra risks and fatigue, a detailed risk assessment together with mechanic calculations need to be performed. Such extensive investigations could not be included in this thesis due to limited time. This risk parameter should include the cost of sending technicians to the site in case of a turbine stopping, loss of generation, fatigue on turbines, etc. Something to consider for future calculations concerning the risk parameter is that the risk of loss of generation also increases due to the fact that the electricity consumption is lowest during the night, meaning that the risk of curtailment is highest during the night. If a turbine stops due to curtailment during the night, the standstill will be longer then if it would happen during the day, when the technicians are working. Equation 7 displays the factors that should be considered when calculating the regulating power revenue needed for the curtailment of a WPP to be beneficial.

$$\boxed{regulating\ power\ revenue = electricity\ certificate\ price + risk\ price + profit} \qquad \text{eq. 7}$$

In order to find out when it will be profitable to use wind power as regulating power, the actual regulating power revenue received for selling the wind power on the regulating market needs to be equal to or higher than the regulating power revenue defined in equation 7. The revenue received when selling regulating power is the difference between the spot price and the regulating power price (ΔR). Figure 7.1 shows an example with real data collected from the Nord Pool web page. The collected data are hour values of the spot price and the down regulating power price during the period 2015-01-01 – 2015-05-17. One of the graphs shows the actual regulating power revenue ΔR (blue graph), and the other graph shows the regulating power revenue as specified in equation 7 above (orange graph). The electricity certificate price is assumed to be EUR 16/MWh according to the present level. The risk parameter is calculated by iteration based on the amount of times that curtailment will occur, the assumption that in 1 of 20 curtailment events a turbine will stop and not start again and a cost of EUR 2500 for sending technicians to the site. The profit parameter is estimated to be 5 % of the real spot price. For calculations see appendix 11.3.

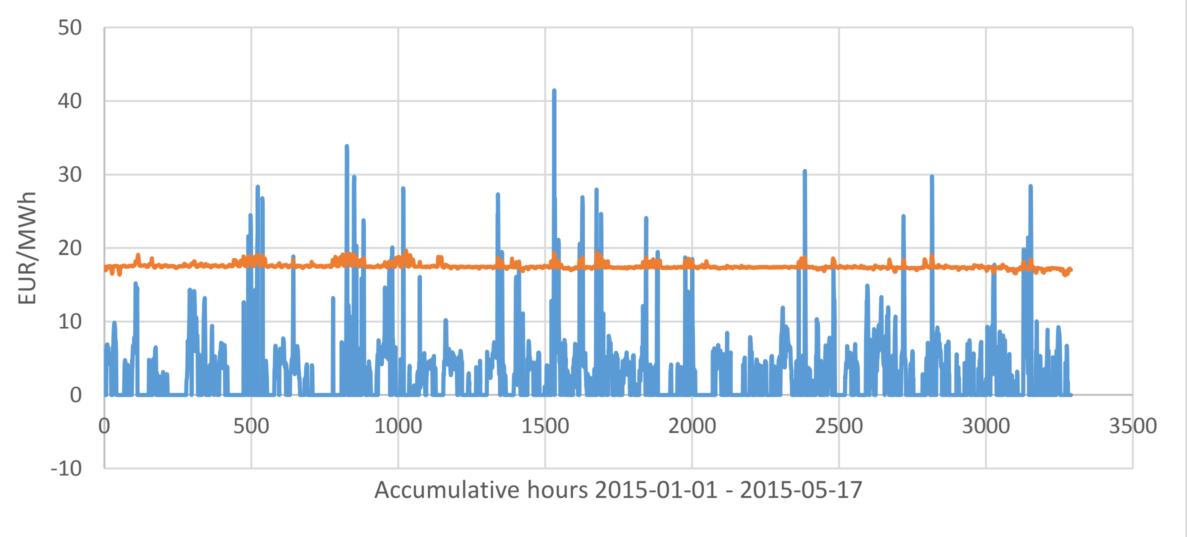


Figure 7.1. Example of how the regulating power revenue needed for curtailment to be profitable (orange graph) and the revenue received when selling regulating power ΔR (blue graph) can look like (Nord Pool Spot 2015a).

Figure 7.1 shows that the regulating power revenue needed for curtailment to be profitable most of the time is above the revenue received on the regulating market, but there are also a number of occasions when the regulating power revenue received on the market is higher. During these occasions the WPP would profit from participating on the regulating market. Although the amount of benefiting occasions are few, they are likely to increase in amount, as the number of WPPs is constantly increasing. This results in a higher risk of low spot prices and even lower regulating prices during high wind conditions in the area. Looking at this development, using wind power as regulating power will not only help assuring that WPP owners do not lose money, but also providing a new profit.

Another reason for providing the possibility of curtailing WPPs without losing money is that this mechanism can act as a protection against negative spot prices. During negative spot prices electricity producers pay to produce electricity, which result in large costs for the producer. If all WPPs act on the regulating power market curtailing the WPPs during negative prices, this would protect the WPP owner from losing money. Also, as described earlier, letting WPPs participate on the regulating power market will help stabilise the market. If WPPs are not participating but instead maintaining their production without curtailment when there is too much capacity in the system, the prices will decrease rapidly. With an increased penetration of wind power in the system this effect will be even stronger. Therefore introducing wind power on the regulating power market will provide extra value for all parties involved.

7.1.2 The economic advantages of coordination

The economic benefit of coordinating the WTGs within a WPP according to the methods described in chapter 6 will be discussed in this section considering the problems that can be avoided if the curtailment is performed as suggested.

Low and medium wind speeds

As the simulations in chapter 6 showed, curtailing the front rows of the WPP letting more wind pass through to the back rows can help avoiding unplanned turbine stoppages, which is the main goal with the coordination. The savings from avoiding a shutdown differs depending on the price of electricity, duration of the stop, accessibility of the site, etc. It very hard to put an exact figure to these savings, but they are likely to be substantial.

High and very high wind speeds

The main objective of the coordination at these wind speeds is to avoid unnecessary fatigue on the turbine, and to make the control fast and smooth. When turbines in the front rows of the WPP are pitching the blades, the turbulence behind the turbine increases, as described in chapter 6. This increased turbulence cases fatigue in the turbines in the back rows, and during higher wind speeds this effect is extra strong, since higher forces are acting on the system. Figure 7.2 shows an example of how the load on a structure is proportional to the turbulence, in this example the fatigue caused by the flapwise (upwind or downwind) bending moment of a blade is presented as equivalent load range versus turbulence (Guzmán Tejada 2014). The figure shows that a wind with high turbulence hitting the turbine will result in a higher load range, meaning an increased fatigue on the turbine.

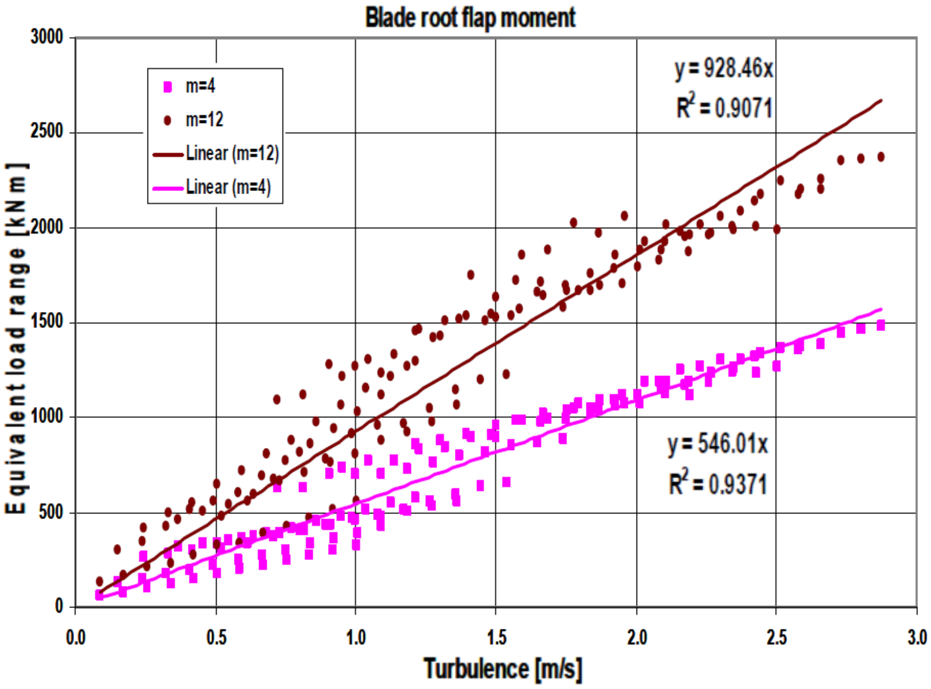


Figure 7.2. The proportionality between equivalent load range (blade root flapwise bending moment) and turbulence (Guzmán Tejada 2014).

The figure is used as an example in order to display how turbulence effect the fatigue on the turbine, which can be reduced if the coordination method presented in this thesis is followed. In order to find the economic gain of the control, calculations considering the turbine mechanics can be made, but the most accurate way would be to test the theory on real WPPs. That would require at least two WPPs that are situated very close to each other so that they will experience approximately the same wind conditions. One of the WPPs would need to be controlled according to the method presented in this thesis, and one would need to be controlled using traditional methods not considering the location of the WTGs in relation to each other. The test would need to go on for several years, preferably the entire lifetime of the WPPs, in order to observe the real effects of the control and thereby the economic gain. Such a test is not likely to be performed, since it would take a lot of time before any results are achieved and when one of the WPPs prove less efficient, keeping this inefficient control would result a great loss of revenue, meaning that this would cause an incitement to abort the test.

With the modern control capabilities of WPPs, implementing this type of control does not have to be expensive. It can be done by adding a new control algorithm to the existing system, or manually if the WPP operator know that the WPP will be curtailed the next day during a certain time, and the wind direction is known through weather forecasts, then the operator can simply schedule the turbines to operate according to this method during the curtailment.

7.2 Reactive power market

7.2.1 Reactive power service

As shown by the simulations in chapter 5, modern WPPs with full-scale converters can help in contributing to keep the voltage balance in the network. This means that WPPs can sell a service to TSOs/DSOs (local grid owner) providing reactive power compensation; or this reactive power compensation might become a requirement stated in grid codes in the future. As mentioned in chapter 3, other power plants experience stronger demands considering reactive power compensation compared to WPPs, and there is a possibility that these demands will also include large future WPPs. However today’s wind industry receives governmental subsidies, which are also described in chapter 3, and with this in mind burdening WPPs with stronger requirements is not a strategy that is likely to be used, a more probable strategy is to let the WPPs trade their reactive power compensation as a service since this approach might be more profitable for the system as a whole in the long run.

If the reactive power compensation is to be sold as a service, there will need to be a contract between the WPP owner and the local grid owner in order to ensure the reliability of the service. As seen in chapter 4 and 5, the WPP can always provide a certain minimum amount of reactive power even when no active power is produced, but when the WPP is running at full production the reactive power output becomes limited. The limitations are stated by the reactive power capability curve of the turbine (an example of such a curve is shown in figure 4.2) and by the capabilities of the cables and transformers within the WPP. If these are chosen considering the desired reactive power output when building the WPP, the range of the possible reactive power capability will become wider. If the WPP is constructed considering an increased reactive power exchange with the external grid, then the price of such a service can be included in the investment plan for the WPP.

As described in chapter 4, the control systems in modern WPPs can use several different external sources for controlling the systems. This means that the local grid owner can control the WPPs if the appropriate software is installed at both ends of the control (WPP and grid owner control station). It is however important that the circumstances of such control is agreed upon in a contract, which is described more in detail below, so that both parties are satisfied with the agreement.

The procedure for the control can be conducted in different ways. When the WPP provides the reactive power service, a preferable way to do this is for the grid owner to send signals to the WPP continuously, providing the WPP with information regarding the amount of reactive power needed. The WPP can then respond to the signal automatically, delivering the requested reactive power. Since there will be a contract between the WPP owner and the grid owner stating the circumstances of the control and the payment, no decisions need to be made in real-time, which provides the possibility for the control to happen automatically. This means that the contract will specify the circumstances for which the grid owner takes over the reactive power control of the WPP. The payment received for the service can happen for example monthly or yearly according to the contract. This way of performing the control also provides extra security for the grid owner, since it will happen automatically. One of the main objectives for grid owners is to maintain the voltage balance in the system, therefore this extra security of making the grid owner responsible for the control of the system can be an important part of the agreement.

The contract will also need to state the exact strategies of the control. For example a certain level of reactive power that the WPP can deliver at all times, also at maximum active power output, need to be specified. This is the simplest way to conduct the service. If the WPP owner and the grid owner can agree on additional reactive power compensation during other conditions, such as when the WPP is not at full active power production and hence can deliver more reactive power, special conditions for this more advanced service will need to be specified. If this more advanced service is used, the WPP will need to provide the local grid owner with continuously updated information on how much reactive power the WPP can provide.

When considering the price for the service, one basic parameter is that it needs to be somewhat cheaper than the costs that the grid owner would have if they would provide the compensation themselves, providing an incitement for the grid owner to buy the service. The price also needs to cover the expenses of the WPP to provide the service. These expenses are however limited, since modern turbines with full-scale converters already have capability to provide the service. Additional costs can be to install compatible systems for one or both of the parties. Another cost for the WPP can be to invest in cables and transformers that have better capabilities when it comes to transporting large amount of reactive power.

The price can also be set at different levels depending on the service required. If for example the more simple service described above concerning reactive power delivery within certain limits that the WPP can provide at all times is considered, a base price can be set for this service. If, the more advanced service is required trading higher amounts of reactive power that the WPP can deliver only if it is not at maximum production, a higher price can be set. This also results in a choice for the WPP owner. If e.g. the electricity spot price is very low due to a local excess of power in the system, it might be more profitable to curtail the WPP and use the extra capability of the WPP to provide the reactive power service, which in this case would be extracting reactive power.

An example of the base price of the service is SEK 25/kVar and year (EUR 2.7/kVar and year) for reactive power extraction and SEK 33/kVar and year (EUR 3.5/kVar and year) for reactive power injection. These examples are taken from the power distribution grid tariff for regional networks provided by E.ON Elnät (the Swedish E.ON network company). The prices of the extraction vary a little between voltage levels in the POC, and the prices presented here are valid for a connection on the low voltage side of a substation with a 130/50-30 kV transformer (E.ON Elnät 2014), which is a common connection level for WPPs. Since these prices are stated by E.ON Elnät it should also reflect the cost that the company need to cover in order to provide the service, plus perhaps a small profit. These prices can act as guidelines when calculating the price of the reactive power service provided by WPPs.

7.2.2 Future ancillary service and capacity market

Traditionally, the power system has relied on conventional power plants to provide ancillary services, such as keeping the system balance considering active power flows, frequency, voltage level, etc. Now that the penetration of wind power and other RES in the system is increasing, new solutions for keeping the system balance need to be considered. The power system is going through a change, adapting to the increased share of RES in the system. The transition to a future power system according to the “smart grid" model is already ongoing. This means a system that uses advanced IT technology involving both suppliers and consumers, so that everyone becomes a part in keeping the power balance. In order for this new system to work the market also needs to change, rewarding those who help maintaining the system balance. Some electricity supply companies have already started to adapt to the new system by introducing hourly fees for their customers, so that their customers can choose to consume more electricity during the hours of the day when the price is lowest, like running the dishwasher or charging the electric car during the night. This helps the entire system, since the price reflects the state of the system. If there is a lot of capacity in the system but a low amount of load, the price will decrease, but this new system with hourly pricing provides an incitement for the customer to use electricity during low load periods helping to maintain the balance of the system.

Another part of the solution to maintain the balance in the changing power system is using the ancillary services that WPPs can provide. This opens up for a new type of market, trading ancillary services. Examples of such services are frequency response, reactive power and voltage control, up- and down-regulation, etc. Modern WPPs can provide these services, but for a certain cost. Selling these services can be an additional source of income for WPP owners in the future. With an increased share of RES in the system, it is important to provide an incitement for these RES to participate in balancing the system through different ancillary services, and introducing and ancillary service market will provide such incitement.

Another way of making sure that the system is always balanced is using an extra capacity reserve for balancing the intermittency of the RES. This can be solved by introducing a separate capacity market with contracts ranging years ahead. This kind of markets have already been introduced in e.g. the UK and the US, and it is only a question of time before these kind of markets are introduced also in other countries (Department of Energy & Climate Change 2014; Clean Energy Wire CLEW 2014).

When meeting the challenges of the future, there is not one simple solution to all the upcoming challenges. The solution need to be a mixture of different concepts complementing each other, like the ones described in this chapter. We have the technology and the knowledge to take the next step towards the future power system, and towards a future that will be independent of finite energy sources.

8 Discussion

8.1 Evaluation of the report

The power system as we know it is changing, as the share of RES in the system is growing. In particular the penetration of wind power is increasing and with future governmental goals, the wind power industry set for an even larger increase. As discussed in this thesis, this transition towards a new power system requires some new thinking, and new strategies. Wind power has historically been viewed as a marginal resource, not affecting the power system to any larger extent. Now that this view is changing, WPPs need to adapt to this change, introducing new types of control helping the power system to maintain its balance. As seen in the studies performed in this thesis, modern WTGs are already equipped with the tools needed to do this.

The chapter describing the grid codes of Sweden, Denmark and Europe show the requirements that are valid today, and also gives a hint of the requirement that Swedish WPPs are likely to experience in the future, as penetration of wind power and other RES increases in Sweden. If Swedish grid codes change to become more like the Danish and European ones, stronger requirements are to be expected considering, for example, tolerance to frequency deviations, tolerance to voltage dips, reactive power supply, and especially control requirements.

Another reason for expecting increased controls of WPPs is the changing energy market. The changes in the power system discussed above will also affect the market. In order for the system to work the market must adapt to these changes. As previously discussed, both the wind power industry and the system itself would have a lot to gain from entering the regulating power market. Extra income generated for the WPP owner during extreme conditions would act as insurance against negative prices and provide an incitement for WPPs to help maintain balance in the system.

In order to further investigate how modern WPPs can contribute to maintain balance in the system, chapter 5 was dedicated to simulations using the program DIgSILENT PowerFactory. The network model used is developed by ENDK for research and education, and in this thesis a WPP consisting of 30 WTGs with an active power output of 6 MW each, full-scale converters and active/ reactive power capabilities taken from real modern WTGs were connected in order to investigate how such a WPP can affect the network. The results showed that the WPP can help maintain system balance using both active and reactive power. Originally, a SVC was connected to the same bus as the WPP in order to maintain the voltage at a certain level, but the simulations showed that this SVC was not needed when the new WPP was connected. When changing the production and loads in the system, the simulations showed that the WPP could compensate for these changes and maintain the network balance.

When WPPs are to be curtailed due to either grid code requirements or acting as regulating power, it is important that the curtailment is performed in an efficient way. If curtailment of WTGs within the WPP is coordinated with wake effects in mind, gains can be made from avoiding stoppages and minimising structural fatigue on the turbines. The results of the different wind speeds and coordination cases tested in chapter 6 show that different control strategies should be applied depending on wind speed. It is also important to consider the wind direction, since this will affect the definition of “front” and “back” rows, and therefore affect the way that the strategy is applied.

The primary concern of the coordination process is to avoid unplanned turbine stoppages, and the risk of this happening is greater at lower wind speeds. At lower wind speeds the strategy is therefore curtailment of the front rows of the WPP rather than the back rows. This will result in reduced wake effects and more wind passing through the WPP thus offering some protection against unplanned turbine stoppages. When a control algorithm for this control is developed, the best result is accomplished if the algorithm considers the increased available power output that the turbines of the back rows will receive when the front rows are curtailed. Of course, the WPP total output is not allowed to increase since it needs to deliver a certain amount of curtailment. Extra available output will however result in more room for adjustment of curtailment requirements allocated to different rows. This also means that coordination can be performed on different levels. An easier level can be chosen simply considering the output of the turbines before the curtailment and coordinating the WTGs with the goal to avoid a stop using these input parameters. The option is to use a more advanced control that also considers the new available active power output.

During higher wind speeds, the focus of coordination shifts. The risk of a turbine stopping is reduced at these wind speeds (although avoiding a turbine stop is always the main concern, and always the first step to consider when deciding on a coordination strategy) and instead the main concern becomes reducing fatigue on the turbines and ensuring that the control is fast and accurate. This is achieved by starting the curtailment from the back row instead of the front rows, since curtailment is performed through pitching of the blades which causes increased turbulence affecting the rows behind the curtailed row. However, if the curtailment is extensive during very high wind speeds it is recommended to curtail the entire WPP equally in order to avoid pushing single turbines too much when stresses on the structure are already high.

Chapter 7 provides an economic analysis, discussing a changing energy market and different ways for WPPs to participate in such a market. As previously mentioned, the advantages of introducing wind power on the regulating power market are many. The economic benefits of coordinating the WTGs within a WPP during curtailment are also discussed. The main goal with the coordination is to avoid a turbine stopping. In doing so, extra costs due to loss of production, and potential costs for technical assistance if the turbine does not start automatically, are avoided. The risk of a turbine stopping is most severe when the WPP is curtailed during lower wind speeds, but there are also economic advantages to the coordination strategies applied during higher wind speeds. As mentioned above, at higher wind speeds the main goals are to avoid increased fatigue on the turbines, and to make the control as fast and smooth as possible. When steps are taken to avoid increased fatigue, the economic advantages are significant; the lifetime of the turbine is not compromised and downtime and extra costs for replacing damaged parts of the turbine are avoided.

The economic advantages of a reactive power service are also presented. Enabling WPPs to sell additional services creates potential not only for new revenue sources, but also provides potential to help maintaining the local voltage balance. A future ancillary service and capacity market is also something which the changing power system is likely to need; in fact such markets are already a reality in some countries. The key to this development will be to find a range of creative solutions for improving the power system of the future, and identifying ways in which the market can reward and support the solutions which benefit the system most.

8.2 Challenges

8.2.1 Establishing the limit value for the coordination strategies

When coordinating WTGs during curtailment of a WPP, the main challenge is to identify the limit wind speed for deciding the appropriate control strategy. This also depends on a number of other factors for example the extent of the curtailment and the number and location of active turbines. The state chart shown in figure 6.9 can be applied when designing the control, but it still does not state the limit value. A guideline can be to use the wind speed at which the turbine reaches its maximum C_p value, since this wind speed is a kind of limit between lower and higher wind speeds, where the slope of the turbine power curve goes from increasing to decreasing. There is, however, no verification that this should be the limit wind speed. In order to find the exact limit wind speed further calculations and tests need to be made which were not possible to perform within the timeframe of this thesis. However, sometimes there is no need to overcomplicate things and, as stated above, the limit value for choosing the right strategy also depends on other factors. This means that if a limit wind speed is identified, it is not likely to be just one value, but a wind speed range also depending on other parameters. The main point here is that coordination can still be performed assuming a limit value and, if the uncertainties surrounding the limit value seem too high, a wind speed deadband can be defined so that coordination is only performed at very low or very high wind speeds. This would be done using the old type of control within the deadband until a certain limit wind speed is defined.

8.2.2 Developing the coordination algorithm

Strategies for coordination are stated above. These strategies could be implemented today quite simply by using manual or scheduled control of the WPP. However, the best way of implementing coordination is the development and application of an algorithm to coordinate WTGs within the curtailment process. The strategies defined in this thesis are applicable and relevant today, but an algorithm to improve this process will still require development using a digital system compatible with the WPP control systems.

8.2.3 Implementing the changes

Overcoming the obstacle of going from theory to practice is always challenging. The results obtained in this thesis can be used in practice, but there are questions which need to be answered along the way. The development of an algorithm to coordinate the curtailment process is one such question, as explained above. But another key issue is how these new methods of controlling active and reactive power can be implemented in reality. A detailed answer to these questions can only be given on a case by case basis, and since this thesis aims to obtain general strategies for use on different sites and different turbines (as long as the turbine is of newer model and has a full-scale converter), these questions have not been investigated further. The strategies and the technology are available, so the implementation of new controls is absolutely possible; the main parameters left to consider are subsequently site specific.

8.3 Future recommendations

8.3.1 Recommendations for E.ON Wind

Some of the findings in this thesis can be applied today, and some are to be viewed as preparations for the future. However, it is always good to be prepared and take the lead in this development. With regards to the introduction of wind power on the regulating power market, especially in SE4, this should be done as soon as possible in order to avoid losing money when negative prices occur. SE4 also needs more regulating power, so starting in this area will be beneficial. The coordination strategies presented in this thesis can be used on WPPs of different sizes, but the effects will be strongest when the strategies are applied on larger WPPs. The strategies can be used on both onshore and offshore wind power, in the event that the turbines are affected by each other’s wake effects. The WPPs in SE4 are still relatively small compared to the expected size of future WPPs, but the coordination strategies in this thesis can still be applied to these WPPs.

If or when the Swedish grid codes change, resulting in stricter requirements for WPPs, this will not be a problem for the E.ONs modern WPPs. The technology is available; the preparations that might be needed are to make sure that the systems are up to date since different versions hold different features. Most systems have a setting especially designed to comply with national grid codes. Older WPPs will probably not be effected by changing grid codes since such changes usually apply to WPPs built after a certain date.

A reactive power service could be tested on Kårehamn, since this WPP already has an advanced control system. The exact details of a contract stating the circumstances of the reactive power exchange needs to be specified, using the guidelines presented in chapter 7.2. Testing this service involves cooperation between E.ON Elnät and E.ON Wind and, by doing this, E.ON will take a leading role in the trading of ancillary services.

8.3.2 Recommendations for future research

A control algorithm for coordination of WTGs within a WPP during curtailment needs to be created using the strategies specified in this thesis. The algorithm would need to be developed using a digital system that is compatible with the digital systems used by WPPs. There are a lot of other parameters that can be considered in order to make the control as efficient as possible. For example, a strategy which can be used during low wind speeds is to enable the rotor speed to increase instead of decrease during curtailment, as described in chapter 6.9. One of many advantages with this type of control is that the curtailed WTG can return to full production very fast after the required curtailment period.

In the future, research should focus on specifying the strategies for coordination even more by testing all coordination parameters such as wind speeds, wind directions, and the full scope of possible curtailment volumes. This will give more specific and perhaps more applicable results. Similarly, the exact limit value/ range for selecting the most appropriate strategy is yet to be found.

In chapter 5.8, the advantages of coordinating WTGs within a WPP also when providing the reactive power service specified above are described. The main objective of such coordination is to minimise cable losses, and use the reactive power capability of the WPP as efficiently as possible.

9 Conclusion

It is clear that the future power system will require WPPs and other RES to provide more advanced control in order to maintain the network balance. As a result all wind power companies need to prepare for these changes. It might happen through stronger grid code requirements or through a changed market, but the most probable scenario is that it will be a combination of the two. As an example, there is a lot to gain if wind power enters the regulating power market also in Sweden; it would be a step further towards the future power system.

The simulations regarding the WPPs capabilities to help maintain local voltage balance showed that this can be done with current technology. This is a great opportunity both for the WPP owner to gain an extra revenue source, and for the grid owner to use a resource that comes with the WPP, i.e. there is no need for the grid owner to install extra devices to perform a task which the WPP is capable of. Introducing a reactive power service is a way towards a power system with fewer components and high flexibility. Being the first to introduce this service will result in a leading position within the market of such services.

The study of different strategies for coordination of WTGs within a WPP resulted in two different main strategies, depending on if the wind is low or high. Looking more closely into the parameters for each case, this control can be tailored depending on wind speed, wind direction, and amount of available turbines for example, but the main strategies remain. This control can be applied to WPPs today but will prove even more useful for future large WPPs that will need to perform curtailment, either due to grid code requirements or, even more likely, due to acting on the regulating power market.

So, how can Swedish wind power plants be controlled to meet future grid codes in a changing power market? This thesis answers many aspects of this question, but there are still many other interesting areas to investigate. Modern WTGs are already capable of doing a lot of things both considering active and reactive power control and development of this technology is ongoing. The sooner WPP owners, grid owners, power markets and all participants of the energy system start using these abilities, the sooner it will become evident that wind power interaction in the transmission system is not a problem to be solved, but a solution to the problem.

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11 Appendix

11.1 Matlab code

11.1.1 Power curve

Figure 6.3

```
clc
clear all
close all

U = [3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11 11.5 12 12.5 13 13.5 14 14.5 15 15.5 16 16.5 17 17.5 18
18.5 19 19.5 20 20.5 21 21.5 22 22.5];
P = [36 99 177 274 393 537 712 919 1161 1436 1747 2082 2421 2741 3011 3185 3267 3293 3298 3300 3300 3300 3300 3300
3300 3300 3300 3300 3300 3300 3300 3300 3300 3300 3300 3300 3300 3300 3300 3300];

figure(4)
plot(U,P)
set(gca,'XTick',[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22],'YTick',[0 500 1000 1500 2000 2500 3000
3500])
xlim([0 22.5])
xlabel('Wind speed (m/s)')
ylabel('Power output (kW)')
grid
```

11.1.2 C_T and C_p curves

Figure 6.5

```
a = 0:0.01:1;

for k = 1:1:101;
    Ct(k) = 4*a(k)*(1-a(k));
    Cpt(k) = 4*a(k)*(1-a(k))^2;
end

figure(2)
plot(a,Ct,'b')
```

```
xlabel('Axial induction factior')
ylabel('Dimensionless number')
hold on
plot(a,Cpt,'r')
grid
```

Figure 6.7

```
rho = 1.225;
A = (126/2)^2*pi;

for z = 1:1:40;
    Cp(z) = (P(z)*1000)/(0.5*rho*A*U(z)^3);
end

figure(5)
[hAx,hLine1,hLine2] = plotyy(U,P,U,Cp)
xlabel('Wind speed (m/s)')

set(gca,'XTick',[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25])
ylabel(hAx(1),'Power output (kW)') % left y-axis
ylabel(hAx(2),'Cp') % right y-axis
grid
```

Figure 6.6

```
Ct = [0.949 0.93 0.91 0.878 0.861 0.855 0.847 0.838 0.828 0.818 0.805 0.774 0.724 0.667 0.602 0.53 0.456 0.39 0.336
0.293 0.257 0.229 0.204 0.183 0.164 0.149 0.135 0.124 0.113 0.104 0.096 0.089 0.082 0.076 0.071 0.066 0.062 0.059
0.055 0.052];
figure(6)
plot(P,Ct)
xlabel('Power output (kW)')
ylabel('Ct')
grid

figure(10)
[hAx,hLine1,hLine2] = plotyy(U,Ct,U,Cp);
xlabel('Wind speed (m/s)')
```

```
ylabel(hAx(1),'Ct') % left y-axis
ylabel(hAx(2),'Cp') % right y-axis
grid
```

11.2 Coordination calculations

11.2.1 Coordination during low wind speed

	Action	**New P row 1 curtailed**	**New Cp row 1 - 2**	**New Ct row 1 - 2**	**Ux/Uo**	**New U row 2**	**New available P row 2 not curtailed**	**New P row 2 curtailed**	**New Cp row 2 - 3**	**New Ct row 2 - 3**	**Ux/Uo**	**New U row 3**	**New available P row 3 not curtailed**	**New P row 3 curtailed**	**New Cp row 3 - 4**	**New Ct row 3 - 4**	**Ux/Uo**	**New U row 4**	**New available P row 4 not curtailed**	**New P row 4 curtailed**
a) 12.5%																				
1.	Curtail only row 1 (40.3 %)	425,00	0,26	0,281	0,98	5,8540211	659,5	-	0,430	0,505	0,953	5,576	565	-	0,427	0,5	0,953	5,315	485	-
2.	Curtail only row 4 (64.1 %)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
3.	Curtail row 1 and 2 equally	568,50	0,345	0,387	0,97	5,7916254	638,5	470,50	0,317	0,351	0,969	5,611	575,5	-	0,426	0,499	0,953	5,349	494	-
4.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	379,00	0,307	0,339	0,97	5,282	473,5	304,00
5.	Curtail entire WPP equally	640,25	0,388	0,445	0,96	5,7551839	628	542,25	0,372	0,423	0,962	5,534	547,5	450,75	0,423	0,494	0,954	5,278	473,5	375,75
b) 25%																				
1.	Curtail only row 1 (80.6 %)	138,00	-	-	-	6	712	-	0,432	0,508	0,952	5,713	610,5	-	0,429	0,503	0,953	5,444	519,5	-
2.	Curtail row 1 50% and 2 and 3 equally	356,00	0,216	0,23	0,98	5,8823966	670	505,00	0,325	0,361	0,968	5,694	603,5	-	0,428	0,502	0,953	5,425	517	-
3.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	235,50	0,191	0,202	0,983	5,352	494	160,50
4.	Curtail entire WPP equally	568,50	0,345	0,387	0,97	5,7916254	638,5	470,50	0,317	0,351	0,969	5,611	575,5	379,00	0,281	0,307	0,973	5,461	525,5	304,00

11.2.2 Coordination during medium wind speed

	Action	New P row 1 curtailed	New Cp row 1 - 2	New Ct row 1 - 2	Ux/Uo	New U row 2	New available P row 2 not curtailed	New P row 2 curtailed	New Cp row 2 - 3	New Ct row 2 - 3	Ux/Uo	New U row 3	New available P row 3 not curtailed	New P row 3 curtailed	New Cp row 3 - 4	New Ct row 3 - 4	Ux/Uo	New U row 4	New available P row 4 not curtailed	New P row 4 curtailed
a) 12.5%																				
1.	Curtail only row 1 (40.0	1048,13	0,268	0,291	0,97	7,798	1622,5	-	0,44806	0,532	0,949	7,4037	1381	-	0,4456	0,529	0,95	7,032	1177,5	-
2.	Curtail only row 4 (64.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	389,63
3.	Curtail row 1 and 2 equally	1397,56	0,357	0,474	0,96	7,648	1529,3	1129,56	0,33058	0,369	0,967	7,3967	1381	-	0,4468	0,531	0,95	7,024	1172	-
4.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	927,06	0,3233	0,359	0,968	6,984	1151,5	739,06
5.	Curtail entire WPP equally	1572,28	0,402	0,464	0,96	7,657	1535,5	913,78	0,26651	0,29	0,975	7,4643	1414	1101,78	0,3469	0,39	0,965	7,203	1271	913,78
b) 25%																				
1.	Curtail only row 1 (80.0	349,25	0,089	0,0911	0,99	7,94	1709,5	-	0,447	0,531	0,950	7,540	1461	-	0,4463	0,529	0,95	7,161	1249	-
2.	Curtail row 1 and 2 equally	1048,13	0,268	0,291	0,97	7,798	1622,5	780,13	0,215	0,229	0,980	7,646	1527	-	0,4474	0,529	0,95	7,262	1177,5	-
3.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	577,63	0,2014	0,213	0,982	7,084	1205	389,63
4.	Curtail entire WPP equally	1397,56	0,357	0,403	0,96	7,709	1566,5	1129,56	0,323	0,359	0,968	7,463	1414,000	927,063	0,292	0,320	0,972	7,254	1298,5	739,06

11.2.3 Coordination during high wind speed

	Action	New P row 1 curtailed	New Cp row 1 - 2	New Ct row 1 - 2	Ux/Uo	New U row 2	New available P row 2 not curtailed	New P row 2 curtailed	New Cp row 2 - 3	New Ct row 2 - 3	Ux/Uo	New U row 3	New available P row 3 not curtailed	New P row 3 curtailed	New Cp row 3 - 4	New Ct row 3 - 4	Ux/Uo	New U row 4	New available P row 4 not curtailed	New P row 4 curtailed
a) 12.5%																				
1.	Curtail only row 1 (44.1 %)	1683,94	0,220	0,235	0,98	9,799	2903	-	0,404	0,467	0,96	9,38	2664	-	0,423	0,496	0,954	8,94	2380,5	-
2.	Curtail only row 4 (58.1 %)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	958,44
3.	Curtail row 1 and 2 equally	2347,47	0,307	0,339	0,97	9,701	2849	2120,47	0,304	0,335	0,97	9,41	2683,5	-	0,421	0,492	0,954	8,98	2407,5	-
4.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	1872,47	0,316	0,35	0,969	8,90	2353	1621,97
5.	Curtail entire WPP equally	2679,23	0,351	0,395	0,964	9,645	2822	2452,23	0,358	0,404	0,96	9,29	2606,5	2204,23	0,360	0,407	0,963	8,95	2387	1953,73
b) 25%																				
1.	Curtail row 1 86.7% and row 2 1.5%	400,00	0,052	0,053	0,996	9,96	2989,5	2740,88	0,364	0,412	0,963	9,586	2789,5	-	0,415	0,483	0,955	9,15	2517	-
2.	Curtail row 3 30.3% and row 4 82.0%	-	-	-	-	-	-	-	-	-	-	-	-	1767,38	0,299	0,329	0,971	8,92	2366	400,00
3.	Curtail row 1 and 2 equally	1683,94	0,220	0,235	0,98	9,80	2903	1456,94	0,203	0,215	0,982	9,621	2811	-	0,413	0,48	0,955	9,19	2549	-
4.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	1208,94	0,204	0,216	0,982	9,02	2664	958,44
5.	Curtail entire WPP equally	2347,47	0,307	0,339	0,97	9,70	2849	2120,47	0,304	0,335	0,970	9,414	2683,5	1872,47	0,294	0,323	0,972	9,15	2517	1621,97

11.2.4 Coordination during very high wind speed

	Action	**New P row 1 curtailed**	**New Cp row 1 - 2**	**New Ct row 1 - 2**	**Ux/Uo**	**New U row 2**	**New available P row 2 not curtailed**	**New P row 2 curtailed**	**New Cp row 2 - 3**	**New Ct row 2 - 3**	**Ux/Uo**	**New U row 3**	**New available P row 3 not curtailed**	**New P row 3 curtailed**	**New Cp row 3 - 4**	**New Ct row 3 - 4**	**Ux/Uo**	**New U row 4**	**New available P row 4 not curtailed**	**New P row 4 curtailed**
a) 12.5%																				
1.	Curtail only row 1 (50.0 %)	1650,00	0,064	0,065	0,995	14,921	3300	-	0,130	0,135	0,989	14,754	3300	-	0,135	0,14	0,99	14,582	3300	-
2.	Curtail only row 4 (50.0 %)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1650,00
3.	Curtail row 1 and 2 equally	2475,00	0,096	0,098	0,992	14,879	3300	2475,00	0,098	0,101	0,992	14,756	3300	-	0,134	0,139	0,99	14,586	3300	-
4.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	2475,00	0,103	0,106	0,99	14,547	3300	2475,00
5.	Curtail entire WPP equally	2887,50	0,112	0,115	0,991	14,858	3300	2887,50	0,115	0,117	0,99	14,714	3300	2887,50	0,119	0,123	0,99	14,565	3300	2887,50
b) 25%																				
1.	Curtail row 2 and 3 25% each, and row 4 50%	-	-	-	-	-	-	2475,00	0,099	0,102	0,992	14,552	3300	2475,00	0,105	0,108	0,99	14,423	3300	1650,00
2.	Curtail row 1 and 2 equally	1650,00	0,064	0,065	0,995	14,921	3300	1650,00	0,065	0,066	0,995	14,841	3300	-	0,132	0,137	0,99	14,672	3300	-
3.	Curtail row 3 and 4 equally	-	-	-	-	-	-	-	-	-	-	-	-	1650,00	0,068	0,069	0,99	14,593	3300	1650,00
4.	Curtail entire WPP equally	2475,00	0,096	0,098	0,992	14,879	3300	2475,00	0,098	0,101	0,992	14,756	3300	2475,00	0,101	0,104	0,99	14,63	3300	2475,00

11.2.5 Coordination during low wind, special cases

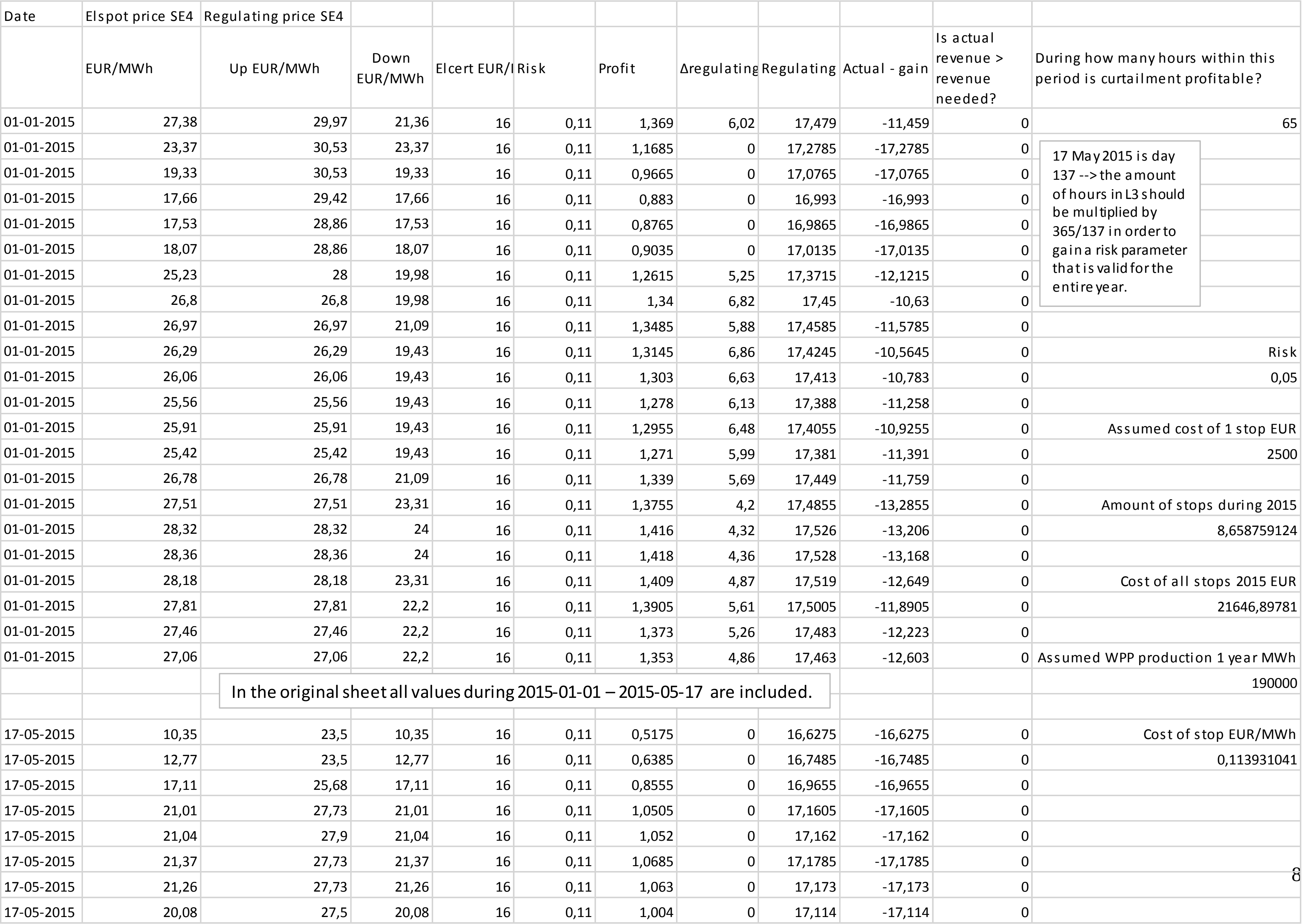
Special case 1

12.5%	**Action**	**New P row 1 curtailed**	**New total power output**	**New Cp row 1 - 2**	**New Ct row 1 - 2**	**Ux/Uo**	**New U row 2**	**New available P row 2 not curtailed**	**Amount of extra kW/WTG row 2**	**New total power output**	**New P row 2 curtailed**	**New total power output**	**New Cp row 2 - 3**	**New Ct row 2 - 3**	**Ux/Uo**	**New U row 3**	**New available P row 3 not curtailed**	**Amount of extra kW/WTG row 3**	**New total power output**	**New P row 3 curtailed**	**New total power output**	**New Cp row 3 - 4**	**New Ct row 3 - 4**	**Ux/Uo**	**New U row 4**	**New available P row 4 not**	**Amount of extra kW/WTG row 3**	**New total power output**	**New P row 4 curtailed**	**New total power output**
	Curtail entire WPP equally	640,25	8897,00	0,388	0,445	0,96	5,755	628	14,00	8953,00																				
	More curtailment	626,25	8897,00	0,380	0,435	0,96	5,762	628	0	8897,00	556,25	8610,00	0,381	0,435	0,96	5,533	547,5	25,00	8710,00											
	More curtailment										531,25	8610,00	0,364	0,412	0,963	5,547	554,5	7,00	8638,00	475,75	8323,00	0,365	0,413	0,96	5,339	491	43,50	8497,00		
	More curtailment																			432,25	8323,00	0,332	0,37	0,97	5,364	496,5	5,5	8345	419,25	8036

Special case 2

25%		New P row 1 curtailed	New Cp row 1 - 2	New Ct row 1 - 2	Ux/Uo	New U row 2	New available P row 2 not curtailed	New P row 2 curtailed	New Cp row 2 - 3	New Ct row 2 - 3	Ux/Uo	New U row 3	New available P row 3 not curtailed	New P row 3 curtailed	New Cp row 3 - 4	New Ct row 3 - 4	Ux/Uo	New U row 4	New available P row 4 not	New P row 4 curtailed
		468,50	0,28	0,305	0,97	5,84	656	421	0,276	0,301	0,974	5,6871	603,5	429	0,305	0,336	0,97	5,519	544	404

11.3 Regulating power revenue calculations



Date	Elspot price SE4	Regulating price SE4									
	EUR/MWh	Up EUR/MWh	Down EUR/MWh	Elcert EUR/I	Risk	Profit	Δregulating	Regulating	Actual - gain	Is actual revenue > revenue needed?	During how many hours within this period is curtailment profitable?
01-01-2015	27,38	29,97	21,36	16	0,11	1,369	6,02	17,479	-11,459	0	65
01-01-2015	23,37	30,53	23,37	16	0,11	1,1685	0	17,2785	-17,2785	0	
01-01-2015	19,33	30,53	19,33	16	0,11	0,9665	0	17,0765	-17,0765	0	
01-01-2015	17,66	29,42	17,66	16	0,11	0,883	0	16,993	-16,993	0	
01-01-2015	17,53	28,86	17,53	16	0,11	0,8765	0	16,9865	-16,9865	0	
01-01-2015	18,07	28,86	18,07	16	0,11	0,9035	0	17,0135	-17,0135	0	
01-01-2015	25,23	28	19,98	16	0,11	1,2615	5,25	17,3715	-12,1215	0	
01-01-2015	26,8	26,8	19,98	16	0,11	1,34	6,82	17,45	-10,63	0	
01-01-2015	26,97	26,97	21,09	16	0,11	1,3485	5,88	17,4585	-11,5785	0	
01-01-2015	26,29	26,29	19,43	16	0,11	1,3145	6,86	17,4245	-10,5645	0	Risk
01-01-2015	26,06	26,06	19,43	16	0,11	1,303	6,63	17,413	-10,783	0	0,05
01-01-2015	25,56	25,56	19,43	16	0,11	1,278	6,13	17,388	-11,258	0	
01-01-2015	25,91	25,91	19,43	16	0,11	1,2955	6,48	17,4055	-10,9255	0	Assumed cost of 1 stop EUR
01-01-2015	25,42	25,42	19,43	16	0,11	1,271	5,99	17,381	-11,391	0	2500
01-01-2015	26,78	26,78	21,09	16	0,11	1,339	5,69	17,449	-11,759	0	
01-01-2015	27,51	27,51	23,31	16	0,11	1,3755	4,2	17,4855	-13,2855	0	Amount of stops during 2015
01-01-2015	28,32	28,32	24	16	0,11	1,416	4,32	17,526	-13,206	0	8,658759124
01-01-2015	28,36	28,36	24	16	0,11	1,418	4,36	17,528	-13,168	0	
01-01-2015	28,18	28,18	23,31	16	0,11	1,409	4,87	17,519	-12,649	0	Cost of all stops 2015 EUR
01-01-2015	27,81	27,81	22,2	16	0,11	1,3905	5,61	17,5005	-11,8905	0	21646,89781
01-01-2015	27,46	27,46	22,2	16	0,11	1,373	5,26	17,483	-12,223	0	
01-01-2015	27,06	27,06	22,2	16	0,11	1,353	4,86	17,463	-12,603	0	Assumed WPP production 1 year MWh
											190000
17-05-2015	10,35	23,5	10,35	16	0,11	0,5175	0	16,6275	-16,6275	0	Cost of stop EUR/MWh
17-05-2015	12,77	23,5	12,77	16	0,11	0,6385	0	16,7485	-16,7485	0	0,113931041
17-05-2015	17,11	25,68	17,11	16	0,11	0,8555	0	16,9655	-16,9655	0	
17-05-2015	21,01	27,73	21,01	16	0,11	1,0505	0	17,1605	-17,1605	0	
17-05-2015	21,04	27,9	21,04	16	0,11	1,052	0	17,162	-17,162	0	
17-05-2015	21,37	27,73	21,37	16	0,11	1,0685	0	17,1785	-17,1785	0	
17-05-2015	21,26	27,73	21,26	16	0,11	1,063	0	17,173	-17,173	0	
17-05-2015	20,08	27,5	20,08	16	0,11	1,004	0	17,114	-17,114	0	

17 May 2015 is day 137 --> the amount of hours in L3 should be multiplied by 365/137 in order to gain a risk parameter that is valid for the entire year.

In the original sheet all values during 2015-01-01 – 2015-05-17 are included.