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Multiterminal DC Connection for Offshore Wind Farms 10 Master Thesis 4.02.2009 to 3.06.2009 30 Florin Iov WPS4 - 1053

	SYNOPSIS:
Adelina Agap	Renewable energy systems are tending to be- come more and more present in the energy market and wind power has already proven its potential. Wind parks of thousands of MW
Cristina Madalina Dragan	are planned to be place into sea fareway from the mainland. Appropriate transmission sys- tems should be designed in order to be able to handle a significant amount of power with
	high efficiency and to be economically compet- itive. This project deals with the investiga- tion of a Multiterminal DC connection, based
	farm and two different grids. The goal of this project was to provide an inovative control al-
Copies: 2	gorithm for the power interchange of the three systems. The modeling and designing of the WF components, of the power converters, of the DC system components and of all the con-
Pages, total: 127	trollers playied a majore role in develope a simulation platform for future studies. Exper- imental verifications follow the theoretical in-
Appendix: 17	the modeled system for different test scenar- ios. The entire system is build and simulated in Power Factory DIgSILENT simulation tool.
Supplements:	

By signing this document, each member of the group confirms that all participated in the project work and thereby all members are collectively liable for the content of the report.

Preface

The present project entitled Multiterminal DC Connection for Offshore Wind Farm is made by group WPS4-1053 formed by degree students in 10^{th} Master semester at the Institute of Energy Technology, Aalborg University, Denmark. The project period is from 4^{th} of February to 3^{rd} of June 2009. Literature references are mentioned in square brackets by numbers (Vancouver style). The appendices are assigned with letters and are arranged in alphabetical order. Equations are numbered in format (X.Y) and figures are numbered in format Figure X.Y, where X is the chapter number and Y is the number of the item. The enclosed CD-ROM contains the project report written in Lyx and Adobe PDF format, the documentation from the Internet, and Matlab scripts used throughout the report. The common interest guided us in our group work.

The WPS4-1053 group would like to thank the supervisor Florin Iov for the constant support and ideas provided during the project period.

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Nomenclature

Parameter	Description
Z_T	Total impedance $[\Omega]$
R_T	Total resistance $\left[\Omega\right]$
X_T	Total reactance Ω
ΔP_{cu}	Copper losses [kW]
Δv	Short circuit voltage [%]
$V_{n_{AC}}$	Nominal AC voltage [kV]
V _{AC}	AC voltage [kV]
V_{DC}	DC voltage [kV]
$V_{n_{DC}}$	Nominal DC voltage [kV]
C_{DC}	DC capacitor [F]
f_c	Carrier frequency [Hz]
f	Grid frequency [Hz]
M	Modulation index
V_{AC_r}	Real part of the AC voltage [pu]
V_{AC_i}	Imaginary part of the AC voltage [pu]
P_{AC}	Active power AC side [MW]
P_{DC}	Active power DC side [MW]
P_{ref}	Active power reference [MW]
P_{meas}	Measured active power [MW]
P_m	Mechanical active power [MW]
P_{rated}	Rated active power [MW]
Q_{rated}	Rated reactive power [MW]
Q_{meas}	Measured reactive power [MVAR]
Q_{ref}	Reactive power reference [MVAR]
S_{rated}	Rated apparent power [MVA]
T_m	Mechanical torque [Nm]
T_r	Rotor torque [Nm]
T_s	Shaft torque [Nm]
κ_{stiff}	Torsional stiffness of shaft [Nm/rad]
	Damping coefficient [Nm/rad]
κ_{gear}	Gear ratio
J _{rotor}	W1 moment of inertia $[kg m^2]$
	DC current [A]
ξ_n	Nominal damping
0 _n	Voltage drop at rated power
ω_l	DC-link voltage controller bandwidth [Hz]
Z_b	Base impedance of the line $[\Omega]$
$\frac{Z_0}{V}$	$\frac{1}{10000000000000000000000000000000000$
	Reactance of the phase reactors $[\Omega]$
ΔV	voltage drop on phase reactor [V]

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Parameter	Description
v_{wind}	Wind speed [m/s]
v _{cut-out}	Cut-out wind speed [m/s]
v_{cut-in}	Cut-in wind speed [m/s]
v _{rated}	Rated wind speed [m/s]
v_m	Average wind speed [m/s]
θ_r	Rotor position [⁰]
P	Aerodynamic power [kW]
C_P	Power coefficient
C_Q	Torque coefficient
ρ	Air density $[Kg/m^3]$
θ	Pitch angle $[^0]$
r	Rotor radius [m]
λ	Tip speed ratio
Ω_r	Nominal WT speed $[rad/s]$
S	Slip [%]
$n_{pole-pairs}$	Number of pole pairs
$cos(\varphi)$	Power factor in nominal operation
η	Efficiency in nominal operation [%]
J_{gen}	Rotor moment of inertia $[kg \cdot m^2]$
X_m	Magnetising reactance $[\Omega]$
R_s	Stator resistance $[\Omega]$
R_r	Rotor resistance $[\Omega]$
X_s	Stator leakage reactance $[\Omega]$
X_r	Magnetising reactance $[\Omega]$
ω_r	Rotor speed of the generator $[rad/s]$
ω_s	Synchronous speed of the generator [rad/s]
u_s	Stator voltage [pu]
f_{sw}	Switching frequency of the converter [Hz]
P_{m-in}	Magnitude of the PWM index [p.u.]
P_{mr}	Real part of the PWM index
P_{mi}	Imaginary part of the PWM index
P_{md}	PWM index of the d-axis
P_{mq}	PWM index of the q-axis
cosref	Cosinus of reference angle
sinref	Sinus of reference angle
i_{d-ref}	Current reference in d axis [p.u.]
iq-ref	Current reference in q axis [p.u.]
f_0	Input frequency for the PWM Converter [p.u.]
dphiu	Voltage angle
f_s	Set-point frequency
V_s	Set-point voltage
V _{meas}	Measured voltage
I_{meas}	Measured current

Nomeclature continued

Parameter	Description
ω_n	Natural frequency
ξ	Damping ratio
L	Inductance of the phase reactor [H]
R	Resistance of the phase reactor $[\Omega]$
L_f	Inductance of AC filter [H]
R_f	Resistance of AC filter $[\Omega]$
V_g	Generator's voltage [pu]
f_{ref}	Frequency reference [pu]
V_{ref}	Voltage reference [pu]
P_{Tmeas}	Measured output of the wind farm
R_1, R_2	Resistance of the DC cables $[\Omega]$
P_1	Active power demand of Grid A [pu]
P_2	Active power demand of Grid B [pu]
V_{DC1}	DC voltage of inverter A [pu]
V_{DC2}	DC voltage of inverter B [pu]
C	Voltage level sensitivity

Acronyms

Acronym	Description
WF	Wind Farm
WT	Wind Turbine
EWEA	European Wind Energy Association
EU	European Union
PCC	Point of Common Coupling
MTDC	Multiterminal Direct Current
HVDC	High Voltage Direct Current
AC	Alternative Current
VSC	Voltage Source Converter
IGBT	Insulated Gate Bipolar Transistor
TSO	Transmission System Operator
DSL	DIgSILENT Simulation Language
SCIG	Squirrel Cage Induction Generator
PWM	Pulse Width Modulation
PI	Proportional Integrator

Chapter 1

Introduction

1.1 Background

All over the world the countries face with challenges of climate change, increasing demand of power, energy dependence of one country to another and higher energy prices. Nowadays, the global warming is no longer an uncertainty and solutions have to be found in order to limit it. The EU has made an agreement to reduce the greenhouse effect by 2020 with 20%. This requires important efforts for changing the current energy supply share from the different energy resources and also more effective climate policies. Conventional primary energies like coal, oil and gas have finite life expectations. In the same time the global energy demand is increasing [1].



Figure 1.1: New power capacity installed in EU between 2000-2007 (in MW)[2]

The more accentuated concern regarding the energy resources led to the increased use of the wind energy which is an inexhaustible and nonpolluting resource. Figure 1.1 presents the new power capacity in EU for each year between 2000 - 2007. It can be seen that a major growing in wind power generation was taking place over this period. Thirty per cent of all power capacity installed in EU in 2007 was wind power, that makes it the second energy resource after natural gas that has a sharing of 55% [2].

Offshore wind energy is one of the key component in helping the EU to fulfill the agreement to achieve the 20% of renewable energy from the total energy by 2020. Although the offshore market is currently smaller then the onshore one, it is of high interest for the energy policies because of its important capacity of producing energy. The offshore wind market is characterized by projects that are significantly larger and more difficult to implement than most of the onshore projects [2].

1.2 Offshore Wind Energy

Currently limitations are encountered in connecting the large scale offshore wind energy. Also the current onshore transmission networks can not be able to integrate the energy that can be available in most of the large scale offshore projects. To correct these deficiency a redesign of the grid infrastructure, system management, grid regulation and grid codes are needed. The large scale offshore wind farms have to be treated as conventional power plants, thus the necessity for both national and cross border network upgrades is increasing [2].

Figure 1.2 presents the operational offshore wind farms by 2008 and also the ones that are planned to be build within 2008 and 2009. Only in the period 2008-2009, ten projects are planned to be finished. Thus, an increased interest and development in the offshore technologies is shown.



Figure 1.2: Existing and planned offshore wind farms in Europe[1]

In 2003 EWEA organization formulated a prediction target for the offshore generation energy that was established at 70 GW for 2020 [1]. The EU onshore wind market grew with a rate of 33.4% in the period 1992-2006. If the same growing rate is applying for the offshore market, only 50 GW can be reached in the next 14 years til 2020. Because of the long time terms of the offshore projects, the document was modified in 2008 for a more realistic scenario. It relies on a phased approach [1]:

• Market status in 2007 - 25 project were developed and fully operating, many of them are large scale. The total capacity is around 1100 MW and it generates 3.3% of

electricity from wind energy;

- Market outlook by 2010 due to the historical growth rates, the planned projects, the wind potential in Europe and also the targets for all the governments, a total capacity of 3-4 GW is estimated by the end of year 2010;
- Market forecast by 2015 based on the projects that are currently planned and the research that is performed, a capacity of 10-15 GW is forecast for year 2015. The deliver ability of the projects depends on the availability of the wind turbines. For example the projects that relay on 3-3.6 MW wind turbines can start to be built not before 2009-2010 and the ones that are planned to use 5 MW in Germany has to wait for some prototypes and results from the afferent tests;
- Market scenario by 2020 for such a long term prediction more factors were taken in consideration: existing offshore projects, continuously research and technical development in this area, the European Union and its Member States agreements, upgrade of the grid infrastructure that can be able to accommodate the large scale wind energy, implementation of the the interconnections and power exchange mechanisms between the countries. Therefore two scenarios were established - one with "minimal efforts" and one "optimistic" that shows an installed capacity by 2020 of 20 GW and 40 GW respectively.

1.3 Offshore Wind Farm Connection

One of the challenges is to find a suitable type of connection for offshore wind farms, having different power ratings and different distances from the onshore connection point. This selection should be done by taking into consideration power efficiency and economical aspects.

Two alternatives are available for connecting an offshore power plant to the main grid:

- HVAC transmission;
- HVDC transmission.

Until now for the already build WFs, like Horns Rev I, Nysted, Middelgrunden, in Denmark, the only connection used was the AC connection. The reasons for choosing this type are [14]: lower station costs, no power converters needed, a simple layout for the offshore park. A typically offshore WF layout is depicted in Figure 1.3. By choosing the AC transmission for the offshore WF several disadvantages are encountered, like [12]:

- the need of reactive power compensators, such as SVCs or STATCOMs;
- AC cable cost becomes higher as the distance grows;
- long AC cables produce large amounts of capacitive reactive power;
- the decrease of the transmission capability of AC system decreases together with distance because of the dielectric losses and the reactive power that is produced along the cable.

Wind Farm



Figure 1.3: Offshore WF layout for AC transmission [3]

The optimization of the AC system is made by taking into consideration two parameters, the transmission voltage level and the number of cables used in the system[14].

As the future offshore WFs planned to be build are further away from the shore side and become higher and higher in size, an important question will rise: What type of transmission system is more suitable for the WF with high voltage levels and larger distances to the onshore connection point?

The solution could be the HVDC transmission. The benefits of using HVDC transmission instead of AC transmission are [12]:

• less power losses for long distances;

Wind Farm

- lower cost for cables above certain distances;
- it can connect asynchronous AC networks;
- offshore WFs can operate at variable speeds;
- decoupling of the connected AC networks (i.e. it allows asynchronous operation of the offshore WF AC network and the main grid).



Figure 1.4: Offshore WF layout for HVDC transmission [3]

The main structure of an offshore wind farm connected using HVDC transmission is summarized as presented in Figure 1.4. The link to the grid is made through a power converter which guarantees the reactive power control and a smooth grid connection [5].

Depending on the power semiconductors used in the converter topology, the HVDC transmission can be classified as follows:

- thyristor based line-commutated converters (classical HVDC);
- VSC based HVDC technology.

The classical HVDC converter is based on thyristor valves which perform the conversion from AC/DC and DC/AC. This system can be used for the transmission of significant powers at large distances having low losses (voltage level up to 800kV [17]).

When it comes to offshore wind farms the classical HVDC may not be the best solution because it requires large converter station for both, the onshore and the offshore side (see Table 1.1). It is needed also an auxiliary service at the offshore converter station for the operation of the line-commutated converters when there are power failures [17]. For the thyristors based system it is essential to have an AC voltage source in order to commutate and only when they received it they can transfer power between two AC networks. This also makes them not an adequate solution for offshore WF because the offshore grid needs power before they start to operate. Besides, no independent control of the active and reactive power is provided [8].

The second option is the VSC-based HVDC which is a relatively new technology based on the use of high switching frequency transistors like IGBTs. The IGBTs are power semiconductors with self-commutated turn-on and turn-off capability, allowing the generation of reactive power to supply the wind turbines [8]. One of the benefit of using this technology is that it provides voltage and power control. When dealing with isolated and fluctuating power plants, such as offshore WF, the voltage control and reactive power plays an important role in the stability of the system. That is why VSC-HVDC can be the proper solution in connecting a large offshore WF to the shore point.

One disadvantage of HVDC option, compared to AC connection, is that it can increase significantly the costs of the wind farms, mainly because of the power converters used in the systems. However the benefits can justify the costs.

The HVDC-VSC technology is used by several manufacturers, two of them can be mentioned: Siemens which developed HVDC Plus (12 pulses) and ABB which HVDC Light (6 pulses). From the available VSC-HVDC options, HVDC Light technology was the first to be involved in an offshore WF project [9].

1.3.1 HVDC Light

HVDC Light it is ABB's trade mark. This technology is based on voltage source converters (VSC) and it was designed as a power transmission system for underground and submarine cables. Reasons that make HVDC Light a feasible solution for offshore wind farms are that the converters stations are design in compact module, suitable for offshore and also the possibility of connecting this farms to the AC network without any distance limitations. The cables are light weight and oil-free which neutral electromagnetic fields which make them environmental friendly [4]. This technology ensures stable voltage and frequency by controlling rapidly and independently the active and reactive power.

The HVDC Light concept is based on a 6-pulse bipolar VSC with ratings up to 330 MW/ \pm 150 kV DC for one bipolar unit as presented in Figure 1.5 [7]. The IGBTs can switch at high frequency around 2 kHz. This fast commutation reduces the harmonics in the system, thus the number of filters will be reduced compared to the 'classic' HVDC converters.

Each converter can operate as rectifier or inverter at variable frequency and to absorb or deliver reactive power to the AC grid. Four quadrant operation is possible for each power converter thus, a bidirectional active power flow is possible [17].



Figure 1.5: Circuit diagram of HVDC Light

The first commercial project that involved the installation of an HVDC Light system was in Gotland in 1999. The purpose was to connect a wind farm with remote load center to the grid, via a 70 km underground cable. With this project the ABB technology proved to be reliable in terms of [6]:

- stable voltage and reactive power;
- less stresses on both WTs and the connected grid;
- low voltage ride-through-capability in case of grid faults;
- flicker problems eliminated and transient phenomena disappeared;
- power flow control to optimize the overall performance and losses in the adjacent AC grid;
- compact, environmentally adapted converter station design;
- low operation and maintenance costs.

Germany is the country which began the first HVDC Light project for connecting an offshore wind park. Since September 2007 E.ON Netz is building the largest offshore wind park in the world (400 MW) and the largest distance from the mainland (128 km). The wind park Borkum 2 is expected to be finished in 2009 and it will be the first connection to the grid using DC [9].

1.3.2 HVAC vs. HVDC

When it comes to decide which is the best transmission system option, two parameters which have a great impact on transmission efficiency and costs are considered. These are the transmitted power and the distance. Figure 1.6 reveals what is the suitable connection type for electrical systems.



Figure 1.6: Transmission type depending on power and distance[17]

It can be seen in Figure 1.6 that the HVAC is the best solution for small power systems and short distances. One of the reason is the increased price for installations and cables when it comes to transmit high levels of power on long distances. As the power and distances increase the HVDC connection should be considered. The VSC-HVDC technology is preferable to transmit medium amount of power on long distances, but when it comes to transmit on large distances a significant amount of power, the solution is classic HVDC [17].

Figure 1.7 highlights what are the costs involved in building an AC or DC system. As it can be seen DC transmission is a cost effective technology when significant amounts of power must be transmitted on long distances.



Figure 1.7: HVAC & HVDC transmission system costs

The decision should be made by considering other factors such as the expenses of grid reinforcement that may be significant in the AC case compared to VSC-HVDC solution. Also the costs for power flow equipment in the AC system are greater then in the VSC-HVDC solution. One advantage more for the VSC-HVDC system is that it offers the possibility to go further on land with an underground cable at a very moderate cost [6]. A comparison between classic HVDC and HVDC Light can be seen in Table 1.1

HVDC Light	Classic HVDC
Power ratings: 50-1100MW	Power up to 6400MW
IGBT based converters	Thyristor based converters
Footprint (i.e. 550 MW)- 120 x 50 x 11 m	Footprint (i.e. 600 MW)-220x120x22 m
Gate turn-off - Forced commutation up to 2kHz	No gate turn-off - Line commutation $50/60 \mathrm{Hz}$
High speed devices	Most economical way to transmit power for long distances
Ensures reactive power compensation	Does not provide reactive power compensation
Suitable both for submarine and land cable connections	Long submarine cables connections
No minimum DC power flow required	Minimum DC power flow is 5-10% of rated power
Fault ride-through and black start capability	No Fault ride-through and no black start capability

Table 1.1: HVDC Light vs. Classic HVDC [4]

1.3.3 Multiterminal HVDC Connection

Currently one of the concerns is the limited power exchange between the EU country members due to the lack of physical interconnection capacity and the capacity allocation mechanisms. The development of the offshore wind farms is one of the factors that leads to the demand of increased interconnections and improving the possibility of power exchange.

Taking in consideration the advantages of the HVDC-VSC technology from the previous section, the suitable solution that can provide the offshore WFs connection and also that can facilitate the trans-national exchange with a high cost efficiency, is the multiterminal DC transmission system (MTDC).

Most existing connections are point-to-point. The disadvantage in this case is the exchange of power only between two points - the offshore wind farm and the onshore main grid. This limitation does not exist in the multinational connection case because it allows the power flow between more than two points. Of course a more complex control scheme has to be implemented than in the point-to-point systems case.

Some examples of currently operational MTDC in the world are:

- Sardinia-Corsica-Italy is an extension of the two terminal DC system Sardinia- Italy build in 1967. A third terminal was added at Corsica in 1991. It's a classical HVDC three terminal with a power rating of 200 MW for two terminals and 300 MW for the other one. The DC voltage level is +/-200 kV [16].
- Hydro Quebec in New England, Canada is the first large scale multiterminal HVDC transmission in the world. The commissioning years 1986-1992. It's also a classical HVDC three terminal with a power rating of 2000 MW each, AC voltages of 315 kV, 230 kV, 345 kV and a DC voltage level of +/-450 kV [15].
- Shin-Shanano Substation of Tokio Electric Power Company (1999) with 3 back to back VSC converters. The power Rating is 53 MVA for each and +/- 10.6 kV DC voltage[10].

Similarly, other MTDC projects can expand from a point to point connection or new projects are developed based on the previous experiences.

In the nearly future a trans-national offshore grid would facilitate the access to the offshore energy resources, it would balance the wind power variations and also it would improve the cross-border exchange between the EU countries. Figure 1.8 shows the proposed 'Super grid' concept introduced by the project developer Airtricity in 2005. The 'Super grid' will allow the wind farms to operate collectively at variable speed and frequency, independent of the TSO's requirements. It is expected that the wind turbine generating efficiency will be improved and the losses due to the large distances will decrease. Also it will led to an update of the grid codes at the EU level, in this way the countries that are connected to the same network would have the same grid codes [13].



Figure 1.8: Version of high voltage 'super grid' to transmit wind power through Europe[5]

Greenpeace has made a study in 2008 on an offshore grid for the North Sea to interconnect the countries around it and also to connect the offshore wind farms that are in this region. The target is to connect up to 70 GW of wind power from North Sea, between 2020 and 2030 [5]. Figure 1.9 shows the proposed grid structure and also the new wind farms that will be build in this region. Below the figure it can be seen the forecast of wind energy production for each country connected to the North Sea grid.

The proposed grid should have the fallowing features:

- connecting the offshore wind farms;
- providing a trans-national exchange;
- balancing the demand and supply;
- maximization of the cable utilization;
- improving power systems operation efficiency.

Another example which was studied in [11] is the MTDC based on VSC technology that can be implemented in the North Sea for connecting the offshore wind farms with the oil and gas platforms and the onshore grid. In this way the emission of CO_2 from the oil and gas platforms that use gas turbines, can be avoided. For economic and environmental reasons the tendency is to replace gas turbines for the platforms with the electric supply from the onshore grid. Besides reduced CO_2 emission, the use of a MTDC connection between the offshore wind farm, the oil and gas platform and the onshore grid will led to reduced costs and better utilization of the transmission lines.



Figure 1.9: Offshore grid examined in the Greenpeace study[12]

There are two types for the MTDC configuration [16]:

- Constant voltage parallel scheme where the converters are connected in parallel and operate at the same voltage;
- Constant current series scheme where the converters are connected in series with a common direct current. The DC line has to be grounded at one point.

It is possible to have a hybrid system with both types of configurations. Most of the studies and the applications are based on the parallel configuration because of the fewer line losses, an easier control, more flexibility and possibility of future extension. The series configuration can be chosen if it is considered more economical to operate at high current and lower voltage [16].

A MTDC parallel configuration with four terminals is depicted in Figure 1.10 where is assumed that two terminals are generator point that can be conventional power plants or a wind farms and the other two are two different grids.



Figure 1.10: MTDC parallel configuration with four terminals

In the parallel connection case, one of the terminals establish the operating voltage of the DC system and the other terminals operate at constant current control. Maintaining a constant DC voltage during all conditions is one the important condition that MTDC has to fallow. Thus the VSC technology is proper for the implementation of the MTDC because it is no need to reverse the voltage polarity when changing the power flow and additionally the control of active and reactive power is made independently.

1.4 **Project Definition**

Up to now all offshore wind farms have used AC connection. This was a feasible solution mainly because of the low cost for the stations and cables at a short distance to the shore, also it is a proved reliable technology and it uses standard components (cables, transformers, reactors). Advances in power electronic technology have led to the development of HVDC systems more reliable and cost effective, making them a suitable solution for connecting a large offshore wind farm.



Figure 1.11: MTDC system description

The project investigates new control methods for connecting systems that are using DC transmission. The study is focused on the MTDC based on VSC technology.

The considered system layout is described in Figure 1.11 where System A and System B are two different grids and System C is an offshore wind farm. Another important target besides controlling the system was the modelling of the entire wind farm with all its components. Each wind turbine was designed to have its own rectifier. The output power of the wind farm is linked in a common point offshore, followed by a step up DC/DC booster. Next two DC links will connect each grid. An inverter is placed on both of the grid sides. All components and control of the system are studied and modelled in simulation tool Power Factory DIgSILENT.

In this project the VSC-HVDC technology (HVDC Light) was found to be the best option for connecting an offshore WF situated far out from the land connection point, offering low cable costs, it is more effective for power transmission on long distances and has high power capabilities. The implementation of this solution guarantees power exchanges between the three systems. Two converter stations are assigned to ensure the control of the DC voltage and the reactive power, meanwhile the other converter is controlling the AC voltage and the active power.

Different study cases will be carried out in order to verify the model.

1.5 Project Goals

The project is focused to offer an alternative way of connecting the offshore WF with two asynchronous grids. The solution comes with the *Multiterminal HVDC* concept which gives this possibility of connection.

The project goals are summarized as follows:

- implementation of the entire system in Power Factory DIgSILENT;
- overview of the possible transmission system that can be suitable for offshore wind farms;
- description of the VSC-HVDC transmission systems;
- study of the multiterminal HVDC connecting possibility;
- modelling of the offshore WF including all the components of the wind turbine (generator, aerodynamic model, mechanical model), the wind model and the pitch controller;
- modelling of the HVDC system including the PWM converters, the DC cables, the filters and the control structure for the converters;
- proper sizing of all of the system components;
- finding an efficient method of control of power sharing for the considered multiterminal system;
- verification of the implemented system by investigating realistic study cases.

1.6 Summary

The report investigates different aspects in finding an efficient way of connecting and controlling offshore wind farms and also tends to provide possible solutions to achieve that. A very useful simulation tool in developing and analyzing the power system was used. Power Factory DIgSILENT simulation software has been chosen because it is a specialized tool for building and studying the electrical energy generation, transmission and distribution in industrial systems. The project is organized in six chapters.

First the report begins with an introduction chapter which contains an overview of the offshore wind energy status, a short presentation of the possible transmission systems used in offshore projects and also the goals and problem statement of this project.

Chapter 2 begins with a presentation of the operation of Voltage Source Converters and the design of the DC transmission system components, followed by a steady state analysis of the multiterminal DC system.

The third chapter presents the development and implementation of the wind farm with the control (pitch controller) and all its components (the wind model, the aerodynamic model, the mechanical model, the generator model). The following chapter contains the description of the control technique implemented in DIgSILENT Power Factory for the generator side converter and the grid side converter

Chapter 5 includes all the results obtained during the simulation study. In order to better organize the analysis, different study cases were defined, each of them covering a particular subject. For each of the study case the results are analyzed and conclusions are taken.

Chapter 6 concludes the report and presents future work that the project has not yet covered. Improvements on the system are also pointed out.

Chapter 2

VSC Based MTDC System

2.1 Introduction

This chapter offers an overview of the VSC-HVDC transmission network. A brief description is made for all the components of the investigated system. The modelled elements of the DC system, the converters, phase reactors, AC filters, DC link capacitors and the DC cable are built-in models in DIgSILENT Power Factory. The dimensioning for all the components plays an important role in having a stable operation of the system. That is why a proper dimensioning must be done for calculating and defining the parameters of each element.



Figure 2.1: Layout of the proposed MTDC System

Figure 2.1 shows the overall structure of the considered MTDC transmission model. Three systems are interconnected through phase reactors in parallel with AC filters via VSC technology. The main function of the VSC-HVDC is to transmit constant DC power from the rectifiers to the inverters. It is considered that two of the converters work in the inverter mode, controlling the DC voltage and the reactive power and the third is working in the rectifier mode controlling the AC voltage and the active power. System C is considered to be the power generating system which supplies power for two different grids represented by System A and System B, as depicted in Figure 2.1. After the rectifier, DC/DC converters are used to boost up the voltage level to a higher voltage suitable for the HVDC transmission cable and on the grid side transformers are used for AC voltage boosting and galvanic isolation.

2.2 Components of the DC Transmission System

2.2.1 Converters

The voltage source converters are built based on power semiconductors and can operate in two way: as a rectifier (converts AC voltage in DC voltage) or as a inverter (converts DC voltage in AC voltage). The converters are joined through a DC link that will connect the two systems.

The HVDC technology uses two-level bridge topology and is the simplest circuit configuration which can be used for building up a three-phase forced commutated VSC bridge [4].

As depicted in Figure 2.2 the two-level converter consists of six values with anti-parallel diodes, one phase reactor for each phase and capacitors at the DC side. The converter is capable of generating two voltage levels $-0.5V_{DC}$ and $+0.5V_{DC}$. Each phase has two values, one between the positive potential and the phase terminal and one between the phase terminal and the negative potential [4]. The DC bus capacitors are used to separate the AC side from the DC side, thus no disturbances will be induced from one system to the other [20].



Figure 2.2: Two-level HVDC converter

The converter produce non-sinusoidal current and voltage waveforms which consist of the fundamental AC frequency plus higher order harmonics. AC filters are mandatory for reducing the harmonic content due to the switching operation of the IGBTs. Otherwise, the injection of these harmonics into the AC system will cause disturbances in the grid.

The outputted waveform by the converter contains harmonics of $m \cdot f_c \pm n \cdot f$ order, where f_c is the carrier frequency, f is the fundamental frequency and m, n are integers. One way of representing the modulation index M is the ratio between f_c and f (see equation 2.1) [19]:

$$M = \frac{f_c}{f} \tag{2.1}$$

The number of switching losses and harmonic losses can vary function of the modulation ratio. If M has a higher value then it will increase the switching losses and decrease the harmonic losses. As the value of the modulation ratio increases, the frequency of the lowest order harmonics produced is higher. So the passive high-pass damped filters are chosen to filter the high order harmonics [19].

The PWM converter implemented in this project is a built-in model and it is a selfcommutated VSC which not includes the the DC capacitance model. Based on (2.2) and (2.3) the converter can be modelled [21]:

$$V_{AC_r} = K_0 \cdot P_{mr} \cdot V_{DC} \tag{2.2}$$

$$V_{AC_i} = K_0 \cdot P_{mi} \cdot V_{DC} \tag{2.3}$$

where:

 V_{AC_r} real part of the AC voltage;

 V_{AC_i} imaginary part of the AC voltage;

 V_{DC} DC voltage;

 P_{mr} real part of PWM index;

 P_{mi} imaginary part of PWM index.

The load flow and RMS calculation are made always for the 50 Hz since the converter model is based on the fundamental frequency approach.

The converters can have a sinusoidal or rectangular modulation and depending on this, the factor K_0 can have different values. For the sinusoidal modulation this factor equals to:

$$K_0 = \frac{\sqrt{3}}{2\sqrt{2}} \tag{2.4}$$

2.2.2 Transformers

Power converters are frequently connected to the AC network through a transformer. Transformers have the function of converting the AC voltage to a suitable value for the converter. DIgSILENT Power Factory simulation tool has already implemented a model block for the two-windings transformer.

The transformer can be defined as an impedance. The total impedance, resistance and inductance of the transformer are given by the equations and these values are provided by the manufacturers in standard datasheets [18]:

$$Z_T = R_T + jX_T \tag{2.5}$$

$$Z_T = \frac{\Delta v [\%] \cdot V_{n_{AC}}^2}{100 \cdot S_n} \tag{2.6}$$

$$R_T = \frac{\Delta P_{cu} \cdot V_{n_{AC}}^2}{1000 \cdot S_n} \tag{2.7}$$

$$X_T^2 = Z_T^2 - R_T^2 (2.8)$$

where:

- $V_{n_{AC}}$ nominal AC voltage;
- Z_T total impedance;

 R_T total resistance;

 X_T total reactance;

 ΔP_{cu} copper losses;

 $\Delta v[\%]$ short circuit voltage.

2.2.3 Phase Reactors

The reactors are vertical coils, standing on insulators and are situated between the transformers and converters. There is one reactor per phase. The benefits of having phase reactors are [4]:

- limitation of short-circuit currents;
- blocking the harmonic current generated by the converter.

The phase reactors are very important elements in a VSC system. They are in charge of regulating currents through them, they work also as filters reducing the high frequency harmonics of the AC currents produced by the switching action of the VSCs [19].

Equation (2.9) shows how the reactance of the inductive filter is computed [20].

$$X_l = x_l \cdot Z_b \to L \cdot \omega = x_l \cdot Z_b \to L = \frac{x_l \cdot Z_b}{2 \cdot \pi \cdot f}$$
(2.9)

where:

- *L* Inductance of phase reactor;
- x_l Reactance of phase reactor;

 Z_b Base impedance of the converter $(Z_b = \frac{V_{nAC}^2}{S_n})$.

The detailed dimensioning of the phase reactors for the sending end and receiving end converters is to be found in Appendix C.4. and D.4, respectively.

2.2.4 AC Filters

When connecting a VSC to the transmission system the voltage must be sinusoidal and this is accomplished by using reactors and AC filters. VSC based on PWM is controlling the ratio between the fundamental voltage frequency on the DC and AC side.

The impedance corresponding for filtering different switching frequencies are calculated using formula (2.10):

$$\begin{cases} Z_o = z_o \cdot Z_b \\ Z_0 = \sqrt{\frac{1}{L_f \cdot C_f}} \end{cases}$$
(2.10)

where:

 z_o Impedance of the filters;

 L_f Filter inductance;

 C_f Filter capacitance.

One advantage of using VSC is that no reactive power compensation is needed, therefore the number of filters will be reduced and the current harmonics on the AC side are related only to the PWM frequency.

The calculation for the AC filter parameters of the is described in Appendix C.5. and D.5.

2.2.5 DC Capacitors

DC capacitors are placed on the DC side and the main goal is to provide a low inductive path for the turned-off current and an energy buffer to control the power flow [4].

If disturbances happen in the AC system the result will be variations in the DC voltage. The aim of there capacitors is to limit these variations. The proper sizing of these capacitors is essential in an HVDC system. Because of the switching frequency of the PWM converter, the current flowing to the DC side contains harmonics which will result in a ripple on the DC side voltage. The magnitude of ripples depends on the size of the DC capacitor and on the switching frequency [19].

The DC capacitor is calculated based on formula (2.11) [20]:

$$C_{DC} = \frac{P_{rated}}{V_{n_{DC}}^2} \cdot \frac{2 \cdot \xi_n^2}{\omega_l} \cdot \frac{1}{\delta_n (1 - \delta_n)}$$
(2.11)

where:
C_{DC} DC capacitor;

 $\omega_l = 2\pi \cdot 30 rad/s$ Voltage controller bandwidth;

 $\xi_n = \frac{1}{\sqrt{2}}$ Nominal damping for ripple;

 $\delta_n = 0.05$ Relative converter output voltage drop at rated power.

The computation of the DC capacitors is in Appendix C.6. and D.6.

The DC link capacitor size is characterized as a time constant τ , and represents the ratio between the stored energy at the rated DC voltage and the nominal apparent power of the converter [19]:

$$\tau = \frac{1}{2} \cdot \frac{C_{DC} \cdot V_{n_{DC}}^2}{S_{rated}} \tag{2.12}$$

where:

 S_{rated} rated apparent power.

Equation (2.12) shows the necessary time to charge the capacitor from zero to rated power when the converter is supplied with a constant active power. If the value of the time constant is small then a fast control of active and reactive power is possible.

2.2.6 DC Cable

Using DC cables for connecting the offshore wind farms to different systems offers several advantages such as better transmission efficiency for long distances and high powers, no magnetic losses, less weight then AC cables. The used cables have polymeric insulating material which provides them strength and flexibility, reasons that makes then suitable for severe installation conditions like submarine use [4].

For modelling the DC cables, a π model is used as depicted in Figure 2.3. DIgSILENT provides a built-in model for the HVDC lines. Two DC cables are defined in this project, having the transmission length set to 10 km and 30 km.



Figure 2.3: DC cable π link model

The total capacitance of the DC link model is characterized by the converters and the cable DC bus capacitance.

2.2.7 DC/DC Converter

The DC/DC converters are build-in models and are modelled as ideal components, having no losses. The purpose of their use is to step up the DC voltage to high DC voltage which is proper for the DC transmission cable. In this project a set of 4 DC/DC converters connected in series were used, having a gain factor for stepping-up the voltage set to 2.

2.3 Operation of VSC based HVDC Systems

The simplified equivalent circuit of one terminal single line voltage source converter is shown in Figure 2.4 where it was considered the rectifier mode. The operation of the HVDC-VSC can be expressed by a voltage source connected to an AC system through series reactors. The AC system is represented by an AC source u_f and it is connected with the VSC through the phase reactor X_l [19].



Figure 2.4: Equivalent circuit for VSC based HVDC one terminal

On the DC side the converters are modelled as a current controlled source I_{DC} . The current controlled source is calculated based on the power balance at the AC and DC side converter if the losses of the converter are neglected:

$$P_{AC} = Re(\overline{u}_v \overline{i}_v) = V_{DC} I_{DC} = P_{DC}$$

$$(2.13)$$

On the AC side the converter is modelled as a controlled voltage source u_v , where u_v has the following expression [19]:

$$u_v = \frac{1}{2} V_{DC} \cdot M \cdot \sin(\omega t + \delta) + harmonics \qquad (2.14)$$

where:

M is the modulation index (0 < M < 1) defined by the ratio between the peak value of the modulating wave and the peak value of the carrier wave. It is assumed that the space vector PWM method is adopted. Thus, the modulation index is [22]:

$$M = \frac{2\sqrt{2u_v}}{\sqrt{3}V_{DC}} \tag{2.15}$$

 ω the frequency of the u_v voltage;

 δ the phase shift between u_v and u_f voltages.

The amplitude, the phase and the frequency can be controlled independently of each other as it can be see in (2.14). The voltage drop ΔV on the phase reactor X_l can be adjusted by modifying u_v . Therefore, the active and reactive power flow can be controlled.

The active power P_f and the reactive power Q_f of the two voltage sources u_f and u_v from Figure 2.4 coupled with the impedance X_l , can be calculated using (2.16) and (2.17). The losses on of the phase reactor are neglected [19].

A phase shift δ between the two voltage sources u_f and u_v , determine the active power transmission, that can be calculated after formula:

$$P_f = \frac{u_f u_v \sin\delta}{X_l} \tag{2.16}$$

The reactive power flow is determine by voltage drop ΔV that is related to the amplitude of converter's voltage u_v as follows:



 $Q_f = \frac{u_f(u_f - u_v \cos\delta)}{X_v} \tag{2.17}$

Figure 2.5: Phasor diagram of the converter in rectifier and inverter mode

The phasor diagram of the VSC for both rectifier and inverter mode is depicted in Figure 2.5. If the voltage source u_v of the converter is in phase lag with the voltage u_f of the AC system, the power flow is directed from the AC to the DC side and the converter is in rectifier mode. If u_v is in phase lead, the power flow is form the DC to AC side and the converter acts as an inverter.

Figure 2.6 shows the phasor diagram of the reactive power regulation. If $u_f > u_v$ there is reactive power consumption. Otherwise, if $u_f < u_v$ there is generation of reactive power from the AC system [4].



Figure 2.6: Reactive power flow - Reactive power consumption and generation

The P-Q diagram depicted in Figure 2.7 presents the functioning area of the VSC function of active and reactive power regulation. Ideally the VSC are able to operate anywhere in the unity circle. Limitations are applied in the real functioning restricting the active and reactive power to the area delimited by the red curve [4].



Figure 2.7: P-Q diagram of the converter: ideal (circle area) and typical (red polygon area)[3]

The active power balanced condition of the HVDC system is fulfilled if one of the two terminals converters controls the active power flow while the other converter controls the DC voltage. The reactive power consumption or generation can be used to control the AC voltage.

2.4 Power Sharing Control Analysis for MTDC Systems

In the previous sections only the point-to-point HVDC connection was considered. In the multiterminal connection case, the configuration of the components remains the same, only that one or more DC links are added to main connection point.

The system that is considered for the steady state analysis is presented in Figure 2.8. It is a simplified equivalent model that contains one sending end station and two receiving end stations. In this analysis only the converters are considered and they are represented by current or voltage sources. The rectifier is modelled as a DC current source I_{DC} and the other two inverters are modelled as DC voltage sources, V_{DC1} and V_{DC2} . The losses of the converters are neglected and the DC cables are modelled as resistors, R_1 and R_2 . Each of the resistors is depending on the cables data and the DC link length.



Figure 2.8: Steady state model for the MTDC system

The problem that is raised is how to control the power flow through all the terminals connected to the DC grid. To solve this issue the following considerations are taken in this study:

- the two inverters are controlling the DC voltages for each DC link, V_{DC1} and V_{DC2} ;
- the rectifier is controlling the active power;
- the available power from the rectifier and the power demands of the two inverters are variable and they are known;
- the losses of the multiterminal system are represented by the two resistance R_1 and R_2 , it is considered that the DC cable represented by R_2 is three times longer than the DC cable R_1 ;
- all the parameters are represented in per unit system.

The problem can be reduced to finding the voltage levels of the inverters V_{DC1} and V_{DC2} knowing: the losses on each DC link R_1 and R_2 , the total available power from the rectifier P_T and the power demands of each inverter P_1 and P_2 for a given input power.

Based on Figure 2.8 the equations which are used for the steady state analysis of a MTDC are computed .

The active power generated by the rectifier terminal is:

$$P_T = V_{DC} I_{DC} \tag{2.18}$$

where:

 V_{DC} the voltage on the three terminals connection point

 I_{DC} the DC current output from *Rectifier*.

The current I_{DC} is the sum of the currents I_1 and I_2 that are flowing to the two terminals that are working in inverter mode. Both of the currents can be expressed function of the connection point voltage V_{DC} , the voltage sources that represents the inverters V_1 and V_2 and the cables resistance R_1 and R_2 , as follows:

$$I_1 = \frac{V_{DC} - V_1}{R_1} \tag{2.19}$$

$$I_2 = \frac{V_{DC} - V_2}{R_2} \tag{2.20}$$

The power absorbed by the two inverters P_1 and P_2 can be calculated as:

$$P_1 = V_1 I_1 \tag{2.21}$$

$$P_2 = V_2 I_2 \tag{2.22}$$

Based on (2.18) and (2.22), the dependence of the voltages V_1 and V_2 on the power demands of the *Inverter* 1 and *Inverter* 2 has to be found.

First, the common point voltage is calculated as:

$$V_{DC} = RI_{DC} + \frac{R}{R_1}V_1 + \frac{R}{R_2}V_2$$
(2.23)

where:

R the equivalent parallel resistance of the circuit: $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$.

Equation (2.23) represents the relation between the current source I_{DC} and the voltage sources V_1 and V_2 .

The rectifier output is given by:

$$P_T = R \cdot I_{DC}^2 + I_{DC} \left(\frac{R}{R_1} V_1 + \frac{R}{R_2} V_2 \right)$$
(2.24)

The first term in (2.24) represents the power losses in the multiterminal system and the second one represents the power absorbed by the two inverters. A new parameter can be introduced, the voltage level sensitivity, with the expression defined as:

$$C = \frac{R}{R_1} V_1 + \frac{R}{R_2} V_2 \tag{2.25}$$

Because all the parameters are in the per unit system, the voltage level sensitivity is considered to be adimensional. It is an important parameter because it shows the dependence between the two voltage levels V_1 and V_2 . The proper value has to be found for C in order to maximize the power transfer to the inverters and minimize the losses, while keeping a constant ratio between V_1 and V_2 . Both DC voltage levels depend on the power demand of each grid and in the same time they have to vary with respect to (2.23) in order to maintain a balanced power flow. C is varying function of the total power P_T and it must be kept constant while the voltage in the main connection point, V_{DC} is maintained to its rated value 1 pu. Figure 2.9 shows the relation of the voltage level sensitivity function of V_{DC} at different values of the total available power. The suitable value for C is chosen from this graphic, for example at full power generation C is 0.948 and at 0.4 pu power C is 0.98.



Figure 2.9: Voltage level sensitivity function of V_{DC} for different values of the total power

After introducing (2.25) in (2.24) a second order equation is obtained:

$$RI_{DC}^2 + I_{DC}C - P_T = 0 (2.26)$$

The independent expression for each inverter is found, function of:

- total power P_T ;
- losses of the system R_1 and R_2 ;
- voltage level sensitivity C;
- power demand for each terminal P_1 or P_2 ;
- voltage level for each inverter V_1 or V_2 .

$$P_1 = \frac{V_1}{R_1} \left(R \frac{-C + \sqrt{C^2 + 4RP_T}}{2R} + C - V_1 \right)$$
(2.27)

$$P_2 = \frac{V_2}{R_2} \left(R \frac{-C + \sqrt{C^2 + 4RP_T}}{2R} + C - V_2 \right)$$
(2.28)

Based on (2.27) and (2.28) the control of the MTDC system can be implemented. The DC voltage set-points of each inverter can be calculated independently to obtain the proper power sharing between the two terminals.

Furthermore, a dependence of the voltage level sensitivity on the total power available from the inverter can be found. Figure 2.10 shows how the voltage level sensitivity varies function of the total power.



Figure 2.10: Linear depend ace of the voltage level sensitivity C on the total power P_T

From this graphic the linear depend ace can be found:

$$C = 1 - 0.052P_T \tag{2.29}$$

By using (2.29) in (2.27) and (2.28), the equations of the two voltages V_1 and V_2 can be expressed only by the total power P_T and the and the power sharing for the two inverters P_1 and P_2 .

Several simulations were performed in Matlab to prove the accuracy of the described control method from above.

It is supposed that the total power P_T of the rectifier is varying. The distance between *Rectifier* and *Inverter2* is three times greater than the distance between *Rectifier* and *Inverter1*. Also it is considered that the *Inverter 1* imposes its power demand and *Inverter 2* is connected with a strong grid which can absorb or generate all the power needed for the grid connected with *Inverter 1*.

Figure 2.11 and 2.12 describes how the two inverters have to set their DC voltages function of the power sharing, considering also a variable P_T generated power. The power demand of *Inverter 1* is between 0% to 100% from all the available power that is varying from 0 to 1 pu. *Inverter 2* adjusts its DC voltage function of the two variables, inverse proportional with the voltage level of *Inverter 1*. The range in which V_{DC1} varies is 0.92 to 1 pu while the range for V_{DC2} is 0.79 to 1.02 pu. The variation interval depends on the losses on each terminal that are represented in this study case by R_1 and R_2 .



Figure 2.11: DC voltage levels for *Inverter 1* function of the power demand of *Inverter 1* for different values of the total power



Figure 2.12: DC voltage levels for *Inverter 2* function of the power demand of *Inverter 1* for different values of the total power

Figure 2.13 shows the power regulation of the two inverters in per cents from the total generating power when this varies. It can be observed that P_2 has an inverse proportional dependence on P_1 . If the power demand for *Inverter 1* is 0 the *Inverter 2* will absorb all the available power minus the power losses from the DC link. The power sharing for *Inverter 2* is decreased by a higher demand from *Inverter 1*.



Figure 2.13: P_1 and P_2 sharing power when the total power is varying

It is considered that *Inverter 1* can demand up till 100% from all the available power. In this situation the power sharing for *Inverter 2* is going down to the negative axis meaning that it will have to provide power to complete the necessary of power demand for *Inverter 1* and also to cover the losses. It will work in rectifier mode.

The losses of the entire system P_{losses} are varying function of the current I_{DC} thus function of the power outputted by the rectifier P_T .

In Figure 2.14, the variation of the losses function of the power demand P_1 and generated P_T is presented.



Figure 2.14: Power losses function of power sharing of *Inverter 1* and the total generated power

The highest losses are when *Inverter* 2 takes all the available power. This is due to the fact that *Inverter* 1 is considered to be situated at a greater distance than *Inverter* 2 from the *Rectifier*. The lowest power losses are for 70 % power demand from *Inverter* 2.

Minimum losses are obtained for a power sharing $P_1 = 70\%$ and $P_2 = 24.8\%$ at full power generation when the cable that connects *Inverter 2* is three times longer than the one that links to *Inverter 1* from the *Rectifier*.

The steady state study presented in this section is used to develop the control strategy of the HVDC-VSC converters that are working in inverter mode in the multiterminal system described in this project. This procedure can be further extended to more receiving end stations.

2.5 Summary

In this chapter an overview of the VSC-HVDC transmission system was presented. The configuration of the system with all the components were described in detail. An equivalent model of the VSC-HVDC was depicted in order to explain the functioning for both rectifier and inverter mode of the converter. Based on the study of the VSC-HVDC operation some important features are highlight[4][19]:

- independent control of active and reactive power without use of additional communication equipment;
- reduced risk of commutation failure because the IGBTs are self commutated devices;
- power quality improved by means of reactive power capabilities that control the AC network voltage and the increased switching frequency of the IGBTs;
- a suitable solution for connecting wind farms or feeding industrial installations because it is capable to generate a predetermined AC voltage with a specific frequency;
- a suitable solution for multiterminal connections since communication between the converters is not needed and the control of the multiterminal system can be performed even if one of the terminals fails.

Based on the point-to-point VSC-HVDC transmission system, a new control method of the DC voltages for a multiterminal connection was presented. It is further used for the converters control in the following chapters.

Chapter 3

Wind Turbine Modeling

3.1 Introduction

The present chapter aims to offer a detailed depiction of the particular wind turbines studied in this project with all of their basic elements. The simulation model was built and developed in power system tool DIgSILENT Power Factory. Two different models have been used: the built-in models, models provided by the software and DSL models which are designed implemented by the user.

A simplified block diagram of the wind turbine components is presented in Figure 3.1. As shown in the scheme, the elements of wind turbine are the wind model, the aerodynamic model, the mechanical model, the generator model, the rectifier and the pitch control block model. The input of the system is the wind and the output is the electrical power. The wind model provides a realistic characteristic of the wind which is modeled based on an average wind speed profile. This wind is further on applied to the rotor blades. The aerodynamic model computes the rotor torque (T_r) which is the input for the mechanical model that makes the conversion of the mechanical torque of rotor into a torque proper for the the high speed shaft.



Figure 3.1: Wind Turbine Model

For the generator model a squirrel cage induction generator is used. This performs the conversion of the mechanical power outputed by the mechanical model (P_m) into the electrical

power (P_{meas}) , followed by the transformation from an AC to DC transmission system made by the rectifier.

The aim of the pitch controller is to ensure that the wind turbine, depending on the available wind is producing the desired power imposed by the TSO. Based on the measured power of the system and the reference value for power, the pitch control has to adjust the angle of the blades in order to maintain a constant reference power when higher winds are applied to the WT. The power reference can be set to be the rated power of the WT but depending on the demands of electricity. The grid operator can change this reference in order to maintain the stability of the grid.

The offshore wind farm is the third terminal in the MTDC and is represented by 'System C'. The WF is scaled to a number of three wind turbines connected in parallel and it have been designed and modelled.

3.2 Modelling WT components

3.2.1 Wind Model

Due to the fluctuations present in wind, the power quality is significantly influenced. The wind model outputs the wind characteristic, an important parameter in the implementation of the system.

The wind model provides an equivalent wind speed (v_{wind}) which is further applied to the aerodynamic model. For computing the value of v_{wind} , the rotational turbulence, the tower shadow and the variations in the whole wind speed field over the rotor disk are considered[29]. The model is based on the Matlab model developed by RISØ presented in [26].

Figure 3.2 shows the structure of the wind model which is based on two sub-models: the hub and the rotor wind model. The wind model was developed in DIgSILENT Power Factory using DSL.



Figure 3.2: Scheme of the wind model

The output v_{wind} represents the wind speed that is extracted by the wind turbine's rotor for each simulation time step, based on two inputs: the average wind speed and the rotor position. The average wind speed input is a 'ElmFile' block in Power Factory. This can be a profile defined by user or real data obtained by measurements of the wind speed. Each v_m value can be obtained as the average of the instantaneous speed over a time interval, t_p , around 10 to 20 min [7]:

$$v_m = \frac{1}{t_p} \int_{t_o - t_{p/2}}^{t_o + t_{p/2}} v_{wind}(t) dt$$
(3.1)

The second input is the rotor position (θ_r) that contains information from the mechanical system. It has a notifiable impact upon the fluctuations in the power with three times the rotational frequency. Therefore the rotational sampled turbulence is modeled as a 3p fluctuation with variable amplitude [27].

As presented in [26] both the hub and the rotor subsystems are composed by a cascade of Kaimal, zero order and third order filters (see Appendix A.1). The wind model contains also three identical noise generators. The 'ElmNoise' built-in models in Power Factory are used to produce noise signals based on random numbers.

The hub model describes the fixed point wind speed at the hub high of the wind turbine having as inputs one white noise generator and the average wind speed.

The wind speed v_{hub} , resulted from the hub model, the rotor position and two noise generators are the inputs of the second sub-model, the rotor. The rotor wind models add the effect of the integration of the fixed-point fixed speed over the whole rotor. The variations caused by the rotational turbulence and tower shadow in the wind speed field over the rotor disk are taken into account through a Kaimal filter and an admittance filter for the third harmonic [29].

The parameters of the wind model are: the sample time, the blade radius, the average wind speed, the length scale and turbulence intensity. The turbulence intensity includes all the wind speed fluctuations in the range of seconds or minutes and it has a major impact on aerodynamic loads and power quality. The wind turbulence in a certain point can be described by the Kaimal filter (see Appendix A.1) [7].

Figure 3.3 shows the simulation results of the wind model built in Power Factory DIgSI-LENT. The input .txt file is a user defined vector with average wind speeds that varies from 6 to 22 m/s. As may be seen, the equivalent wind speed has variations with a mean value around the input average wind speed and it follows the ramp variations of the input.



Figure 3.3: Wind time series

To validate the wind model, the power spectra density method was used. For this analysis

a time interval of 600 was taken. The rated average wind speed was applied at the input as presented in Figure 3.4. Knowing that the rated rotor speed is equal to 16.5rpm in Figure 3.4 can be observed that the 3p turbulent component resulted in the wind power content is at the frequency that corresponds to 3 times rotor speed (0.82 Hz).



Figure 3.4: Wind speed profile for rated average value (a) Power spectra density of the wind (b)

3.2.2 Aerodynamic Model

Figure 3.5 shows the structure of the aerodynamic model. The purpose of the aerodynamic model is to simulate the torque of the rotor shaft. The inputs are the pitch angle (θ) from the pitch controller block, the wind from the wind model and the speed of the rotor fed back from the mechanical model.

This block is modeled by using:

- a look-up table of the power coefficient, C_p , which is a function of the pitch angle and tip speed ratio and represents the capability of the WT to extract energy from the wind;
- a DSL simulation model for the aerodynamic torque that describes a non linear formula of the aerodynamic torque of the WT's main shaft, presented in (3.3) [7].



Figure 3.5: The aerodynamic model structure

The power that the rotor of the wind turbine can generate from the available wind is direct proportional with the rotor aria (r^2) , the air density (ρ) , the cubic of the wind speed and the power coefficient $C_P(\lambda, \theta)$.

$$P = \frac{1}{2}\rho\pi r^2 C_P(\lambda,\theta) v_{wind}^3 \tag{3.2}$$

while the aerodynamic torque has a cubic dependence of the blade radius and a square dependence of the wind:

$$T_r = \frac{1}{2}\rho\pi r^3 C_Q(\lambda,\theta) v_{wind}^2 \tag{3.3}$$

The torque coefficient (C_Q) , which is in direct relation with C_P is implied in the torque expression, where:

$$C_Q = \frac{C_P}{\lambda} \tag{3.4}$$

The tip speed ratio λ is an important parameter in the control scheme since it varies function of the rotational speed of the rotor (Ω_r) , the blade radius and the speed of the wind:

$$\lambda = \frac{\Omega_r r}{v} \tag{3.5}$$

The C_P look-up table that is used can be found in the attached CD of this report. Based on (3.2) the aerodynamic torque is:

$$T_r = \frac{P}{\Omega_r} = \frac{1}{2}\rho\pi r^2 \frac{C_P(\lambda,\theta)}{\Omega_r} v^3$$
(3.6)

The power coefficient is specific for each wind turbine. It varies function of the tip speed ratio (λ) and the pitch angle (θ) and usually is provided by the wind turbine manufacturer as a look-up table.



Figure 3.6: Variations of power coefficient function of tip speed ratio for different pitch angles

Figure 3.6 shows how the power coefficient varies function of the tip speed ratio. Due to the fact that the aerodynamic power is direct proportional with the power coefficient, the maximum aerodynamic power is reached when C_P has its maximum value. Figure 3.6 shows the power coefficient variation function of the tip speed ratio for different pitch angles. The maximum C_P value is obtained for a pitch angle of 0° and a tip speed ratio corresponding to the rated wind speed. For pitch angles exceeding 0° , C_P is decreasing.

The power coefficient is the expression of the efficiency of the wind turbine. According to Betz Law the wind turbine can not convert more than 16/27 (59.3%) of the kinetic wind energy into mechanical energy [5]. Therefore the maximum limit imposed for C_P is 16/27. By plotting C_p as a function of θ values from 0° to 46^0 are obtained for the pitch angle as it can be seen in Figure 3.7. This represents the range in which the pitch angle can be varied to regulate the output of the wind turbine.



Figure 3.7: Power coefficient as function of pitch angle

In DIgSILENT Power Factory a special block is used to import the $C_p(\theta, \lambda)$ look-up table. This block is a built-in model called 'ElmChar2' where the limits of the inputs θ and λ can be defined and also the step size for each column and row. The inputs of the 'ElmChar2' block are the pitch angle and the tip speed ratio. Having these coordinates on the lines and the columns of the look-up table, the afferent C_P value is picked.

Afterwords the torque of the rotor is calculated in the *Aerodynamic Torque* DSL block. It uses the formula (3.6) where the torque coefficient is function of the inputs of the simulation block (the power coefficient, the wind speed and the speed of the rotor). Torque is shown in Figure 3.5.

When initial conditions are performed, the aerodynamic torque, T_r must be proper initialized. This is done by making the correct initialization of the wind, pitch angle and WT rotor speed. It were considered the initial values for v_{wind} , and Ω_r to be the rated one.

Figure 3.8 presents the variations of the power in p.u. function of the speed of the rotor, at different wind speeds, by keeping the pitch angle to the optimum value. The base value for the power is $P_{base}=2.3$ MW and the rated speed of the rotor is $\Omega_r = 1.72$ rad/s, taken from the data sheet of the wind turbine [23]. Seven different wind speeds are considered.

The first value is the cut-in speed (4m/s). It represents the speed of the wind from which the WT starts to operate and it has the minimum output power. At the rated rotor speed $\Omega_r = 1.72$ rad/s and the rated wind speed 11.9 m/s, the rated power is obtained. For wind speeds above these value the aerodynamic power is increasing. A control techniques have to be implemented in order to limit the power extracted from the wind in order to maintain the rated range of wind turbine's operation. *Power maximum curve* contains the maximum aerodynamic power afferent to each wind speed and the rotor operating points.



Figure 3.8: Power vs. rotor speed at different wind speeds, with zero pitch angle

For the same wind speeds, Figure 3.9 presents the variations of aerodynamic torque in p.u. function of the rotor speed.

The base value for the torque is:

$$T_{base} = \frac{P_{base}}{\Omega_r} = 1.34MNm \tag{3.7}$$

For the rated value $\Omega_r = 1.72$ rad/s, the rated torque is obtained (T=1 p.u.).

Torque maximum curve contains the speeds of the rotor for which the torque has maximum values. As it can be seen in the Figure 3.9, *P* maximum and *T* maximum curves do not mach - they contain different speeds of the rotor at which the power and torque, respectively, are maximum.



Figure 3.9: Torque vs. rotor speed at different wind speeds, with zero pitch angle

The function of the aerodynamic model is to determine the aerodynamic torque based on the equivalent wind speed and on the tip speed ratio that determines the angle of attack.

3.2.3 Mechanical Model

The wind turbine is usually connected to the generator by means of a gearbox and a drive train. The drive train is in charge of delivering the mechanical power to the generator model. The mechanical model has a significant influence on the interaction of the wind turbine with the grid. From the electrical point of view a two mass model representation of the drive train is sufficient [31]. The masses considered for a two mass model correspond to the WT's moment of inertia and to the generator's moment of inertia. The moment of inertia for the shafts and the gearbox wheels are neglected because they are small compared to the previous two. The gearbox ratio has influence on the system. In this project an ideal gearbox which makes the conversion from low speed to high speed is considered, having the radio $1: k_{gear}$.

In Figure 3.10 are shown the components of two mass model [7]:

- the large rotor inertia (J_{rotor}) representing the blades and the hub;
- small rotor inertia (J_{gen}) corresponding to the generator.

The low speed shaft is characterized by the torsional stiffness k_{stiff} and the damping coefficient c_{damp} . The high speed shaft is considered to be stiff.



Figure 3.10: Equivalent mechanical model of the WT: two mass model

For the implementation of the mechanical model in Power Factory DIgSILENT a DSL block was used. The scheme of this model is presented in Figure 3.11.



Figure 3.11: Drive train block in Power Factory

The purpose of the drive train is to convert the mechanical torque, calculated in the aerodynamic model, into a torque suitable for the high speed shaft. This conversion is made by using differential equations based on [7], [31]:

$$\theta_k = \theta_r - \frac{\theta_{gen}}{k_{gear}} \to \dot{\theta}_k = \dot{\theta}_r - \frac{\theta_{gen}}{k_{gear}} = \Omega_r - \frac{\omega_r}{k_{gear}}$$
(3.8)

$$\theta_r = \Omega_r \tag{3.9}$$

$$\dot{\Omega}_r = \frac{T_r}{J_{rotot}} - \frac{c_{damp}}{J_{rotor}} (\Omega_r + \frac{\omega_r}{k_{gear}}) + \frac{k_{stiff}}{J_{rotor}} \cdot \dot{\theta}_k$$
(3.10)

where θ_k is the difference between the rotor angle and the generator angle. On the low speed shaft, the mechanical torque T_s is computed using (3.11):

$$T_s = c_{damp} (\Omega_r - \frac{\omega_r}{k_{gear}}) + k_{stiff} \cdot \theta_k$$
(3.11)

The relation between the low shaft speed and high shaft speed is given by the gear radio:

$$k_{gear} = \frac{\omega_r}{\Omega_s} \tag{3.12}$$

On the high shaft speed the torque T_m is calculated as follow:

$$T_m = \frac{T_s}{k_{gear}} \tag{3.13}$$

As it can be seen in Figure 3.10 the drive train outputs the mechanical power 'pt' which is applied to the generator. This power must be a per unit values and is calculated using (3.14):

$$pt = \frac{T_m \cdot \omega_r}{P_{base}} \tag{3.14}$$



Figure 3.12: Low shaft speed (Ω_r) response of the drivetrain

In Figure 3.12 and Figure 3.13 are presented the low shaft speed and the mechanical power obtained by applying a constant wind speed with the value equal to the rated one. Figure 3.12 shows that Ω_r is kept constant to its rated value. This proves that the model of the drive train was correctly implemented.

The mechanical power represents the power that is applied to the generator. As it can be seen in Figure 3.13 the mechanical power outputed by the drive train is as expected 1 pu therefore the model was properly defined.

where
$$P_{base} = P_{rated}$$



Figure 3.13: Mechanical power (pt) outputed by the drive train

The datasheet of the drive trains is given in Appendix A.2.

3.2.4 Generator Model

In designing the WTs, another element must be defined that plays an important role in the electrical system. For this project the WTs are considered to be equipped with squirrel cage induction generators. This asynchronous machine is implemented in DIgSILENT Power Factory as a built-in model.

In Figure 3.14 is presented the built-in model for the SCIG is 'ElmAsmo' which has as input the turbine power ('pt'), meaning the mechanical power which comes from the mechanical model and as outputs the active power 'pgt' and the generator speed 'xspeed'.



Figure 3.14: SCIG block diagram in DIgSILENT [3]

The input parameters for the SCIG can be defined in two ways:

- by directly specifying the electrical parameters (the rotor and stator resistances and reactances);
- by specifying the slip-torque and slip-current characteristic of the generator.

If the electrical parameters are not given they can be calculated from the nominal operation point and slip-torque/slip-current characteristics. The nominal operation point is specified by the rated mechanical power, the rated power factor, the efficiency at nominal operation and the nominal speed [30].

The steady state parameters of the SCIG are defined by (3.15) and (3.16).

Figure 3.15 describes the squirrel cage induction generator model in steady state operation.



Figure 3.15: Equivalent circuit of SCIG in steady state operation

In Power Factory the voltage equations are expressed in per unit quantities [7]:

$$u_s = R_s \cdot i_s + j \cdot \omega_s \cdot \psi_s + \frac{d\psi_s}{dt}$$
(3.15)

$$0 = R_r \cdot i_r + j(\omega_s - \omega_r)d\psi_r + \frac{d\psi_r}{dt}$$
(3.16)

where:

 $\begin{array}{lll} R_s & \mbox{winding resistance;} \\ \omega_s & \mbox{synchronous speed;} \\ \omega_r & \mbox{angular speed of the rotor;} \\ \psi_s, \psi_r & \mbox{space vectors for flux of the stator and the rotor;} \\ i_s, i_r & \mbox{space vectors for flux of the stator and the rotor;} \\ u_s & \mbox{space vector for the stator voltage.} \end{array}$

In this project the input parameters for the generators have be set to be electrical parameters. The electrical parameters must be in p.u. thus using the datasheet of the generator the R_s, X_s , R_r, X_r, X_m and J_{qen} are obtained.

After obtaining all the parameters needed, which can be found in Appendix A.3, the generator model can now be defined in Power Factory.



Figure 3.16: Active power output of the generator at rated wind speed

Simulations were performed to verify the accuracy of the implemented block. As may be seen in Figure 3.16 for the constant wind speed kept constant to its rated value the generator outputs the rated power as expected.

3.3 Pitch Angle Control

Wind turbines are designed to extract electrical energy from the kinetic energy given by the wind. At stronger winds, the excess power must be canceled by pitch-controlling the WTs to avoid damaging the wind turbine.

The pitch controller is mostly applied for variable speed WT but it can be used also for fixed speed WT [24]. The purpose of this controller is to regulate the output power by pitching the rotor blades in or out of the wind. By changing the pitch angle, the power limitation or optimization can be performed depending on the wind value. The operation of the pitch controller is divided in three main parts:

- *power limitation block* -increase the pitch angle to limit the power that the blades can extract from the wind;

- *power optimization block* - keeps the pitch angle to the optimal value in order for the blades to extract maximum aerodynamic power;

- *switching block* - makes the selection between power optimization and power limitation modes.

The operational modes of the WT are depicted in Figure 3.17. The minimum value of the wind from which the WT starts operating v_{cut-in} is set to be between 3-5m/s. The maximum value of the wind speed at which mechanical overloading is avoid, is $v_{cut-out}$ that is equal to 25m/s. These values are taken from the datasheet of the SCIG [23]. The decision of changing between power limitation and power optimization is dependent on the rated wind speed, v_{rated} . This represents the wind value at which the generator works at its rated power.



Figure 3.17: Static power curve of a pitch controlled WT

The principle of the control system is depicted in Figure 3.18 where X represents the controlling signal and X_{ref} the reference signal. The error ΔX is applied to a PI controller which outputs the reference value of the pitch angle, θ_{ref} .



Figure 3.18: Model of pitch angle controller

In order to have an accurate and realistic response of the blade angle control system, a number of delay mechanisms are implemented in the control model such as: the servomechanism and the rate limiter for both the pitch angle and the gradient. The pitch servo has the time constant T_s set to be 0.25 and the pitch rate limits between ± 3 and $\pm 10^0/s$ [25].

The input system of the blade angle controller can be defined to be either the power or the speed. In this project the input was chosen to be the power. The power reference is compared to the measured mechanical power and the difference is sent to the PI block which will produce the reference pitch angle, θ_{ref} . This reference is limited in the range of optimal angle (θ_{optim}) and maximum value of the angle (θ_{max}). Further, θ_{ref} is compared to the actual pitch angle and then the error is corrected by the servomechanism [7].

The output of the blade angle controller is the pitch angle (θ) which is the input for the aerodynamic model, where the y (C_P) is calculated.

Figure 3.19 shows the power variations function of the pitch angle. In order to observe how the pitch angle has to be adjust to obtain the rated value for active power (1p.u), different values for the wind speed above the rated one were chosen. As it can be seen in Figure 3.19, for the selected range of wind speeds, to output the rated power of the WT , the suitable values for the pitch angle are between 0^0 and 34^0 .



Figure 3.19: Measured active power function of pitch angle for different wind speeds

3.3.1 Gain Scheduling for the PI Controller in Power Limitation

The 'Power limitation' block has as input the difference between the electrical power measured at the output of the generator, P_{meas} , and the power reference set-point, P_{ref} as it can be seen in Figure 3.20. The result of this simulation block is the pitch angle that has to be applied to the blades in order to maintain the P_{ref} value.

The power reference point can be defined as the rated power of the WT and also can vary function of the demands of power from the TSO for all the wind farm. For example if the demand for one WT is 0.6 p.u., looking at Figure 3.19, the pitch angle has to be 12° for the rated wind speed and it is increasing up to 35° for a value of 24 m/s for the wind speed.

For calculating PI's parameters it is considered that P_{ref} is fixed, equal with the rated active power. P_{meas} from the output of the generator is in p.u, thus P_{ref} is considered to be 1 p.u.

Ideally, the wind speed has to be the control parameter for the pitch controller. The wind speed can not be measured precisely, therefore the measured active power of the generator and the pitch angle are used as the gain scheduling parameters.

The 'Power limitation' block (see Figure 3.20) consists from the following simulation models:

- *PI Controller* is a DSL block used for finding the pitch angle value based on the difference between the reference and the generator's measured value of the active power;
- *Limiter* is included in the PI controller DSL block; it keeps the values of the pitch angle between 0⁰ and 90⁰;
- Anti-windup scheme used to avoid the integration of the PI while the power control is not active or while the pitch angle is held constant [11]. It is included in the PI controller.

• Gain Scheduling - DSL block.

The purpose of the gain scheduling is to find the adequate value of the proportional gain K_{PI} from the transfer function of the PI:

$$G(s) = K_{PI} + \frac{1}{Ts} \tag{3.17}$$

The integral gain $\frac{1}{T}$ is considered to be equal to one [7].

A linear control of the pitch would lead to errors in limiting the power to its rated value at high wind speeds. Therefore, a non-linear method (gain-scheduling) is needed to establish the right control strategy.



Figure 3.20: Power limitation model

Based on the reference [7] the gain scheduling method was implemented for this model. The total propertional gain (K) can be apprecised function of the the perodynamic sensi

The total proportional gain (K_t) can be expressed function of the the aerodynamic sensitivity of the system $\frac{dP}{d\theta}$:

$$K_t = K_{PI} \frac{dP}{d\theta} \tag{3.18}$$

The aerodynamic sensitivity depends on the variations of the wind or the pitch angle.

Figure 3.21 shows how the aerodynamic sensitivity varies function of the pitch angle for different wind speeds. A value for K_{PI} has to be found in order to minimize $\frac{dP}{d\theta}$.



Figure 3.21: Input of the PI controller function of the pitch angle for different wind speeds

 $\frac{dP}{d\theta}$ variations can be approximated by a linear expression function of the pitch angle:

$$y = a\theta + b \tag{3.19}$$

Figure 3.22 shows the aerodynamic sensitivity approximation at 20m/s. The linear variation of the aerodynamic sensitivity is $\frac{dP}{d\theta} = y$, where y = ax + b and x represents the the pitch angle. By applying the line equation, the parameters a and b are found and y has the following expression:

$$y = -0.1843x + 3.4231 \tag{3.20}$$



Figure 3.22: Approximation of the PI controller input variation for a fixed speed

Next, the proportional gain for this particular wind speed (K_{basis}) is calculated. It is the value for which the y variation is closest to zero.

The controller gain K_{PI} is function of the K_{basis} fixed value and the reciprocal of the aerodynamic sensitivity variations:

$$K_{PI} = K_{basis} \left(\frac{dP}{d\theta}\right)^{-1} \tag{3.21}$$

If the aerodynamic sensitivity is high (determined by high wind speeds thus, by large pitch angles), the controller gain has to be small and vice-versa. Therefore, the gain scheduling enables an adequate control of the pitch angle over whole range of wind speed.

The pitch angle can vary in a predefined period of time. This is given by the size of the blade radius and also by financial issues, usually pitch angle can be modified with $3-10^{0}$ per second [11].

3.3.2 Pitch Controller Verification

To verify if the pitch controller works properly, the active and reactive power obtained for wind variations for 300 seconds, is analyzed. Figure 3.23 presents the wind speed profile that is applied to the blade angle controller. The wind speed is changing between 5m/s until 23m/s. The pitch angle is changing together with the wind, the greater are the wind speeds the biggest are the values of the pitch as can be observed in Figure 3.25. In order to limit the power output for wind above v_{rated} the pitch is taking values from 0^0 to 22^0 .



Figure 3.23: Wind speed profile

The PI controller starts working as soon as the wind speed exceeds 11.9m/s. Therefore the error signal between the measured power and the reference power must be hold to zero. As can be observed in Figure 3.24 this achieved.



Figure 3.24: Error signal of the pitch controller loop

When v_{rated} is exceeded the output power must be hold constant to P_{rated} and Q_{rated} . In the time [0, 40s] the wind is at the rated value so, there is no need to pitch the rotor blades (the pitch angle is kept constant) but from the time interval [130, 300s] the wind starts to vary from 18 to 23 m/s and and the pitch is continuously changed in order to limit the power to the nominal value, as shown in Figure 3.25. By not exceeding the rated values for the power means that the pitch controller model is working and the simulations results can be considered reliable.



Figure 3.25: Pitch angle response

The power coefficient is a function based on two variables: the wind speed and the pitch

angle. This is computed using a look-up table. Having the wind profile from Figure 3.23, it can be observed that the power coefficient is changing together with the wind as presented in Figure 3.26.



Figure 3.26: Response of the pitch angle and C_p for different wind speeds

The purpose of implementing a pitch model is to have a better control on the power injected by the wind turbines into the grid. The simulation results obtained in Power Factory DIgSILENT validates the pitch controller model.

3.4 Conclusions

Modelling of the wind turbines components have been the goal in this chapter. A detailed description of the WT system was included. This chapter was also focused on investigating and developing the power regulation control block. Simulations are performed to prove the WT system reliability and to have a better understanding of the functioning for each block.

Chapter 4

System Control Design

This chapter describes the converters control structures of the three systems implicated in the MTDC. The detailed description for the converters models is included together with results and simulations which intent to prove the proper functioning of the models and of the control schemes. The three PWM converters are modeled using the built-in models provided by the simulation software DIgSILENT Simulation Language. Also the control schemes for the converters were implemented using the same simulation tool. Depending on the applications of the PWM converter, there can be used different control methods. The inputs of the converter are the control variables and they can be defined in 4 ways depending on the application [30]:

- the real and imaginary part of the PWM converter $(P_{mr} \text{ and } P_{mi})$;
- the magnitude and the phase of the PWM index $(P_{m-in} \text{ and } dphiu)$;
- the PWM index in d-axis and q-axis $(P_{md} \text{ and } P_{mq})$ and the cosine and sine of the reference angle (cosref, sinref);
- the magnitude of the PWM index (P_{m-in}) and the input frequency (f_0) .

The first two options are used only for grid-connected applications because phase measurements are needed to obtain the right angle of the output voltage. The last option gives the possibility to change the frequency of the output voltage making this method suitable only for scalar control schemes like V/f.

4.1 Control of the WF Side Converters (System C)

Three wind turbines are modeled and each of them is equipped with a PWM Converter. The rectifiers are responsible for managing the AC voltage and active power. The active power flow between the converters is controlled by changing the phase angle between the fundamental frequency of the voltage generated by the converter V_{gen} and the voltage V_c on the busbar. The control variables for the converter are the magnitude of the PWM index (P_{m-in}) and the input frequency (f_0) .

For optimizing the power output of the SCIGs, the constant voltage/frequency control has been implemented for the generator side converters. This strategy is based on keeping the stator flux constant. This is done by feeding the induction machine with constant voltage/frequency ratio. The maximization of active power is accomplished by identifying the proper synchronous speed for a given wind.

Each wind turbine is equipped with a 2.3 MW squirrel cage induction generator. Figure 4.1 shows the generator's power output having the pitch angle set to its optimal value and having a wind speed that varies from the cut-in wind speed (4m/s) to the rated wind speed (11.9m/s).

Even if the pitch angle is equal to the optimal value, the operating points of the active power are not optimal due to low wind speeds. Figure 4.1 indicates that the rated active power is achieved for the rated synchronous speed that corresponds to the frequency of 50 Hz. Therefore, for wind speeds below the rated values, the optimum operational points of the WT must be found. This is done by varying the generator's synchronous speed. The interval of variation for the synchronous speed is considered between 500 and 1500 rpm. The black line drawn in Figure 4.1 shows these points. The range of speed operation is obtained for a maximum output of the WT for all the considered wind speeds.



Figure 4.1: Power output of the generators for different wind speeds

Considering Figure 4.1 the optimal frequency for the stator side of the SCIG for different wind speed is computed. This is done by looking into the Figure 4.1 and find for each wind speed the right values of the synchronous speed that gives maximum power. Figure 4.2 shows the linear variation that is obtained between the wind speed and the frequency. f_s is the optimal frequency set-point provided by rectifier in order for the WT to generate maximum power at the considered wind speed. For the cut-in wind speed a frequency of 17 Hz is needed for the WT to produce 0.09 pu active power. For the rated wind speed of 11.9 m/s, applying the frequency of 50 Hz the rated output power is generated.

The control scheme of the rectifiers implemented in DSL is based on the dependence of frequency on active power and voltage on reactive power from Figure 4.3.



Figure 4.2: Optimal frequencies as function of wind speeds

As may be seen in Figure 4.3 the control of the rectifier is composed of voltage-frequency control, frequency droop control block, voltage droop control block and PI regulators for voltage and current. Using the Pulse Width Modulation (PWM) technique in the VSC converter, it is possible to obtain the desired voltage waveform at the AC terminals. Limitations apply due to the power ratings of the converter, the DC voltage and the maximum switching frequency. The inputs of the PWM model are P_{m-in} and f_0 and they can be adjusted independently by the VSC converter to give any combination of voltage magnitude and phase shift in relation to the fundamental frequency-voltage in the WT side.

A measurement block is used to obtain information about the AC current and voltage on the AC side. This signals are used for the current and voltage loops in order to minimize the errors. I_{meas} and V_{meas} are also used to calculate the active and reactive power on the AC side.

The variations of the active and reactive power of the generators are function of wind speed, therefore the voltage stability is in close connection with the demand of reactive power of the WTs. Since the induction generator will always draw reactive power from the PWM converter, the voltage reference should be increased when the generator's demand for reactive power increases. A small error in the voltage reference can generate very large reactive currents that may produce instability. This is the reason that voltage loop control is used to minimize the error thus no large reactive currents are flowing in the wind farm.

The Voltage-Hertz control method is an open loop method no feedback from the generator is required. This control strategy is based on keeping the stator flux constant and this is achieved by feeding the induction machine with constant voltage/frequency ratio. The only reference variable is the supply frequency. So, the constant flux operation can be maintained by adjusting the supply voltage amplitude. The voltage must decrease together with the frequency in order to prevent the flowing of large currents through the generator. The values of wind speed are used in the control scheme for calculation of the optimal frequency setpoint f_s based on Figure 4.2.



Figure 4.3: Control structure of the rectifiers

So, according to the V/f constant principle the optimal output voltage can be calculate according to (4.1):

$$\frac{V_{rated}}{f_{rated}} = ct \tag{4.1}$$

Therefore by keeping the ratio between voltage and frequency constant, the voltage setpoint V_s is obtained. :

$$\frac{V_s}{f_s} = \frac{V_{rated}}{f_{rated}} \tag{4.2}$$

The setpoints for frequency and voltage provided by the *Voltage and Frequency setpoint* calculation block are optimized by the *Voltage droop control* and *Frequency droop control* blocks. The principle on which they are based is described in Figure 4.4.



Figure 4.4: Frequency and voltage droops for the sending end station

The setpoint voltage calculated by the V/f controller will be optimized through a PI controller, and V_{ref} obtained with the droop control as reference voltage point. The value obtained with the voltage droop controller will be compared with the measured current and an inner current PI control loop will produce the optimum power modulation index (P_{m-in}) , which will control the current flowing through the phase reactor and thus, the power flow.

Knowing the setpoint frequency the setpoint voltage is computed using (4.2). So, based on the V_s and f_s the voltage reference and the frequency reference is calculated [18]:

$$f_0 = f_s - K_f \cdot (1 - P_{meas})$$
(4.3)

$$V_{ref} = V_s + K_v \cdot Q_{meas} \tag{4.4}$$

where:

 K_f frequency droop coefficient $(K_f = \frac{\Delta f}{\Delta P});$

 K_v voltage droop coefficient;

 V_s voltage setpoint fed by the V/f control system.

For the calculation of the voltage reference, the reactive power absorbed by the WT is measured, based on measured current and voltage. This value is compared to the nominal reactive power and the exceeded drawn reactive power must be compensated for by generating a voltage reference, calculated with the nominal voltage and the K_v coefficient.

The AC voltage controlled by the rectifier is computed based on the following formula:

$$V_{AC} = K_0 P_{m-in} V_{DC} \tag{4.5}$$

For the control of the output frequency, the magnitude will be proportional to the generator frequency which is the base value, so that the generator stator frequency is:
$$f_{stator} = 50Hz \cdot f_0 \tag{4.6}$$



Figure 4.5: Control loops of the sending end station

As described before for the generator side converter two control loops based on proportional integrators (PIs) controllers are designed: the current control loop and the voltage control loop. These are depicted in Figure 4.5. As can be observed the error between the desired voltage (V_{ref}) and the measured voltage (V_{meas}) is amplified by a PI controller in order to produce the reference signal (I_{ref}) for the current loop. Further on the error between I_{ref} and the measured current (I_{meas}) is amplified by another PI controller and this will generate the magnitude of the PWM index.

For the inner current control loop the plant is considered to be the phase reactor having the following transfer function:

$$G(s) = \frac{1}{L \cdot s + R} \tag{4.7}$$

where

G(s) transfer function of the phase reactor;

L inductance of the phase reactor of the rectifier side;

R resistance of the phase reactor of the rectifier side.

Therefore the closed loop transfer function is:

$$Y_i(s) = \frac{K_i(1 + \frac{1}{T_i s}) \cdot \frac{1}{Ls + R}}{1 + K_i(1 + \frac{1}{T_i s}) \cdot \frac{1}{Ls + R}}$$
(4.8)

$$Y_{i}(s) = \frac{\frac{K_{i}}{L}s + \frac{K}{L \cdot T_{i}}}{s^{2} + s\frac{R + K_{i}}{L} + \frac{K_{i}}{L \cdot T_{i}}}$$
(4.9)

where

 K_i proportional gain of the PI controller for the current loop;

 T_i integration time constant of the PI controller for the current loop.

From (4.9) it can be obtained the characteristic equation of the closed loop system:

$$s^{2} + s\frac{R+K_{i}}{L} + \frac{K_{i}}{L\cdot T_{i}} = 0$$
(4.10)

The proportional gain and the integration time constant of the PI controller are computed using Matlab sisotool. The values of the PI parameters are found using equations which are based on the natural frequency (ω_n) and the damping ratio (ξ) which has been assumed to be 0.707 [34].

$$\begin{cases} K_i = 2 \cdot \xi \cdot \omega_n \cdot L - R\\ T_i = \frac{2 \cdot \xi \cdot \omega_n \cdot L - R}{\omega_n^2 \cdot L} \end{cases}$$
(4.11)



Figure 4.6: Closed loop step response of the current controller

Figure 4.6 shows the step response of the current control loop which brings out clearly that the system reaches stability to unity value after applying a step input. Therefore it can be concluded that the system is stable.

Having obtained the parameters of the current control loop they are entered in the simulation model. By comparing the measured current (in green) with the reference current (in blue) it can be seen in Figure 4.7 that the error signal is kept to zero. Therefore Figure 4.7 shows that a proper dimensioning of the PI parameters was made.



Figure 4.7: Simulation result of the current control loop response

After defining the parameters of the current loop, the transfer function of the voltage control loop can be find out as can be seen in Figure 4.5.

In the case of the voltage controller loop the transfer function of the plant is obtained based the transfer function of the current controller and the impedance of the induction machine.

$$G_v = G_i \cdot Z_m \tag{4.12}$$

where

 G_v transfer function of the current loop;

$$G_i \qquad \text{transfer function of the current loop } (G_i = \frac{\frac{1}{L_{s+R}} \cdot (1 + \frac{1}{T_{is}}) \cdot K_i}{\frac{1}{L_{s+R}} \cdot (1 + \frac{1}{T_{is}}) \cdot K_i + 1});$$

 Z_m impedance of the induction machine.

Thus, the closed loop transfer function is:

$$Y_{v}(s) = \frac{K_{v}(1 + \frac{1}{T_{vis}}) \cdot G_{v}}{1 + K_{i}(1 + \frac{1}{T_{is}}) \cdot G_{v}}$$
(4.13)

where

 K_v proportional gain of the PI controller for the current loop;

 T_v integration time constant of the PI controller for the current loop.



Figure 4.8: Closed loop step response of the current controller

Same as for the current control loop, the PI parameters K_v and T_v of the voltage control loop are computed based on the natural frequency (ω_n) and the damping ratio (ξ) and using Matlab sisotool. In Figure 4.8 can be seen the step response of the voltage control loop. As expected the response is characterized by a slower rise time then the response of the current control loop.

After dimensioning the PI controller parameters and defining them in DIgSILENT model their verification was made. Figure 4.9 shows that error signal (in red) between the measured voltage (in green) and reference voltage (in blue) is kept to zero. This proves the well function of the PI controller.



Figure 4.9: Simulation result of the voltage control loop response

A description of the parameters used for the generator side converter is detailed in Appendix C.2 and C.3.

4.2 Control of the Grid Side Converters (System A and System B)

While the converters connected to each wind turbine from $System \ C$ control the active power flow and the AC voltage, the receiving end stations from $System \ A$ and $System \ B$ are designed to control the DC link voltage and the reactive power.

For the grid connected applications, the typical control strategy of the VSC-HVDC receiving end station that is used, is the voltage oriented control. The overall control structure of the receiving end stations of System A and System B is presented in Figure 4.10. It is based on the linear dependence of the DC voltage on the active power. The control method is described in section 2.4. The control block implemented in DIgSILENT Power Factory contains the MTDC Controller that handles with the active power sharing between the two grids, function of the measured output of the wind farm P_{Tmeas} , the power demands of each grid (P_1 for GRID A and P_2 for GRID B) and the DC voltage levels from each inverter. Communication lines are needed between the three terminals and the MTDC Controller for real time acquisition of the terminals parameters. It takes in consideration also the losses from the transmission system that are represented by intern parameters. For a more accurate computation, the losses have to be monitored in real time also. Based on this parameters the MTDC Controller block supplies the DC voltage setpoints for both of the controllers for GRID A and GRID B.



Figure 4.10: Overall control structure of the receiving end stations implied in MTDC

The control blocks for each inverter are identical and a detailed structure is shown in Figure 4.11. The main control blocks contain a fast current controller that outputs the real and inaginary part of the modulation index. The references values for the current controller block are provided by additional controllers for the DC voltage and reactive power.



Figure 4.11: Detailed control structure of receiving end converter

The references for the 'Reactive Power Controller' are given by each TSO of GRID A and GRID B. The setpoint for the DC voltage controller are sent by the MTDC controller for each inverter. The measuring points of DC voltage, AC voltage and AC current are placed in each of the system as indicated in Figure 4.10. A PLL block is used in order to synchronize the phase of the dq references with the AC source voltage.

GRID A and GRID B are built-in blocks in DIgSILENT Power Factory with the parameters from Appendix F.

The equivalent circuit of a single phase receiving end converter is shown in 4.12 where the converter and the grid can be considered as voltage sources V_v and V_g . It is considered that

the circuit is functioning at the nominal frequency 50 Hz, thus the AC filter can be neglected [18].



Figure 4.12: Equivalent circuit of the receiving end station

Looking at the circuit from Figure 4.12, the voltage on the phase reactor can be derived as:

$$V_v - V_g = L\frac{di_v}{dt} + Ri_v \tag{4.14}$$

In order to decouple the DC voltage and the reactive power controllers, the synchronously rotation dq reference frame is used.

First (4.14) is translated from the *abc* stationary frame in the $\alpha\beta$ orthogonal coordinates using the Clarke Transform given in Appendix B.

The voltage droop on the line reactor in $\alpha\beta$ coordinates is [3]:

$$\begin{cases} V_{v\alpha} - V_{g\alpha} = L \frac{di_{v\alpha}}{dt} + Ri_{v\alpha} \\ V_{v\beta} - V_{g\beta} = L \frac{di_{v\beta}}{dt} + Ri_{v\beta} \end{cases}$$
(4.15)

where the voltages V_v and V_g have the following expression in $\alpha\beta$ stationary frame function of the *abc* coordinates:

$$V_{\alpha} = \sqrt{3}V_{ab} + \frac{\sqrt{3}}{2}V_{bc} \tag{4.16}$$

$$V_{\beta} = \frac{3}{2} V_{bc} \tag{4.17}$$

Furthermore, using the Park transformation (see Appendix B), equations (4.15) are expressed in the dq coordinates:

$$\begin{cases} V_{vd} - V_{gd} = L\frac{di_{vd}}{dt} + j\omega Li_{vq} + Ri_{vd} \\ V_{vq} - V_{gq} = L\frac{di_{vq}}{dt} + j\omega Li_{vd} + Ri_{vq} \end{cases}$$
(4.18)

The relation between the dq and $\alpha\beta$ quantities is [33]:

$$\begin{cases} V_d = \frac{2}{3\sqrt{2}} (V_\alpha cos\theta - V_\beta sin\theta) \\ V_q = \frac{2}{3\sqrt{2}} (V_\beta cos\theta + V_\alpha sin\theta) \end{cases}$$
(4.19)

where:

 θ the angle between the α and β axes: $\theta = \arctan \frac{V_{\beta}}{V_{\alpha}}$;

 ω the angular frequency : $\omega = \frac{d\theta}{dt}$;

Based on (4.18) the VSC equivalent circuit is obtained in the dq axes representation as shown in Figure 4.13.



Figure 4.13: VSC equivalent circuit in dq reference frame

By assuming that the *d*-axis is aligned with the axis of one phase voltage V_v from stationary *abc* reference frame, it results that $V_{vq} = 0$ and $V_{vd} = V_v$ [33]. From Figure 4.13, the apparent power injected by the converter in the AC grid can be written as [11]:

$$S = 3(V_{vd} + j0)(i_d - ji_q) \tag{4.20}$$

Therefore, the active and reactive power are:

$$P_{DC} = P_{AC} = 3V_{vd}i_d \tag{4.21}$$

$$Q = -3V_{vd}i_q \tag{4.22}$$

It can be observed that the active power is related to the current i_d and the reactive power to i_q .

Relation (4.21) must be satisfied in order to ensure the stability of the system. Any unbalance in the active power flow transferred through the converter will cause DC voltage fluctuations. Therefore, to provide reference values for the currents i_d and i_q which are responsible for controlling the DC voltage and reactive power control loops must be used.

Equation (4.21) can be written as:

$$V_{DC}i_{dc} = 3V_{vd}i_d \tag{4.23}$$

The real part of the modulation index of the inverter corresponding to the d axis is [21]:

$$P_{mr} = \frac{v_{gd} 2\sqrt{2}}{V_{DC}} \tag{4.24}$$

From (4.23) and (4.24) the relation between the current of the d axes and the DC current is:

$$i_{dc} = \frac{3}{2\sqrt{2}} P_{mr} i_d \tag{4.25}$$

The variation of the DC voltage is given by the voltage droop V_D on the capacitor from the DC side of the converter:

$$\frac{dV_{DC}}{dt} = \frac{1}{C}(I_D - i_{dc})$$
(4.26)

If it is assumed that the DC voltage is constant, the voltage on the capacitor is zero and $I_D = i_{dc}$.

By using this assumption in (4.25) and (4.26) the DC voltage can be written as:

$$V_{DC} = \frac{1}{C} \int \left(I_D - \frac{3P_{mr}i_d}{2\sqrt{2}} \right) dt \tag{4.27}$$

The fast current controllers used for obtaining the i_d and i_q currents are complemented with additionally controllers that output the reference values needed for the voltage controller and reactive power. Therefore the current controllers represents the inner controller and the outer controllers are the DC voltage and reactive power controllers. The control scheme for the DC voltage is described in Figure 4.14. The control loops for d and q axes are the same, resulting in design of identical PIs for each loop.



Figure 4.14: Outer loop and inner loop controllers of the receiving end station

The inner loop contains the PI controller and the phase reactor transfer function.

From Figure 4.14 it can be seen that the closed loop transfer function of the current controller is:

$$Y(s) = \frac{\frac{K_C}{L}s + \frac{K_C}{LT_v}}{s^2 + s\frac{R+K_C}{L} + \frac{K_C}{LT_C}}$$
(4.28)

The characteristic equation of Y(s) is:

$$s^{2} + s\frac{R + K_{C}}{L} + \frac{K_{C}}{LT_{C}} = 0$$
(4.29)

For the dimensioning of the PI parameters Matlab sisotool has been used.

Using the damping ratio ξ and the natural frequency ω_n parameters, the controller's gain and integration time constant of the current controller can be found:

$$\begin{cases} K_C = 2\xi\omega_n L - R\\ T_C = \frac{2\xi\omega_n L - R}{\omega_n^2 L} \end{cases}$$
(4.30)

The damping ratio has been assumed $\xi = \frac{\sqrt{2}}{2} = 0.707$ [34]. The step response plot in Figure 4.14, shows that the controller is stabilizing to unity value after a step input and that the system is stable as expected.



Figure 4.15: Closed loop step response of the inner loop

After finding the transfer function of the inner loop, the analysis of the controller can be reduced to the outer loop scheme as shown in Figure 4.14.

By looking at Figure 4.14 it can be seen that the plant for the outer loop of the DC voltage controller is:

$$G(s) = \frac{V_{DC}(s)}{i_d(s)} = \frac{3P_{mr}}{2\sqrt{2}Cs}$$
(4.31)

The time constant of the outer loop PI controller has been selected to be slower than that of the current controller. This cause a response that is characterized by a slow rise time in comparison to the inner loop controllers.



Figure 4.16: Step response of the closed loop DC voltage controller

The PI's outer loop parameters were tuned also with Matlab Sisotool. As mentioned before, the reactive power controller have the same parameters as the DC voltage controller in order to obtain symmetric operation on both d and q control blocks.

All the control parameters of the grid side converter can be found in Appendix D.2 and D.3.

Figure 4.17 demonstrates the functioning of the DC voltage and reactive power controllers. It is supposed that the MTDC controller sends different DC voltage setpoints to the invert. In the same time the TSO sends commands for reactive power reference values. It can be observed that both controllers are reliable, keeping the DC voltage at the terminal inverter's and the reactive power in the grid PCC at the imposed reference values.



Figure 4.17: (a) Vdc controller and (b) Reactive power controller simulation results

As mentioned before, the DC voltage controller outputs the reference for the current controller i_{dref} and the reactive power controller manages with the reference i_{qref} . Figure 4.18 shows the variation of both i_d and i_q measured and reference currents. The measured value has some overshoots when the reference is changing. Because these errors do not have a significant influence in resulting modulation index, it can be conclude that the current control is reliable.



Figure 4.18: (a) i_d and (b) i_q current control results

The outputs of the controller block are depicted in Figure 4.19. It can be observed that the real part of the modulation index P_{mr} fallows the variation of the DC voltage level, while the imaginary part P_{mi} has the variations function of the reactive power.



Figure 4.19: (a) Real part and (b) imaginary part of the modulation index

Some tests were performed in order to verify the receiving end stations control. The simulation results leads to the conclusion that the implemented control is reliable. In this section only the functioning of one inverter was tested. The functioning of the MTDC system will be presented in the following chapter.

4.3 Summary

This chapter is entirely focused on defining the converter models and their specific control technique. A closely and detailed analysis is made for all the control structures implemented for the converters on the wind turbine side and for the converters situated on the grid sides.

All the controller proved to be reliable. Brief simulation results are shown in order to provide more understanding on the behavior of each developed block.

Chapter 5

Simulation Results

The following chapter presents different study cases in order to verify and illustrate the performance of the studied MTDC system.

First several simulation results of the wind farm control are presented taking in consideration all the three operation modes of the wind turbines (limitation, transition and optimization). In the limitation mode the pitch control is verified and in optimization the voltage/frequency control strategy is tested.

In the second section is presented the evaluation of the control method of the MTDC that was developed in this project. The wind farm is connected with two grids that are situated at different distances. Several tests are performed to verify the power sharing control method.

All the tested parameter are illustrated in pu values. The base values are given in Appendix E.

5.1 Wind Farm Control

Different scenarios are performed in order to demonstrate the reliability and the performance of the pitch controller and of the voltage/frequency control of the wind farm. Therefore the power regulation is done by using both of the controllers and having as input for the simulations different wind profiles.

5.1.1 Pitch Controller - power limitation

After designing the parameters of the PI for the pitch controller loop, the WF must be able to limit the power output as the wind speed increases over the rated value. The testing will be made using the real wind profile provided by the wind model of each WT. The simulations are run for 100 seconds.

The average wind speeds vary from the rated value 11.9m/s until they reach 23m/s as may be seen in Figure 5.1.



Figure 5.1: Average wind profile

Based on the average wind, the wind profiles outputed by the wind model are obtained. They are depicted in Figure 5.2. It can be seen that the three winds start to rise until they reach 23m/s and then drop to the rated value.



Figure 5.2: Wind speed profile

By activating the pitch control, the blades start to be pitched in and out of the wind in order to keep constant the power. The pitch angle variations should be directly proportional with the wind.

In the first time interval the wind speed is at the rated value, the pitch controller is inactive - thus, the pitch angle is maintained to zero in order to obtain the rated power value. When the wind becomes greater than v_{rated} , the blade control angle is varying in such a way that it holds the powers to the nominal value (see Figure 5.3).



Figure 5.3: Active and reactive power regulation

As can be observed the active and reactive power limitation is achieved.

5.1.2 Voltage/Hertz Control - power optimization

The purpose of this simulation is to test the efficiency of the voltage/frequency controller implemented for the generator side converters.

The wind profile applied for this study case may be seen in Figure 5.4. For testing the controller, the averaged wind speed is computed by a moving average filter (green signal). The moving average function is used to smooth out short term fluctuations. Having set the wind speed, two tests are made for analyzing the power generation: with and without V/f control.



Figure 5.4: Wind profile for V/F controller

When the wind speed starts to have values below 11.9m/s, the frequency is adjusted in order to maximize the WT's power output. Based on Figure 4.2 from section 4.1 the frequency setpoint (f_s) is find out. Knowing that the ratio between voltage and frequency must remain constant and having obtained the frequency setpoint, the voltage setpoint (V_s) is calculated. Figure 5.5 shows clearly that as the wind decreases, f_s and V_s are changing compared to the rated values of frequency and voltage.



Figure 5.5: Frequency (a) and voltage (b) setpoints

Figure 5.6 presents the active power production of the induction generator. In green is presented the power outputted by the WT without enabling the V/f control algorithm on the generator side converter. In this case the SCIG is working at the rated frequency and rated voltage as may be seen in Figure 5.5. By activating the controller, the generation of active power (in blue) is maximized by modifying the voltage and frequency setpoints.



Figure 5.6: Generator's active power with and without V/F control

Comparing the results shown in Figure 5.6 it can be concluded that the power production with V/f control is higher than without it.

From Figure 5.6 the gain in active power can be obtained. In the first time interval when the wind is kept constant to the rated value, the gain is zero because no control is active. When the wind speed drops the V/f controller starts actuating. Figure 5.7 highlights the gain in the power production by activating the voltage/frequency control for wind speeds within the interval $[v_{cut-in}; v_{rated}]$.



Figure 5.7: Active power gain

The generator side converter proved its use in operation control for different wind speeds situations.

5.1.3 Transition Between Power Limitation Mode and Variable Speed Operation

Power limitation mode and variable speed operation are both enabled when the wind profile is within the interval $[v_{cut-in}; v_{cut-out}]$. The selection between the two operation modes is based on the rated wind speed:

- if $v_{wind} > v_{rated}$ then the blade angle controller is active;
- if $v_{wind} < v_{rated}$ then the V/f controller is active.

This simulation intends to demonstrate that the switching between is done properly. Two wind speeds are considered for this study case: the average wind speed and the real wind speed.

Case 1 - Wind profile: average wind

The first test was made with the wind speed profile as shown in Figure 5.8. This case was investigated in order to have a clear understanding of the switching operation between the two operation modes.



Figure 5.8: Wind speed profile

As expected the power limitation for both active and reactive power is achieved in the time interval when the wind increases over 11.9m/s as depicted in Figure 5.9. The same goes for the interval when the wind speed is below v_{rated} the maximization of the power output is accomplished by enable the V/f controller.



Figure 5.9: Active and reactive power outputted by the WF for the average wind speed

Case 2 - Wind profile: real wind

The analysis in this case is based on applying the real wind speed as shown in Figure 5.10. Each of the WT has it own wind model thus, there will be three different wind speed profiles. The simulation is run for 300 seconds and is divided in two intervals. In the first time interval [0;150s] the wind speed varies from 11.9m/s until 23m/s therefore, the PI of the pitch controller starts actuating in order to limit the power output. In the second time interval [150; 300] the wind starts decreasing below the rated value of the wind. This means that the pitch controller becomes inactive and V/f is enabled.



Figure 5.10: Wind profile

As proved by the previous simulations, for this case the power control is also accomplished as displayed in Figure 5.11.



Figure 5.11: Active and reactive power of the WF

The total active power outputed by all three wind turbines in the offshore PCC can be seen in Figure 5.12,



Figure 5.12: Total active power outputted by the WF

The aim of this study case was to demonstrate that the models of the pitch controller and V/f controller were correctly implemented. Several simulation were performed in order to verify that the power regulation is achieved.

5.2 Active Power Sharing

This study case deals with the analysis of the power sharing between the two grids. The simulations are based on the control algorithm investigated in section 2.4.

Different tests are carried out in order to verify the reliability of the power sharing method. The simulation conditions are:

- One WF and two grids situated at different distances are connected through the MTDC:
 - GRID A 10 km from the offshore WF;
 - GRID B 30 km from the offshore WF.
- The wind farm is functioning at the rated parameters. Some simulations are performed with constant output power from the wind farm in order to analyze the DC voltage level fluctuations of the inverters of each of the grids depending on their power demands. Another set of simulations are made with a variable output power from the WF, to present a realistic behavior of the MTDC system where the power generated by the WF is varying function of the wind speed.
- For all the simulations is considered that GRID A TSO settles the active power request. GRID B is adjusting its power consumption function of GRID A, meaning that is taking the excess of power from the WF or it is generating extra power for the GRID A in order for the active power demand to be accomplished. Figure 5.13 shows the active power request of GRID A that was considered. In all the simulation time the active power request varies from 100% to 10% from the total active power generated by the WF.



Figure 5.13: Active power request from GRID A TSO

5.2.1 Rated WF Output Power

First it is considered the functioning of the wind turbines at nominal parameters and at constant wind speed conditions. Thus the WF output active power is kept constant to its rated value of 0.8 pu.

Two cases were taking into account function of the two grids:

- 1. GRID A and GRID B are identical;
- 2. GRID B is stronger than GRID A having the short circuit power ten times greater;

The parameters of the grids are presented in Appendix F.

By sending the power demand of GRID A shown in Figure 5.13 to the MTDC controller, the DC voltage reference points V_{DCA} and V_{DCB} of the grid side inverters are set. Both DC voltage levels follow an inverse proportionality dependence according to the active power consumptions as presented in Figure 5.14. Also the variation in DC voltage is proportional with the distance between the WF and the receiving end. Converter_{GRIDA} which is closer to the WF's PCC has smaller variations comparing to Converter_{GRIDB}. The DC voltage level has to be maintained in $\pm 5\%$ limits of the rated value [35]. The maximum deviation of the DC voltage from the acceptable limit is recorded when GRID A demands only 10% of the total power. MTDC controller is sending to Converter_{GRIDB} a reference value for the DC voltage that is lower than the the allowed limit, in order to fulfill the power sharing.

Therefore an additional control method has to be implemented in order to maintain the variations of the DC voltages in the allowed limits. One of the solution would be for the MTDC controller to be able to vary the DC voltage in the PCC of the WF in order to obtain smaller variations at the inverters terminals.



Figure 5.14: DC voltage set points for $Converter_{GRIDA}$ and $Converter_{GRIDB}$

By knowing the DC voltage setpoints according to the power request of GRID A, the power sharing that was obtained between the two grids is shown in Figure 5.15. The power injected into the networks has the same variation in both cases. Also no notifiable change exist between the two cases when the short circuit power of the grids are different.



Figure 5.15: Active power sharing between GRID A and GRID B in Case 1 and Case 2

The power sharing for GRID A follows the active power request from Figure 5.13. A small error exist between the imposed value for requested power power and the one that is obtained as shown in 5.16 for GRID A. The maximum error is 6.5% and it occurs for the smallest power demand 10%. By looking at the error for all the MTDC system in Figure (b), the error is 11% for the same 10% value of power request from GRID A.

This errors can be justified by the losses that exist in the system besides the losses from the DC cables. This difference in power is due to the power losses on the phase reactors and converters. For the power sharing algorithm based on steady state analysis only the losses of the DC cables were taken in consideration.



Figure 5.16: Power sharing error for (a) GRID A and (b) MTDC system

The different values of short circuit power influence the current injected into to grid and also the voltage and frequency in the PCC. Figure 5.17 presents the variation of currents injected in GRID A and GRID B for both cases, when the grids have the same short circuit power and when they don't have the same short circuit power. The currents curves have the same shape as the active power flowing into the grids. It can be also observed that for GRID B, the current variation is smaller in the case of greater short circuit power.



Figure 5.17: Current injected in GRID A and GRID B

Figure 5.18 describes the variations in voltage and frequency on the PCC of the two grids. It is shown that the stronger grid has less significant variations in both voltage and frequency in the PCC. The voltage and frequency have the same variation according to the power changing in each grid.



Figure 5.18: Voltage (a) and frequency (b) on the busbar of GRID A and GRID B

5.2.2 Variable WF Output Power

Typical wind conditions are applied for the wind turbines. The wind profile used in the simulations is depicted in Figure 5.19. Only the mean value of the wind was used for a easier analysis of the simulation results.



Figure 5.19: Wind profile for the wind farm

The power flow of GRID A and GRID B is studied in the case when the WF's power output varies. By applying the wind variation profile, the obtained active power is presented in Figure 5.20. The base value for the active power is the rated apparent power of the WF. The power output is kept constant to 0.84 pu while the wind speed becomes greater than the rated values. For wind speeds below the rated value, lower values for power are obtained as shown in Figure 5.20.



Figure 5.20: Output power of the wind farm

The DC voltage setpoints are modified function of the power generation. The power request of GRID A was considered to be the same as in the previous subsection. If the generated power is decreasing, both DC voltage levels are stabilizing closer to their rated values because less active power must be transferred by the grid side converters.



Figure 5.21: DC voltage reference for $Converter_{GRIDA}$ and $Converter_{GRIDB}$

The power sharing between the two grids is presented in Figure 5.22



Figure 5.22: Active power consumption of GRID A and GRID B

Analyzing Figures 5.21 and 5.22, it may be observed that for the same DC voltage setpoints 0.96 pu and 0.98 pu, the active power injected into the grids is not the same. Different DC voltages setpoints are needed to have the same active power delivered to both grids. The argument for this is that the grids are situated at different distances from the WF.

If the output power of the WF is lower than, the power losses in the transmission system are lower. The error in power sharing from GRID A $P_{dif_{GRIDA}}$ is very close to zero for small values of P_{WF} as can be seen in Figure 5.23.



Figure 5.23: Power sharing error for GRID A

By performing the study case of active power sharing, the developed power sharing algorithm was verified and the functioning of the MTDC controller was tested.

5.3 Reactive Power Control at the Receiving End Stations

The TSO of each grid is responsible for the control of the reactive power. This control is made independently from one converter to another and also from the WF controller. Limitations are applied to the operating conditions in reactive power regulation due to the VSC operation parameters. Based on [4] the limits of the reactive power consumption and generation are considered to be between -0.5 and 0.5 pu, where the base value is the active power. Regarding the simulation conditions the output power of the wind farm is constant and the active power regulation for GRID A and GRID B follows the curves from Figure 5.15 as described in the above section.

During the simulation time different values for reactive power demand were chosen, as shown in Figure 5.24. Q_{TSOA} and Q_{TSOB} represents the TSO's references for reactive power. A positive value of reactive power indicates reactive power generation into the PCC while a negative value corresponds to reactive power consumption from the grid. Figure 5.24 demonstrates that the reactive power obtained in the PCC of each grid follows the TSO requirements and that is limited by the operation points of the converters. The TSO has to demand reactive power in the interval [-0.5; +0.5]. In the simulation it was supposed that the grid operator of the GRID B sends the command for 0.7 pu. It can be seen that the inverter manage to limit the reactive power to the minimum limit of -0.5 pu.



Figure 5.24: Reactive power regulation in the GRID A and GRID B PCC

The reactive power flow is the result of changing the voltage amplitude by means of the phase reactors. If the voltage on the grid side is greater than the voltage on the converter side it will result reactive power consumption mode, otherwise the converter will generate reactive power. The next two figures illustrates the relation between the reactive power and the voltage levels in the PCC and at the AC terminal of the converters.



Figure 5.25: AC voltage fluctuations at CONVERTER A and CONVERTER B

The AC voltage from the converters follows the variations of the reactive power in Figure 5.25. The simulation results of the voltages in the PCCs of the grids are presented in Figure 5.26 and show small variations comparing to the converters AC voltages.



Figure 5.26: Voltage variations in the GRID A and GRID B PCC

The simulation results conclude that the objectives of the reactive power controller have been accomplished. The main goal was to control independently the reactive power for each grid. The reactive power regulation was performed in real time according to the TSOs request and it complies with the nominal operation of the converter. For a more precise control, the active power through the converter has to be considered and the reactive power control should follow the typical PQ diagram for VSC.

5.4 Summary

The main interest of this chapter was to simulate the entire system for the assessment of the control algorithms and all the modeled components. A dynamic analysis of the system confirmed the successful developed model. The wind turbine's controller and components proved to be reliable for different simulation condition. The same goes for the Voltage/Hertz controller that had the expected response for all possible wind speeds which were applied. The MTDC controller has proved that is able the manage the active power sharing. Augmentation has to be considered for the limitation of the DC link voltage variations. The reactive power control was verified for both inverters and simulation were shown that the VSCs are able to comply with the TSOs requirements in real time.

Although improvement of models is always possible, it is reasonable to conclude that the designed system operates satisfactory. Therefore a simulation platform is now available for further studies.

Conclusions

The perspective of DC power interchange between three or more terminals has been in active consideration in the last years.

This thesis presents a proposed three terminal VSC-HVDC model linking two onshore grids and one offshore wind farm. The main focus was on developing the control strategy for connecting these three systems via DC connection. The latest interest in using VSC-HVDC technology for connecting offshore WF and also the advantages proved by this technology was an important factor in deciding the transmission system for this project. A significant interest was shown not only for the modeling and implementation of the transmission system, the converters and their control, but also on the development of the WF components and its control. All the models have been designed and build in DIgSILENT Power Factory.

This project will give a comprehensive review of the theoretical background and of the system's components development. It is organized in five sections:

- Background and problem statement;
- Modelling of the VSC and of the components of the DC transmission system;
- Modelling of the WF;
- Control system design;
- Study Cases.

The first section offers an overview of the importance of the offshore wind energy on the energy market. New ways of connecting large offshore WF which are further away from the sore are presented. A brief review of the main features of HVAC and HVDC transmission systems are included. Taking into account the benefits of the HVDC-VSC technology, the MTDC is considered to be a suitable solution, having the advantage of simplifying the trans-national exchange of power. In the introduction chapter are described also the project definition and the goals.

The second chapter is dedicated to the description and dimensioning of the components for the DC system. A detailed description of the operation of the voltage source converters based on PWM is also included. Three VSC are used in the system one as a rectifier (on the WF side) and two as inverters (on the grid sides). A control technique of the multiterminal DC system was performed based on the steady state analysis and proved to be reliable, therefore ready to be tested in a dynamical simulation of the entire system.

Chapter 3 is focused on modeling of the wind turbine components. It includes the following blocks: the wind model which simulates the wind's characteristic disturbances, the aerodynamic model that implements the power conversion equation from kinetic energy to mechanical torque, the mechanical model describing the operation of the drivetrain and the main mechanical parts, the pitch controller and the generator model.

Chapter 4 deals with designing and implementation of the control system for the grid side converters and the generator side converter. Two different control algorithms for VSCs have been used. The generator side converter is in charge of controlling AC voltage and the active power and the other two inverters are set to manage the DC link voltage and the reactive power. A complete analysis of the systems control is enclosed.

In chapter 5 is studied the performance of the developed system. This last part is divided into different sections that cover individual validation for the system's complements and the control. The first study case is dedicated to the WF control. The analysis of the pitch control and Voltage/frequency controller is made. Different wind speeds profiles are applied in order to see the reaction of the controllers. The second part is dedicated to the verification of the MTDC control of power sharing and also the control of reactive power for the considered grids.

The achievements that were reached within this project can be summarized as follows:

- Study of the MTDC possibility of connecting large offshore wind farms, review of the important projects developed till now and the advantages of the HVDC-VSC technology;
- Designing a MTDC system with all its components;
- Modelling the wind turbine with main components: wind , aerodynamical and mechanical models;
- Implementation of the control for both rectifier and and inverter mode of the VSC. The control of active power and AC voltage was obtained at the rectifier and the control of the DC voltage and reactive power was accomplished at the inverters;
- The major achievement is the assessment of the control method for the 'Multiterminal DC Connection'. This proved to be a feasible solution and could be the solution for futures projects regarding the connection of large offshore wind farms with far distances from the land. By improving the control algorithm, extending it to 'n' number of systems, this might be the answer for the 'Supergrid' project;
- The evaluation of the system under different study confirms the accuracy of the designed model.

In conclusion the developed power system represents a starting point for future studies dealing with the grid integration of offshore wind farms and more complex control strategies.

Future Work

The main purpose of the project was to develop and to implement an innovative way of connecting an offshore wind farm with two grids. This model offers a reliable starting point for more in depth research. As future work this project may include:

- to extend the MTDC control algorithm to a 'n' number of grids (power systems);
- to improve the MTDC controller for real time supervision of the DC voltage levels and to maintain them in the acceptable limits and also to monitor the losses that are in the system and that can influence the accuracy of the active power sharing;
- to increase the performance of the reactive power controller of the receiving end station converter taking into consideration the dynamic ratio between the active and reactive power;
- different control method can be implemented for the sending end converters;
- modeling, implementation and simulation of an aggregated model of an offshore wind farm. This aggregated model should be the equivalent of a hundreds of MW WFs.
- the analysis of the MTDC system behavior during different grid faults;
- implementation and modelling of real grids;
- an in depth research regarding the study of power stability aspects and the impact which large offshore power generating units will have on the grids;
- enclose an economical analysis of the costs for the model proposed in this project.

Bibliography

- [1] European Wind Energy Association. *Delivering Offshore Wind Power in Europe*. [cited 20 February 2009]. Available from: www.ewea.org/fileadmin/ewea_documents/images/publications/offshore_report/ewea-offshore_report.pdf
- [2] European Wind Energy Association. Wind Energy-The Facts. [cited 5 March 2009]. Available from: www.ewea.org/fileadmin/ewea documents/documents/publications/WETF/ 1565 ExSum ENG.pdf
- [3] Adelina Agap, Adrian Constantin, Cristina Madalina Dragan and Borja Imanol Markinez Iurre. Modeling, Operation and Control of HVDC Connected Offshore Wind Farms. Third semester project at Institute of Energy Technology. AAU
- [4] ABB. It's time to Connect. Technical description of HVDC Light (R) technology. ABB Grid Systems -HVDC. SE-771 80 Ludvika, Sweden.
- [5] Fernando D. Bianchi, Hernan De Battista, Ricardo J. Mantz. Wind Turbine Control System. Springer-Velgad London Limited 2007. ISBN 1-84628-492-9
- [6] Bo Normark and Erik Koldby Nielsen. Advanced power electronics for cable connection of offshore wind. Paper to be presented at Copenhagen Offshore Wind 2005. [cited 12 March 2009]. Available from: www.abb.com
- [7] Anca D. Hansen, Florin Iov, Poul Sørensen, Nicolaous Cutululis, Clemens Jauch, Frede Blaabjerg. Dynamic wind turbine models in power system simulation tool DIgSILENT. Risø National Laboratory. Technical University of Denmark. Roskilde, Denmark 2007. ISBN 978-87-550-3553-9
- [8] Stephan Meier. Novel Voltage Source Converter based HVDC Transmission System for Oshore Wind Farms. Royal Institute of Technology. Department of Electrical Engineering Electrical Machines and Power Electronics. Stockholm 2005. ISBN 91-7178-206-0
- [9] Lars Stendius. Nord E.ON 1 400MW HVDC Light Offshore Wind Project. ABB Grid Systems. Berlin December 2007.
- [10] Tatsuhito Nakajima and Shoichi Irokawa. A Control System for HVDC Transmission by Voltage Sourced Converters. Power Engineering Society Summer Meeting. IEEE 1999.
- [11] Temesgen M. Haileselassie, Marta Molinas, Tore Undeland. Multi-Terminal VSC-HVDC System for Integration of Offshore Wind Farms and Green Electrification of Platforms in the North Sea. NORPIE/2008, Nordic Workshop on Power and Industrial Electronics, June 9-11, 2008.
- [12] Lazaros P. Lazaridis. Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Farms under Special Consideration of Reliability. Royal Institute of Technology. Department of Electrical Engineering. Stockholm 2005.
- Platform. [13] European Wind Energy Technology Strategic ResearchAgendaMarketDeploymentFROM2008 TO2030. cited 1 March 2009]. Available from: Strategy www.windplatform.eu/fileadmin/ewetp_docs/Bibliography/Executive_summary.pdf
- [14] K. Eriksson and D. Wensky. System Approach onDesigning Offshore WindanGridABB Utilities. cited 10 March 2009]. power Connection. Available from: library. abb. com/global/scot/scot221.nsf/veritydisplay/34ec041 beda 66334c1256 fda 004c8cc004 beda 66334c1256 fda 004c8c004 beda 66334c004 beda 66334c004 beda 66334c004 beda 66334c004 b/\$File/03MC0132%20Rev.%2000.PDF
- Power [15] ABB. Transmission Distribution. The HVDCTransmis- and cited 2009]. QuébecNewEngland. 27February Available from: sionhttp://www.abb.com/cawp/GAD02181/C1256D71001E0037C12568340029B5C4.aspx
- [16] Prabha Kundur, Neal J. Balu. Power Sytem Stability and Control. McGraw-Hill Professional, 1994. ISBN 007035958X, 9780070359581.
- [17] Ervin Spahić and Gerd Balzer. Offshore Wind Farms VSC-based HVDC Connection. Power Tech, 2005 IEEE Russia. ISBN: 978-5-93208-034-4
- [18] Florin Iov. VSC based DC Transmission System for connecting Active Stall Wind Farms to Grid. Risø Library. Aalborg University 2004.
- [19] Cuiqing Du. VSC-HVDC for Industrial Power Systems. Department of Energy and Environment. Chalmers University of Technology. Goteborg, Sweden 2007. ISBN 978-91-7291-913-6
- [20] Per Karlsson. DC Distributed Power Systems Analysis, Design and Control for a Renewable Energy System. Lund University. Department of Industrial Electrical Engineering and Automation. Sweden 2002. ISBN 91-88934-25-X
- [21] Power Factory DIgSILENT Gmbh. PWM Converter Technical Reference. Power Factory v. 3.2 Help Manual.
- [22] Guibin Zhang and Zheng Xu. Steady-State Model for VSC Based HVDC and Its Controller Design. IEEE 2001
- [23] Siemens. Wind Turbines- Products. [cited 22 April 2009]. Available from: http://www.powergeneration.siemens.com/products-solutions-services/products-packages/windturbines/products/swt-2-3-93/
- [24] Vladislav Akhmatov. Analysis of Dynamic Behaviour of Electric Power Systems with Large Amount of Wind Power. Electrical Power Engineering, Ørsted-DTU. Technical University of Denmark. Kgs. Lyngby. April 2003. ISBN 87-91184-18-5.
- [25] Vladislav Akhnatov, Hans Knudsen, Arne Heijde Nielsen, Jørgen Pedersen, Niels Kjølstad Poulsen. Modelling and Transient Stability of Large Wind Farms. Elsevier. Electrical Power and Energy Systems 25 (2003) 123-144.
- [26] Jørgen Højstrup. Spectral coherence in wind turbine wakes. Wind Energy and Atmospheric Physics Department. Risø National Laboratory. DK-4000 Roskilde, Denmark. July 1998.
- [27] Danish Wind Industry Association. *Energy output*. [cited 22 April 2009]. Available from: http://www.windpower.org/en/tour/wres/powdensi.htm
- [28] Poul Sørensen, Anca Hansen, Lorand Janosi, John Bech and Birgitte Bak-Jensen. Simulation of Interaction between Wind Farm and Power System Poul. Risø-R-1281(EN). Risø National Laboratory, Roskilde December 2001. ISBN 87-550-2912-4
- [29] Anca D. Hansen, Poul Sørensen, Frede Blaabjerg and John Becho. Dynamic modelling of wind farm grid interaction. Wind Energineering Volume 26, No.4, 2002. Risø National Laboratory. Wind Energy Department, DK-4000 Roskilde, Denmark.

- [30] DIgSILENT GmbH (2002). DIgSILENT PowerFactory V13 User Manual
- [31] Florin Iov, Anca Daniela Hansen, Poul Sørensen, Frede Blaabjerg. Wind Turbine Blockset in Matlab/Simulink. General Overview and Description of the Models. Institute of Energy Technology. Aalborg University. ISBN 87-89179-46-3
- [32] J.G.Slootweg, H. Polinder, and W.L.Kling. *Dynamic modelling of a wind turbine with doubly fed induction generator*. Electrical Power Systems, Electrical Power Processing. Faculty of Information Technology and Systems, Delft University of Technology. IEEE, 2001.
- [33] S. Douangsyla, P. Indarack, A. Kanthee, M. Kando, S. Kittiratsatcha and V. Kinnares Modeling for PWM Voltage Source Converter Controlled Power Transfer, 2004. International Symposium on Communications and Information Technologies, Sapporo, Japan
- [34] M. P. Kazmierkowski and H. Tunia. Automatic Control of Converter-Fed Drives. Elsevier, 1995. ISBN 0-7803-1101-9
- [35] B. Burger, A. Engel Fast Signal Conditioning in Single Phase Systems, Institut für Solare Energieversorgungstechnik (ISET) e. V. EPE 2001.

Summary

The project investigates different aspects in finding an efficient way of connecting and controlling offshore wind farms and also tends to provide possible solutions to achieve that. A very useful simulation tool in developing and analyzing the power system was used. Power Factory DIgSILENT simulation software has been chosen because it is a specialized tool for building and studying the electrical energy generation, transmission and distribution in industrial systems. The project is organized in six chapters.

First the report begins with an introduction chapter which contains an overview of the offshore wind energy status, a short presentation of the possible transmission systems used in offshore projects and also the goals and problem statement of this project.

Chapter 2 begins with a presentation of the operation of Voltage Source Converters and the design of the DC transmission system components, followed by a steady state analysis of the multiterminal DC system.

The following chapter presents the development and implementation of the wind farm with the control (pitch controller) and all its components (the wind model, the aerodynamic model, the mechanical model, the generator model). Modelling of the wind turbines components have been the goal in this chapter. A detailed description of the WT system was included. This chapter was also focused on investigating and developing the power regulation control block. Simulations are performed to prove the WT system reliability and to have a better understanding of the functioning for each block.

The fourth chapter contains the description of the control technique implemented in DIgSI-LENT Power Factory for the generator side converter and the grid side converter. In this chapter an overview of the VSC-HVDC transmission system was presented. The configuration of the system with all the components were described in detail. An equivalent model of the VSC-HVDC was depicted in order to explain the functioning for both rectifier and inverter mode of the converter.

Chapter 5 includes all the results obtained during the simulation study. In order to better organize the analysis, different study cases were defined, each of them covering a particular subject. For each of the study case the results are analyzed and conclusions are taken. First several simulation results of the wind farm control are presented taking in consideration all the three operation modes of the wind turbines (limitation, transition and optimization). In the limitation mode the pitch control is verified and in optimization the voltage/frequency control strategy is tested. In the second section is presented the evaluation of the control method of the MTDC that was developed in this project. The wind farm is connected with two grids that are situated at different distances. Several tests are performed to verify the power sharing control method.

Chapter 6 concludes the report and presents future work that the project has not yet

covered. Improvements on the system are also pointed out. The major achievement is the assessment of the control method for the 'Multiterminal DC Connection'. This proved to be a feasible solution and could be the solution for futures projects regarding the connection of large offshore wind farms with far distances from the land. By improving the control algorithm, extending it to 'n' number of systems, this might be the answer for the 'Supergrid' project.

Appendix A

Wind Turbine Modeling

A.1 Wind Turbine Model

The parameters of the wind model are

- Sample time, s_t=0.05 s is the sample time step;
- Blade radius, R=41.2 m taken from the data sheet of the wind turbine ([?]);
- Average wind speed (v_m) inputed by the 'ElmFile' block as a .txt file;
- Length scale, L = 300 m [28];
- Turbulence intensity, $\sigma = 10\%$ [28].

For the wind model performed within this project, the Kaimal spectrum is chose to be used. Both hub and rotor sub-models are contain a cascade of Kaimal, zero and third order filters that are described more in detail in [26].

The Kaimal spectrum can be described by the following second order transfer function:

$$H_{KF}(s) = K_K \frac{s^2 T_4^2 + s T_3 + 1}{s^2 T_2^2 + s T_1 + 1}$$
(5.1)

where K, T_1, T_2, T_3, T_4 are estimated parameters calculated based on the constants C and T that are function of the turbulence intensity, the length scale and the average wind speed.

C determines the frequency bandwidth of the turbulence [7]:

$$C = \frac{L}{2\pi v_m} \tag{5.2}$$

T determines the turbulence power:

$$T = \frac{\sigma}{100} \cdot \sqrt{\frac{Lv_m}{2}} \tag{5.3}$$

Having the values for C and T, the parameters K, T_1, T_2, T_3, T_4 are calculated as follows:

- $K_K = 0.9846T;$
- $T_1 = 3.7593 C$;
- $T_2 = 1.3463 C^2$;
- $T_3 = 1.3866 C$;
- $T_4 = 0.01848 C^2;$

The zero and the third harmonic filters use the length scale and the average wind speed expressed in a constant D,

where D is:

$$D = \frac{R}{v_m} \tag{5.4}$$

The zero order filter is described by the next transfer function:

$$H_{ZF}(s) = K_Z \frac{sT_3 + 1}{s^2 T_2^2 + sT_1 + 1}$$
(5.5)

where:

- $K_Z = 0.9904;$
- $T_1 = 7.3517D$;
- $T_2 = 7.6823D^2$;
- $T_3 = 4.8332D;$

The third harmonic filter is described by the transfer function:

$$H_{TH}(s) = K_{TH} \frac{sT_3 + 1}{s^2 T_2^2 + sT_1 + 1}$$
(5.6)

- $K_{TH} = 0.0307;$
- $T_1 = 1.7722D$;
- $T_2 = 0.3691 D^2$;
- $T_3 = 865.77D$;

A.2 Mechanical Model

Parameter	Value
J_{rotor}	$8.5 \cdot 10^6 [\mathrm{kg} \cdot \mathrm{m}^2]$
k_{gear}	91
k_{stiff}	$1.64 \cdot 10^{8} [\text{kg} \cdot \text{m}^{2}]$
c_{damp}	$7.4 \cdot 10^5 [\mathrm{kg} \cdot \mathrm{m}^2]$
Ω_r	16.5 [rpm]
ω_r	1512 rpm

Table 5.1: Parameters of the drivetrain

A.3 Generator

The values of the electrical parameters in nominal operation from Table 5.2 is used to calculate the apparent power, the current, the voltage and the base impedance as follows:

$$U_{base} = \frac{U_{rated}}{\sqrt{3}} = \frac{690}{\sqrt{3}} = 398.37V \tag{5.7}$$

$$I_{base} = \frac{S}{3U_{base}} = \frac{2598}{3 \cdot 398.37} = 21738A = 2.17kA \tag{5.8}$$

$$Z_{base} = \frac{U_{base}}{I_{base}} = 0.183\Omega \tag{5.9}$$

With the base impedance, Z_{base} , there can be computed the per unit values of the electrical parameters:

$$R_s = \frac{R_s}{Z_{base}} = 0.00639 p.u.$$
(5.10)

$$X_s = \frac{X_s}{Z_{base}} = 0.165 p.u.$$
(5.11)

$$R_r = \frac{R_r}{Z_{base}} = 0.00819 p.u.$$
(5.12)

$$X_r = \frac{X_r}{Z_{base}} = 0.165 p.u.$$
(5.13)

$$X_m = \frac{X_m}{Z_{base}} = 3.66p.u.$$
(5.14)

Parameter	Value
Prated	2300 kW
Q_{rated}	1200 kVAR
U_{rated}	690 V
$cos(\varphi)$	0.9
η	96 %
n _{pole-pairs}	2
R_s	$0.0012~\Omega$
X_s	$0.0307~\Omega$
R_r	$0.0015 \ \Omega$
X_r	$0.0109 \ \Omega$
X_m	$0.7 \ \Omega$
J_{gen}	$60 \text{ kg} \cdot \text{m}^2$

Table 5.2: Parameters of 2.3kW SCIG

Appendix B

Reference frame transformations

The DQ transformation is a transformation of coordinates from the three phase stationary coordinate system to the dq rotating reference system.

The transformation is performed in two steps:

a) from three phase stationary coordinate system to $\alpha\beta$ stationary coordinate system (Clarke Transformation);

b) from $\alpha\beta$ stationary coordinate system to dq rotating reference frame (Park Transformation).

Note: In this project, the software Power Factory DIgSILENT provides the real and imaginary parts of the measured variables, therefore in the models implemented in the project only the Park Transformation has been applied. However for mathematical calculus both steps must be taken.

Consider the complex AC current vector \bar{i} defined by the three phase components $\bar{i}_a, \bar{i}_b, \bar{i}_c$:

$$\bar{i} = \bar{i}_a + e^{j\frac{2}{3}\pi}\bar{i}_b + e^{j\frac{4}{3}\pi}\bar{i}_c \tag{5.15}$$

Figure 5.27 displays the current complex space vector:



Figure 5.27: Current complex space vector representation

B.1 Clark Transformation (a,b,c) to (α,β)

A transformation from the three phase system to a two orthogonal coordinate system can be applied:

$$\begin{cases} i_{\alpha} = \frac{2}{3}i_{a} - \frac{1}{3}(i_{b} - i_{c}) \\ i_{\beta} = \frac{2}{\sqrt{3}}(i_{b} - i_{c}) \\ i_{0} = \frac{2}{3}(i_{a} + i_{b} + i_{c}) \end{cases}$$
(5.16)

where i_{α} and i_{β} are the orthogonal components and i_0 is the homopolar component. See Figure for a graphical description of the transformation.



Figure 5.28: Current complex space vector and its α, β components in stationary reference frame

For balanced three phase components, the homopolar component is null. If this is the case, then the following applies:

$$i_a + i_b + i_c = 0 \tag{5.17}$$

Using equation 5.17 and introducing it in equation 5.16 results the Clark transformation equations for balanced space vectors:

$$\begin{cases} i_{\alpha} = i_a \\ i_{\beta} = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \end{cases}$$

$$(5.18)$$

B.2 Park Transformation

The process can be continued by transforming the stationary system obtained into a rotating synchronous reference frame. For this purpose, an orthogonal coordinate system named dq frame is considered to be rotating synchronously with the complex vector frequency ω . In other words, the angle difference between the d-axis and the α -axis shown in Figure 5.29 is equal to θ , where:



Figure 5.29: Current complex space vector and its d,q components in the rotating reference frame

$$\theta = \omega t \tag{5.19}$$

Applying the transformation, the following equations results:

$$\begin{cases} i_d = i_\alpha \cos(\theta) + i_\beta \sin(\theta) \\ i_q = -i_\alpha \sin(\theta) + i_\beta \cos(\theta) \end{cases}$$
(5.20)

B.3 Inverse Clark and Park transformations

The inverse Park transformation is described by equations 5.21.

$$\begin{cases} i_{\alpha} = i_d \cos(\theta) - i_q \sin(\theta) \\ i_{\beta} = i_d \sin(\theta) + i_q \cos(\theta) \end{cases}$$
(5.21)

The inverse Clarke transformation is described by equations 5.22.

$$\begin{cases} i_{a} = i_{\alpha} \\ i_{b} = -\frac{1}{2}i_{\alpha} + \frac{\sqrt{3}}{2}i_{\beta} \\ i_{c} = -\frac{1}{2}i_{\alpha} - \frac{\sqrt{3}}{2}i_{\beta} \end{cases}$$
(5.22)

Appendix C

Generator Side Converter and DC transmission System Components

C.1 Rectifier

- ElmVscmono built-in component in DIgSILENT Power Factory;
- sinusoidal modulation;
- switching frequency $f_{sw} = 1,95kHz$ [4];
- rated DC voltage $V_{DC} = 1.13kV$;
- rated AC voltage $V_{AC} = 0.69kV$;
- rated apparent power S = 2.59MVA.

C.2 PI current controller

- Ki=2 Found with Matlab Sisotool;
- Ti=0.002 Found with Matlab Sisotool.

C.3 PI AC voltage controller

- Kv=0.01 Found with Matlab Sisotool;
- Tv=0.08- Found with Matlab Sisotool.

C.4 Phase reactor

$$Z_b = \frac{V_{rated}^2}{S_{rated}} = \frac{0.69^2}{2.59} = 0.184\Omega$$
(5.23)

$$\begin{cases} X_l = x_l \cdot Z_b = 0.14 \cdot 0.18 = 0.0252 \\ L = \frac{X_l}{2\pi f} = \frac{0.0252}{2\pi 50} = 80\mu H \end{cases}$$
(5.24)

$$R = r_l \cdot Z_b = 0.01 \cdot 0.18 = 1.84m\Omega \tag{5.25}$$

C.5 AC Filters

$$Z_o = z_o \cdot Z_b = 0.15 \cdot 0.18 = 0.027\Omega \tag{5.26}$$

$$f_1 = 1 \cdot f_{sw} = 1950Hz \tag{5.27}$$

$$\begin{cases} L_{f1} = \frac{Z_o}{2\pi f_1} = \frac{0.027}{2\pi \cdot 1950} = 2.2\mu H\\ C_{f1} = \frac{L_{f1}}{Z_o^2} = \frac{2.2\mu}{0.027^2} = 3mF \end{cases}$$
(5.28)

$$f_2 = 2 \cdot f_{sw} = 2 \cdot 1950 = 3900 Hz \tag{5.29}$$

$$\begin{cases} L_{f2} = \frac{Z_o}{2\pi f_2} = \frac{0.027}{2\pi \cdot 3900} = 1.1 \mu H \\ C_{f2} = \frac{L_{f2}}{Z_o^2} = \frac{1.1 \mu}{0.027^2} = 1.5 m F \end{cases}$$
(5.30)

$$f_3 = 3 \cdot f_{sw} = 2 \cdot 1950 = 5850Hz \tag{5.31}$$

$$\begin{cases} L_{f3} = \frac{Z_o}{2\pi f_3} = \frac{0.027}{2\pi \cdot 5850} = 0.7 \mu H \\ C_{f3} = \frac{L_{f3}}{Z_o^2} = \frac{0.7\mu}{0.027^2} = 1 m F \end{cases}$$
(5.32)

C.6 DC Capacitors

$$\omega_l = 2\pi 30 \tag{5.33}$$

$$\zeta_n = \frac{1}{\sqrt{2}} \tag{5.34}$$

$$\delta n = 0.05 \tag{5.35}$$

$$C_{dc} = \frac{P_{rated}}{V_{dc}^2} \cdot \frac{2 \cdot \zeta_n^2}{\omega_l} \cdot \frac{1}{(1 - \delta n) \cdot \delta n} = \frac{2.3 \times 10^6}{1.13^2 \times 10^6} \cdot \frac{2 \cdot 0.707^2}{188} \cdot \frac{1}{(1 - 0.05) \cdot 0.05} = 0.002F \quad (5.36)$$

Appendix D

Grid Side Converter and DC transmission System Components

D.1 Inverter

- ElmVscmono built-in component in DIgSILENT Power Factory;
- sinusoidal modulation;
- switching frequency $f_{sw} = 1,95kHz$ [4];
- rated DC voltage $V_{DC} = 18kV$;
- rated AC voltage $V_{AC} = 8.8kV$;
- rated apparent power S = 8MVA.

D.2 PI Inner Loop Controller

- Kc=0.402 Found with Matlab Sisotool;
- $\bullet~{\rm Tc}{=}0.0074$ Found with Matlab Sisotool.

D.3 PI Outer Loop Controller

- Kdc=0.5 % Found with sisotool
- Tdc=0.1 % Found with sisotool

D.4 Phase Reactor

$$Z_b = \frac{V_{rated}^2}{S_{rated}} = 9.68\Omega \tag{5.37}$$

$$\begin{cases} X_l = x_l \cdot Z_b = 1.35\Omega\\ L = \frac{X_l}{2\pi f} = 4.31mH \end{cases}$$
(5.38)

$$R = r_l \cdot Z_b = 0.01 \cdot 0.18 = 96.8m\Omega \tag{5.39}$$

D.5 AC Filters

$$Z_o = z_o \cdot Z_b = 2.06\Omega \tag{5.40}$$

$$\begin{cases} L_{fn} = \frac{Z_o}{2\pi f_n} \\ C_{fn} = \frac{L_{fn}}{Z_o^2} \end{cases}$$
(5.41)

$$L_{f1} = 0.000168H \tag{5.42}$$

$$L_{f2} = 8.43e - 05H \tag{5.43}$$

$$L_{f3} = 5.62e - 05H \tag{5.44}$$

$$C_{f1} = 3.948e - 05F \tag{5.45}$$

$$C_{f2} = 1.974e - 05F \tag{5.46}$$

$$C_{f3} = 1.31e - 05F \tag{5.47}$$

D.6 DC Capacitors

$$\omega_l = 2\pi 30 \tag{5.48}$$

$$\zeta_n = \frac{1}{\sqrt{2}} \tag{5.49}$$

$$\delta_n = 0.05 \tag{5.50}$$

$$C_{dc} = \frac{P_{rated}}{V_{dc}^2} \cdot \frac{2 \cdot \zeta_n^2}{\omega_l} \cdot \frac{1}{(1 - \delta n) \cdot \delta n} = \frac{6.9 \times 10^6}{18 \times 10^6} \cdot \frac{2 \cdot 0.707^2}{188} \cdot \frac{1}{(1 - 0.05) \cdot 0.05} = 0.002F = 4mF$$
(5.51)

Appendix E

Base Values

Base Values	Description
$P_{base} = 2.3MW$	Base active power
$Q_{base} = 1.17MVAR$	Base reactive power
$S_{base} = 8MVA$	Base apparent power
$\Omega_{r-base} = 1.72 rad/s$	Base rotor speed
$\omega_r = 1500 rpm$	Base rotor speed of the generator

Appendix F

Grid Parameters

Parameter	Description
$T_{acc} = 1000s$	Acceleration time constant
$S_{k1-max} = 10000MVA$	Maximum short circuit power - case 1
$S_{k1-min} = 8000MVA$	Minimum short circuit power - case 1
$S_{k2-max} = 1000MVA$	Maximum short circuit power - case 2
$S_{k2-min} = 8000MVA$	Minimum short circuit power - case 2