Automated Curtailment of Wind Turbines during Critical Transmission Periods

Maid Delic

LUND
UNIVERSITY

Department of Automatic Control

MSc Thesis
ISRN LUTFD2/TFRT--6004--SE
ISSN 0280-5316

Department of Automatic Control
Lund University
Box 118
SE-221 00 LUND
Sweden

Printed in Sweden by Tryckeriet i E-huset
Lund 2016

Abstract

The Swedish energy policy is guided by two government bills which were approved by the Swedish parliament in 2009 stating that at least 50 percent of the electricity share should be provided by renewable energy sources by 2020. This thesis focuses on the wind power production and it is a part of the Smart Grid Gotland (SGG) project. One of the goals stated by the SGG project is to have an optimal integration of large hosting capacity for wind power on an existing distribution grid.

The main purpose of this thesis is to automate the curtailment of the wind power plants during critical transmission periods on Gotland, and doing so in a fair manner. The critical transmission periods occur on Gotland when one of the two HVDC links are under service. During this period, there can only be a power flow from the mainland to Gotland and this power flow cannot fall below 20 MW due to grid security and Gotland Energy AB (GEAB) are curtailing the wind turbines using a manual workflow from a Distribution Center (DC) where a safety margin for the HVDC link is set to 20 MW. The consequence of using a manual curtailment process is that the power flow from the mainland to Gotland is on an average of 40 MW during the critical transmission periods. This indicates that there is a waste of energy that could be used.

The main goal of the thesis is to reduce the waste of wind power by automating the curtailment process. The approaches that were considered in this thesis were to document the presently used manual workflow for curtailing the wind power. This was done by using different techniques such as; Use Cases, BPMN charts and SGAM models. A solution with minimum set of modification on the present system and environment at GEAB, which automates the present workflow and reduces the waste energy was developed using a PI-controller with feedforward. In addition a generic state-of-the-art solution taking standardization and performance as the main driver was developed for potential future use. Lastly, a concept for fair curtailment was investigated for distribution of the total wanted power reduction to the wind turbines.

The results indicated that the set-point for the HVDC could be lowered to 23 MW by using the automated process. The approach for the fair curtailment that was considered was based on the contracted power for each wind power plant. Each

wind power plant is to be curtailed according to the ratio of the contracted wind power of the wind power plants to the combined contracted power of each wind power plant.

Acknowledgements

First of all I wish to thank my family, my mother Jasmina, my father Senad and my brother Aldin. You have always supported me no matter what. I want to extend my gratitude to my supervisor at Vattenfall, David Erol. David has helped me through out the entire time during the thesis work and never hesitated to help me, for this I am tremendously thankful. To the people at GEAB I want to say thank you, Christer Liljegren, Tord Johansson, Axel Fogelberg and Thomas Erlandsson, thank you for providing me with information and all the necessary data that was needed to conduct this thesis work. I also want to thank Rolf Johansson, who was my supervisor from the Faculty of Engineering in Lund for his help during the thesis work and during the course of my student time at the faculty. Lastly, I want to thank everyone at Vattenfall. Since the first day that I arrived at Vattenfall I felt welcome. Thank you All!

Abbreviations

Abbreviation	Write-out
BPMN	Business Process Modeling Notation
DC	Drift Central
GEAB	Gotland Energy AB
HMI	Human Machine Interface
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
MPC	Model Predictive Control
PID	Proportional-Integral-Derivative
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SGG	Smart Grid Gotland
WTC	Wind Turbine Controller
WTG	Wind Turbine Generator
WPP	Wind Power Plant

Contents

1

Introduction

1.1 Background

The world as we know it is facing drastic climate changes, and this is due to our constant need for energy. We as residents on this world have the responsibility to provide a sustainable future for the generations to come. This pressure has been noticed by the governments and the politicians. Taking Europe in consideration, the European Union (EU) has set a goal to the year 2020 to reduce the fossil fuel use and invest in renewable energy production. EU has set the 20-20-20 objectives with 20% reduction in emissions, 20% increase in renewable energies and 20% improvements in energy efficiency by 2020. It is also stated that major countries, such as the United States of America, could reduce their emissions by 30% [Kemfert, 2014].

Focusing on Sweden, the Swedish energy policy is guided by two government bills which were approved by the Swedish parliament in 2009. The bill "En integrerad energi- och klimatpolitik" or "integrated climate and energy policy" has ambitions to support the 20-20-20 objectives in pursuit of a sustainable policy for the environment, competitiveness and long term stability [Government, 2015]. The short to medium targets for 2020 are: 40% reduction in greenhouse gases (GHGs), at least a 50% share of renewable energy in the gross final energy consumption, at least a 10% share of renewable energy in the transport sector and 20% more efficient use of energy compared to the year 2008. Looking at the long term priorities for Sweden, the goal is to phase out fossil fuels in heating, reduced vulnerability and increased security of electricity supply by using wind and other renewable power production by 2020. 2050 Sweden will have a sustainable and resource-efficient energy supply with zero net emissions of GHGs.

The road towards reaching the 20-20-20 objectives is not easy since the demand on electricity, which is the most versatile and widely used form of energy, is increasing continuously. The demand, or even responsibility, of integrating renewable energy generation, such as wind power and solar power, in today's electricity infrastructure poses technical challenges such as: grid stability, controlling demand and supply, and electrical transmission capacities. Since wind power and other renewable sources with intermittent power generation increase in demand, and the customer becomes more active in relation to their energy use intelligent, flexible and more reliable distribution networks are needed. To be able to reach the objectives the concept of "smart grids” was presented which will provide the required system, market and tools to meet these demands[Vattenfall, 2014].

The concept behind a smart grid is that an electricity network uses digital and advanced technologies for monitoring and managing the transport of electricity from all power generation sources to meet the demands of end-users and that the end-user meets the limitations of the electrical power grid. The smart grid approach will not only meet the challenges but also develop a cleaner energy supply that is more energy efficient, more affordable and more sustainable. One has to take in consideration the regard of each region’s technical, financial and commercial regulatory environment. Smart Grid Gotland (SGG) is a Swedish project developing and researching the smart grid concept where Vattenfall, Gotland Energy AB (GEAB), ABB, Schneider Electric, Svenska Kraftnät, Royal Institute of Technology (KTH) and Energimyndigheterna are all collaborators. The SGG project has stated three overall goals [*Smart Grid Gotland* 2015]:

1. Optimal integration of large hosting capacity for wind power on an existing distribution grid.
2. New technical solutions to improve the power quality to the customer in a rural grid.
3. Enable the customer to be a part of the electricity market.

This master thesis is a part of the SGG project where the focus is on automating the curtailment of wind turbines during critical power transmission periods, and dispatching the curtailment signal in a fair manner. By curtailing the wind power generation of a wind turbine is to reduce the power generation due to different circumstances. Two High Voltage Direct Current (HVDC) links connect Gotland and the Swedish mainland. Each year one of these cables undergo service and only one of these links are operational. During this period only power flow from the mainland to Gotland is possible and it is during this period that curtailment of wind power might be necessary.

The thesis is divided into four major deliverables: an As-Is description of the currently used manual system for curtailing the wind turbines, a short term solution with minimum set of modifications on the currently used system, generic state-of-art solution taking standardization and performance as the main driver, and a concept of fair curtailment where dispatch, follow up, and settlement are taken in consideration.

1.2 Outline

1. **Introduction -** A background with general description of the topic and related projects and goals of the thesis. Presentation of purpose with the thesis together with goals and objectives that were set together with Vattenfall.

2. **Method -** Description of the methodology used during the thesis work to obtain knowledge during the work and to be able to reach the presented results

3. **Theory -** The general theory behind the thesis for the reader to get sufficient knowledge concerning the topic.

4. **Background Study and Findings -** A presentation of the findings made during the thesis work where the presently used curtailment work process, components and actors are presented.

5. **System Identification -** This chapter presents a curtailment test of a wind power plant that was conducted at Gotland and a model that was derived using the acquired data.

6. **Control Design -** Two control designs that were used for the automated curtailment are presented together with two scenarios and the results of these scenarios.

7. **Fair Dispatch -** An evaluation of different approaches of the fair dispatch concept was conducted. Different concepts, where an economical approach was adopted are presented.

8. **System Architecture -** Two solutions of the system architecture are presented in this chapter where the second solution takes standardization in to consideration.

9. **Conclusive Results -** The conclusive results of the thesis work linked together with the project goals to ensure goal fulfillment.

10. **Discussion -** A general discussion about the results of the thesis together with sources of error and benefits of the made study.

11. **Conclusion -** A summary of the thesis and possibilities for future investigation.

1.3 Purpose

The main purpose of this master thesis is to develop a solution for automating the curtailing control of wind turbines on Gotland during critical power transmission periods. The curtailment of the wind power plants has to be fair since the wind turbines are not owned by one entity.

1.4 Thesis Goals and Objectives

The following goals and objectives have been taken in consideration for the master thesis.

Thesis Goals:

Goal 1:
Develop a solution with a minimum set of modifications on the present system environment at GEAB, which automate the present workflow and reduce the waste energy measured in GWh.

Goal 2:
Develop a generic state-of-the-art solution taking standardization and performance as the main driver, which automate the present workflow and reduces the waste energy even more, measured in GWh.

Goal 3:
Develop a concept for fair curtailment where the following criteria have to be considered:

- Dispatch:

  Develop a function for fair dispatch that automatically distributes the total wanted power reduction to the wind turbines in a fair manner.

- Follow Up:

  To reach a suitable level of knowledge to be able to describe a follow up procedure, after curtailment have been executed, as well as requirements on a supporting information system.

- Settlement

  To reach a suitable level of knowledge to be able to describe the procedure for how the producer are going to be compensated after curtailment has been executed as well as the requirements on a supporting information system.

The Master Thesis goals from Vattenfall are interpreted and further broken down into measurable project objectives.

Thesis Objectives:

Objective 1:

- Obtain knowledge about the presently used work flow caused by an event of required curtailment of the wind power including economical settlement between GEAB and affected wind producer.
- Collect information from experts related to the master thesis scope.
- Produce an overview describing presently involved systems/components that support the workflow.
- Produce an overview describing the information flow (measured values, set points, etc.) between the components and how the information is communicated, as well as presently used protocols.
- Select suitable control design for automating the presently used workflow of curtailing the wind turbines

Objective 2:

- Obtain knowledge about optimizing the presently used workflow caused by an event of required curtailment of wind turbines.
- Decide the optimal control design and system architecture for automating the curtailment of wind turbines.

Objective 3:

- Obtain knowledge about fair curtailment and the concepts of dispatch, follow up and settlement.
- Collect information through workshops with related actors at Vattenfall and GEAB to be able to determine an optimal solution for fair curtailment.

2

Method

To be able to reach the goals of the master thesis, a methodology had to be applied to obtain sufficient information, knowledge and data of the presently used manual system and workflow. This chapter presents the methods that were used during the master thesis to be able to identify the presently used system and workflow, and to be able to automate the process and develop a concept of fair dispatch.

2.1 Use Case

To be able to describe, in textual form, the presently used workflow for curtailment of the wind power plants and their wind turbines, the approach of drafting use cases was conducted.

The methodology of the use case was developed in the Software Engineering industry in the 1990s. The general goal was to identify and describe requirements for complex software systems. The Use Case describes actors interacting with a system as well as information exchanges that are necessary to realize system functionalities. Electric Power Research Institute (EPRI) sponsored the Intelligrid project for adopting the Use Case methodology. The goal was to describe the requirements for the Smart Grid system that control the electrical power networks. This resulted in an International Electrotechnical Commission (IEC) Public Available Specification (IEC PAS 652599) that formed the basis for the IEC 62259 international standards. The second part of the IEC 62559 provides a MS Word template for describing use cases [OFFIS and KTH, 2013]. This template was used for documenting the use cases in this thesis. To be able to document Use Cases of the presently used system, interviews, workshops and continuous communication with experts from GEAB had to be conducted. To represent the use cases in a visual way, use case diagrams were drawn.

A use case diagram shows a static representation of the users interaction with the described system. It portrays the users of a system, where a user does not have to be a person, it can be a component or a function in the process. A use case diagram is often accompanied with a more dynamic diagram. In this thesis the Business Process Modeling Notation was chosen for the dynamic representation.

2.2 Business Process Modeling Notation

To be able to represent the work process of the currently used system in a dynamic fashion, Business Process Modeling Notation (BPMN) was chosen. According to Chinosi & Trombetta [Trombetta, 2012] BPMN is a generic language which does not focus on a specific domain and has enough power and expressivity to model business processes from multiple domains. BMPN is an initiative that tries to involve domain experts in the definition of business processes as a way of reducing some of the difficulties found in the requirement engineering stage. This approach is based on the use of modeling notations that combine both the domain experts language and the system experts knowledge. BPMN can be classified in two groups: (1) graphical notations and (2) textual notations. The textual notation is conducted through the Use Cases, and a graphical representation example can be seen in *Figure 2.1*. The use of graphical notations are commonly easier to understand and use by non-technical people. The main goals for BPMN, as stated by White (2004) in the introduction, are: Provide the domain experts a notation they could use and understand and reduce the variety of existing notations and modeling tools.

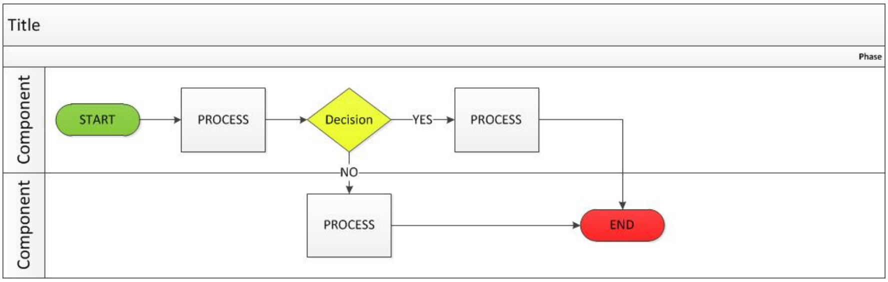

Figure 2.1 Simplified BPMN showing the functions, start and end blocks, process blocks and decision blocks

2.3 Smart Grid Architecture Model

The Smart Grid Architecture Model (SGAM) framework is intended to present the design of the smart grid use cases in an architectural, but solution and technology neutral manner. The model was developed by CEN-CENELEC-ETSI for representing Smart Grid architectures [OFFIS and KTH, 2013] and as shown in *Figure 2.2*, the SGAM comprises five layers covering different interoperability aspects:

- Business Layer: The business view on the information exchange related to smart grids. This layer is used to map regulatory and economic structures and policies, business models, business portfolios of market parties involved.

- Function Layer: Describes functions and services including their relationships from an architectural viewpoint. The functions are represented independently from actors and physical implementations in applications, systems and components. The functions are derived by extracting the use case functionality.

- Information Layer: Description of the information that is being used and exchanged between functions, services and components. Contains information objects and canonical data models that represent the common semantics for functions and services in order to allow an interoperable information exchange via communication means.

- Communication Layer: Description of the protocols and mechanisms for the interoperable exchange of information between components in the context of the underlying use case, function or service, and related information objects or data models.

- Component Layer: The emphasis of this layer is the physical distribution of all participating components in the smart grid context. This includes actors, applications, power system equipment and telecontrol devices, network infrastructure, and any kind of computers.

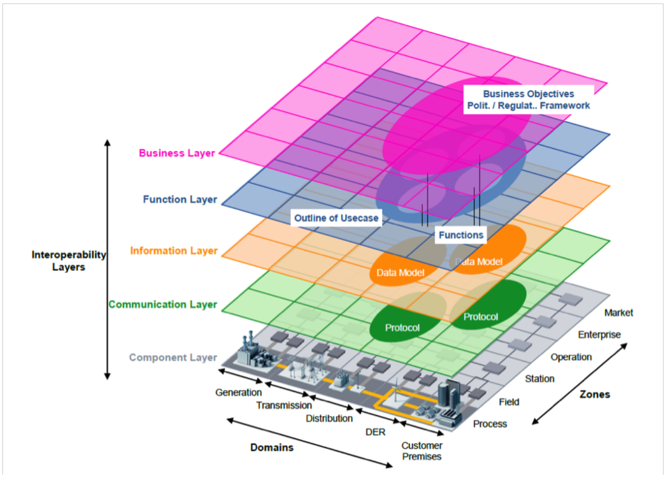

Figure 2.2 SGAM showing the five layers[Rune Gustavsson, 2015]

2.4 Test Case

After conducting a use case, BPMN chart and SGAM, a test case could be derived. A test case is a sequence of steps that need to be followed to test the different aspects of a system. Every test case consists of a test description, guidelines to conduct the test, and information on the expected results. The main purpose of a test case is to document the steps and conditions under which a particular test scenario must be executed, along with the expected results [Udemy, 2015].

The test that was conducted during this thesis was to curtail wind power production with a certain amount of power. The active power flow on the HVDC links was measured to be able to identify the impact of the curtailment. Data acquisition was conducted during the test to be able to model the system which was to be controlled. Since the test was executed by personal at GEAB, a well-documented test case was vital.

2.5 Theory

The approach of the theory part is to obtain sufficient knowledge of the Gotland electric power grid, the behavior of the High Voltage Direct Current (HVDC) links, the wind power production on Gotland, and the concept of fair dispatch.

Basic Knowledge

To be able to obtain basic knowledge, background studies had to be made. Different articles and commercial websites of electric power grids, HVDC theory, wind power production, and fair dispatch were read and analyzed.

Control Theory

The theory for different control method was conducted to be able to find the suitable control method for the automated curtailment of the wind power plants during the critical transmission periods.

Fair Dispatch

A study of the concept of fair dispatch was conducted. The goal with the research was to obtain knowledge of implemented and thought of concepts used today to be able to expand the concept and find a suitable concept for the GEAB system.

2.6 Data Acquisition

The objective with the data acquisition during the thesis is to obtain information about the manual process used today, component identification, communication identification, system identification and realization of the automation, and fair dispatch function.

As-Is

Workshops and interviews with specialist at GEAB with expertise in the field of electric power grid of Gotland, HVDC, wind power production were conducted to obtain information to be able to document an As-Is description.

Control Theory

A test case was derived to be able to acquire data from measurements of a curtailment test. This was used to be able to conduct a system identification and to design two control methods for automating the curtailment of the wind power plants during the critical transmission periods.

Fair Dispatch

Interviews with specialist at GEAB were conducted where discussions were held to be able to receive information of how the dispatch function could be realized.

2.7 Analysis

This part of the thesis was dedicated for analyzing the data that was acquired during the thesis work.

As-Is

The acquired information that was given from the interviews and workshops was handled and the information that was within the scope of the manual curtailment process was documented.

Control Theory

The data that was acquired from the curtailment test was analyzed using plots in Matlab and Excel. An model was derived using the System Identification toolbox and two control designs were analyzed. The first control design involves a PI controller and Model Predictive Controller was used as the second control design.

Fair Dispatch

Information that was given from the data acquisition was used and listed. Interviews with different employees at Vattenfall were conducted to analyze the concept of fair dispatch.

2.8 Verification

Verification of the thesis work was essential. This was done iteratively throughout the thesis work.

As-Is

To be able to verify the As-Is description, written reports were sent to GEAB where specialists verified the documentation.

Control Theory

The control theory was verified by using Matlab where different scenarios were simulated. Scenarios were simulated using the knowledge obtained from the theory part and data acquisition.

Fair Dispatch

A presentation of different approaches of fair dispatch was conducted for the specialist at GEAB to verify the realization of the derived concept of fair dispatch.

2.9 Documentation

The documentation throughout the thesis work was done iteratively and presented to Vattenfall. This thesis report will serve as a overall documentation of the thesis work.

As-Is

Use cases, BPMN charts and SGAM models were derived to be able to document the As-Is in a proper manner.

Control Design

The control design was documented in Matlab script and Simulink models where plots were derived to be able to document results of the two control designs.

Fair Dispatch

Power point presentations with tables and mathematical formulas were derived to be able to present different concepts of fair dispatch.

2.10 Matlab

Matlab was used in this thesis work to be able to design and simulate different scenarios.

Matlab is a high-level language and interactive environment used by students, engineers and scientist worldwide. One can use Matlab in projects for modeling energy consumption to build smart power grids, develop control algorithms, run simulations and visualize results. During this thesis work the control system toolbox was used. This toolbox lets the user specify a system as a transfer function, state-space, zero-pole-gain or frequency-response model. Step response diagram and Bode diagram visualize the system behavior in the time and frequency domain. Different control designs can be derived such as; PID, LQE/LQG design and other interactive and automated techniques.

Model Predictive Control Toolbox

The Model Predictive Control Toolbox was used during the thesis work [MathWorks, 2015b] to investigate if a better controller could be found for the automated curtailment.

The toolbox provides functions and Simulink blocks for designing and simulating Model Predictive Controllers (MPCs). One can specify plant models, horizons, constraints and weights. To be able to use the MPC toolbox one has to define internal plant models. This can be done by either using the Simulink Control Design to extract a linearized form of the Simulink model or one can use a linear-time-invariant (LTI) system from the Control System Toolbox[MathWorks, 2015b]. In this thesis work a curtailment test was conducted to be able to use the System Identification Toolbox to derive a plant model that was used with the Model Predictive Control Toolbox [Bemporad Manfred Morari, 2015].

3

Power Distribution

This chapter presents the general theory for the Gotland grid as well as the aspects of control designs and concept of fair dispatch when automating the curtailment of wind power production at Gotland during the critical transmission periods.

3.1 Electrical Power System at Gotland

Gotland is an island located east of the Swedish mainland in the Baltic Sea. *Figure 3.1* shows the power distribution grid on Gotland. The grid consists of 2000 km of 10 kV lines, 300 km of 70kV lines and 100 km of 30 kV lines. The Gotland power distribution grid is connected to the mainland by two HVDC cables, which were installed 1983 and 1987. The purpose of the cables is to increase the safety of the power grid on the island and to satisfy electricity need when the consumption reaches high peaks. The HVDC links are 100 km and connect the city of Västervik on the mainland and Ygne on Gotland. The maximum transmission of the HVDC cables are 170 MW where power flow from the mainland to Gotland often runs on full capacity [ABB, 2015b] [Kraftnät, 2012].

Wind power is the main deliverable of electric power on Gotland. There are gas and diesel power production on the island to cover the demand in case of unexpected circumstances [ABB, 2015c]. The maximum limit on the power distribution grid on Gotland is currently 195 MW and the installed wind power capacity is estimated to be around 170 MW. The wind power production seldom produces in full capacity due to low or to high wind speed or wind turbines that are out of order. The power production from wind in 2011 was calculated to be around 40% of the total consumption of Gotland, 340 GWh of power production. [Gotland, 2015]

The power flow from the mainland to Gotland is directly dependent on the wind power production and the consumption on the island. There are periods where service is needed on one of the two HVDC links. During these service times, only power flow from the mainland to Gotland is possible due to stability purposes. Since the possibility of exporting power from Gotland when the production exceeds the consumption is limited and curtailment of wind power is necessary. The following section describes identified scenarios and the working process used by GEAB for curtailing the wind power plants during these critical transmission periods. Components in the system, roles, system architecture and communication between different components were also identified and documented.

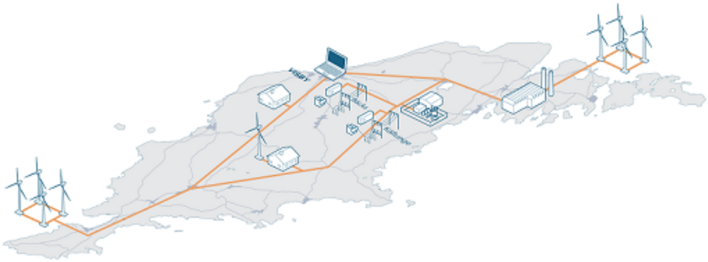

Figure 3.1 Power Distribution grid [ABB, 2015a]

3.2 Glossary

A glossary is presented in *Table 3.1*. The glossary provides an overall description of the actors and components that was used in todays manual curtailment. Chapter 4 describes how GEAB and the current system uses these actors and components.

Name	**Description**
Wind Power Producer	A person that owns a wind power plant.
Wind Power Coordinator	A person who works for the DSO.
DC-Operator	A person who interacts with a system from a operation center.
IED	Device which incorporates one or more processors with the capability to receive and send data to an process device, process data and communicate information to other devices or systems.
RTU	Intermediate device in a communication network.
SCADA	Application that provides communication with the substations for monitor and control.
HMI	Used for monitoring information for a user to interact with.
PPC	Device that controls the production of a WPP.
WTC	The controller for production of a WTG.

Table 3.1 Components and actors that were of importance in the manual curtailment process

3.3 Communication

The following subsection presents different protocols and standards for the communication between some form of drift central and wind power plant as well as the communication between different electrical grid components and a operation center.

IEC 60870-5-101

The IEC 60870-5-101 protocol was released at the beginning of the '90s and has found its place in the energy sector and is still used today. It is based on the Enhanced Performance Architecture (EPA) [Community, 2010] and was only defined on the physical link and the application layer of the OSI model. According to [IPComm, 2015a], the IEC 60870-5-101 protocol is primarily used with relatively slow transmission media on a asynchronous V.24 interface.

The protocol was extended and more precisely defined in 2001. Aspects as interoperability was ensured in the new extension, making it possible to completely understand the interface to be able to work with other devices or systems, present or future without any restricted access or implementations.

One of the major advantages of the protocol is the ability to cope with change of its link layer and for the simple structure of the application layer. Since IEC 60870-5-101 uses interoperability list, the data decoding is not a big issue. The disadvantage of the protocol is fragmentary protocol definition [IPComm, 2015a].

IEC6870-5-104

The IEC6870-5-104 was released in 2000 by the International Electrotechnical Commission (IEC) and is an international standard. The protocol enables communication between control stations and substations through the TCP/IP network. The use of the TCP protocol is for connection-oriented secure data transmission.

The advantage of the protocol is that it enables communication via a standard network. This allows simultaneous data transmission between several devices. The disadvantage of the IEC6870-5-104 protocol is that communication with redundant systems or networks and, with the use of internet, data encryption need to be dealt with. The protocol does not support short time stamps, the length of the different address elements is set to a maximum value. That is why most vendors combine the IEC6870-5-104 protocol with the IEC 60870-5-101 protocol [IPComm, 2015b].

IEC 61850

IEC 61850 is an information model and communication architecture standard developed to allow interoperability within power utility automation systems [IEC, 2013]. This standard has been extended to cover new domains, such as the one used in this thesis, IEC 61400-25. The standard uses logical nodes, data objects that can contain multiple attributes.

The standard as a communication solution has shown good performance in terms of scalability, efficiency, reliability and availability compared to the IEC 60870-5-104, that is used as a standard in today's system [N. Etherden, 2014].

IEC 61400-25

The IEC 61400-25 standard comprises all communication between components as wind turbines and actors like SCADA systems and different drift centrals. It supports different drift modes, single wind turbines or whole wind power plants. The standard can be defined as following [Johnsson, 2010]:

- Model information in a wind power station.
- Exchange of data.
- Use of specific communication protocols.
- Verification of correct implementation.

The wind power specific information that is described in the standard is based on general datatypes that are specified in the IEC 61850 standard. IEC 61400-25 does not put any requirements on the communication interface which enables implementation in optional topology. The contribution of the standard is a uniform communication platform for control and supervision of wind power plants and minimization of communication barriers due to the large amount of varying protocols, data names and semantics used by different components[Johnsson, 2010].

Figure 3.2 shows logical nodes that can be used when using the 61400-25 and 61850 standards. The logical nodes contain attributes that are mapped to them.

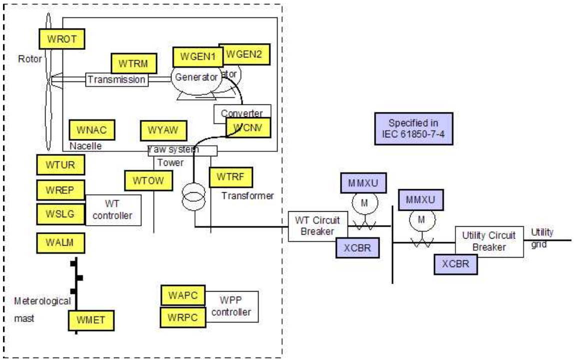

Figure 3.2 Use of instances of logical nodes. Yellow nodes are specified in IEC 61400-25 standard and blue in IEC-61850-7-4 [Comittee, 2015]

3.4 Fair Dispatch

Since the wind turbines on Gotland are not owned by one entity, there must be a fair way to curtail the wind power generation. One cannot curtail the same wind power producers wind turbines every time curtailment is needed. The main focus was to investigate the controllable wind power plants and to investigate how to realize a fair dispatch function to curtail these wind power plants. The fair dispatch for curtailment has been a issue in countries as United Kingdom. Research on different techniques that were applied on the UK grid, such as Last-In-First-Out and Pro-Rata were done and the goal for this thesis was to extend the research and investigate if there is a more fair way to realize the fair dispatch function on Gotland.

A more thorough presentation of the fair dispatch used in the United Kingdom and the thought of functionality in this thesis work will be presented in Chapter 5.

3.5 Curtailment of Wind Turbines

The main reason for curtailing the wind power production is to maintain the stability of the electric power system. This is to maintain the 50 Hz frequency where the production and consumption has to be in equilibrium. There are several other approaches for maintaining stability of a electric power system. Interviews and workshops at GEABs head office in Visby were conducted to be able to identify different scenarios when curtailment is executed on Gotland. Four scenarios were identified: (1) Planned curtailment of controllable wind turbines, (2) Unplanned curtailment of controllable wind turbines, (3) Planned curtailment of uncontrollable wind turbines and (4) Unplanned curtailment of uncontrollable wind turbines. The major goal of this thesis is to automate the curtailment of the wind turbines, the controllable scenarios were mostly investigated and documented where Use Cases were drafted, BPMN charts drawn and SGAM pictures were conducted. All of this will be presented in Chapter 4.

4

Background Study and Findings

Findings were made during this thesis work and this chapter will present how GEAB uses the components listed in the Glossary in the previous chapter. Four scenarios of curtailment used today were identified during this part of thesis work and will be presented in this chapter.

4.1 Components and Actors

Conducting interviews and workshops with specialists at GEAB, the main components, actors and their functionality were identified during the thesis work

GEAB Wind Power Producer

GEAB personal responsible for contacting the involved Wind Power Producers before and after the curtailment of the wind power generation on Gotland.

DC-Operator

GEAB personal who execute the curtailment of the controllable wind turbines. Uses the HMI and SCADA system in the Distribution Center to interact with the power distribution grid on Gotland.

Wind Power Cordinator

Owner of the wind power plant that is to be curtailed during the critical transmission periods. If the wind turbine is not controllable from the Distribution Center, the Wind Power Producer is responsible for curtailing the wind turbines themselves.

HVDC Supervisors

HVDC Supervisors are IEDs named IED-HVDC-R4 and IED-HVDC-R5 and measure the current and voltage of the HVDC-R4 link and HVDC-R5 link. With the measured values the active power flow can be calculated for each link. The HVDC-Supervisors also monitor the state of the link to be able to see if the link is operational/active. The status of the two links are sent in a binary signals stating if the link is operational/active or not. All of the measurements are sent to RTU-HVDC.

RTU-HVDC

The RTU-HVDC is a Netcon 500 utility ICT outstation used for receiving the measured and monitored values from the HVDC-Supervisors. This RTU has a lot of functionality such as controlling the direction of the power flow of the HVDC links, but in the manual process the main functionality is the connection with the HVDC Supervisors and the SCADA system.

SCADA

Monitors and control the HVDC links and Wind Turbine Controllers (WTCs). Located in Visby and used by the DC operator through a HMI for curtailment of the wind turbines and observation of the HVDC links and the power distribution grid on Gotland.

HMI

Used by the DC operator for monitoring the state of the HVDC links and the power distribution grid on Gotland. Interactive actions such as curtailment of wind turbines and switching the power flow direction of the HVDC links are possible, and power reference values for the wind turbines are set using this HMI.

RTU-WPP

The RTU for the Wind Power Plant (WPP) located near the wind turbines that are to be curtailed, works as a gateway for the sent power reference from the SCADA and sends the actual generated power from the wind power plant to the SCADA. It consists of two CPUs where protocol conversion is executed. *Figure 4.1* shows how the RTU is built up and how the sent signal from the SCADA is sent in the IEC 60870-5-104 protocol, and then converted to the IEC 60870-5-101 to be sent to the second CPU where it then is converted back to the IEC 60870-5-104 protocol. This is due to security reasons and the RTU-WPP works as a firewall converting TCP/IP communication to Serial communication.

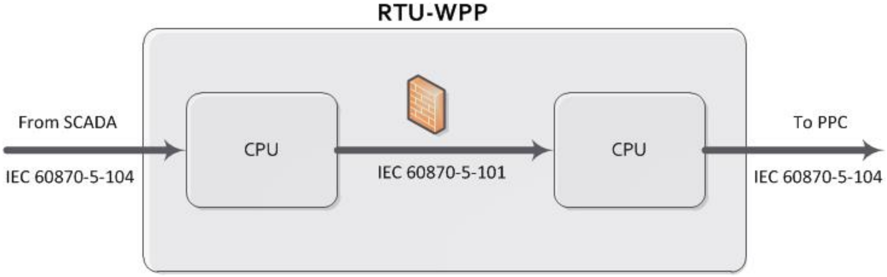

Figure 4.1 RTU-WPP is built up by two CPUs where protocol conversion from TCP/IP to Serial communication is executed

PPC

Device that controls the power generation of a Wind Power Plant (WPP). The PPC controls several Wind Turbine Controllers (WTCs) and is an external system.

WTC

Executes the curtailment of the Wind Turbine Generator (WTG), which has a direct effect on the active power flow of the HVDC cables.

4.2 GEABS current Curtailment Scenarios

After interviews and workshops with specialists at GEAB, different scenarios were identified. It was noted that there were wind power plants that were controllable from the drift central through a SCADA system, and that there were wind power plants that were not controllable. During the thesis work the controllable wind power plant scenarios were mainly investigated and used for the automation and fair dispatch concept.

Figure 4.2 shows the system setup of the currently used system at Gotland for curtailing controllable wind power plants from a Distribution Center (DC) in Visby using a Human Machine Interface (HMI) together with a SCADA system.

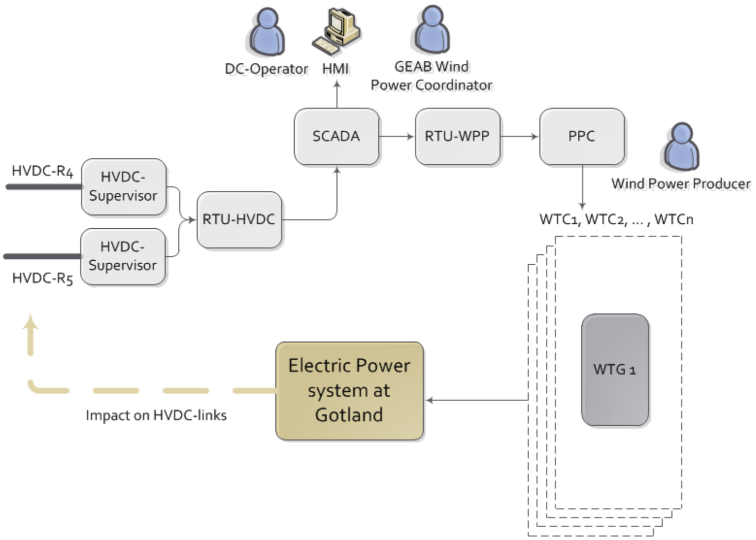

Figure 4.2 System topology of Controllable wind turbines at Gotland

Scenario 1 - Planned Curtailment of Controllable Wind Turbines

The planned curtailment of controllable wind turbines scenario is divided into three phases: (1) Information phase where a GEAB Wind Power Coordinator contacts the Wind Power Producers to inform them that curtailment might be necessary due to service on one of the HVDC links and exporting power to the mainland will not be possible. (2) Maintenance phase, the technical action of the curtailment. (3) Follow up phase where the DC operator contacts the GEAB Wind Power coordinator to inform that service on the HVDC link has ended so that the Wind Power Producer know that wind power generation has initiated normal production.

The use case of the scenario can be described as following:

Current and voltages are measured and calculated to active power flows on the HVDC links by two IEDs (HVDC Supervisors). IED-HVDC-R4 measures and calculates the active power flow of the R4 HVDC link and IED-HVDC-R5 measures and calculates the active power flow of the R5 HVDC link. The HVDC Supervisors are connected to a RTU located in Ygne (RTU-HVDC). The SCADA system receives the current measurements of the links through the RTU-HVDC and a DC operator in Visby can see the status of the HVDC links and, the production and consumption of the wind power plants. This use case describes the functionality of curtailing controllable wind turbines from the central SCADA system when an planned service on one of the two HVDC links is scheduled and curtailment of

Wind Turbine Generators (WTGs) are necessary. Necessary phases and steps to realize this Scenario are:

Information Phase

1. Approximately one month before the service on one of the HVDC links is to be executed, a GEAB Wind Power Coordinator contacts the wind power producers with an email. The email states that export of electrical power from Gotland will not be possible and curtailment of wind production might be necessary during this period.

Maintenance Phase

2. Intelligent Electronic Devices (IEDs) measure current and voltage of the HVDC link and calculate the active power flow. The active power flow values are then sent to RTU-HVDC.
3. The measurements are sent from the RTU-HVDC to the central SCADA system in Visby where it can be monitored through a Human Machine Interface (HMI). Two outcomes are possible in this scenario:
    a) The measured value is above 40 MW. No action will be taken.
    b) The measured value is below 40 MW and an alarm is activated in the DC. The alarm is generated by the SCADA system. In this case the DC operator needs to take action.
4. The HMI shows the current active power of the HVDC link together with the actual production generated by wind power, possible production of wind power, consumption on Gotland and availability of wind turbines. When the DC operator needs to take action, the following steps are taken:
    a) Identification of which Wind Power Plants are possible to curtail. There might be cases where some wind turbines are out of service, or there is a case where a Wind Power Plant is not generating any power at all. In this case cutting of the power production of uncontrollable Wind Power Plants might be necessary.
    b) The used HMI has a window for each controllable Wind Power Plant. If curtailment is possible, the DC operator sets a power reference value of the Wind Power Plant in a window and presses submit.
5. The HMI shows the current active power of the HVDC link together with the actual production generated by wind power, possible production of wind power, consumption on Gotland and availability of wind turbines. When the DC operator need to take action, following steps are taken:

a) The power reference value is sent from the central SCADA system in Visby to a RTU-WPP (RTU- Wind Power Plant) which is placed near the Wind Power Plant.

b) RTU-WPP is built up with two CPUs. The first CPU (CPU-r) receives the reference value through the 101 protocol and sends it to the second CPU (CPU-d) where it is converted to the 104 protocol and then converts it back to the 101 protocol to be sent to the PPC. Hence this works as a firewall for secure communication to and from the Power Plant Controller (PPC).

c) RTU-WPP sends the power reference value to the PPC where the PPC has a connection to several Wind Turbine Controllers (WTC).

d) The curtailment is executed by the WTC. If the curtailment is not enough and the wanted active power flow of the HVDC link has not been meet the maintenance phase is reiterated.

Follow Up Phase

6. When the service of the HVDC link has come to an end, the DC operator contacts a GEAB wind power coordinator who then sends an email to the wind power producers stating that they can go back to normal generation of wind power.

Figure 4.3 shows the dynamic representation of the work process (BPMN) for this scenario

Scenario 2 - Unplanned Curtailment of Controllable Wind Turbines

This scenario differs from Scenario 1 in the way that there is no information phase. The components and roles are all the same, but in this case a binary signal sent from the HVDC Supervisors to indicate if the HVDC cable is operational is monitored. If the HVDC link is not operational the binary signal will change value and an alarm will be generated by the SCADA system and the DC operator will be able to identify if curtailment will be necessary.

Scenario 3 - Planned Curtailment of Uncontrollable Wind Turbines

A scheduled service on one of the HVDC cables is planned and the GEAB Wind Power Coordinator sends out an email, approximately one month before the planned service, to the Wind Power Producers. The email states that the Wind Power Producers need to curtail their wind turbines by a given percentile value of the contracted power generation. The Wind Power Producer needs to reply with an acceptance email and a technical description on how they will curtail their wind turbines. The technical description can state that they will shut down a number of wind turbines and let the other go on full effect, curtailing all wind turbines by the given percentile value or shutting down all the wind turbines during a certain time of the day. If the active power flow of the existing link reaches the safety margin of 20 MW and there are no possibilities of curtailing the controllable wind power plants, cutting of the wind power production of the uncontrollable wind power plants might be necessary.

When the service of the HVDC cable has come to an end, the GEAB Wind Power Coordinator sends out an email to the Wind Power Producers informing them that they can resume in normal wind power generation.

Scenario 4 - Unplanned Curtailment of Uncontrollable Wind Turbines

When an unplanned disruption on one of the HVDC cables occurs and the power flow transmission from the mainland to Gotland reaches the threshold value of 20 MW and there is no possibility to curtail the controllable wind turbines, cutting of the uncontrollable wind power plants will be necessary. The Wind Power Producers are contacted when the disruption of the HVDC cable has ended. GEAB Wind Power Coordinator sends out an email stating why the wind power had to be cut off.

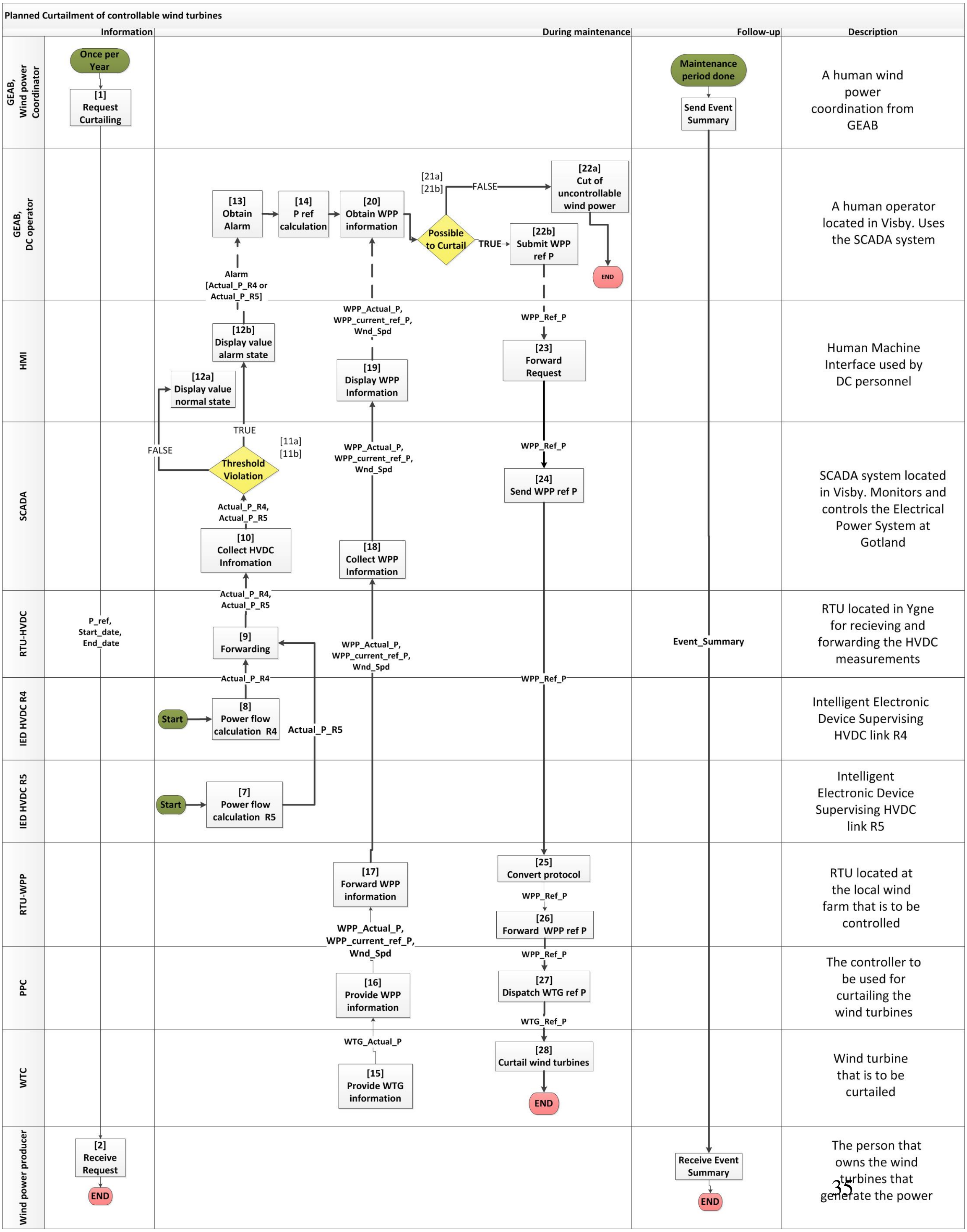

Figure 4.3 BPMN of Planned Curtailment of Controllable wind turbines

5

System Identification

This chapter describes the system identification that was conducted using the data acquired from the curtailment test. Description of the curtailment test is presented together with the model structure that was chosen and derived is presented.

5.1 Curtailment Test

The main principle of the system identification was to curtail a wind power plant manually from the DC, using the SCADA, by a certain amount of power and see how the HVDC link would respond to the decrease of power generated by the wind power plant. The HVDC power flow behavior is directly tied to the frequency of the power grid of Gotland. The frequency on Gotland is 50 Hz and this is when the power generation and the load are in equilibrium. If the load exceeds the production the frequency decreases. The HVDC link responds to the frequency decrease and increases its power flow to the power grid to maintain the 50 Hz frequency. If the frequency of the power grid would increase the HVDC power flow would decrease its power flow. The power flow of the HVDC can be calculated as following:

$$P_{HVDC}(t) = P_{load}(t) - P_{prod}(t) \tag{5.1}$$

In this thesis the control loop would be implemented in the RTU-HVDC. This leads to limitations in the inputs for the control. The only input that was possible to obtain was the active power flow of the HVDC. The production were the parameters that were able to control and the consumption could not be measured or controlled.

Since the curtailment test had to be done by a DC Operator at Gotland, a test case had to be written and sent to GEAB. This was to be sure that a correct data acquisition was conducted. It was important to make sure that the measured values had the same sampling period. During this test the sampling period in the SCADA system was set to one second. This was the fastest sampling that was possible in the SCADA system.

Table 4.1 shows the parameters that were acquired during the curtailment test.

Nr	Signal name	Unit	Description	System/Application
1	P_R4	MW	Active P measured at HVDC R4	SCADA
2	P_R5	MW	Active P measured at HVDC R5	SCADA
3	Actual_P_ref_P1	MW	Latest P_ref value of curtailed park	SCADA
4	Actual_P_ref_P2	MW	Latest P_ref value of neighbor park	SCADA
5	P_prod_PPC_P1	MW	Produced P from curtailed park	SCADA
6	P_prod_PPC_P2	MW	Produced P from neighbor park	SCADA
7	Wind_speed_P1	m/s	Wind speed at curtailed park	SCADA
8	Wind_speed_P2	m/s	Wind speed at neighbor park	SCADA
9	Freq_system	Hz	Frequency of the grid	Elspec

Table 5.1 Showing the signals needed from the curtailment test, the unit of the signals, description and from which system/application the signal was acquired. Elspec is a device for measuring the active power flow and frequency of the HVDC links in high resolution

During the curtailment test, the HVDC R5 link was under service. This meant that the signal P_R5 was at 0 MW, and it is during these conditions that the critical transmission periods occur. For modeling purposes the needed signals from the test was: P_R4, Actual_P_ ref_P1 and P_prod_PPC_P1. The input signal is the inverse of the power reference value for the curtailed park, *Actual_P_ref* and the output signal is the active power of the HVDC link, *P_R4*. This is due to the desired outcome of the active power of the HVDC. Curtailing the wind power production by a certain amount of power will increase the active power flow of the HVDC link by the same amount. That is if the consumption in the island and the other power production entities are held consistent.

The measured values were sent in an Excel format and extracted to Comma Separated Value (CSV) files for use in MATLAB. The System Identification Toolbox was then used and an autoregressive exogenous model (ARX) was estimated using the test data.

5.2 Modeling

Together with the System Identification Toolbox and *A Manual For System Identification* [Andersson and Bengtsson, 2012] an ARX model was chosen to be derived. Since no knowledge of the considered system was used, *black-box identification* was conducted.

The steps taken during the modeling can be seen in the sections below.

Experiment

The curtailment test that was conducted could be seen as a experiment procedure . A step response experiment was performed and system characteristics such as stationary gain, dominant time constants, and time delay were obtained. An indication of the disturbance acting on the system could also be obtained.

Data Examination

The input, measured active power flow from the HVDC, and the output, the inverse of the curtailment signal to the wind power plant was used as column vectors (y as output, u as input) in Matlab. The collected data was then put in a *iddata* object containing a time-domain output signal and input signal with a specific sample time of the experimental data, *data = iddata(y,u,Ts)* [MathWorks, 2015a], where Ts was one second. The data was then plotted to identify outliers, aliasing effects or trends and non-stationariy.

Filtering

According to [Andersson and Bengtsson, 2012] it is often a good idea to filter the input signals with a lowpass filter. Applying a filter, the identification concentrates to the desired frequency range of interest and high frequency measurement noise is reduced. During this system identification a lowpass filter with a Cut-off frequency, in fractions of the Nyquist frequency, of 0.35 HZ. The Matlab command used was: *data = idfilt(data,N,Wn)*, where *data* is the input and output measurements, N is the order of the filter, in this case a sconed order low pass filter was chosen (N=2), and Wn is the cut-off frequency ($Wn = 0.35$).

Model Structure and Model Estimation

The choice of model structure for the behavior of the HVDC link was a ARX model. An ARX model is an input-output (inverted production-consumption) with a exogenous input signal, and a noise sequence *e(t)* which can be seen as white noise. The ARX model structure can be seen in Eq. 5.2.

$$A(q)y(t) = B(q)u(t-n_k) + e(t) \tag{5.2}$$

$$A(q) = 1 + a_1 q^{-1} + ... + a_{n_a} q^{-n_a} \tag{5.3}$$

$$B(q) = b_1 + b_2 q^{-1} + ... + b_{n_b} q^{-n_b+1} \tag{5.4}$$

where q is the delay operator, n_k is the dead time in the system, n_a is the number of poles and n_b is the number of zeros of the system. After adopting a ARX model an appropriate model order had to be chosen and and estimation of the parameters of the polynomials had to be conducted. The *model = arx(data, [n_a n_b n_k])* command in Matlab estimates the parameters using the least-squares method. The least-squares estimation method aims to minimize the sum of the squared errors between the model output and the measured observations [Johansson, 2012].

$$V(\overline{\theta}) = \frac{1}{2}\varepsilon^T\varepsilon = \frac{1}{2}\sum_{k=1}^{N}\varepsilon_k^2 = \frac{1}{2}(Y_N - \phi_N\overline{\theta})^T(Y_N - \phi_N\overline{\theta}) \tag{5.5}$$

with the minimum

$$min_{\overline{\theta}}V(\overline{\theta}) = V(\hat{\theta}) \tag{5.6}$$

where the optimal estimate, $\hat{\theta}$, is obtained as

$$\hat{\theta} = (\phi_N^T\phi_N)^{-1}\phi_N^T Y_N \tag{5.7}$$

where Y_N is the observation vector obtained from the test.

$$Y_N = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{pmatrix} \tag{5.8}$$

The regressor matrix ϕ_N and error vector e are

$$\phi_N = \begin{pmatrix} \phi_1^T \\ \phi_2^T \\ \vdots \\ \phi_N^T \end{pmatrix}, \qquad e = \begin{pmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{pmatrix} \tag{5.9}$$

and the linear regression model:

$$\mathscr{M}: \qquad Y_N = \phi_N\theta + e \tag{5.10}$$

The mismatch vector ε, which is also called the *prediction errors*, between the measured observations and the linear regression model (5.10) for the parameter estimate $\overline{\theta}$ is

$$\varepsilon(\overline{\theta}) = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_N \end{pmatrix} = Y_N - \phi_N\overline{\theta} \tag{5.11}$$

In this thesis the following parameters were chosen to estimate the ARX model using the Least-Squres estimation. $n_a = 2$, $n_b = 1$ and $n_k = 5$. The choice of the dead time of the system is an estimation from the curtailment test. It was estimated that the HVDC link would react to the sent curtailment signal to the wind turbines in approximately 5 seconds.

5.3 Result

After conducting the system identification of the behavior of the HVDC link when curtailing a wind power plant, the overall dynamic of the HVDC link, without taking the inertia in consideration, at time step $t+1$ could be derived:

$$P_{HVDC}(t+1) = P_{HVDC}(t) + P_{load}(t+1) - P_{load}(t) - P_{prod}(t+1) + P_{prod}(t) \tag{5.12}$$

The collected data from the curtailment test can be seen in *Figure 5.1*

Since the consumption parameter could not be controlled nor measured at the RTU-HVDC, the following dependency of the HVDC and the production at time step $t+1$ could be derived:

$$P_{HVDC}(t+1) = P_{HVDC}(t) - P_{prod}(t+1) + P_{prod}(t) \tag{5.13}$$

Using the system identification toolbox to estimate an ARX-model, the following structure could be obtained:

$$A(q) = 1 + 1.689q^{-1} + 0.7077q^{-2} \tag{5.14}$$

$$B(q) = 0.01853q^{-5} \tag{5.15}$$

where the prediction focus was 96.3 %, FPE : 0.02645 and MSE: 0.02871.

Using the *getcov* command in matlab the covariance matrix for $\widehat{\theta}$ was computed and gave the following result:

$$\hat{\sigma_e^2}(\phi^T\phi)^{-1} = \begin{pmatrix} 0.8842 & -0.8547 & 0.0328 \\ -0.8547 & 0.8358 & -0.0230 \\ 0.0328 & -0.0230 & 0.0116 \end{pmatrix} \cdot 10^{-3} \tag{5.16}$$

where the unbiased estimate of σ_e^2 given p number of parameters and N number of data points is

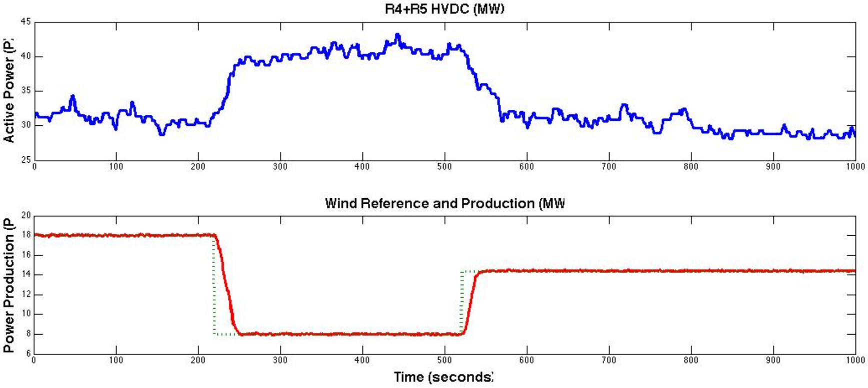

Figure 5.1 Blue line: Active power flow of the HVDC (R4 and R5) during the curtailment test. Green dotted line: Power reference signal to the wind power plant. Red line: The actual power production of the wind power plant that is being curtailed

$$\hat{\sigma_e^2} = \frac{2}{N-p} V(\widehat{\theta}) \tag{5.17}$$

Since the model was used in Matlab and Simulink for simulation and control design purposes, the model was converted to state-space using the *ssdata* command in matlab. The following discrete state-space notation was derived and used in Simulink for simulations.

$$x(k+1) = \begin{pmatrix} 1.689 & -0.7077 \\ 1 & 0 \end{pmatrix} x(k) + \begin{pmatrix} 0.125 \\ 0 \end{pmatrix} u(k) \tag{5.18}$$

$$y(k) = \begin{pmatrix} 0.1483 & 0 \end{pmatrix} x(k) \tag{5.19}$$

6

Control Design

Using the model derived in the previous chapter, it was possible to conduct control design to be able to automate the curtailment of wind power plants during the critical transmission periods.

6.1 Open-Loop System

The control problem in this thesis could be seen as an open-loop problem. The reason that it can be seen as an open-loop system is that the measured value is the active power flow of the HVDC, and the controlled value was the production of the wind power plants. The measurement of the production and consumption was not used in the control loop design, which is presented in this chapter.

A set-point of the measure active power flow of the HVDC was set and used to determine the magnitude of the curtailed power that is to be dispatched to the wind power plant.

Figure 6.1 shows a simplified figure of the open loop control problem.

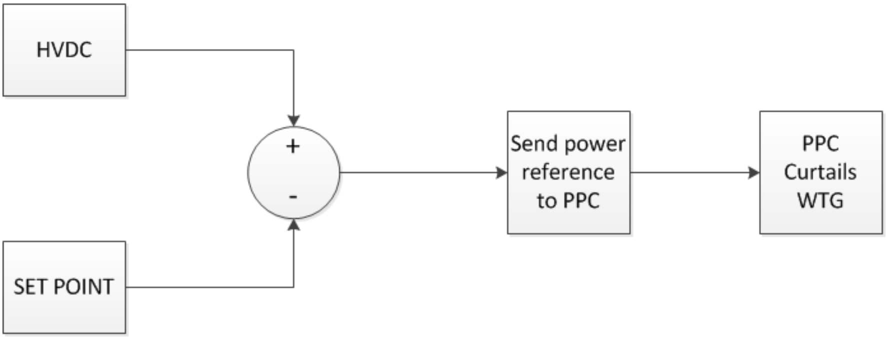

Figure 6.1 Simplified figure of the open loop problem of the curtailment of wind power plants

6.2 Deadband

A deadband can be seen as a filter where no action occurs between a range of given values [AGG, 2008]. In this thesis a deadband had to be adopted on the measurements of the HVDC link. The main reason for using a deadband filter was to avoid sending unnecessary curtailment signals to wind power plants when the HVDC link was in steady state.

To determine the width of the deadband filter, data investigation from the acquired data from the test had to be done. Investigation of how the active power flow of the HVDC varies during normal drift mode was conducted. One limitation with this approach was that more data might be necessary to be certain on how wide the deadband filter should be. *Figure 6.2* shows the measured active power of the HVDC during normal drift mode. During this period the mean value of the HVDC link was 38.6 MW. giving a deadband width of $\pm 2.7 MW$ from the mean value of the active power flow of the HVDC. The upper limit was then set to 41.3 MW and the lower limit was set to 35.9 MW. The deadband operates 2.7 MW over and under the mean value. *Figure 6.3* shows the normal drift mode after the curtailment test was conducted. Here it can be seen that the HVDC active power flow converges to a mean value of 29.3 MW. Applying the same deadband width as in *Figure 6.2*, it can be seen that the HVDC active power flow does not breech the dead band. The upper limit was set to 31.9 MW and the lower limit was set to 26.5 MW.

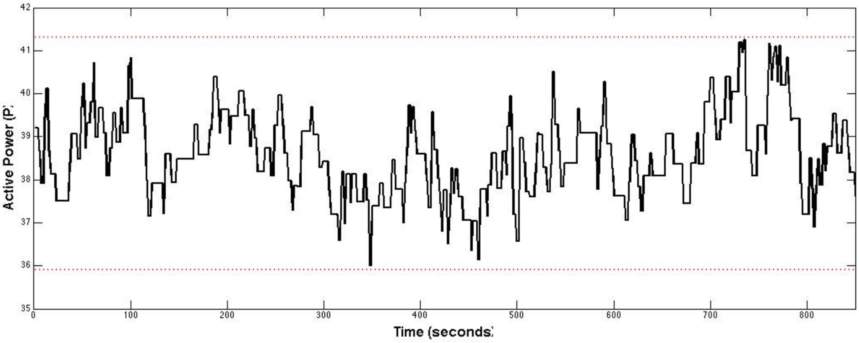

Figure 6.2 Active power flow (P) during normal drift (black line) with a deadband filter (red line)

Active power flow differentiation was also investigated. A data set where the active power flow was fluctuating the most was used and *Figure 6.4* shows the active power flow during this period and *Figure 6.5* shows the differentiation of the data set.

It can bee seen in *Figure 4.6* that the biggest variation during one second was ap-

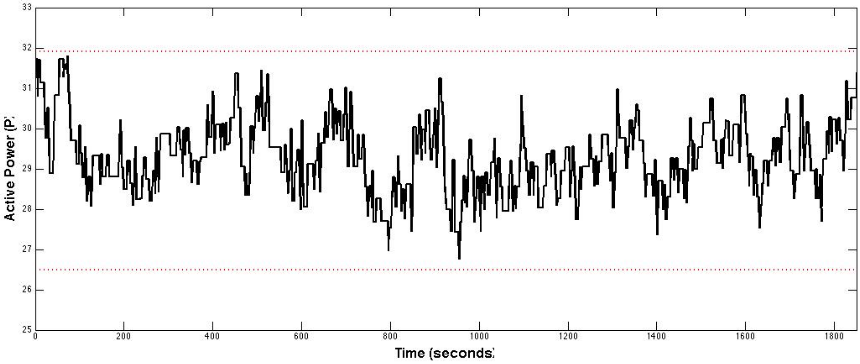

Figure 6.3 Active power flow (P) during normal drift, directly after the curtailment test (black line) with a deadband filter (red line)

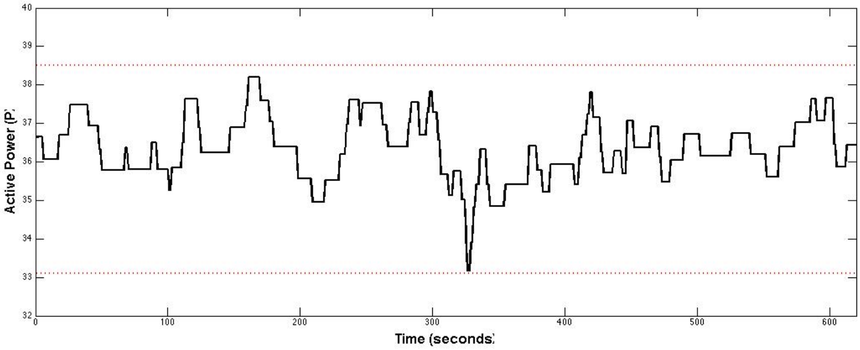

Figure 6.4 Active power flow (P) during normal drift (black line) with a deadband filter (red line)

proximately 2.7 MW. One should note that this was a extreme case and was considered as a worst case scenario during the thesis work. Using the acquired data where the HVDC link was in steady-state (3350 data points, one second sampling), the 2.7 MW variation of the HVDC link occurs two times, $2/3350 = 5 \cdot 10^{-4} = 0.00059\%$ during the measured time.

6.3 Control Design - Concept 1

The first concept to automate the curtailment process during the critical transmission periods was to adopt a PI Controller using the deadband described in previous

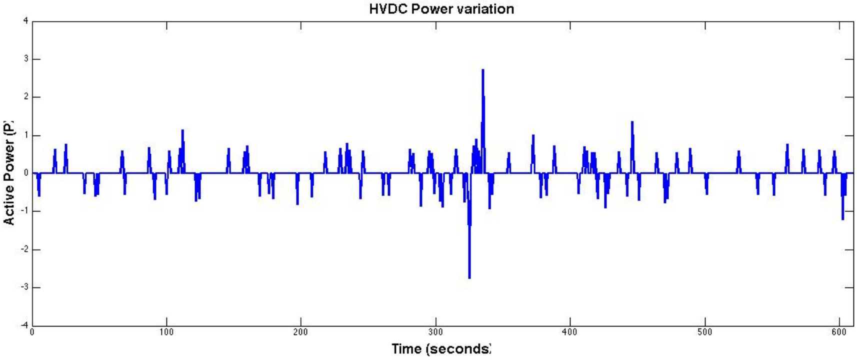

Figure 6.5 Differentiated active power flow measurements of HVDC link

section. The basic principle was to measure the actual active power of the HVDC link and compare it to the HVDC set point value to be able to calculate the error e. The goal was to keep the error close to zero with a deadband width of $\pm 2.7MW$ The Proportional-Integral (PI) algorithm computes and transmits a output, in this case the output was the power reference signal to the wind power plants, every sampling instance. The output of the PI is influenced of the error e and the tuning parameters. The controller has two tuning parameters, the Proportional gain (P) and the Integral (I) parameters. Integral part enables elimination of offset, which is a weakness of the P controller. The PI controller provides balance of complexity and capability that makes it the most used controller algorithm in process control applications [*Integral Action and PI control*]. A discrete PI controller was applied in this thesis work and the compensator formula using the forward Euler approximation has the following characteristics, with T_s as the sampling period of the controller:

$$P + I \cdot T_s \cdot \frac{1}{z-1} \tag{6.1}$$

The following parameters were chosen when using the PI controller in Simulink for calculation of the sent power reference signal to the wind power plants while measuring the HVDC link.

$$P = 1 \tag{6.2}$$

$$I = 0.042 \tag{6.3}$$

$$T_s = 5 \tag{6.4}$$

The choice of $T_s = 5$ for the PI controller was determined by conversation with specialist at GEAB and the curtailment test that was conducted. It was approximated that the HVDC link would respond to a sent power reference signal to the wind power plants in five seconds. The general approach was to send a new power reference signal every fifth second, if needed. The P and I parameters were tuned during simulations in Simulink to get a desired performance, using the estimated model of the HVDC when increasing or decreasing the power production.

P Controller

The major problem with this control problem was that it was not desired to send "unnecessary" power reference signals to the wind power plants. This would effect the wind turbines and a risk for fluctuation of the active power flow of the HVDC would occur.

Two scenarios had to be dealt with, one was when a rapid disturbance (decrease or increase of the active power flow) occurred and a power reference signal had to be sent to the wind power plants. The other scenario was when the active power flow slowly drifted away from the set point of the HVDC link. To be able to deal with these two scenarios, two control modes were designed. The PI controller would handle the rapid disturbances at a sampling period of 5 seconds, while a slower external P controller, with a sampling period of 30 seconds, would handle the slow drifting disturbances by comparing the actually active power flow measurements and a internal calculation of the HVDC active power flow response. *Figure 6.6* shows the control design setup during the simulations.

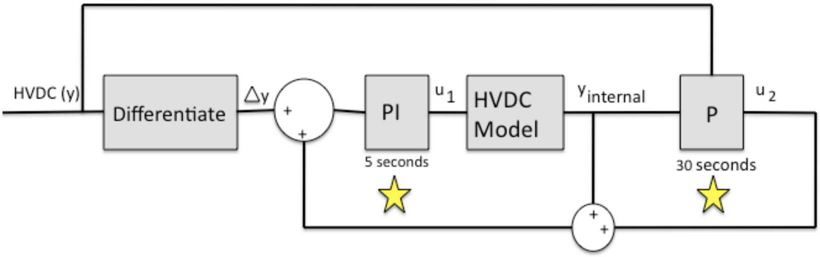

Figure 6.6 Showing the control design setup. Yellow star indicates where the sent power reference to the wind power plant might be sent from, depending on the measurements of the HVDC (y)

The *Differentiate* block in *Figure 6.6* extracts the disturbance from the measurements from y. During simulations it was noticed that a difference of 0.5 MW per second was the maximum difference during no disturbance. That was why Δy was chosen to be saturated at ±0.5 This was to be able to use the same disturbance in the internal control loop were a feedback was used. if the disturbance was bigger then 2.7 MW, the power reference signal (u_1) is dispatched to the wind power plants, if not, then it is sent to the HVDC model to be able to calculate $y_{internal}$. $y_{internal}$ was used for the 30 second P control where the actual HVDC active power measurements, y was compared with $y_{internal}$. If the difference e_2 was greater than 2.7, the difference between y and the Set-Point (s) is dispatched to the wind power plants.

6.4 Control Design - Concept 2

The second concept to automate the curtailment process during the critical transmission periods was to adopt Model Predictive Control.

Model Predictive Control (MPC) is a predictive and model based control strategy. The current control action is obtained by solving on-line an open-loop finite-horizon optimal control problem where the initial states are the current measurements [Johansson, 2013]. The optimal control problem is recalculated over a prediction horizon H_p at each new measurement. The MPC solves the control problem by minimizing an optimization problem using the model and the prediction horizon H_p. An control horizon H_c provides a $H_c - step - ahead$ control sequence of future control actions, that is the amount of samples where the new control signal (power reference signal) is allowed to be sent. The control horizon, H_c, and the prediction horizon, H_p are user parameters and can be changed during control design. The parameters handle the trade-off of stability and control performance.

State-space formulation is most often used, where the MPC can use all past and current measurements together with the model. Given a state-space formulation

$$x(k+1) = Ax(k) + Bu(k) \tag{6.5}$$

$$y(k) = Cx(k) + Du(k) \tag{6.6}$$

Just as the PI controller in previous section, the goal was to keep the measured value y equal to the set-point value s, or as it is also named the reference value r. A optimization cost function can be chosen

$$J(u) = \sum_{k=1}^{H_p} (y(k+1) - s)^T Q_y (y(k+1) - s) + \sum_{k=1}^{H_c} (\Delta u(k+1))^T Q_u (\Delta u(k+1)) \tag{6.7}$$

where Q_y and Q_u are weighting matrices for the control output $u(k)$, the error $y(k) - s$, and the output [Keskikangas, 2014]

$$y(k+1) = C(Ax(k) + Bu(k)) + Du(k+1), \quad if \quad 0 \leq k < H_c \tag{6.8}$$

or

$$y(k+1) = C(Ax(k) + Bu(H_c)) + Du(H_c), \quad if \quad H_c \leq k \leq H_p \tag{6.9}$$

The goal with applying a MPC control for the automated curtailment of the wind power plants was to investigate if it would be a more better,generic-state-of art, solution than the PI - Feedforward design described in previous sections. A better solution would reduce the waste of energy produced by the wind power plants or/and a faster convergence to the given set-point of the active power flow of the HVDC link. One should keep in mind that the same restrictions apply in this control design. That is that sending power reference signals to often was not desired, since it might effect the wind turbines in an negative fashion.

The same control design was adopted as in the previous section, a deadband filter and a slower 30 second P controller that deals with the slow drifting of the active power flow was still used. The MPC replaced the PI controller which dealt with instant decreases or increases of the active power flow. The goal was to be able to get a faster control of the internal HVDC model so that $y_{internal}$ would converge faster and that the drifting characteristics would be noticed faster and dealt with. *Figure 6.7* shows the control design setup, using the MPC controller.

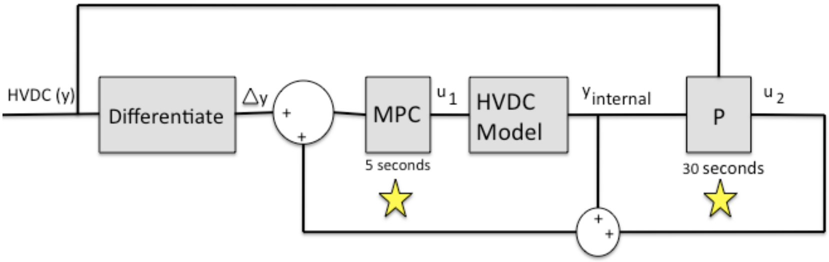

Figure 6.7 Showing the MPC control design setup. Yellow star indicates where the sent power reference to the wind power plant might be sent from, depending on the measurements of the HVDC (y)

Control Algorithm

Figure 6.8 shows the flowchart of the control algorithm that was thought of to be used for dispatching the decrease or increase in power for the wind power production. One should note that the flowchart uses a PI controller. In the case of using the MPC controller, the PI controller is exchanged with the MPC.

The concept of the control algorithm is that set-point s is subtracted with the internal model output, $y_{internal}$, where $y_{internal} = y_{internal} + \Delta y$, and Δy is derived from the *Differentiate* block. This value is then sent to the PI controller where a control signal is calculated. If this control signal is bigger than 2.7, it is dispatched to the SCADA system. The same control signal is sent to the HVDC model to be able to recalculate $y_{internal}$.

$y_{internal}$ is then subtracted with the real measured value of the HVDC y. if this value (e_2) is larger than 2.7, u_2 is dispatched to the SCADA system ($y - s = u_2$), and the algorithm is reiterated.

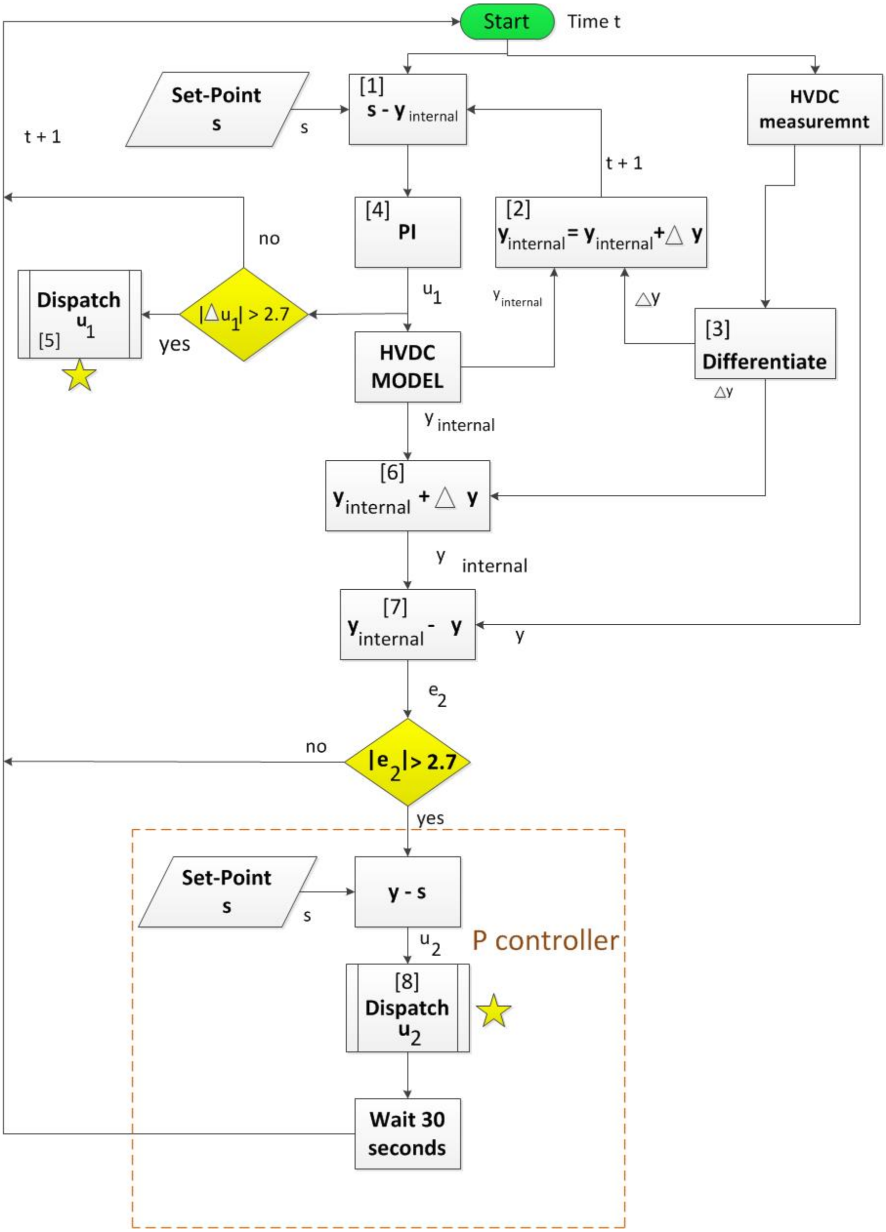

Figure 6.8 Flow chart of the control algorithm using two modes. One PI mode dealing with rapid changes, and one P mode dealing with slow drifting of the active power flow of the HVDC

6.5 Simulation Setup and Test Scenarios

Simulation were done with different scenarios. To show how the control design works, one scenario with one instant rapid decrease of 5 MW of the active power flow on the HVDC, and a slow increase of the active power flow was simulated to be able to show how the control design responds to the two different disturbances. *Figure 6.9* shows the sent curtailment signal, the dispatched to the wind power plants (simulated) and to the internal HVDC model. *Figure 6.10* shows the simulated response of the internal result, $y_{i}nternal$ and the actual response of the HVDC y. One should keep in mind that the real HVDC link was not used during the simulation.

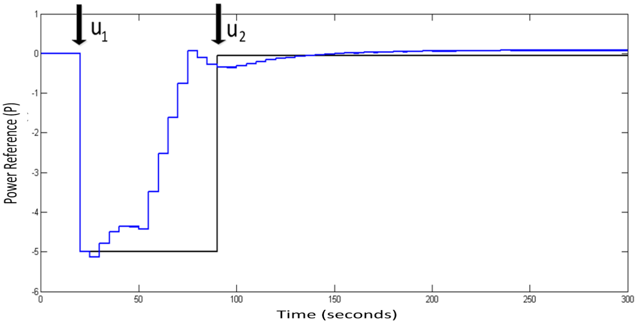

Figure 6.9 Showing the sent dispatch signal (black), where u_1 is sent from the 5 second PI controller, and u_2 is sent from the 30 second P controller. The blue line is the sent signal to the internal HVDC model u_2.

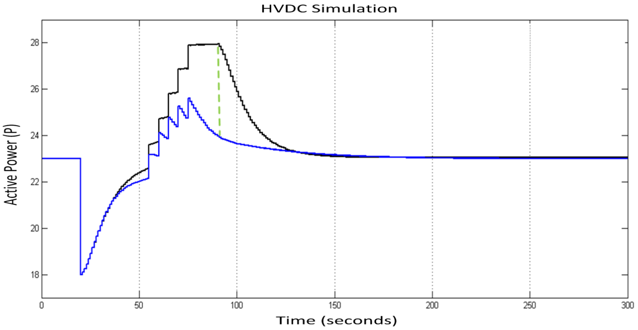

Figure 6.10 Showing the simulated response of the HVDC link y (black). The green line is where the 30 second P controller react du to a difference between $y_{internal}$ and y is greater than 2.7 and u_2 is dispatched.

Different scenarios were derived and the following figures will show two scenarios.

SCENARIO 1

This scenario shows a drop of the active power at time 20 and 40, then there is a slow drifting increase of the active power at time 60.

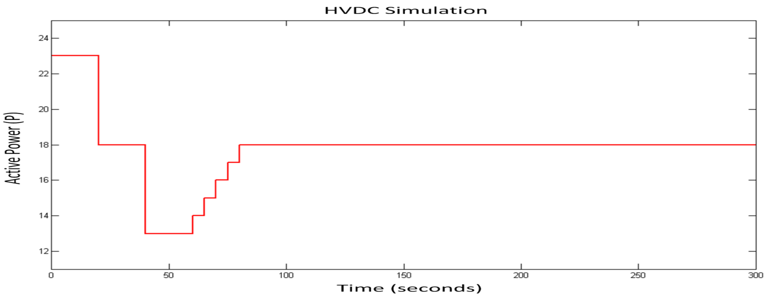

Figure 6.11 The simulated active power flow of the HVDC without any control

SCENARIO 2

This scenario shows a drop of the active power at time 20 and 40, then there is a slow drifting increase of the active power at time 60. An increase of the active power at time 200 and 220, then there is a slow increase of the HVDC link at 230.

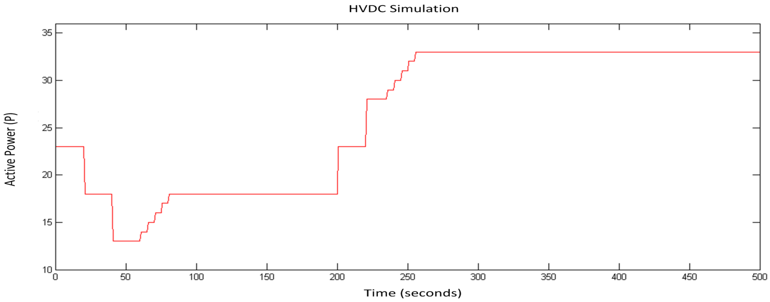

Figure 6.12 The simulated active power flow of the HVDC without any control

6.6 Result

This section is dedicated to present the result of the scenarios simulated in simulink.

SCENARIO 1

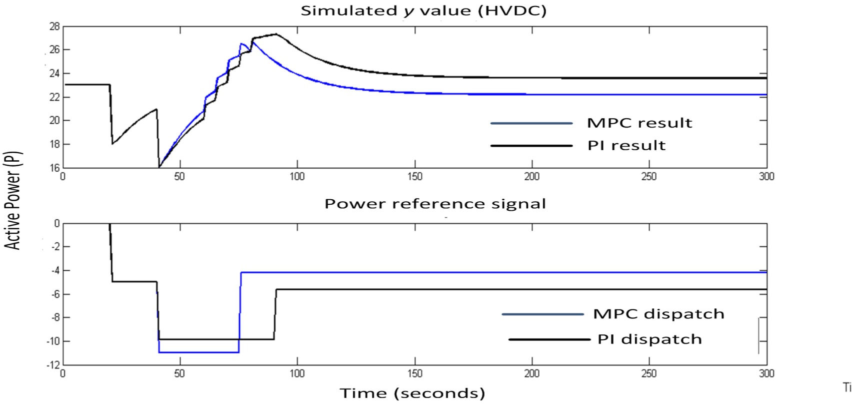

Figure 6.13 Upper plot: Simulated tesult of the HVDC active power flow with dispatched power reference signals to the wind power plants. Lower plot: Dispatched power reference signal.

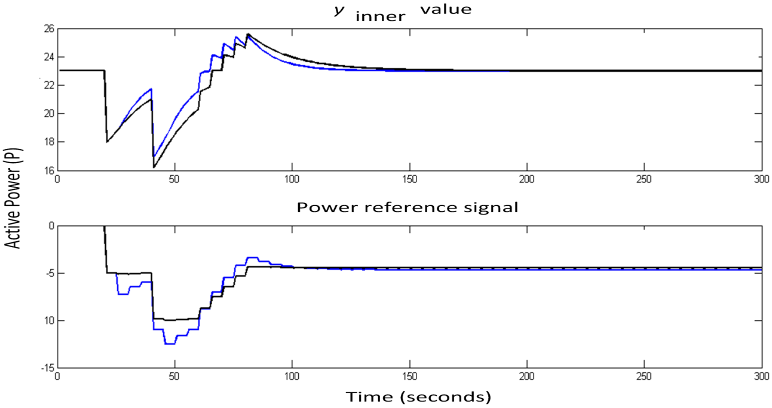

Figure 6.14 Upper plot: Output of the HVDC-Model Lower plot: control signal to the HVDC-Model

SCENARIO 2

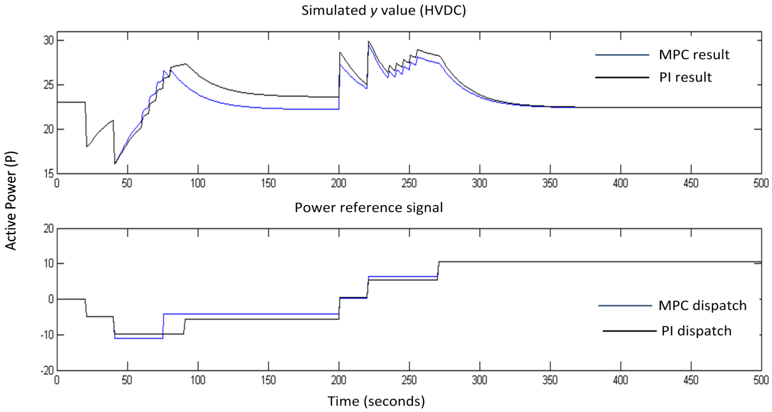

Figure 6.15 Upper plot: Simulated tesult of the HVDC active power flow with dispatched power reference signals to the wind power plants. Lower plot: Dispatched power reference signal.

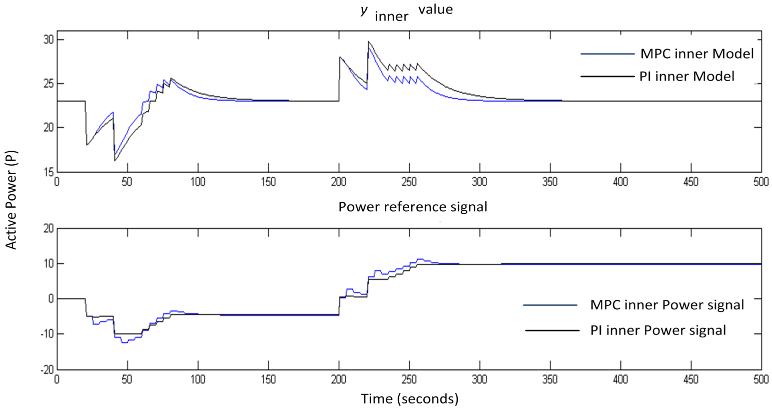

Figure 6.16 Upper plot: Output of the HVDC-Model Lower plot: control signal to the HVDC-Model

7

Fair Dispatch

When a curtailment signal is sent from the automated system described in the previous chapter, it has to be distributed to the wind power plants in a fair manner. This chapter investigates the currently used dispatching used in the United Kingdom (UK) and research that has been conducted. An approach from the student was taken to investigate if there is an even more fair way to dispatch the curtailment signal. In general the dispatch functionality would be implemented in GEABs system if found sufficient. One should keep in mind that what someone seems to be fair might not be fair to others, that is why different solutions were investigated and presented in this chapter.

7.1 Evaluation of different approaches

Todays manual curtailment system, described in Chapter 2, is a manual system. The dispatch of the curtailment signal is as well a manual procedure. When the situation occurs that curtailment is necessary, the DC operator looks at an Excel document as an daily curtailment diary. The controllable wind power plants are listed together with: actual power production of the wind power plant, time of the dispatch, the power reference to the wind power plant and a commentary at the time of the newly sent power reference to the given wind power plant. The DC operator uses the table to decide which wind power plants is to be curtailed during critical transmission periods. The main parameters that are being overseen during the dispatch is the actual power being produced by a given wind power plant and the amount of time the wind power plant have been curtailed before.

GEABs desire is to have a system that solves the dispatch issue together with the automated system. For the sake of the wind power producers, this system has to dispatch the curtailment signal in a fair manner.

UK Case Study

Two articles [Kane, 2014] [Kane, 2015] and a conducted project in the UK (Flexible Plug and Play) [Baringa Partners, 2012b] was used as background study for the fair dispatch. The articles and the Flexible Plug and Play (FPP) project deals with similar problematics as this thesis, such as curtailing the wind power plants due to grid security, and how to curtail the wind power plants in a fair manner. For the sake of this chapter, no deep investigation was conducted of the grid security and curtailment procedures. The main focus was on the dispatch functions to the wind power plants during the curtailment. There are certain criteria a dispatch function should possess. The criteria listed in [Kane, 2014] are:

1. Support safe, secure and reliable power system operation.
2. Encourage efficient investment and operating decisions by the distribution companies, generators and customers such that he overall cost of electricity is minimized.
3. Not present undue barriers to the utilization of low carbon electricity.
4. Be fair, equitable and transparent.
5. Be robust against future generation, demand and network changes.
6. Be practicable.
7. Be as simple as possible to achieve the objectives, and no simpler.
8. Not have an unduly negative impact on existing connection agreements.
9. Gain sufficient support of stakeholders to allow implementation.
10. Allow investors to be able to estimate, with sufficient confidence, future income and expenditures in order to secure investment from financial backers.
11. Comply with all generator technical standards and network design standards.

The criteria that is highlighted in this thesis are number: 4,6,7,8 and 10 and the main focus lies there. The following subsections describes different approaches and researches mad in the UK when it comes to curtailing the wind power plants in a so called fair manner.

Generator Size

This approach curtails the largest wind power plant that is contributing at the time of the constraint, that is the wind power plant who has the largest power production at the time. Easing network congestion quickly by regulating or removing the largest wind power plant is one advantage with this method but the disadvantage is that it can be seen unfair and installation of large wind power plants might be seen as pointless.

Last In First Out

Last In First Out (LIFO) is a straight forward method [Kane, 2014]. The first wind power plant that is to be curtailed during some form of constraint is the chronologically last wind power plant to connect to the network, or in GEAB's case, the last to become controllable from their SCADA system. A LIFO priority list is used where the recent wind power plants added are at the bottom of the list. If the wind power plant on the bottom of the list is not available for curtailment, due to non power production, the dispatch is sent to the second to last on the LIFO priority list. This method is consistent, transparent and easy to implement in almost any system but it is far from fair.

Rota

The Rota method uses, just like LIFO, a priority list with all the wind power plants [Kane, 2014]. Instead of having fixed priorities as in the LIFO method, the list is rotated ever day, week, or month, depending on how the network operator wishes to use the method. The goal with the rota method is to let every wind power plant stay on every position equally. If four wind power plants are in the list, WPP 1 will spend 25 % of the year on each position.

Pro Rata

In this method the amount of power that needs to be curtailed is divided to all the contributing wind power plants at the moment [Kane, 2015]. The amount curtailed would be shared by each of the wind power plants based on the ratio of rated or actual power production to the total amount needed to be curtailed.

Taking an example from the FPP project [Baringa Partners, 2012b]. Considering three wind power plants, WPP-1, WPP-2 and WPP-3. WPP-1 is producing 1 MW, WPP-2 has 3 MW and WPP-3 has 4 MW power production. Their combined contribution is 8 MW. A constraint has occurred and the combined production needs to be reduced to 6 MW, that is a combined curtailment amount of 2 MW. This implies that each wind power plants needs to curtail 2 / 8 = 0.25 MW per 1 MW. WPP-1 would get a power reference signal of 0.75 MW, WPP-2 will get 2.25 MW and WPP-3 3 MW power reference signal [Kane, 2014].

This has been seen as a more fair way to curtail different wind power plants since the curtailment is shared to the wind power plants contributing to the network at the moment. According to FPP and their documentation, a Pro rata implementation for the dispatch of the curtailment signal will provide higher long term Capacity Factors (CFs) for wind power plants when compared to LIFO. The derivation of the capacity factor for a wind power plant during a certain amount of days (t_{days}) is shown in equation (5.1). FPP has decided to use this method in the UK and their full technical description can be found here [Baringa Partners, 2012a]

$$CF(days) = \frac{E_{prod,days}(MWh)}{days \cdot 24(hours/day) \cdot P_{installed}(MW)} \tag{7.1}$$

- $CF(days)$: the capacity factor of a wind power plant during the certain amount of *days*.
- $E_{prod,days}$: the total energy production (MWh) during the days.
- *days* : number of days.
- $P_{installed}$: the maximum installed power output (MW) of the wind power plant.

7.2 Studied Fair Dispatch

One of the goals with this thesis was to develop a concept for fair curtailment with dispatch, follow up and settlement as criteria. After interviews with GEAB, it was stated that no settlement was conducted. The wind power producers do not get any compensation when curtailed. This drives a fair dispatch to be even more important since the dispatch of the curtailment signal should be fair amongst all the producers.

One approach that was considered during the thesis work was to involve the economic aspect of the power production. Investigation of the spot price, as well as the wind power producers contracted wind power production were used to derive different dispatch methods. The following subsections will present some methods that was developed using the previous section as inspiration.

Four wind power plants were used in this section for example purposes. These four wind power plants are the controllable wind power plants at Gotland and are to be curtailed by the automated system during the critical transmission periods. *Table 7.1* shows the specifications of these wind power plants.

ID	Nr of Wind Turbines	Maximum Installed P (MW)	Contracted P (MW)
1	12	24	12
2	3	6	3
3	24	48	24
4	24	48	24

Table 7.1 Controllable wind power plants on Gotland and their specifications

Equal Amount of Loss in Revenue

The approach of this method was to include the Elspot day-ahead market power price. The hourly spot prices for the coming day is usually announced at 12.42 CET or later with a four minute notice [Nordpool, 2015]. The goal is to use the market price ,during the time of curtailment, to decide the amount of curtailment power that should be dispatched to each wind power plant. The objective with this method is that each wind power plant should lose equal amount of revenue in Swedish crowns (SEK) in one year due to curtailment.

The implementation of this method could be done by using two tables that are updated each second, minute or hour. Tables can be used to determine the amount of power that is to be curtailed for each wind power plant. The first table, *Table 7.2* presents the actual spot price during the actual hour and the total amount of loss in revenue for all of the wind power plants combined. The second table, *Table 7.3* shows the loss in revenue for each wind power plant, the percentage of the total revenue loss and the actual power output at that time, updated every second.

Actual Spot-Price (SEK)	Total loss in revenue (SEK)
X	X

Table 7.2 The actual spot-price and the combined total loss in revenue (SEK) for all wind power plants

ID	Loss in Revenue (SEK)	Loss in % of total	Actual P (MW)
1	X	25	X
2	X	25	X
3	X	25	X
4	X	25	X

Table 7.3 Used for calculation of the penalty parameters

Penalty Parameters

Penalizing parameters for each wind power plant was presented to decide the amount of power that is to be curtailed, using this dispatch method. To be able to present the calculation of the penalty parameters and the amount of curtailed power that is to be dispatched for each wind power plant, some other parameters had to be defined and used together with the parameters from *Table 7.3*. *Table 5.4* shows these parameters.

Considering that all of the wind power plants start from non loss in revenue and a curtailment order of 5 MW is to be dispatched. The penalty parameter for each wind power plant is then equal, $S_{ID} = P_{curtail}/WPPs$. The dispatch order for each wind power plant would be $5MW/4 = 1.25MW$. This will result in an equal loss in revenue since all parks are curtailed by the same amount of power, at the same spot price value. The loss in revenue was calculated by using the actual spot-price and the amount of power that was curtailed during that period of time.

Parameter name	Description
WPPs	Number of active wind power plants
$P_{Curtail}$	Amount of P that is to be curtailed in total
$P_{Curtail_{ID}}$	Amount of P that is to be curtail for a specific WPP
L_{ID}	Loss in revenue for a specific WPP
LP_{ID}	Percentage loss in revenue of combined loss of all WPPs
S_{ID}	Penalty parameter WPP

Table 7.4 Used for calculation of the penalty parameters

If a wind power plant cannot curtail the given amount that is necessary, the other parks will lose more in revenue during that curtailing period. This leads to a penalty on the the wind power plant that could not curtail, The penalty parameters can be presented by using the wind power plant that has lost the most in revenue. Taking *Table 7.5* for scenario example purposes.

ID	Loss in Revenue (SEK)	Loss in Revenue (%)	Actual P (MW)
44	100	33	10
45	100	33	3
46	75	25	15
47	25	9	17

Table 7.5 Scenario example for penalty parameter calculation

$$S_4 = LP_1/100 = 0.33 \tag{7.2}$$
$$S_3 = LP_2/100 = 0.33 \tag{7.3}$$
$$S_2 = LP_3/100 = 0.25 \tag{7.4}$$
$$S_1 = LP_4/100 = 0.09 \tag{7.5}$$

If a case of a new curtailment order, 5 MW, the following curtailment orders would be dispatched:

$$P_{Curtail_4} = P_{Curtail} \cdot S_4 \Rightarrow 5 \cdot 0.33 = 1.65MW \tag{7.6}$$
$$P_{Curtail_3} = P_{Curtail} \cdot S_3 \Rightarrow 5 \cdot 0.33 = 1.65MW \tag{7.7}$$
$$P_{Curtail_2} = P_{Curtail} \cdot S_2 \Rightarrow 5 \cdot 0.25 = 1.25MW \tag{7.8}$$
$$P_{Curtail_1} = P_{Curtail} \cdot S_1 \Rightarrow 5 \cdot 0.09 = 0.45MW \tag{7.9}$$
$$\tag{7.10}$$

When the curtailment has ended the tables are updated as well as the penalty parameters. The overall goal with the penalty parameters is that it will compensate the wind power plants that have lost more in revenue during a certain time of curtailment. A follow up can be done each year where GEAB present the total loss in revenue for the wind power producers to show them how much they have lost and who is to be curtailed more the upcoming year to compensate for the previous year.

Resource Based Loss in Revenue

Instead of sharing the loss in revenue equally for all all wind power plants, a wind power plants loss in revenue should be determined by its resources. Resources in this sense is the maximum installed power. The concept of this method is the same as for the previous method, except for the use of tables and the penalizing parameters.

The more installed power posses the bigger the loss in revenue during a year. The amount of loss in revenue can be derived by taking the ratio between the maximum installed power and the total maximum installed power of all the controllable wind power plants. *Table 7.6* shows the desired outcome after a period of time for the specifications shown in *Table 7.1*.

ID	Loss in Revenue (SEK)	Loss in Revenue (%)	Actual P (MW)
1	X	19.05	X
2	X	4.76	X
3	X	38.10	X
4	X	38.10	X

Table 7.6 Ideal table for Resource Based Loss, the loss in Revenue (%) is distributed by the WPPs resources.

When a curtailment order arrises, the dispatch for a wind power plant will be determined by its resources. Given an example of a curtailment order of 5 MW, the dispatch for each wind power plant will be:

$$P_{Curtail_4} = 5 \cdot 0.3810 = 1.905MW \tag{7.11}$$

$$P_{Curtail_3} = 5 \cdot 0.3810 = 1.905MW \tag{7.12}$$

$$P_{Curtail_2} = 5 \cdot 0.0476 = 0.2380MW \tag{7.13}$$

$$P_{Curtail_1} = 5 \cdot 0.1905 = 0.9520MW \tag{7.14}$$

$$\tag{7.15}$$

As it was mentioned in previous section, if a wind power plant is out of order, it will be penalized during the next curtailment instance. The goal is that the loss in revenue (%) is equal (if possible) to the values given in *Table 7.6*.

Contract based Dispatch

Using the Pro-Rata approach as inspiration, this approach combines the actual power generated by the wind power plants at the moment of curtailment and the contracted power production of each wind power plant. The concept of this method of dispatching curtailment signals is to take in consideration of how much power each wind power plant is generating and to curtail it by the ratio of the contracted power and the total contracted amount of all wind power plants. This method of dispatch leaves out the spot-price market and all the market based parameters and focuses on the contributing power at the moment of curtailment and the contract that each wind power producer has signed. Using *Contracted P* from *Table 5.1* to derive the dispatch signal to each wind power plant. *Table 7.7* could be used if implementing this method for derivation of the dispatch signals.

ID	Actual P (MW)	Contracted P (MW)	Distribution (D)
1	X	12	0.1905
2	X	3	0.0476
3	X	24	0.3810
4	X	24	0.3810

Table 7.7 Used for dispatch.

Figure 7.1 shows a flow chart of the contract based dispatch.

When a curtailment order $P_{curtail}$ arises, the power that needs to be curtailed is distributed by using *Table 7.7*. The curtailment for each wind power plant can be calculated as:

$$P_{Curtail_{ID}} = P_{Curtail} \cdot D_{ID} \tag{7.16}$$

If a wind power plant cannot curtail its power production by the amount that is dispatched, the rest of the wind power plants will distribute its curtailment order with the same distribution order given in the table. The follow up procedure would be done by GEAB by logging the $P_{Curtail}$, $P_{Curtail_{ID}}$ and $P_{Actual_{ID}}$ during the curtailment. These values could then be presented to the wind power producers to show how much they have been curtailed and how much they actually have been producing during that period. *Figure 7.1* shows the flow chart for the contract based dispatch method.

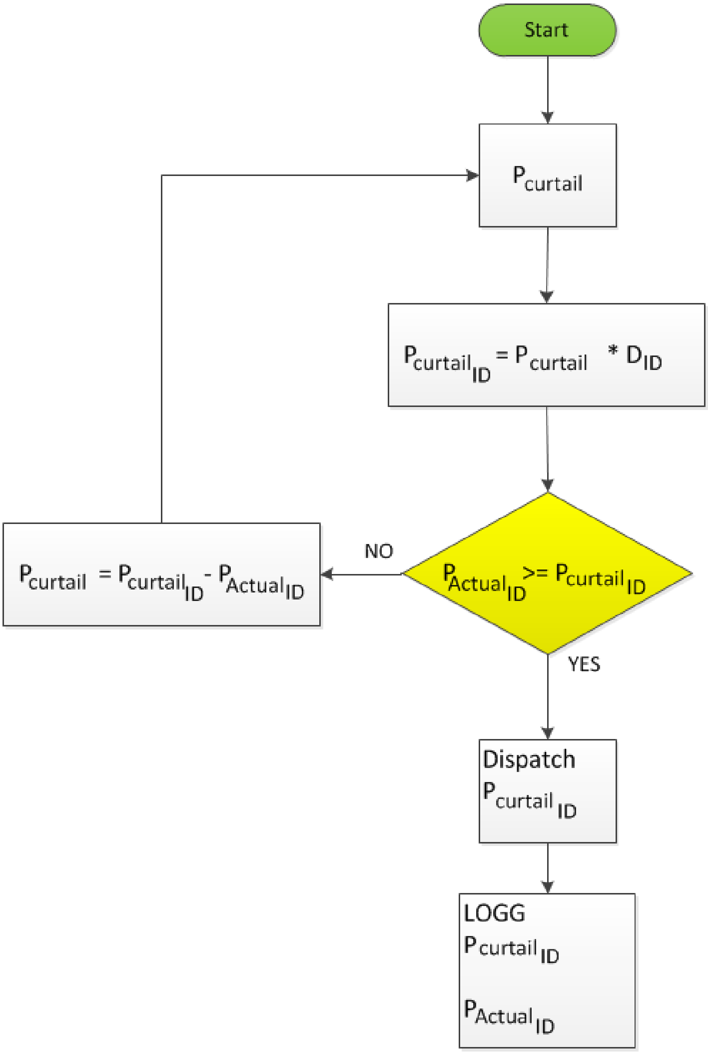

Figure 7.1 Flowchart of the contract based dispatch function

8

System Architecture

This chapter presents two solutions to the system architecture where the first solution is the system used by GEAB today. The second solution is a concept to standardize the communication between the different components used for the curtailment of wind power plants during critical transmission periods.

8.1 Solution 1

According to GEAB, the control design would most likely be implemented in the RTU-HVDC in Ygne. The RTU-HVDC is a Netcon 500 and is a automation system that works as a data concentrator and protocol converter. Distributed processes can be controlled and observed on a wide geographic area, while internal internal automation tasks can be executed. The Netcon 500 is also designed to operate in a hard environment with high electric and magnetic interference [Netcontrol, 2015].

It can be seen in the SGAM model in Appendix A, the communication layer, that the IEC6870-5-104 standard is used for the communication from the IEDs that measures the active power of the link all the way up to the SCADA system through the RTU-HVDC, and from the SCADA down to the PPC that controls the wind power plants. As described in the Use-Case, there is a protocol conversion in the RTU-WPP, IEC60870-5-104 to IEC60870-5-101 and back to IEC60870-5-104, for security reasons.

The SGAM model in Appendix A uses the IEC6870-5-104 standard. The information layer in the SGAM model shows the information flow between the different components. One should note that the signal names are not standardized according to any known standard.

8.2 Solution 2

Using a standard for the communication between the measurements of the HVDC links to the SCADA system and the communication from the SCADA to the wind power plants will ease the integration of new wind power plants into the Gotland grid. A standard between the HVDC link and the SCADA was chosen as well as a standardization between the SCADA and the controllable wind power plants. This is to make the communication, information and functional requirements more interoperable.

The standards that was considered for the communication between the HVDC up to the SCADA was IEC 61850-7-4, and the communication between SCADA and the wind power plants was IEC 61400-25-2. These two standards are compatible with the exciting standard that is used in GEABs systems. The main reason of applying a new standard was to map different attributes from the wind power plant and applying this standard to all wind power plants.

The SGAM model for the standardization can be found in *Appendix B*.
The logical nodes that were used in the thesis work for automation of the curtailment was MMDC and MMXU (modeled in IEC 61850-7-4) .The MMXU can be used for calculation of currents, voltages ad power and impedances in a three-phase system. The attribute that is essential from this logical node is the total active power (TotW). The MMDC node can be used to represent measurements in a DC system: current, voltage and power can be retrieved from this node. The attributes that are vital for the automated system are: current (Amp) and voltage (vol) from the HVDC links.

The logical nodes from the IEC 61400-25 standard used during this thesis were WAPC (IEC 61400-25-2) and WTUR (IEC 61400-25-2). The attributes used from the WAPC node were: active power output reference for the wind power plant (SetPlW) and the wind power plant active power output (PlW). These attributes are from the wind power plant and the PPC uses the WTUR node to set a active power output for a specific wind turbine (DmdW). The WTUR node is also used for retrieving the active power generation of the wind turbine (W).

9

Conclusive Results

9.1 System Identification

In conclusion of the system identification of the HVDC link when curtailing a wind power plant by 10 MW a simulation was done using the *lsim* command in matlab. This was to to see how the derived model relates to the true measurements of the curtailment test.

The derived state-space model was used and the same input signal (inverted curtailment signal for the wind turbines) was used. *Figure 9.1* shows the result of the simulation and relation between the output of the estimated model and the true behavior of the HVDC link during the curtailment test.

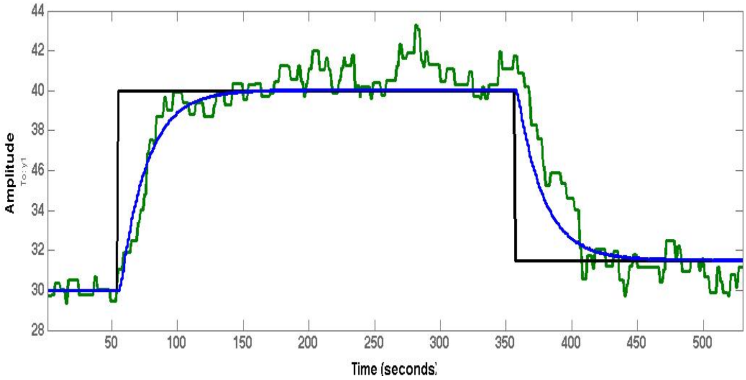

Figure 9.1 Simulation of derived model and real measurements of the HVDC. Black line shows the input signal to the model, blue shows the output of the model and green shows the real measured values of the HVDC during the curtailment test of 10 MW

Figure 9.1 shows that the output can be seen as an valid estimation of the active power flow behavior of the HVDC link when curtailing by 10 MW and then ramping up by 8 MW.

9.2 Control Design

Two control theories were adopted and both of the control theories were proven successful during simulations. The problematic with the control problem in this thesis was to avoid unnecessary control signal dispatch, so the goal with the MPC was to be able to enhance the internal control problem to be able to get a more faster convergence of the $y_{internal}$, and to be able to get a faster detection when the active power flow slowly drifted away from the set point (s).

Figures 6.15 in *Chapter 6* presented the result for both the PI and MPC approaches and it could be seen that the MPC did not prove to be a better solution. The internal model output was proven to converge to the given set-point faster. This is a result of a control signal sent more frequently, and that was not desired to be sent to the wind power plant.

9.3 Fair Dispatch

The approach of finding a suitable way of distributing the power reference signal to the different wind power plants was to fin existing methods and expand them. The approaches that were used in the UK were found to be unfair for use at Gotland, except for the Pro-Rata approach. The approach that was taken during this thesis work, where one should involve the price could not be realized since GEAB can be seen as the Distribution System Operators (DSO) at Gotland and they should not be involved in the electricity market at all. The economical approach of fair dispatch could lead to legal problems and this was not investigated in the thesis work. The Contract Based Dispatch was found to be realizable since the wind power plant owners sign a contract for the wind power production.

9.4 System Architecture

Using the automated system and the standardized solution 2 for the information exchange, the following BPMN (*Figure 9.2*) chart was drawn. Note that the DC-operator swim lane was eliminated.

Figure 6.8 in *Chapter 6* can be located in box 9 (Control loop) in *Figure 9.2*. That is where the thought of control design would be executed in the process. *Figure 7.1* in *Chapter 7* is the flow chart of the contract based dispatch concept. If this concept would be adopted in the automated process, it would be located in box 16 (Dispatch SetPlW) in the BPMN chart..

The full Use-Case documentation with the description of each box and information exchange can be seen in *Appendix C* and the SGAM for the standardized solution can be found in *Appendix B*.

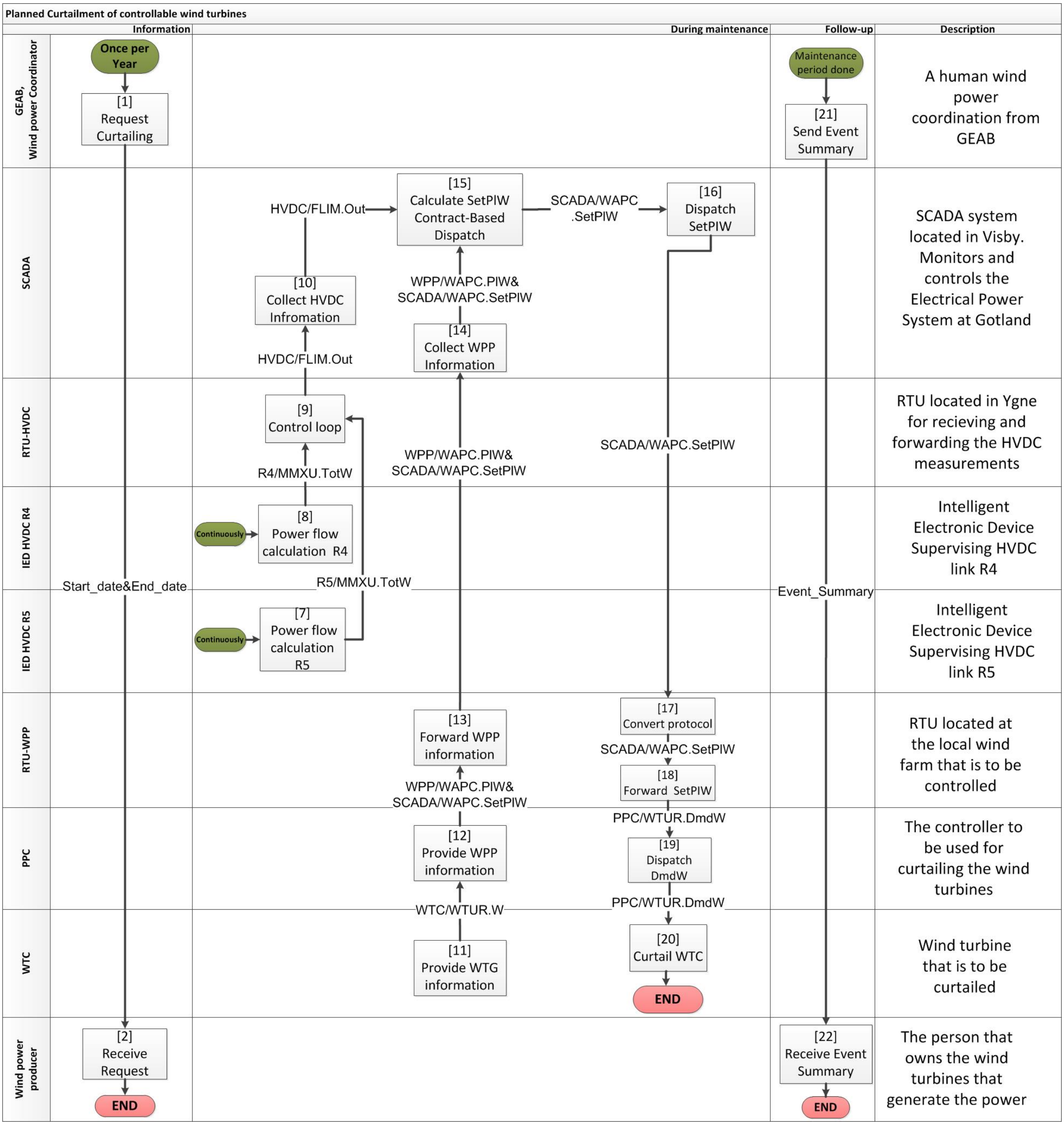

Figure 9.2 BPMN of the automated curtailment process during critical transmission periods with the standardized information exchange

9.5 Reduction of Waste Energy

As it was stated in the Introduction, the Swedish ambitions is to have 50% share of renewable energy in the gross final energy consumption. Using an automated curtailment system at Gotland is one step towards that goal. As it was mentioned in this thesis report, the set-point of the HVDC link can be decreased to 23 MW during the critical transmission periods on Gotland. Since the active power flow from the mainland Sweden to Gotland has to be 20 MW due to grid safety issues, the decrease is a 85% decrease in wind power energy waste. Since the average set-point of the HVDC link, when manually curtailing the wind power production, is set to 40 MW, according to a risk assessment, the span that can be used is 17 MW of 20 MW possible, $17/20 = 85\%$.The red zone in *Figure 7.1* shows the span that can be used if the automated curtailment system is adopted.

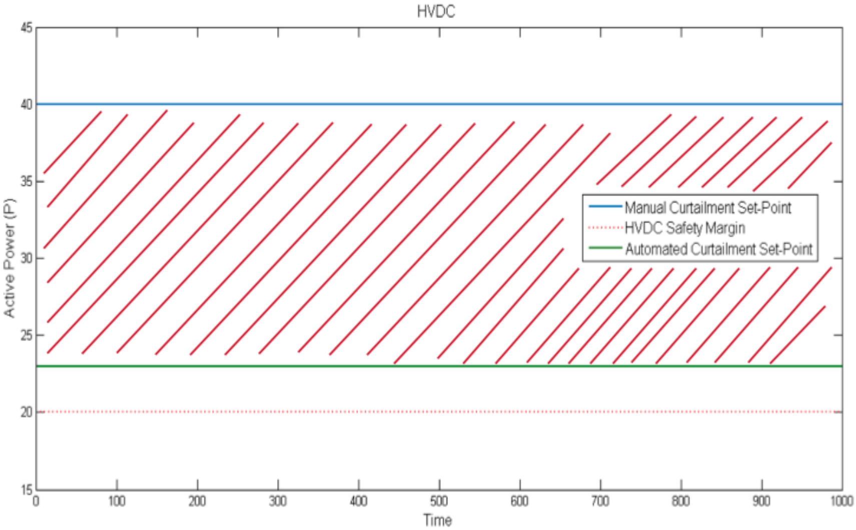

Figure 9.3 Blue line: set-point of the manual curtailment. Green line: set-point of the automated curtailment. Red dotted-line: Safety margin of the HVDC link. Red zone: the span that is used if the automated system is used

9.6 Goal Fulfillment

Goal 1 : *Develop a solution with a minimum set of modifications on the present system environment at GEAB, which automate the present workflow and reduce the waste energy measured in GWh.*

A system that automates the present workflow and reduces the waste energy with minimum set of modifications can be realized and is shown in the thesis work. Adopting the control design presented in *Chapter 6* the waste energy could be decreased by 85%.

Goal 2 : *Develop a generic State-Of-Art solution taking standardization and performance as the main driver, which automate the present workflow and reduces the waste energy even more, measured in GWh.*

Using the IEC 61850 and IEC 61400-25 would standardize the communication and eliminate communication barriers between measurements of the active power flow of the HVDC up to the SCADA system, and the communication from the SCADA system to the wind power plants. Using this standard solution the waste energy would also be reduced as in Goal 1.

Goal 3 : *Develop concept for fair curtailment*

Different approaches were taken to be able to reach this goal. The economical approach, taking the spot price in consideration was proven to be hard for GEAB to adopt, since they are the DSO on Gotland. The contract-based dispatch concept is fully realizable, GEAB will not have any legal issues and are held outside of the electricity market.

10

Discussion

10.1 Benefits with Automation

The benefit with automating the curtailment of wind power plants during critical transmission periods were clear in the previous chapter. There are both environmental benefits as well as economical.

There are also one benefit for the wind power plants that are controllable by GEAB. Since the uncontrollable wind power plants are curtailed on a static value throughout the critical period, they cannot be a part of the red marked span shown in *Figure 9.3*.

GEAB had an internal goal with the thesis work, and that was to present a solution that would tempt the uncontrollable wind power park owners to join the controllable scheme. Using the IEC 61400-25 standard, the connection from the SCADA to the new wind power plants would be easier as it was stated in the thesis.

10.2 Scenarios and Limitations

Different scenarios of active power drop and increase were tested during the thesis and as it was shown in the previous chapter, both the PI and MPC were sufficient to lower the set-point of the HVDC which in other words decreases the waste energy off the wind power on Gotland during the critical transmission periods.

It can be seen in *Figure 6.6* that the MPC is a more aggressive controller and sends new power reference signals more often to solve the control problem. One should keep in mind that the MPC is very computational heavy and might not be recommended since the goal of this thesis work is to reduce the waste energy by lowering the set-point of the HVDC link during the critical transmission periods. An decrease of the set-point could not be achieved by using the MPC in this thesis work.

10.3 Sources of Error

System Identification and Control Design

The system identification that was conducted during the thesis work can be seen as a source of error. The input data that was used was a simple decrease of 10 MW of a wind power plant. The model does not take the inertia of the system in consideration which could lead to unaccountable simulation results. If a more accurate model was to be derived, new control design would have to be conducted to get the desired results.

The active power flow from the mainland to Gotland during the curtailment test was approximately 30 MW. Since this was the only data that was used to be able to conduct the modeling, there are limitation to the model. The behaviors such as respons time and settling time might not be the same for different active power values on the HVDC. There is also an uncertainty if the same dynamics of the model would be found if the test would be executed with a curtailment of less or larger than 10 MW.

Deadband

The estimation of the deadband width is not arbitrary since deeper research of how the active power flow of the HVDC link fluctuates during normal drift was not conducted.

Control Design

The model was used to calculate the reference signal to the P controller which would be used to handle the slow drifting of the active power flow of the HVDC link. Since the model cannot be stated at fully accurate, the control design might not be fully usable.

No form of implementation of the control design, on the RTU-HVDC or SCADA, was conducted. The possibility that the MPC control design is to complex and to computationally heavy exists since no deeper research in the configuration of the Netcon 500 was conducted.

Fair Dispatch

Interviews with different wind power producers was not conducted during the thesis work. This could contribute that no of the presented solutions of fair dispatch are realizable since the wind power producers have to agree with the dispatch function.

10.4 Thesis Benefits for the SGG project

One of the goals stated by the SGG project is: Optimal integration of large hosting capacity for wind power on an existing grid. The thesis result has shown that more wind power could be used during the critical transmission periods. The other aspect is the standardization. If the IEC 61400-25 standard would be adopted, it would minimize communication barriers due to large amount of carrying protocols, data names and semantics.

11

Conclusion

11.1 Conclusive Summary

The Island of Gotland has to deal with critical transmission periods each year due to service on one of the two HVDC links connecting the mainland and Gotland. It is during these periods that GEAB uses a manual system for curtailing the wind power plants to be able to keep the active power flow from the mainland to Gotland above 20 MW. The result of using the manual curtailment process, the active power flow of the HVDC is on average at 40 MW, wasting 20 MW. The safety margin of the exciting HVDC link is 20 MW due to safety issues. The thesis presented a solution for automating the curtailment of the wind power plants to be able to keep the active power flow of HVDC closer to the 20 MW safety margin, which would reduce the waste energy of the wind power plants.

After the introduction in the thesis report, the second chapter focused on different methods that were used to be able to conduct a research on the presently used system and work process of the manual system. Different components, actors, functions and information exchanges were identified.

The third chapter focused on the Gotland electrical power distribution grid and the problematics that might occur during the critical transmission periods. Different scenarios were presented by using the different methods from the seconds chapter. A presentation of different tools were presented and the concept of fair dispatch was brought upp.

The fourth chapter describes the findings that were made during the thesis work. Different components and actors that are relevant to the thesis scope are described together with a explanation of the manual curtailment process that is used on Gotland today.

The fifth chapter introduced the so called system identification. A test case was derived and sent to GEAB. The test case stated that curtailment of 10 MW of a wind power plant should be conducted and measurements of the active power on the HVDC link should be logged together with the power reference signal to the curtailed wind power plant and the actual produced power of the wind power plant. Using this data an ARX model could be derived using the least-squares estimation.

When the model was derived, it was used in Matlab/Simulink to be able to design an PI controller and an MPC controller for the curtailment of the wind power plants. This part was presented in the sixth chapter. Different scenarios were simulated to be able to get the desired behavior of the two controllers. The goal with the control design was to avoid unnecessary curtailment signals, so a dead band was presented and used during the simulations.

The seventh chapter presented the concept of fair dispatch. The main concept is that during curtailment, the amount that needs to be curtailed to be able to reach the given set-point should be distributed in a fair manner. A background study of the concept was made and an approach from the United Kingdom was found. The approaches that were presented in these pappers were found to be slightly unfair considering the Gotland grid. One of the methods that were mentioned in the background study was Pro-Rata and can be seen as a fair way to curtail wind power plants during the critical transmission periods. An approach of involving the market price of electricity, to be able to get the amount of loss in revenue each wind power plant has each year was presented. Two methods of curtailing the wind power plants were derived where the first method presented a solution were all wind power producers would loos equal amount of money each year due to curtailment. The second method presented a solution were the bigger wind power plants had to loos more in revenue since they earn more during a year due to their size. Since these solutions were not accepted, since GEAB is the DSO a third method was derived where the focus lies on the contract that the wind power producer signs. The contract states how much a wind power plant is allowed to produce.

Chapter eight was dedicated to present a standardized communication solution that would enhance the interoperability for the wind power plants to the Gotland Grid. A communication standard between the HVDC links and the SCADA (IEC 61850-7-4) together with a standard for the wind power plants communication the the SCADA (IEC 61400-25-2) was presented in this chapter.

The last chapters presented a conclusive result of the chapters previous chapters and a discussion were benefits and sources of errors were identified.

The implementation of the automated curtailment system together with a fair dispatch function is technically feasible in todays system at Gotland. The hardware and signals all are there. There could be a problem of implementing the MPC since it is computationally heavy.

11.2 Future Work

This thesis has shown an technical solution of automating the curtailment of wind power plants during critical transmission periods. This could be used as a reference for GEAB and the SGG project but it might also be used in other systems facing similar problems. There are improvements to this thesis work that need to be carried out to be able to fully implement the system.

The width of the dead band of the active power flow of the HVDC link should be investigated further to able to determine the suitable width of the dead band.

The ARX model has some limitations since the test that was conducted only used one wind power plant for curtailment. There is a chance that curtailing a different wind power plant with different wind turbines would give a different outcome of the production which leads to different behavior of the active power flow of the HVDC link. A model for the wind power production and a model for the consumption on Gotland could be derived for a more precise modeling of the behavior of the active power flow of the HVDC link since it is directly dependent on the consumption and production on the island.

In conclusion, the thesis has shown that using an automated system could reduce the waste energy with 85 %. Introducing a standard would minimize communication barriers with the wind power plants and increase the reliability of the communication from the measurements of the HVDC to the SCADA system.

Bibliography

ABB (2015a). *Pioneering smart grids on gotland, sweden.* URL: `http://www.abb.com/cawp/seitp202/077f92def9668579c1257a400037425b.aspx`.

— (2015b). *The gotland hvdc link.* URL: `http://new.abb.com/systems/hvdc/references/the-gotland-hvdc-link`.

— (2015c). *The gotland hvdc power link.* URL: `http://www.abb.com/cawp/seitp202/0ff25e4cc9f4b9c2c1256e860043fda2.aspx`.

AGG (2008). *Deadband module PRINTED MANUAL.* AGG software.

Andersson Jönsson, K. H. J. and J. Bengtsson (2012). *A Manual For System Identification.* Department of Automatic Control at Lund University, p. 8.

Baringa Partners, U. P. N. (2012a). *Flexible plug and play.* URL: `http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Flexible-Plug-and-Play-(FPP)/`.

— (2012b). *Flexible Plug and Play, Principle of Access Report.* Tech. rep. Baringa, LCN Fund, UK Power Networks.

Bemporad Manfred Morari, N. L. R. (2015). *Model predictive toolbox user's guide.* URL: `http://cn.mathworks.com/help/pdf_doc/mpc/mpc_ug.pdf`.

Comittee, I. T. (2015). *Communications for monitoring and control of wind power plants.* URL: `http://www.nettedautomation.com/standardization/iec_tc88/index.html`.

Community, S. (2010). *Enterprise architecture governance procedure.* URL: `http://semanticommunity.info/EPA/EPA_Enterprise_Architecture/Policy`.

Cooper, D. J. *Integral action and pi control.* URL: `http://www.controlguru.com/wp/p69.html` (visited on 06/07/2015).

Gotland, R. (2015). *The power of the everlasting breeze.* URL: `http://www.gotland.se/54547`.

Government, S. (2015). *Overall eu-goals for europe 2020.* URL: `http://www.regeringen.se/sverige-i-eu/europa-2020-strategin/overgripande-mal-och-sveriges-nationella-mal/`.

IEC (2013). "IEC 61850 communication networks and systems for power utility automation". *Technical Committee 57.*

IPComm (2015a). *IEC 60870-5-101.* URL: `http://www.ipcomm.de/protocol/IEC101/en/sheet.html`.

— (2015b). *IEC 60870-5-104.* URL: `http://www.ipcomm.de/protocol/IEC104/en/sheet.html`.

Johansson, R. (2012). *System Modeling and Identification.* Prentice Hall.

— (2013). *Predictive and Adaptive Control.* Lund University, Dept. Automatic Control.

Johnsson, A. (2010). "Projekt tk 88 vindkraftsstandardisering – presentation av IEC 61400-25". *IEC 61400-25.*

Kane, G. A. (2014). "A review and analysis of renewable energy curtailment schemes and principle of access: transitoning towards business as usual". *Elsevier.*

— (2015). "Evaluation of wind power curtailment in active network managment schemes". *ESCR.*

Kemfert, C. (2014). *The eu energy and climate objective: a combination of market economy and regulatory policy. does it make sense?* URL: `http://www.europeanenergyreview.eu/site/pagina.php?id=35`.

Keskikangas, S. (2014). *Design and Implement a model Vehicle Platoon with Longitudinal Control.* MA thesis. Lunds University.

Kraftnät, S. (2012). *Svenska kraftnät (svk).* URL: `http://www.svk.se/PageFiles/47517/SvK-Samradsunderlag-ej-bilagor.pdf`.

MathWorks (2015a). *Iddata, time- or frequency-domain data.* URL: `http://se.mathworks.com/help/ident/ref/iddata.html`.

— (2015b). *Model predictive toolbox.* URL: `http://se.mathworks.com/products/mpc/`.

N. Etherden, V. V. (2014). "Virtual power plant for grid services using iec 61850". *IEEE.*

Netcontrol (2015). *Netcon 500 specifications.* URL: `http://www.netcontrol.com/swe/produkter/stationsautomation/fordelningsstationer/netcon-500-gw-and-rtu/teknisk-data/`.

Nordpool (2015). *Day-ahead market elspot.* URL: `http://www.nordpoolspot.com/#/nordic/table`.

OFFIS and KTH (2013). "Tool support for managing use cases and sgam models". *Discern.*

Rune Gustavsson, L. M. (2015). "Increasing energy efficiency by reducing losses and promoting value propositions". *CC BY 3.0 license.*

Smart Grid Gotland (2015). URL: `http://www.smartgridgotland.com/aim.pab`.

Trombetta, M. C. A. (2012). "Introduction to the standard computer standards and interfaces". *Computer Standards and Interfaces* **34**, p. 134.

Udemy (2015). *How to write test cases: catch software defects effectively.* URL: `https://blog.udemy.com/how-to-write-test-cases/`.

Vattenfall (2014). *Smart grids, vattenfall.* URL: `http://corporate.vattenfall.com/about-vattenfall/operations/research-and-development/smart-grids/`.

White, S. (2004). "Introduction to bpmn". *IBM Corporation* **1**, p. 11.

12

Appendix A, As-Is SGAM

All of the following SGAM figures were derived during the thesis work

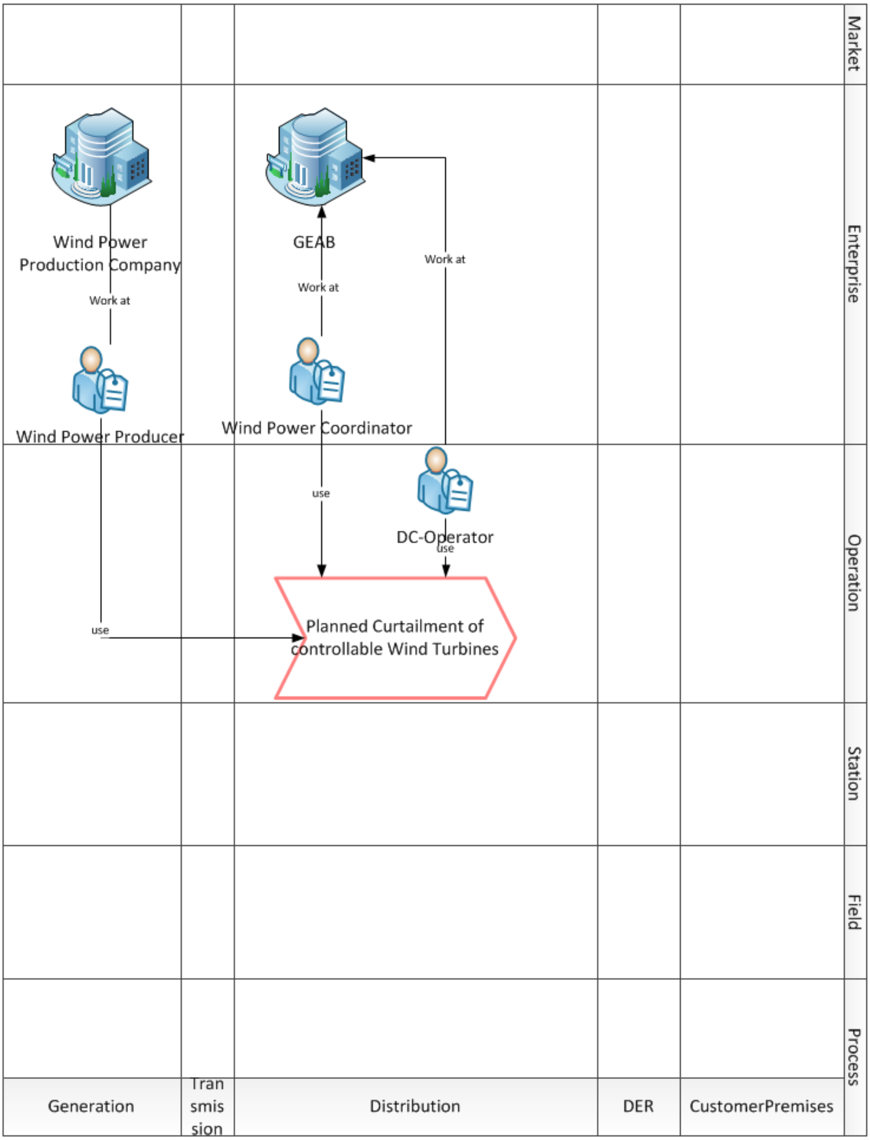

Figure 12.1 Business Layer

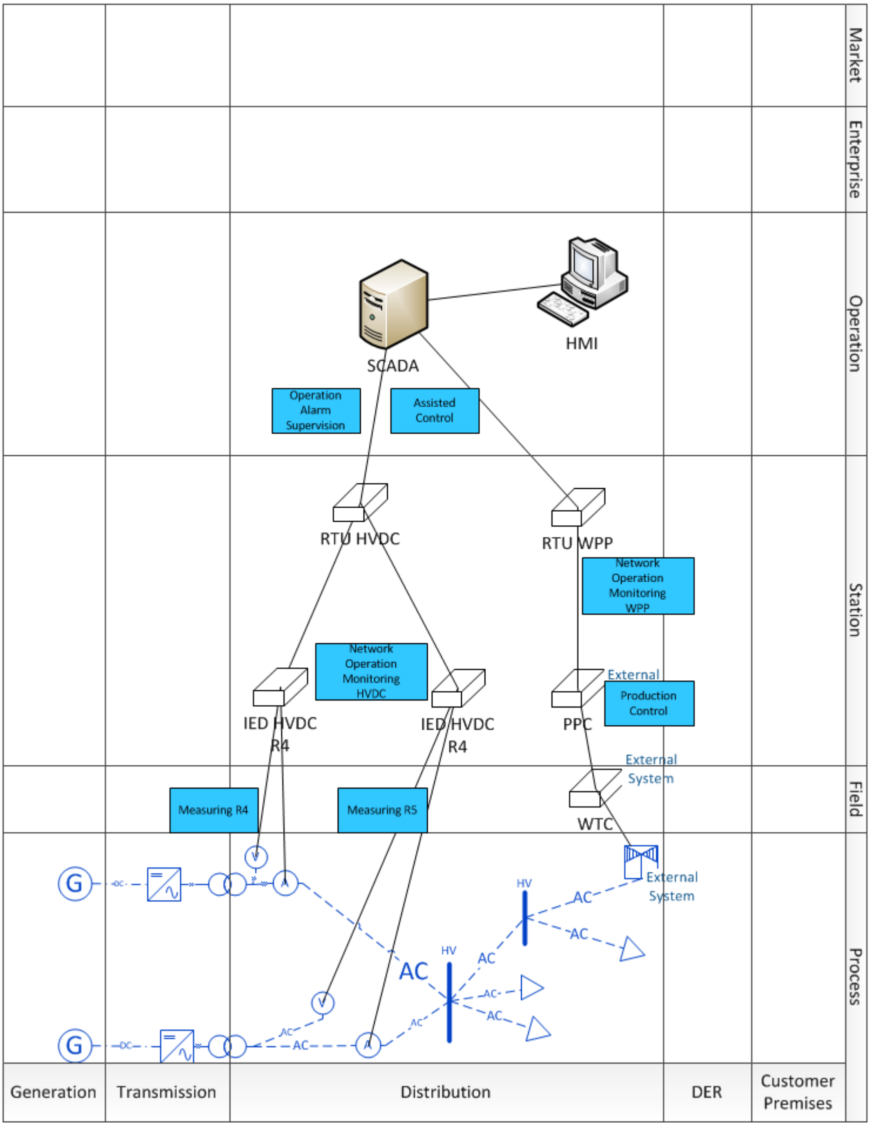

Figure 12.2 Function Layer

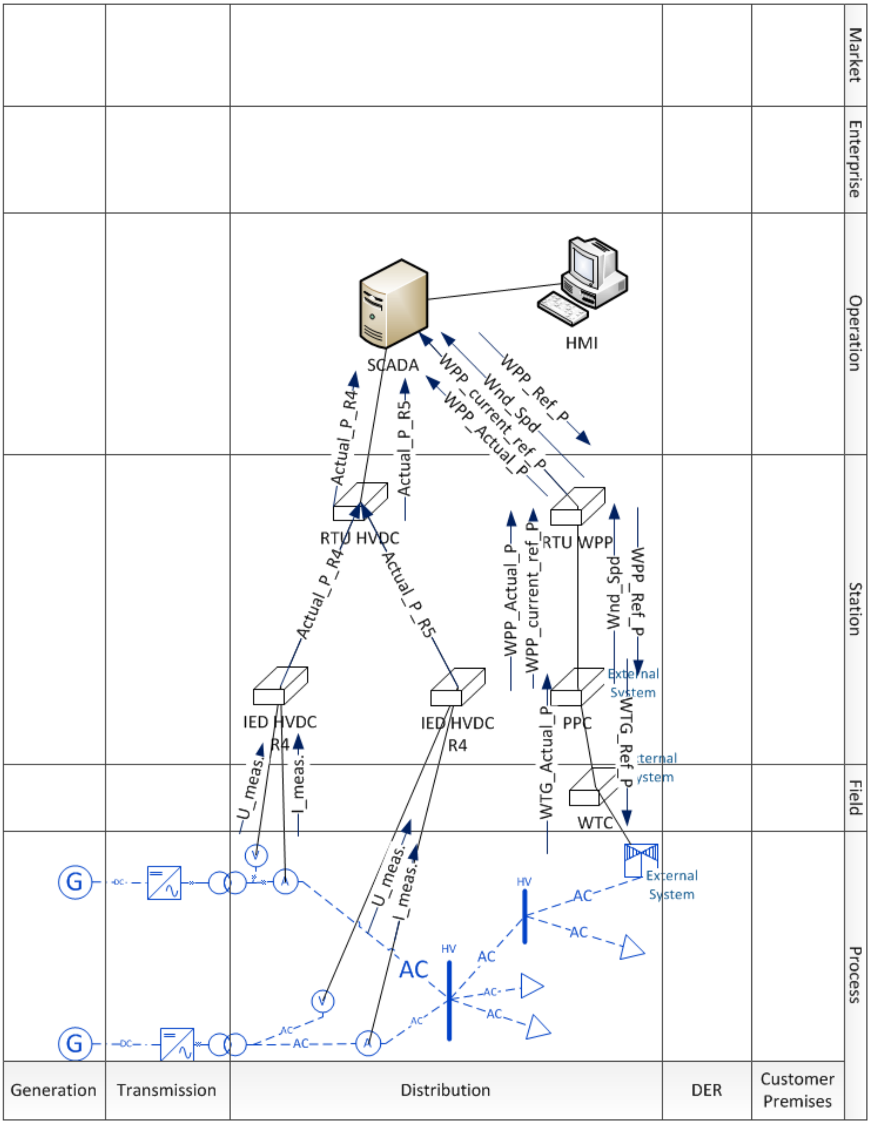

Figure 12.3 Function Layer

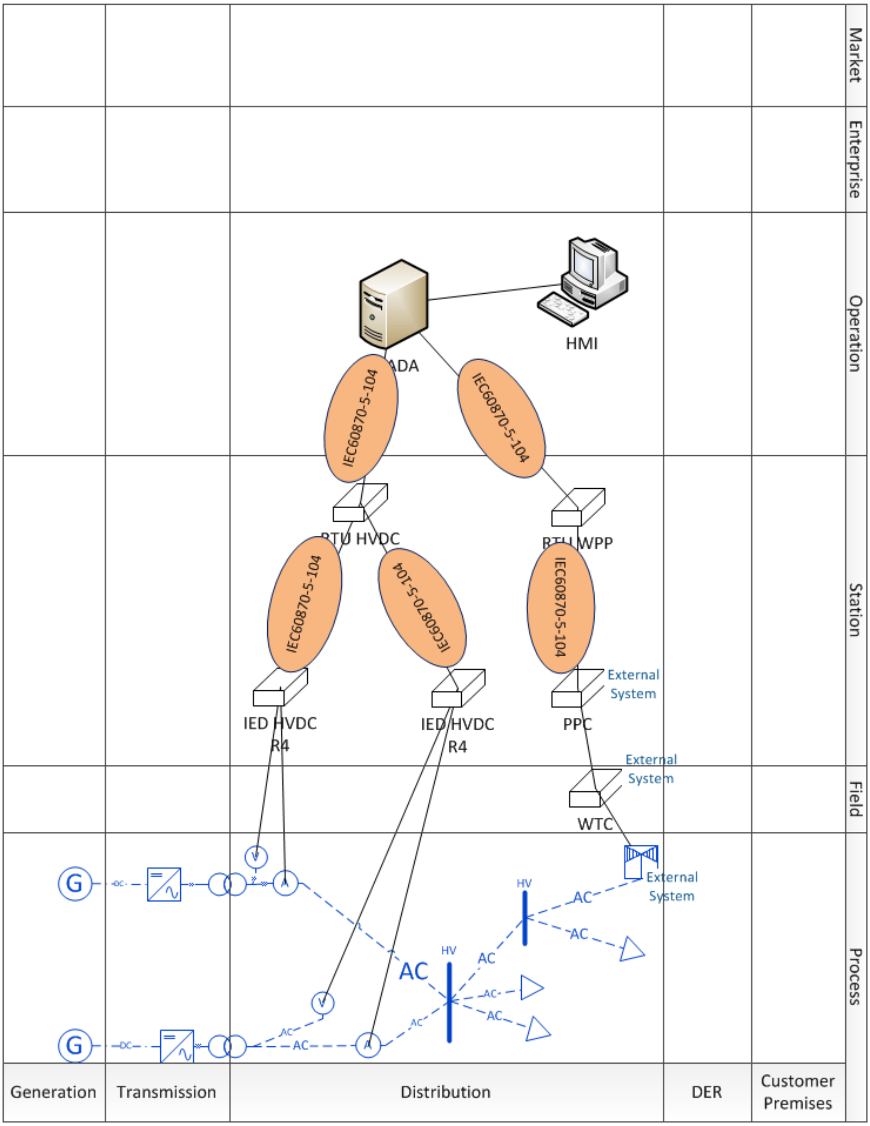

Figure 12.4 Function Layer

Communication Layer

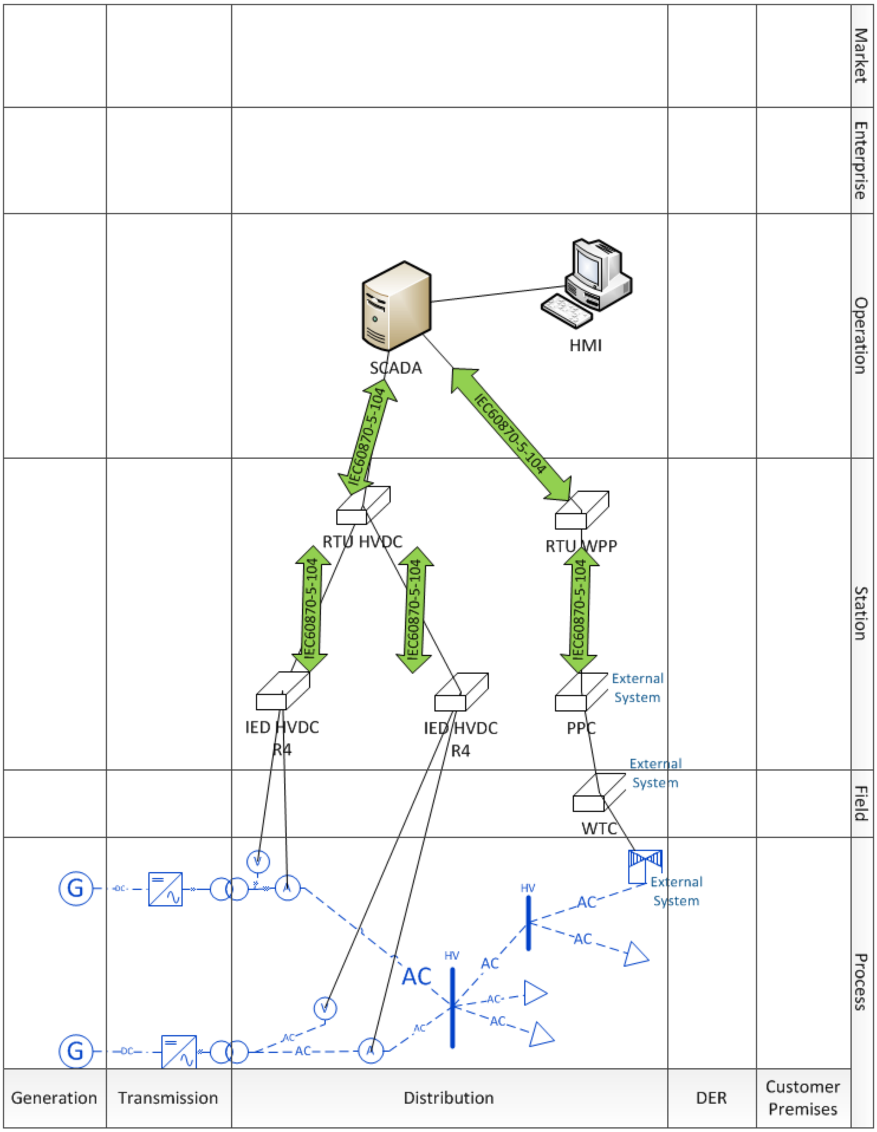

Figure 12.5 Function Layer

Component Layer

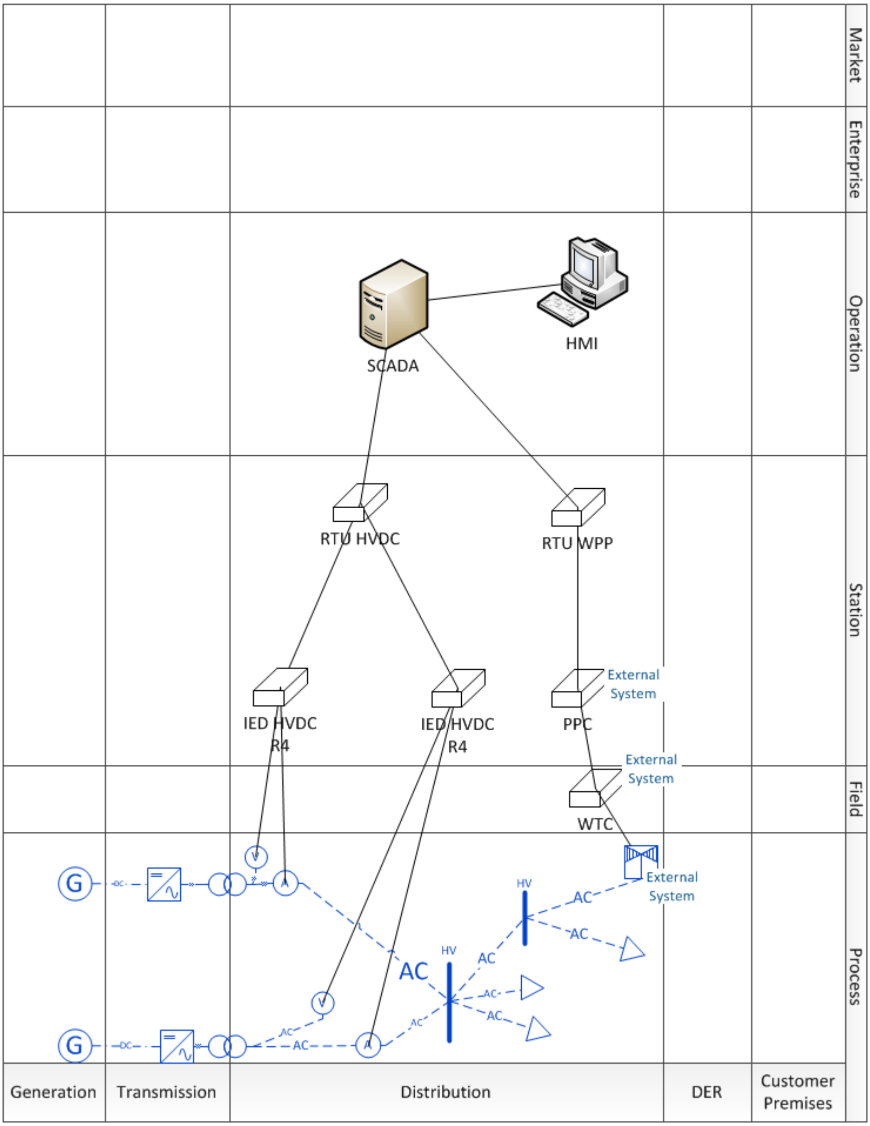

Figure 12.6 Function Layer

13

Appendix B, Standardized SGAM

The following SGAM figures were derived during the thesis work.

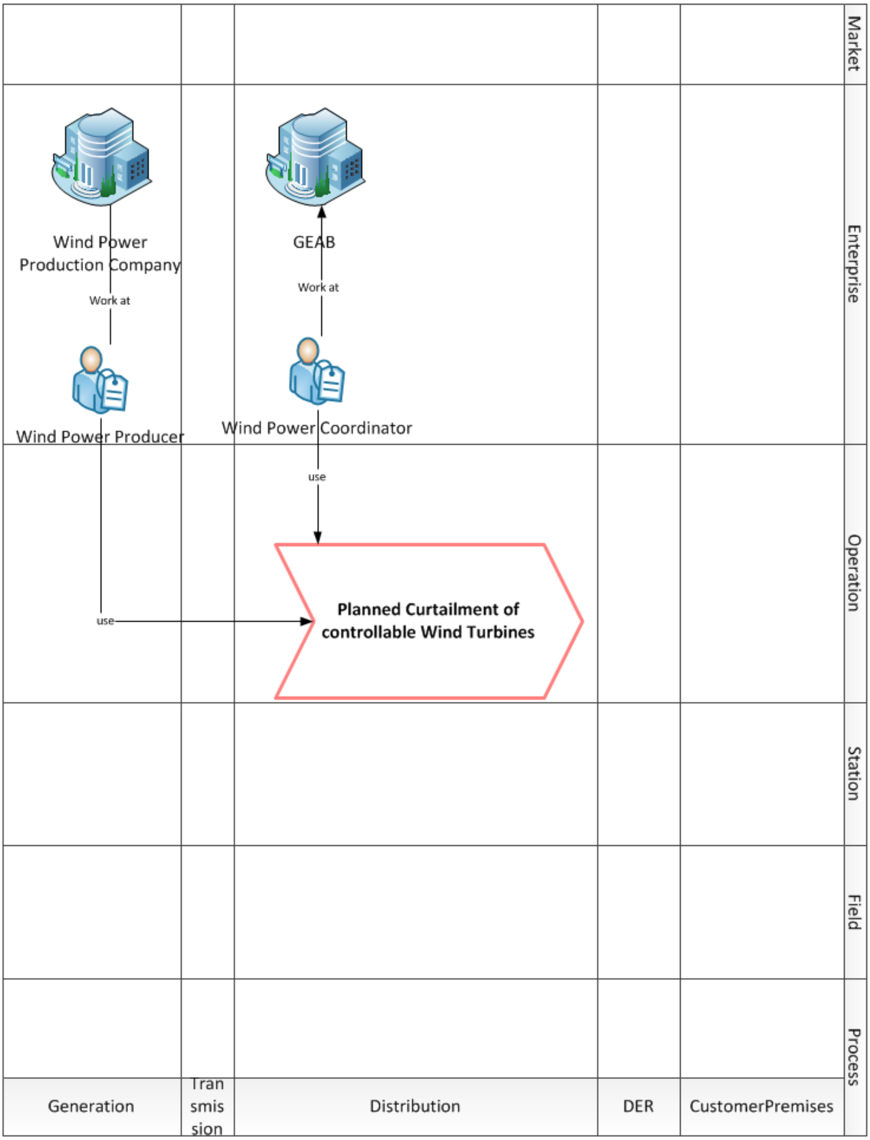

Figure 13.1 Business Layer

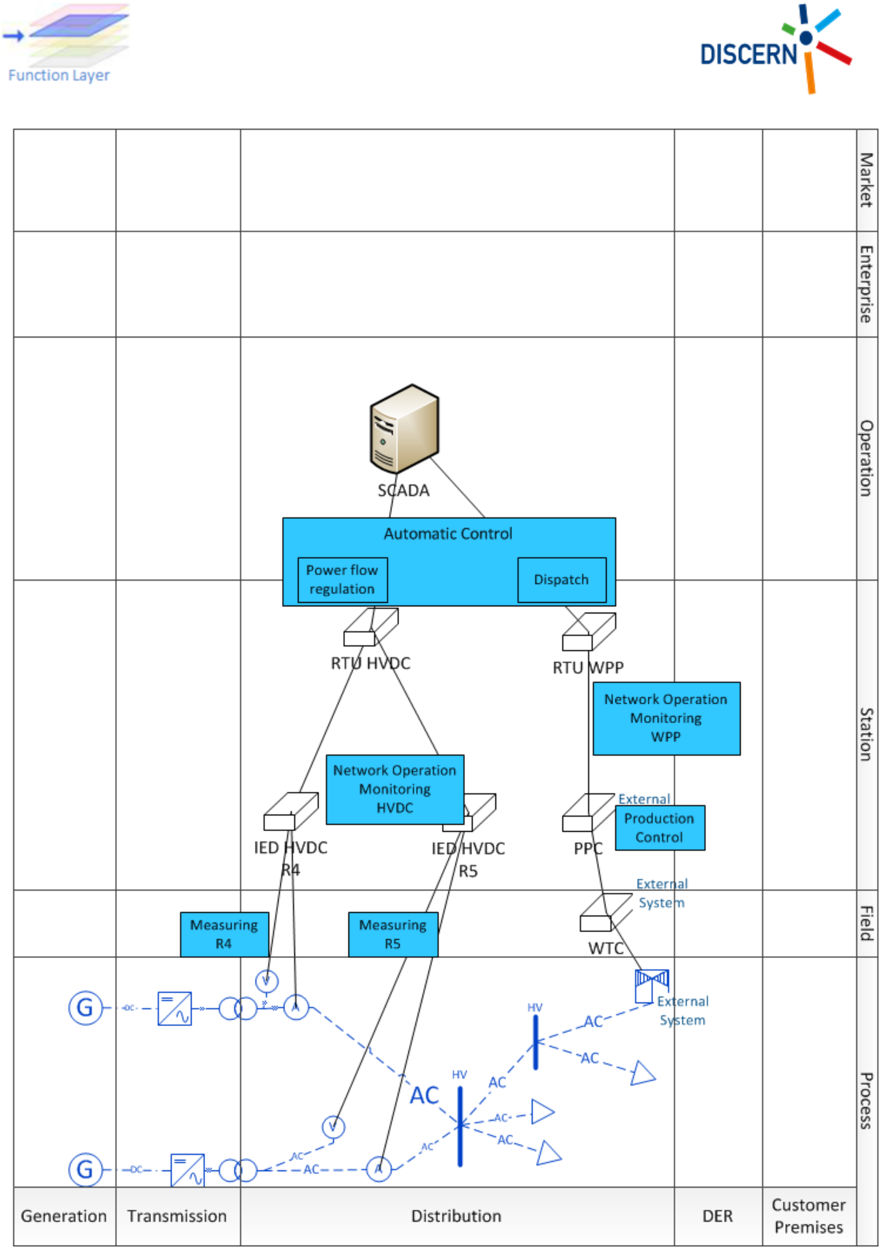

Figure 13.2 Function Layer

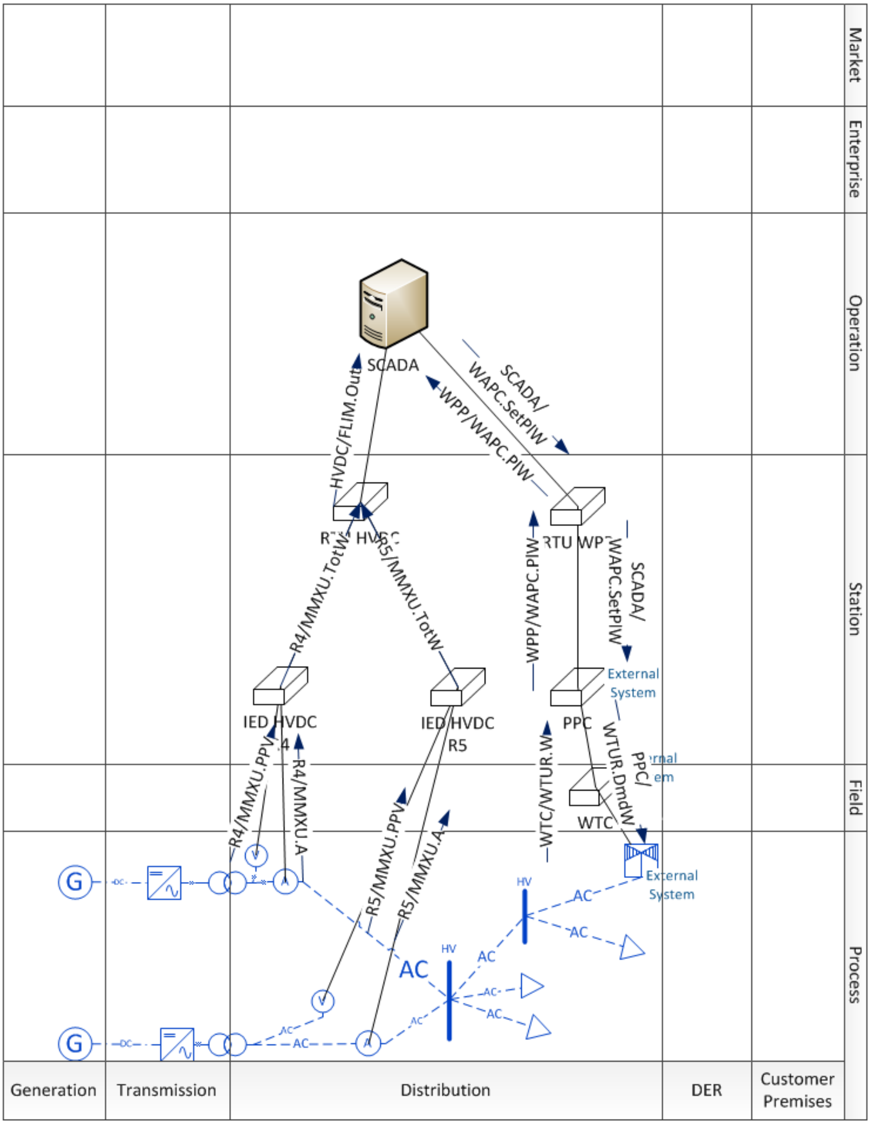

Figure 13.3 Function Layer

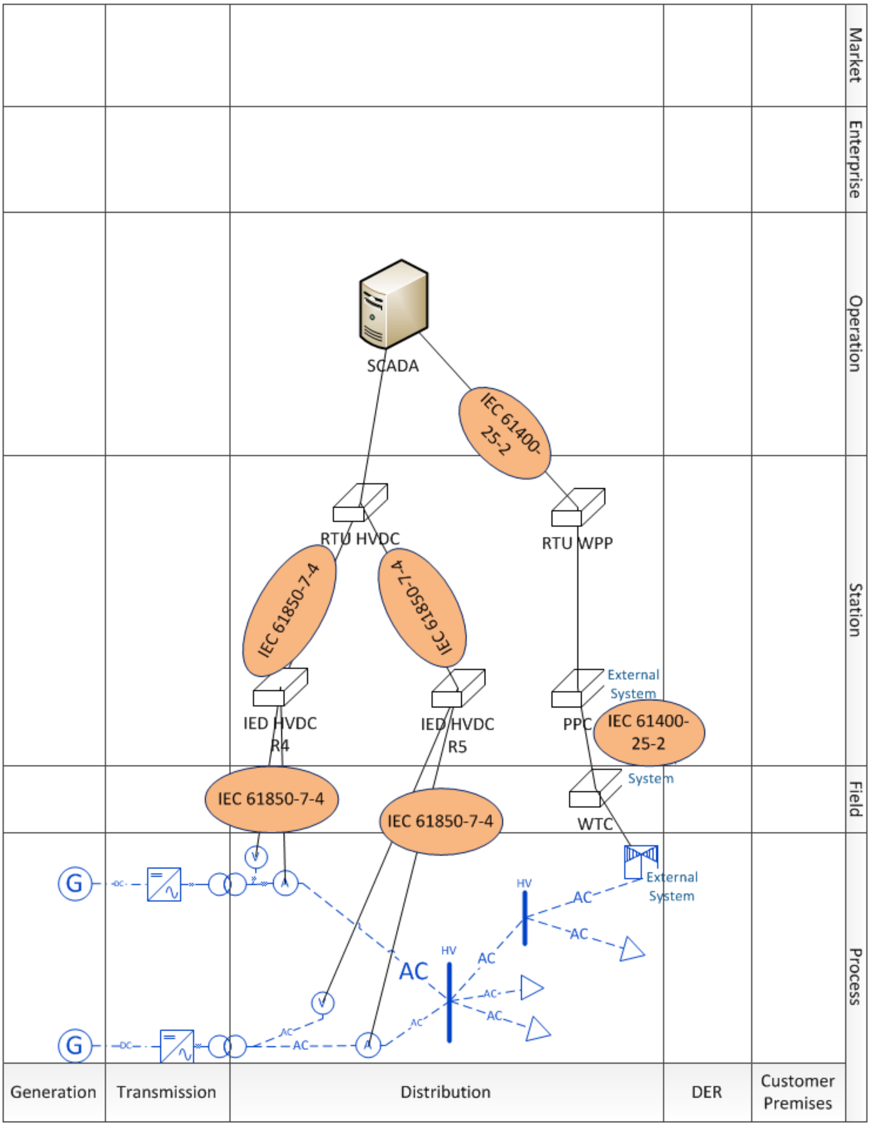

Figure 13.4 Function Layer

Communication Layer

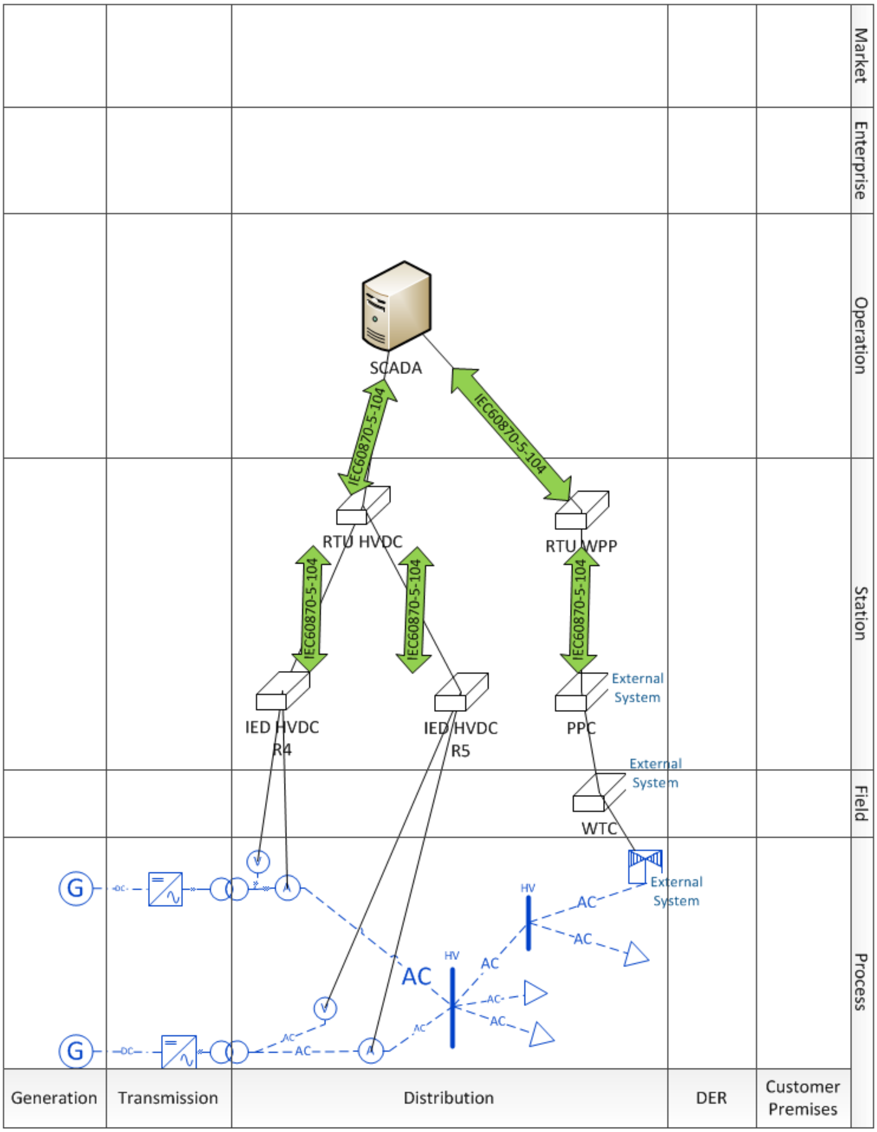

Figure 13.5 Function Layer

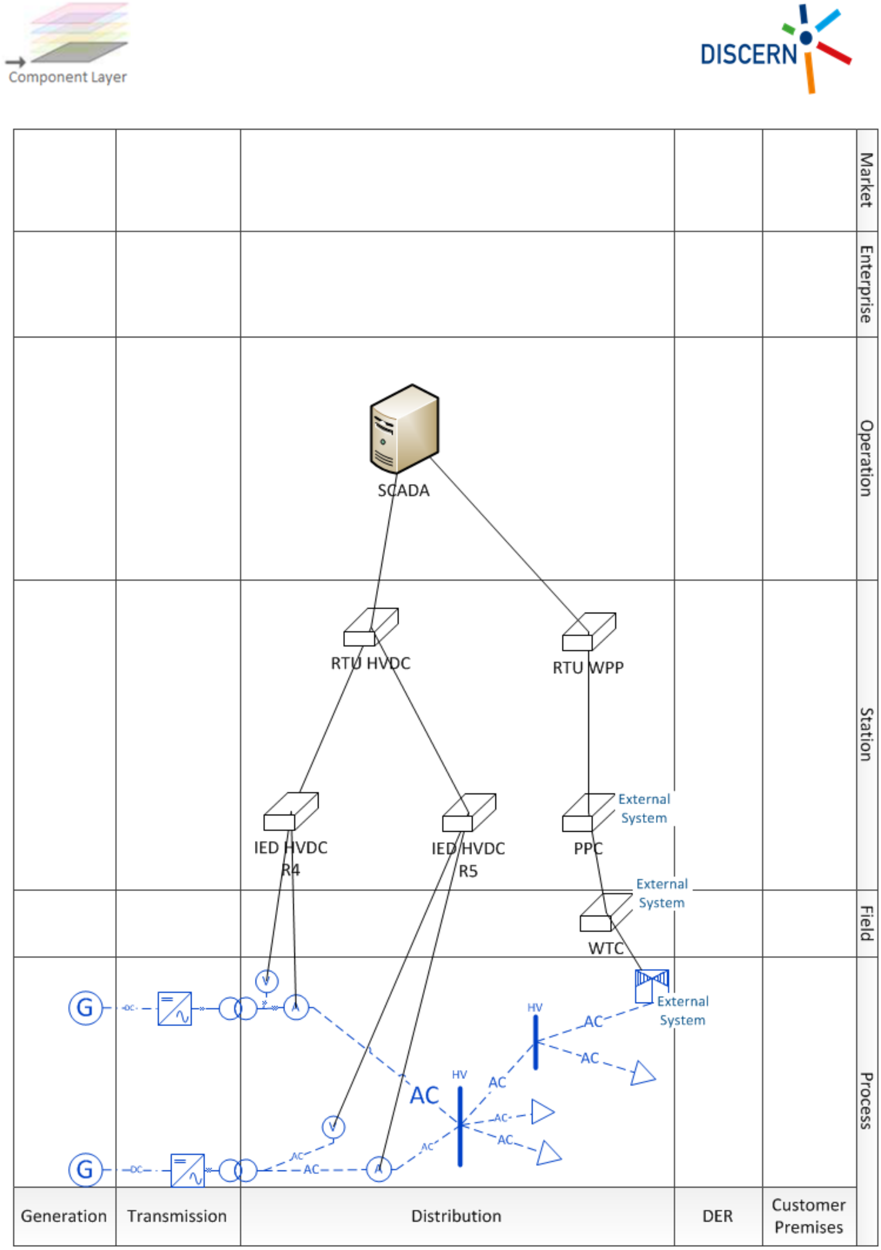

Figure 13.6 Function Layer

Lund University
Department of Automatic Control
Box 118
SE-221 00 Lund Sweden

Document name
MASTER´S THESIS

Date of issue
March 2016

Document Number
ISRN LUTFD2/TFRT--6004--SE

Author(s)
Maid Delic

Supervisor
David Erol, Vattenfall AB
Rolf Johansson, Dept. of Automatic Control, Lund University, Sweden
Karl-Erik Årzén, Dept. of Automatic Control, Lund University, Sweden (examiner)

Sponsoring organization

Title and subtitle
Automated Curtailment of Wind Turbines during Critical Transmission Periods

Abstract

The Swedish energy policy is guided by two government bills which were approved by the Swedish parliament in 2009 stating that at least 50 percent of the electricity share should be provided by renewable energy sources by 2020. This thesis focuses on the wind power production and it is a part of the Smart Grid Gotland (SGG) project. One of the goals stated by the SGG project is to have an optimal integration of large hosting capacity for wind power on an existing distribution grid.

The main purpose of this thesis is to automate the curtailment of the wind power plants during critical transmission periods on Gotland, and doing so in a fair manner. The critical transmission periods occur on Gotland when one of the two HVDC links are under service. During this period, there can only be a power flow from the mainland to Gotland and this power flow cannot fall below 20 MW due to grid security and Gotland Energy AB (GEAB) are curtailing the wind turbines using a manual workflow from a Distribution Center (DC) where a safety margin for the HVDC link is set to 20 MW. The consequence of using a manual curtailment process is that the power flow from the mainland to Gotland is on an average of 40 MW during the critical transmission periods. This indicates that there is a waste of energy that could be used.

The main goal of the thesis is to reduce the waste of wind power by automating the curtailment process. The approaches that were considered in this thesis were to document the presently used manual workflow for curtailing the wind power. This was done by using different techniques such as; Use Cases, BPMN charts and SGAM models. A solution with minimum set of modification on the present system and environment at GEAB, which automates the present workflow and reduces the waste energy was developed using a PI-controller with feedforward. In addition a generic state-of-the-art solution taking standardization and performance as the main driver was developed for potential future use. Lastly, a concept for fair curtailment was investigated for distribution of the total wanted power reduction to the wind turbines.

The results indicated that the set-point for the HVDC could be lowered to 23 MW by using the automated process. The approach for the fair curtailment that was considered was based on the contracted power for each wind power plant. Each wind power plant is to be curtailed according to the ratio of the contracted wind power of the wind power plants to the combined contracted power of each wind power plant.

Keywords

Classification system and/or index terms (if any)

Supplementary bibliographical information

ISSN and key title
0280-5316

ISBN

Language
English

Number of pages
1-94

Recipient's notes

Security classification

http://www.control.lth.se/publications/