Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Mona Martinsen

Control Design of a Low-Cost Hybrid Converter for HVDC Connection of Offshore Wind Farms

Master's thesis in Energy and Environmental Engineering
Supervisor: Olimpo Anaya-Lara and Raymundo Torres-Olguin
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NTNU
Kunnskap for en bedre verden

Summary

Offshore wind is considered one of the most promising technologies to increase the energy production from renewable energy sources, but one main limitation is the high cost. Recently, HVDC connections with voltage source converters (VSCs) have become more relevant for offshore wind as the wind farms are increasing in size and are moved further offshore. In this master thesis a new converter topology combining a VSC with a diode rectifier (DR) is studied. This combination aims to combine the low cost and high efficiency of the DR with the flexible operation of the VSC. The hybrid topology consist of a VSC connected in series with a 12-pulse VSC on the DC side. The hybrid VSC-DR will be used on the offshore side, while a conventional VSC is used on the onshore side of the HVDC-link.

The main challenge of this system is to control the offshore VSC to manage several tasks simultaneously: forming the AC grid, balance the active power between the converter types, cancel characteristic harmonics from the DR and deliver reactive power compensation to the DR. In this thesis, a control system is proposed where the offshore VSC has a cascaded control of the AC voltage in synchronous reference frame. The VSC is also controlled to have active power filter control loops to filter harmonics for the DR. The design of the transformer ratios is used to determine the power sharing between the VSC and the DR. The reactive power compensation is automatically fulfilled from either the turbine converter or the VSC if no other reactive power source is added. The onshore VSC controls the DC voltage in the HVDC link and the reactive power flow to the grid.

The control system was first developed and implemented when the hybrid converter consisted of 1/2 VSC and 1/2 DR of the full power rating. This rating was chosen because it is easier to develop a control system with a larger VSC. The performance was verified through simulations in PSCAD/EMTDC and fulfils the defined control objectives. The active power filter was able to completely eliminate the filtered components - the 11th and the 13th, harmonics in offshore current. It was later attempted to decrease the size of the VSC to further improve cost savings from the DR. It was shown through simulations that the size of the VSC could be reduced to 1/4 of the full power rating and still have a stable offshore AC grid. This is a smaller VSC than what have been reported in earlier studies, where the smallest have been 1/3. More work should still be carried out to examine the

impact of the VSC size on the stability and performance of the system to find an optimal sizing.

All in all the results from the control system, the active power filter and the reduced size of the VSC show positive indications that the proposed topology can reduce the cost and losses of HVDC, and still perform according to the control objectives.

Sammendrag

Havvind er sett på som en av de mest lovende teknologiene for å øke produksjonen fra fornybare energikilder, men så langt har utviklingen vært begrenset av høye kostnader. I det siste har nye havvindprosjekter blitt større og er ofte lokalisert lengre fra kysten. På grunn av dette har det blitt mer lønnsomt og relevant å bruke HVDC overføring med VSC-omformere. Denne masteroppgaven tar for seg en ny omformer-topologi som kombinerer en VSC med en diode likeretterbro (DR). Det er ønsket å se om denne kombinasjonen kan utnytte den lave kostnaden og høye effektiviteten fra diode likeretteren og samtidig beholde kontrollegenskapene fra VSCen. Hybrid omformeren består av en 12-puls diode likeretter som er seriekoblet med en VSC på DC siden. Denne hybridomformeren vil bli brukt på offshore siden, mens en vanlig VSC blir brukt på landsiden.

Hovedutfordringen med dette systemet er at VSCen på offshore siden må utføre flere kontrolloppgaver samtidig: den skal forme offshore AC nettet, regulere effektbalansen mellom omformerene i hybrid-konfigurasjonen, filtrere karakteristiske harmonsiske fra diode-likeretteren og kompensere for reaktivt effekttap i diode-likeretteren. Her er det foreslått et reguleringssytem hvor VSCen bruker en dobbel løkke regulering av AC spenningen i dq-roterende referansesystem. VSCen brukes også som et aktivt effektfilter (APF) for å filtrere harmoniske komponenter i strømmen. Transformatorer som er koblet til hver av omformerene brukes til å bestemme effektbalansen mellom omformerkomponentene, med å utnytte at AC og DC spenningen for en diode likeretter er proporsjonale. Kompenseringen av reaktiv effekt skjer automatisk fra enten VSCen eller VSCer i turbinene dersom ingen andre kilder til reaktiv effekt er tilkoblet. På landsiden kontrollerer VSCen DC spenningen i HVDC linken og den reaktive effekten som leveres til strømnettet.

Reguleringssystemet var først laget og implementert der VSCen var satt til å være 1/2 av den totale aktive merkeeffekten til hybridomformeren. Simuleringer i PSCAD/EMTDC har verifisert at denne omformeren kan oppfylle kontrollmålene. Det aktive filteret klarte å fullstendig eliminere de filtrerede komonentene, den 11th og den 13th, fra strømmen offshore. Det ble deretter testet om det var mulig å minke den relative størrelsen på VSCen for å redusere kostnaden ytterligere. Gjennom simuleringer ble det vist at størrelsen på VSCen kunne reduseres til 1/4 av den totale merkespenningen og systemet forble stabilt. Dette er en mindre VSC enn hva som har blitt brukt i tidligere studeier, hvor den minste

størrelsen har vært 1/3 av total merkespenning. Det trengs fremdeles mer arbeid for å bestemme stabilitetsgrensene og den optimale størrelsen av VSCen.

Alt i alt viser resultatene, både fra kontrollsystemet, fra det aktive filteret og fra den reduserte størrelsen av VSCen, gode indikasjoner på at den foreslåtte topologien kan redusere kostnadene og effekttapene i HVDC, og fremdeles oppfylle alle de definerte kontrolkravene.

Preface

This master thesis is the product of my final semester as a student at the Department of Electrical Engineering at the Norwegian Institute of Science and Technology (NTNU). The work is a continuation of my specialization project *"Control Design of a Low-Cost Hybrid Converter for HVDC Connection of Offshore Wind Farms"* which was completed in the fall 2019.

The work has been supervised by Prof. Olimpo Anaya-Lara and by co-supervisor Dr. Raymundo Torres-Olguin from SINTEF. I would like to sincerely thank them both for helping me carrying out this work. There have been many obstacles along the way, including new concepts, new software and technical issues and their help in all aspects have really helped to keep me the motivated throughout this year. I am really thankful that good help and motivational speeches were never more than a skype call away.

Trondheim, June 11th, 2020

Mona Martinsen

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Abbreviations

AC	Alternating Current
APF	Active Power Filter
DC	Direct Current
DR	Diode Rectifier
FRC	Fully Rated Converter
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IGBT	Insulate-Gate Bipolar Transistor
IHDi	Individual harmonic distortion (current)
LCC	Line Commutated Converters
MMC	Multi-Modular Converters
OWF	Offshore Wind Farm
PCC	Point of Common Coupling
PI controller	Proportional Integral controller
PR contorller	Proportional Resconnant controller
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
RMS	Root Mean Square
SRF controller	Synchronous Reference Frame Controller
THDi	Total Harmonic Distortion (current)
VSC	Voltage Source Converter

Chapter 1

Introduction

1.1 Background and motivation

Offshore wind is considered one of the most promising technologies for increasing the large-scale integration of clean energy in the world. During the last decade, there has been a huge development within this industry, both in terms of the number of ongoing projects as well as in the technical solutions that are being used. Europe and, the North Sea especially, have been the centre of the development and offshore wind have been suggested as one of the core energy sources that can help make Europe fossil-free within 2050 [2]. The total installed capacity in Europe was in 2019 22GW across 110 wind farms [3], but the potential for the future is significantly higher. New markets are also in the US, China and Japan [4].

The benefits of building wind farms offshore compared to onshore include larger available areas, better wind resources and fewer conflicts due to visual impact and noise. On the other hand, wind farms at offshore are more expensive and technologically challenging to build. The high cost of offshore wind is still one of the main limitations, and although the cost is decreasing, most projects are still relying on subsidies to be cost-competitive [2]. One of the main priorities in the planning and development of new projects is to find solutions that will decrease the investment cost or increase the efficiency and hence reduce the operational costs.

One trend is offshore wind farms with bigger turbines and larger wind farms located far away from shore [3]. This evolution poses challenges for the transmission system and grid integration, which is a crucial part of the wind farm design. High voltage direct current (HVDC) transmission is generally economically preferable for distances greater than 100km or power rating above 200MW [1] and is becoming increasingly relevant for offshore wind. With the development, it is predicted that HVDC will become the new standard for offshore wind in the future [5].

Traditionally HVDC connections have been using line commutated converters (LCC), but the complexity of offshore wind integration has made voltage source converters (VSC) the preferable option for offshore wind farms. The concept of VSC based HVDC for the integration of offshore wind is still relatively new, and it is associated with high costs and large losses. An interesting point for research has been to find new solutions for connecting wind farms with HVDC that will reduce these drawbacks. This thesis investigates a hybrid converter with a diode rectifier (DR) and a VSC. It aims to combine the advantages of DR and VSC technology.

A hybrid converter consisting of a voltage source converter (VSC) in series with a diode rectifier (DR) could reduce the cost and increase the efficiency of the offshore converter substation. In this topology the size (or rating) of the VSC can be reduced as parts of the power is delivered from the DR. This gives cost savings and increased efficiency as the DR is cheaper and have lower losses than the VSC. The converter configuration connected to a wind farm is shown in fig. 1.1. From here on this converter topology will be referred to as the *hybrid VSC-DR converter* or the *hybrid converter*.

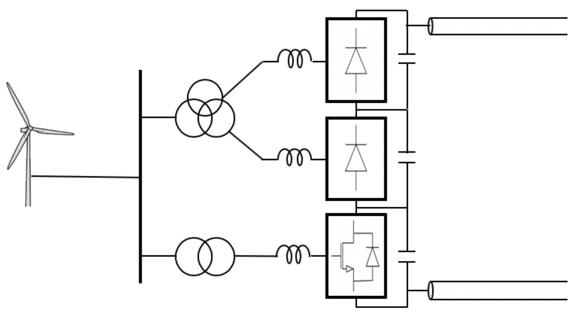

Figure 1.1: A hybrid VSC-DR converter connected to a offshore wind farm.

The VSC-DR hybrid converter was first proposed by Korean researchers Thanh Hai Nguyen and Dong-Choon Lee in [6] from 2012. Later there have been published a handful of papers investigating this topology with focus on control system operation and performance, but more research is still needed. The control system required for this transmission system becomes complex when the uncontrollable DR is introduced in the system. In addition, the combination of the characteristics of both systems creates some interesting challenges related to reactive power compensation and harmonic cancellation. Lastly, the sizing of the VSC in the hybrid converter needs more consideration. In earlier studies, the proportion of the full rating have been 1/2 VSC - 1/2 DR [6] and 1/3 VSC - 2/3 DR [7], but optimisation of the VSC size has not been addressed. Important questions that will be investigated in this thesis are:

- Will the VSC still be able to control the power flow in the system?
- How will the power balance between the VSC and the DR in the hybrid converter be ensured?
- Can the offshore VSC be used to compensate reactive power and harmonics from the DR?
- Can the size of the VSC be reduced to less than 1/3 of the full converter rating?

1.2 Objectives

The main objectives of this master's thesis are:

- Determine a control strategy for the hybrid converter and the onshore VSC, which ensures maximum active power flow.
- Develop a model of the full transmission system in PSCAD/EMTDC that can simulate different cases that are relevant in the research. The model includes a simplified model of the wind farm and the grid.
- Implement a control system to utilise the VSC in the hybrid converter as an active filter to eliminate harmonics from the diode rectifier.
- Through simulations, test the transmission system operation under normal conditions, including variations in wind speed and start-up.
- Analyse the impact of the sizing of the VSC in the hybrid converter and try to find the minimum size of the VSC for a stable system.

1.3 Methodology

The methodology used for this thesis is described in seven steps as follows:

1. To conduct a literature review on previous research on converter topologies for HVDC. This includes earlier studies on the hybrid VSC-DR converter.
2. To define control objectives and develop control strategy for maximum active power transfer and power balancing in the hybrid converter.
3. Design a model-based controller in the synchronous reference frame for both the offshore and the onshore VSC.
4. To implement control loops for an active power filter in the offshore VSC to eliminate the 11th and the 13th harmonics from the DR.
5. To develop a simplified model of a wind farm based on an ideal current source and a varying power injection from a wind profile.
6. Test and validate the performance of the proposed control system and active power filter done through simulations in PSCAD/EMTDC.
7. Determine the theoretical optimal size of the VSC based on minimising the total apparent power rating. Test the performance of the system when the size of the VSC is reduced. system.

1.4 Assumptions and scope

Several assumptions and simplifications have been made to adjust the work to the available time period of this master's thesis and to concentrate on the control of the hybrid converter in the system. The main simplifications are:

- Since the research is focused on the transmission, the wind farm has been simplified, ie. the detailed modelling including control and power electronics are omitted.
- Since the hybrid converter is on the offshore side, a simplified model of the onshore grid is used. The grid has been modelled as a constant voltage source, acting as a very stiff grid. VSC-HVDC connections can be used to integrate wind farms to weak grid [8], but this outside the scope.
- The VSCs were implemented as two-level converters, where one switch represents several switched in series. Some of the conclusions can be extended to converters like MMCs.

- The losses in the system have not been considered. This includes the resistive losses in lines, cables and transformers, as well as switching losses in the converter IGBTs and diodes.
- Ideal transformers have been used.

1.5 Contribution

The main contributions of this thesis, as given in the conclusion, is summarised here:

- A control strategy for a hybrid-VSC-DR HVDC system has been developed. It has a cascaded AC voltage control for the offshore VSC, which can compensate for variations in input current due to power variations for the wind farm. The AC voltage control also indirectly controls the power balancing of the hybrid converter. The onshore converter uses a conventional control method for a VSC. The control system has been verified through simulations in PSCAD/ETMDC.
- It has been shown that the characteristic harmonics in the current from the DR can be eliminated by using the VSC as an active power filter. The IHDi for the filtered harmonics is decreased significantly and is almost zero when the APF is used.
- It has been shown that the control system can, in theory, operate with a VSC smaller than 1/3. Through simulations, the system is stable and fulfilling the control objectives when the VSC is 1/4 of the full rated converters. This result indicates that the size of the VSC can be smaller than 1/3 of the full rating, which would increase the cost-benefit of the converter.
- The optimal size for minimising the apparent power rating of the offshore VSC if reactive power compensation is regarded is calculated to be approximately 1/4 of the total active power rating. It was shown that the control objectives of the transmission system are still fulfilled when this size of the VSC is used. This is the first step towards optimising the hybrid VSC-DR converter.

1.6 Outline of the report

The master's thesis is organised in eight chapters, as follows:

- Chapter 1 provides an introduction by motivating the study, outlining the scope, stating the main objectives and contributions of this thesis.

- Chapter 2 gives relevant background information about the situation today and traditional HVDC-systems. It states the pros and cons of different types of HVDC systems and presents an overview of previous research conducted on hybrid converters.
- The hybrid VSC-DR transmission system is introduced in Chapter 3. Here the topology is presented, and the main components are explained. In addition, the simplified model used for the wind farm is presented.
- Chapter 4 focuses on the control system for the transmission system. It first presents the control objectives for the system, and then the controllers for each objective are derived and explained. This chapter includes the challenges of controlling the offshore VSC in this hybrid system.
- Chapter 5 focuses on harmonic filtering of the characteristic harmonics form the DR. A method where the offshore VSC is used as an active filter is explained and the control loops for this method is derived.
- Chapter 6 tests the performance of the system through simulations in PSCAD/ETMDC. The responses for each controller are presented, as well as the results of the active power filter.
- Chapter 7 is dedicated to the sizing of the VSC in the hybrid converter. The stability issues and economic considerations related to this concept are presented, and simulations are shown for reduced sizes of the VSC in the hybrid converter.
- Finally, Chapter 8 summarises the main conclusions and gives suggestions for future work that could be of interest in future research projects.

Chapter 2

HVDC systems for offshore wind farms

This chapter aims to give a more in-depth background of the offshore wind industry and its characteristics. It explains the benefits of using HVDC transmission and why this is becoming more relevant. The two available HVDC systems are described, and the motivation behind using a hybrid system is elaborated. Finally, an overview of previous research on hybrid-HVDC and other relevant research is presented.

2.1 Characteristics of the offshore wind transmission

There are special considerations that must be regarded when designing a transmission system for a offshore wind farm. The challenges relate to the harsh offshore environment and to the operation of the wind farm. Some of the main considerations when designing an offshore wind transmission system are listed below:

- The offshore station must be robust to tolerate the harsh offshore environment, including tear from weather, waves and salt.
- The offshore station should be reliable as it is more challenging to carry out maintenance.
- The size of the offshore station should be limited, because it is technically difficult and expensive to build large stations offshore.

- The cost of building offshore is expensive; therefore, the efficiency should be high to lower the costs.
- Because of the intermittent wind power, the control system must be able to handle large variations in the current flow.
- The wind farm should according to grid codes be able to deliver reactive power to the grid if requested to help operate the grid [9].

2.2 Transmissions systems with HVDC

HVDC systems have been a well-established way for bulk power transmission between two grids, and it is only recently these have also become relevant for use in large-scale integration of renewable sources, e.g., offshore wind integration. The benefits of using HVDC increase when the transmission distance is long, and the power rating is high. Until now, most offshore wind projects have been using HVAC, but some projects with HVDC are already developed, and more are planned. It is expected the HVDC will become the standard transmission type for offshore wind in the future. The decision between HVDC or HVAC is often economically motivated, but there are also other benefits of using HVDC. The main benefits of HVDC over HVAC are listed below [1]:

- There are no capacitive currents in HVDC, and thus there is no need for reactive compensation of the cable.
- The power losses are much lower than for HVAC.
- Converter stations on each side of the cable give full control of the power flow.
- The offshore grid is decoupled from the onshore grid. Disturbances on one side will not affect the other.
- No theoretical limit on the transmission distance.

2.3 Characteristics of LCC and VSC transmission systems

An HVDC system needs to have converter stations on each side to transform between AC and DC. There are today two well-established converter configurations for HVDC, namely line commutated converters (LCC) and voltage source converters (VSC). Generally, LCC has been preferred for HVDC connections between two grids, but have not been suitable for offshore wind due to technical limitations. Below, there is a comparison of the most important characteristics and pros and cons of each of the converter types [10, 11, 1]:

- LCC is generally cheaper than VSC. In [12] an overview of cost for different systems are given, and it shows that VSC is more expensive in all cases and on average up to 50% more expensive.
- LCC has lower power losses than VSC. The average losses for LCC are 2-3% compared to 4-6% for VSC [12].
- VSC has a smaller footprint as it does not need large filters in the offshore station.
- VSC can have black start, which is not possible with the LCC since it needs a commutation voltage source offshore.
- VSC can have independent control of active and reactive power flows. LCC consumes reactive power dependent on the active power flow.
- VSC can operate with weak AC grids and passive AC grids.

2.4 VSC-HVDC system

The VSC-HVDC transmission system is the standard for HVDC transmission in offshore wind. They are described in detail in many source such as [11],[13] and [14]. In this system, both the rectifier and inverter consist of voltage source converters that control the power flow in the transmission system. In this thesis, the VSC-HVDC system acts as the present conventional system and is, therefore, the reference system to the study. A schematic of the typical VSC-HVDC configuration is shown in fig. 2.1[15].

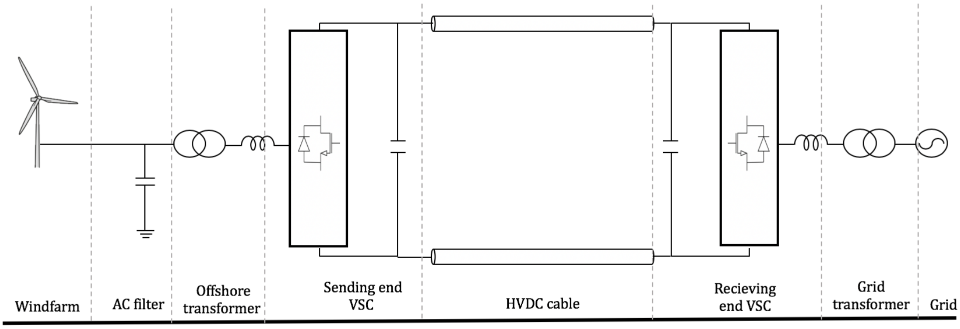

Figure 2.1: Topology for a VSC-HVDC integrating an offshore wind farm

2.5 New topologies for HVDC systems

As a widespread use of offshore HVDC is expected in the future, the motivation for researching other alternatives to the VSC-HVDC system have become evident. The interest for new converter topologies and more knowledge on the interactions between converter types are very relevant problems in research on transmission systems.

Hybrid converter topologies are one of the areas where new research is showing potential. Examples of these are the hybrid VSC-DR converter of this thesis and topologies where one side is an LCC, and one side is a VSC, which is studied in [12]. A full review of hybrid converter topologies proposed for offshore wind is given in [16].

There is also a high interest in finding solutions for how LCC-HVDC or DR-HVDC can be used for offshore wind integration. A schematic diagram of a DR-HVDC is shown in fig. 2.2 [17]. In this system, the control system of the turbine converters must be changed, such that the VSCs in the turbines are establishing the AC grid. The control of the turbine VSCs is explained in [18], and the full control system for the DR-HVDC is described in [17] and [19]. A schematic diagram of this topology is shown in fig. 2.2.

In addition to new converter topologies, the use of multi-terminal HVDC systems is given more and more attention. They are HVDC links with more than two converter interfaces. These systems could radically change how wind farms are being integrated to the grid. Proposed solutions are wind farms integrated to existing LCC HVDC link, several wind farms sharing one transmission link or even interconnected offshore grids with integrated offshore wind farms. The concept of how a multi-terminal HVDC system can be used for offshore wind integration is explained in [20] [21] and [22].

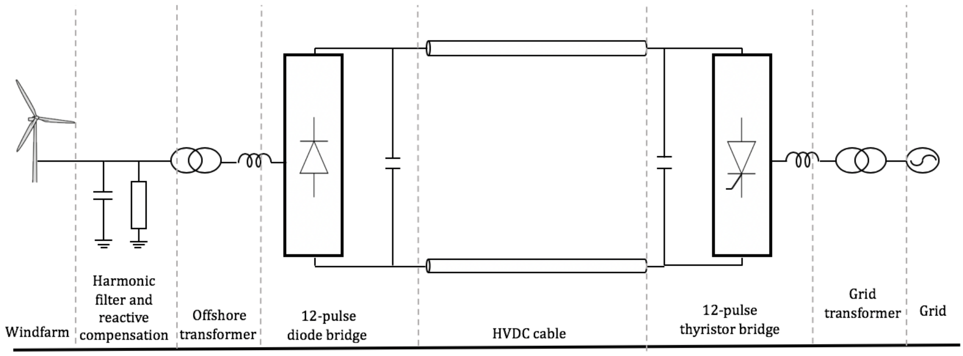

Figure 2.2: Topology for a DR-HVDC integrating an offshore wind farm

2.6 Literature review of VSC-DR hybrid converter

This thesis concentrates on the hybrid VSC-DR hybrid transmission system. This transmission system was first proposed by Nguyen and Lee [6] and has later been studied in a handful of papers and a master's thesis. However, most of the studies are reported in concise papers where many details are left out. There are still lacking in-depth studies on the performance, operation and stability issues related to this topology, in addition to a cost-benefit analysis to accurately determine the potential savings. Below is a summary on the studies that have been published on the hybrid VSC-DR topology until now. The first four studies are all carried out by Nguyen et al., who first proposed this topology.

1. In [6] a control system with only a direct voltage controller on the offshore side is presented. The onshore VSC is controlled as in the conventional VSC-HVDC system. The rating of the offshore VSC is 1/2 of the full power rating. Simulations are used to prove the concept. The paper also proposes a control strategy for operation during grid stags to provide fault ride-through capability.

2. In [23] the offshore VSC control is changed. It now controls both the offshore AC and DC voltage balance in the hybrid converter in the synchronous reference frame, and it acts as an active power filter with PR controllers to filter the characteristic harmonics for the DR. The size of the VSC is also decreased to 1/3 of the full rating. This paper also presents calculations of the efficiency and cost improvement of the new topology.

3. In [24] the VSCs for [23] are exchanged for multi-modular converters (MMCs), but the control strategy is kept the same.

4. In [7] the hybrid VSC-DR is used on both the offshore and the onshore side of the HVDC-link. The offshore control is active power in the VSC and AC voltage. The onshore control is reactive power and DC voltage in the HVDC-link. Both sides also have active power filter capabilities with PR controllers. Still, the VSC is 1/3 of the full rating on both sides.

5. The master's thesis in [25] investigates several converter topologies, including the hybrid VSC-DR. It explains the steps in deriving a control strategy with active power filter capabilities in the stationary reference frame.

6. The paper in [26] was published in April 2020. It uses a 6-pulse diode rectifier, instead of the 12-pulse and cancels the harmonics with an active power filter control loop using multiple synchronous reference frames. The offshore VSC uses a direct AC voltage controller, and the onshore VSC is similar as in VSC-HVDC. The simulations are carried out where the VSC is approximately 60% of the full rating.

2.7 Other relevant research

It has also been relevant to study previous research that has been carried out on other hybrid configurations and DR or LCC integration of offshore wind. These studies often share some of the same characteristics and challenges as in this thesis. Another benefit is that many of them are PhD-thesis' which includes more context and details than the papers in the previous section. A summary of the most useful research is listed below:

- In [27] a hybrid VSC-DR converter is used for grid to grid connection. The control system is different, but the motivation and many of the characteristics are the same. This is also the only study that discusses the sizing of the VSC in the hybrid converter and it proposes a strategy for finding the optimal size.

- In [12] a hybrid converter where the offshore side is a VSC, and the onshore side is an LCC is used for offshore wind integration. The VSC is controlling the offshore AC grid, and this controller inspired the controller used in this thesis.

- In [19] a diode rectifier is used as the offshore converter, and an LCC is used as the onshore converter in offshore wind transmission. The challenge of controlling the AC grid without a VSC in the HVDC presented, and it explains how the control of the offshore wind farm must be changed to accommodate this.

- [11] and gives an in-depth explanation of the conventional VSC-HVDC system connected to an offshore wind farm and its control system. This is used as the base for developing the control strategy for the hybrid converter.

Chapter 3

Hybrid VSC-DR transmission system

In this chapter, the hybrid VSC-DR transmission scheme is presented. First, the complete system topology is introduced, then the converter types and other main components of the system and their values are determined. Finally, the last section focuses on the wind farm and the operation of the turbine converters, and a simplified model for simulations is presented.

3.1 System topology

The transmission system investigated in this thesis consist of a hybrid VSC-DR on the offshore side and a VSC on the onshore side of an HVDC link connecting an offshore wind farm to the grid. The components that make up the system are similar to those of the VSC-HVDC system in fig. 2.1, but the offshore converter is different. The hybrid converter consists of a 12-pulse diode rectifier (or two 6-pulse DRs) connected in series to a VSC on the DC side and in parallel on the AC side. In addition, the transmission system consists of transformers, reactors on the AC side, capacitors on the DC side, and the HVDC cable. In the following sections, each of the main components will be elaborated, and their values will be determined. The schematic diagram of the hybrid VSC-DR transmission system is found in fig. 8.7.

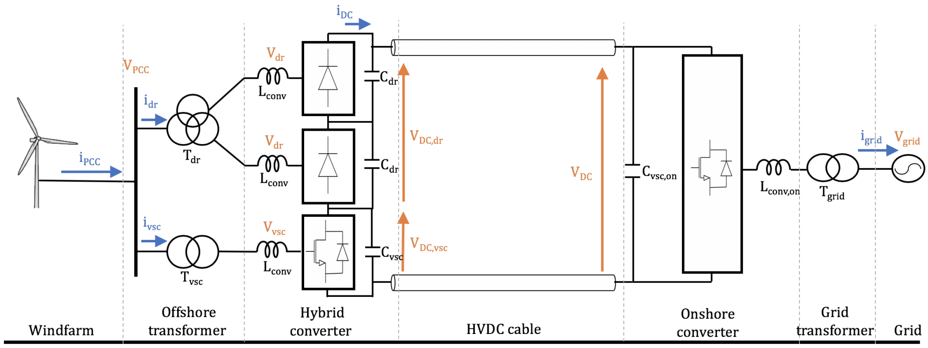

Figure 3.1: System topology for hybrid VSC-DR HVDC.

3.2 Base values and per-unit system

The voltages and the power in the system are chosen to imitate a realistic wind farm with an HVDC transmission system. The wind farm used a medium to a large wind farm based on the power rating. The voltage levels at the point of common coupling offshore and at the grid connections are also based on common standards in the industry. The control system will ensure that the voltages are at their rated values.

It is common to implement the control system is a per-unit system, where the parameters are scaled by a base. This makes it easier to notice if values in the control system are outside the normal range, and it also gives better transferability of the control system to similar systems. The per-unit system is added in the Appendix.

The rated values of the system, which are also the basis for the per-unit system, are found in table 3.1.

Table 3.1: Base values for the hybrid VSC-DR transmission system

Quantity	**Symbol**	**Base value**
Apparent power	S_{base}	400MVA
Voltage at offshore PCC	V_{PCC}	33kV
DC voltage in HVDC link	V_{DC}	300kV
Voltage at grid connection PCC	V_{grid}	170kV
Frequency	f	50Hz

3.3 Voltage source converter

The voltage source converter is possibly the most important component in the system as it is controlling the system operation. A VSC consists of IGBT-switches that can be turned on and off at a very high frequency. The high-frequency switching makes it possible to generate any AC voltage amplitude and angle at the converter terminals and makes the converter able to act as a controlled voltage source [1].

3.3.1 Two-level VSC

There are different topologies for VSCs, but for HVDC systems there are three commonly used types: the two-level VSC, the three-level VSC and the modular multilevel converter (MMC) [28]. The MMC consists of many smaller VSC-modules that are interconnected, and it is becoming increasingly popular in high power applications due to the lower harmonic content and better cost efficiency [29]. In this report the two-level VSC will be used as it is simpler to model and has a simpler control system. It was considered appropriate to facilitate the investigation of the hybrid converter and development of proposed controllers. The use of the term VSC will in this report refer to the two-level type unless otherwise stated. A circuit diagram of the VSC is found in fig. 3.2.

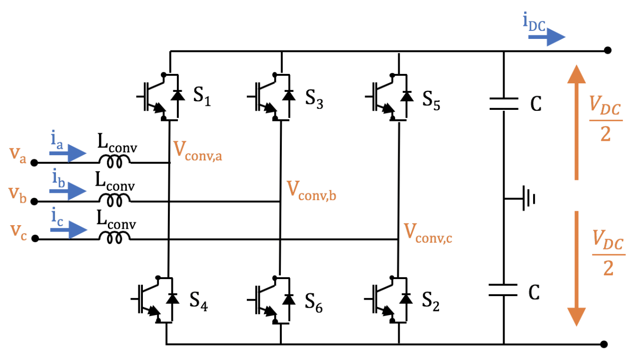

Figure 3.2: Circuit diagram of a two-level voltage source converter.

In the two-level VSC six IGBTs are connected in two levels and three converter legs. Capacitors are connected in parallel to the DC side and functions as short-time energy storage during commutation to limit the ripple in the DC voltage. Similarly, there are inductors connected in series on the AC side, which limits the harmonics in the AC system.

In fig. 3.2 the voltages and current in the circuit are also defined. Here $\mathbf{V}_{conv,abc}$ is the average voltage at the switching terminal and is thus considered a continuous signal. The direction of the current is defined from AC to DC, independent of weather the VSC is operated as a rectifier or inverter.

3.3.2 Sinusoidal Pulse Width Modulation

Sinusoidal pulse width modulation (S-PWM) is a commonly used method for defining the switching signals in the VSC [30]. In the PWM generator a three phase sinusoidal signal, called the control signal, is compared to with a carrier signal that consists of a high-frequency triangular waveform. It is preferred that the control signal has a smaller amplitude than the carrier signal as this gives fast switching in the entire period and a linear relationship between input and output voltage. Operation outside this limit is called overmodulation and should be avoided as it makes the control difficult and creates more harmonics. The correct modulation is ensured as long as eq. (3.1) is fulfilled.

$$V_{LL} < \sqrt{\frac{3}{2}}\frac{V_{dc}}{2} \tag{3.1}$$

3.3.3 Control modes

The control system of the VSC can be designed for operation in different control modes. The control modes are [15]:

- DC voltage control mode
- Active power control mode
- AC voltage control mode
- Reactive power control mode

Which control modes that are used depend on the application, but not all can be used at the same time. These control modes can be combines such that each control signal component, d and q in the synchronous reference frame, can control have one control mode.

3.4 Diode rectifier

The other converter component in this system is the robust, simple and well-known diode rectifier (DR). In contrary to the VSC, where the switches have forced commutation from a control system, the DR is line commutated and can not be controlled. In the circuit it acts as a passive component converting AC voltage to DC voltage and the DC voltage is determined by varying the AC voltage level by using a tap changing transformer. The relationship between the AC voltage and DC voltage is given from eq. (3.2).

$$V_{dc} = 1.35V_{LL} - \frac{3}{\pi}\omega L_{conv} I_{dc} \tag{3.2}$$

In the transmission system two 6-pulse DRs are used to form one 12-pulse DR.

3.4.1 Six-pulse DR

In fig. 3.3 a six pulse DR is shown. It has the same configuration as the VSC, and also has inductances on the AC side and capacitors on the DC side.

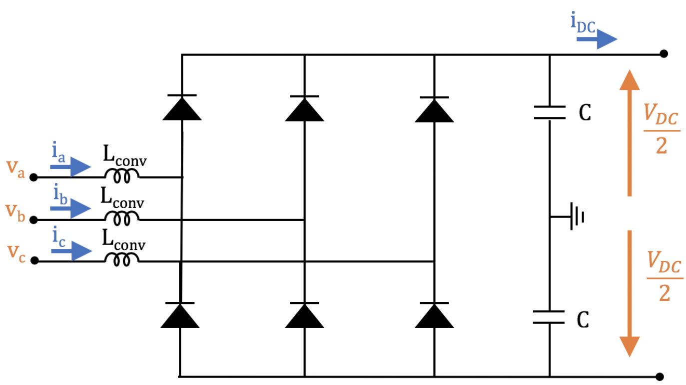

Figure 3.3: Circuit diagram of a 6-pulse diode rectifier.

3.4.2 Characteristics

The characteristics of the DR are very similar to the LCC discussed in section 2.3, as the it, is essentially an LCC with 0° firing angle. Some important characteristics of the diode rectifier are:

- The diodes can only conduct in one direction, and therefore the diode rectifier can only operate as a rectifier, and bidirectional flow is not possible.
- It consumes reactive power proportional to the active power it is transmitting. Studies suggest that this is about 60% for a thyristor bridge dependent on the firing angle [11], and it is assumed that the diode bridge would be in the same scale.

- The current drawn from the AC grid by the DR is highly distorted and contains many characteristic harmonics with low frequency.

These system characteristic established by the DR in the hybrid VSC-DR transmission system makes the system operation and control system different from the one used in VSC-HVDC.

3.5 AC side reactors

The inductors, which are connected to the AC side off all the converter terminals, has an important role in enabling the control of the active and reactive power. It also helps to stabilise and reduce the harmonic distortion of the AC side current [31]. The value should be chosen to 15% of the system impedance [32] and is calculated using eq. (3.3).

$$L_{conv} = \frac{X_L}{\omega} \text{ where } X_L = 0.15 Z_{base} \text{ and } Z_{base} = \frac{V_{base}^2}{S_{base}} \tag{3.3}$$

Based on this the inductance values are presented in table 3.2.

Table 3.2: Values for AC reactors

		S_{base}	V_{base}	Z_{base}	L_{conv}
Offshore	VSC	200 MVA	80 kV	32.0 Ω	0.015 H
	DR	100 MVA	55 kV	30.5 Ω	0.015 H
Onshore	VSC	400 MVA	170 kV	72.5 Ω	0.035 H

3.6 DC side capacitors

The DC side capacitors are connected to the terminals of each converter to reduce the ripple in the DC voltage and to help keep the power balance during transient conditions. The value of the DC voltage can be determined by using eq. (3.4) [15]. From this equation, it is seen that a large capacitor (C) will make the system time constant (τ) larger and thus give slower dynamics. However a small capacitor will give larger ripples in the DC voltage.

$$\tau = \frac{0.5 C V_{dc}^2}{S_{base}} \tag{3.4}$$

Table 3.3: Values for DC capacitors

		C
Offshore	VSC	200 μF
	DR	200 μF
Onshore	VSC	200 μF

In this system there is no direct DC voltage control in the offshore side and simulations have shown that this gives a large ripple in the DC voltage. The capacitor value is found by testing different values in the system until the trade off between ripple and speed of dynamics is considered satisfactory. The final values for the DC capacitors are shown in table 3.3.

3.7 Transformers

Transformers are connected to each of the converter components on the AC side to get the appropriate voltage level on the terminals. The VSC is connected throug a star-delta transformer. This is advantageous because it eliminates the impact of the zero sequence current and voltages [33]. The star-delta transformer does also introduce a phase shift between the primary and secondary side [34], which later becomes a challenge when harmonic components from the DR should be compensated by the VSC.

Star-delta transformers are used for the VSCs to eliminate the impact of zero sequence current components in the converters [33]. The delta side is on the converter side, while the star is on the grid side. The star is grounded, which also eliminates the zero-sequence voltage components. A star-delta transformer introduces a phase shift of 30° [34]. The transformer ratios are chosen to keep the AC voltage on the VSC terminals high, but well within the acceptable modulation area. This is because it is beneficial to have a low current in the converter.

For the DR a three winding star-star-delta transformer is used. This transformer is often referred to as an harmonic cancellation transformer when used together with a 12-pulse DR, because it cancels some characteristic harmonics. This is further elaborated in chapter 5. The transformer ratio is determined to get the appropriate DC voltage on the DR terminals which determines the DC voltage balance in the hybrid converter.

An overview of the transformer configurations and ratios are given in table 3.4.

Table 3.4: Transformer configurations and rating

		Configuration	Rating
Offshore	VSC	star-delta	33 kV : 80 kV
	DR	star-star-delta	33 kV : 65 kV : 65 kV
Onshore	VSC	star-delta	170 kV : 170 kV

3.8 Onshore grid

The onshore grid is modelled as a constant voltage source. This gives the impression of a really strong grid since the voltage is completely stiff. This is a simplification, and the model does not take into account how variations in the AC grid could affect the transmission system. In reality, one of the main benefits of using a VSC on the onshore substation is that the transmission system could also be connected to weak grids, but this is outside the scope for this thesis.

3.9 Wind farm

Since this thesis focuses on the control of the transmission system, it is wanted to use a simplified model for the wind farm. The design of the actual wind farm is, of course, a very important part when developing a new offshore wind project, but it is outside the scope of this work. The following sections will present a typical wind turbine configuration and a simple model that will be used in simulations of the transmission system.

3.9.1 Fully rated converter turbine

One commonly used turbine configuration in large wind farms is a permanent magnet synchronous generator connected through fully-rated back to back converters (FRC) [15] with VSCs. These VSCs can be controlled to help the transmission system operation, e.g. the VSC can be controlled to deliver reactive power to the offshore grid. A schematic showing this general topology is shown in fig. 3.4.

For the hybrid VSC-DR transmission system, the operation of the turbine converters can be the same as for a VSC-HVDC system, where standards already exist. This is a benefit for this system compared to other new topologies, i.e. in the DR-HVDC the control system the turbine converters change. With the hybrid VSC-DR converter on the offshore side, the turbine converters do not need to help out with the transmission system operation, although it can be beneficial that they help provide reactive power.

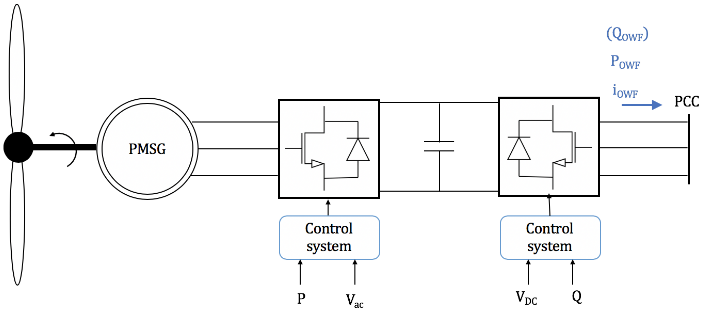

Figure 3.4: Typical turbine configuration with FRC.

3.9.2 Modelling assumptions

The simplified model of the wind farm needs to have the right level of detail, such that the important interactions with the transmission system is included, but the model is simple enough not to draw focus from the main objectives. For the testing of the transmission system, in this case, the wind farm must be able to: 1.) Deliver active power as generated from a varying wind source. 2.) Inject the power as a balanced sinusoidal current to the PCC. 3.) Harmonics from the DR must be visible at the PCC.

A simplified model for simulations is developed based on a controlled ideal current source. This omits the need for extra control loops for the wind farm model. The current injection is determined from a wind profile converter to power output mimicking the power generation from the wind farm. One important objective in this thesis is to eliminate harmonics in the current at the PCC with the wind farm. The ideal current source will automatically cancel all harmonics in this current, but if a large AC filter is connected in shunt, a path for the harmonic components is added. Unfortunately, this AC filter does also have some other influences on the system: It acts as a reactive power source, and it affects the harmonics in the system. This simplified model can still be used to test all the most important aspects of the objectives of this thesis, and it is therefore preferred over more complicated wind farm models. A schematic diagram of the wind farm model is shown in fig. 3.5, and the current reference to the current source is shown in fig. 6.1.

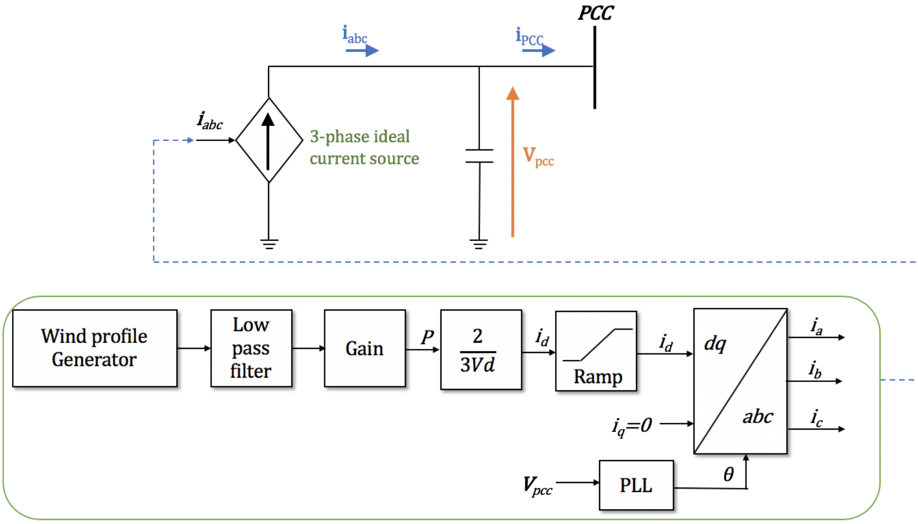

Figure 3.5: Simplified wind farm model.

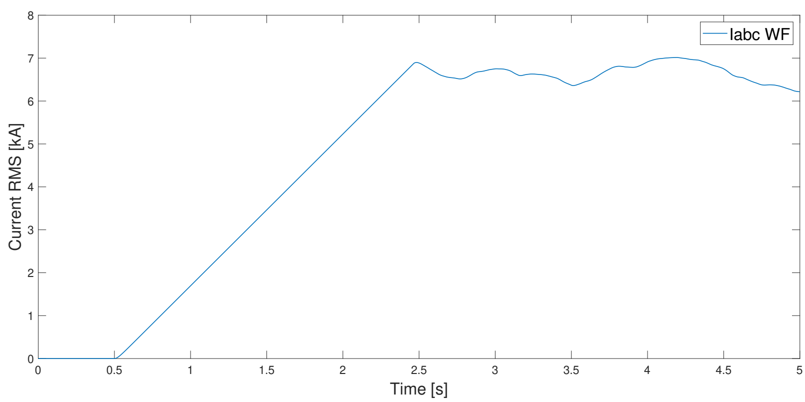

Figure 3.6: Current reference to wind farm source.

Chapter 4

Control system design

In this chapter, the general control system is described. The control objectives are first defined, then the control loops for the offshore and onshore VSC is derived from the mathematical model of the system.

4.1 Control strategy

The overall objective for the control system is to ensure safe, stable and efficient operation of the control system and to comply with local grid codes. Control objectives are defined to describe the concrete tasks that must be carried out by the control system. They are similar to the control objectives for a VSC-HVDC system, but some additional objectives are added related to the characteristics of the diode rectifier and the hybrid topology. The six defined control objectives are:

1. **Offshore grid forming.** There is no existing grid in the offshore station, and the grid forming needs to be carried out by the control system. The AC voltage should be controlled to a constant value with rated frequency.

2. **HVDC-link control.** The control system must ensure a constant voltage in the HVDC-link.

3. **Power balance control.** The power which is transmitted through the VSC and the DR in the hybrid converter must be controlled. The power balance control should avoid that the ratings of the components are violated.

4. **Reactive power compensation onshore.** The reactive power at the PCC with the grid should be controlled to a reference as requested by the grid owner.

5. **Reactive power compensation offshore.** The DR consumes reactive power, and this should be delivered from one of the offshore converters to avoid larger passive compensation banks in the system.

6. **Harmonic control.** The characteristic harmonics in the current drawn by the DR should be filtered to avoid problems related to high harmonic distortion.

The control objectives are carried out through controlling the onshore VSC, the offshore VSC and by proper design of the system. An overview of the control objectives carried out by each component is shown in fig. 4.1. The offshore VSC is controlled in the AC voltage control mode, which establishes the offshore grid. It is also operated as an active power filter to cancel harmonics from the DR, and it delivers reactive power to the DR. The onshore VSC is responsible for the control of the DC voltage in the HVDC-link and to deliver the required reactive power to the grid. The last control objective, to balance the power in the hybrid converter, is ensured by the system design and will automatically be achieved if the other objectives are controlled. The control system is developed in the synchronous reference frame.

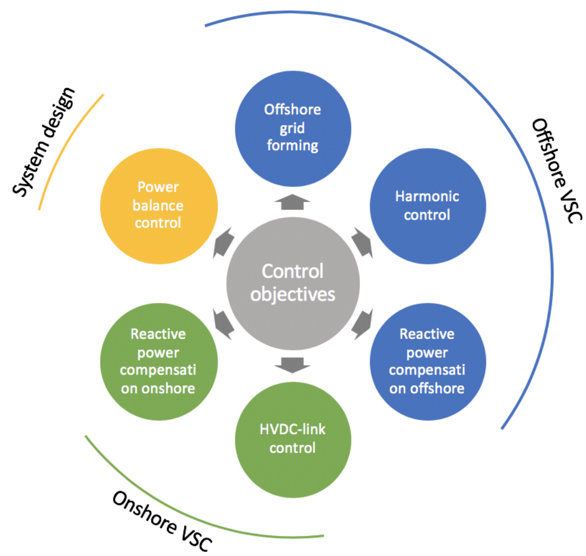

Figure 4.1: Control objectives carried out by each component.

4.2 Control in synchronous reference frame

4.2.1 Reference frames

Control of a two-level VSC is usually carried out in either the stationary $\alpha\beta$-reference frame or the synchronous dq-reference frame. In this thesis, the synchronous reference frame will be used. There are three main advantages of using this axis system in the control design:

- There are only two phases, instead of three in the regular axis system. This gives one less control loop and one less controller to tune.
- The balanced sinusoidal quantities at fundamental frequency will appear as DC quantities, and a simple PI controller can be used without steady-state error.
- The active and reactive power can be decoupled in the synchronous reference frame.

A visual comparison between the $\alpha\beta$- the dq- and abc-reference frame is given in fig. 4.2.

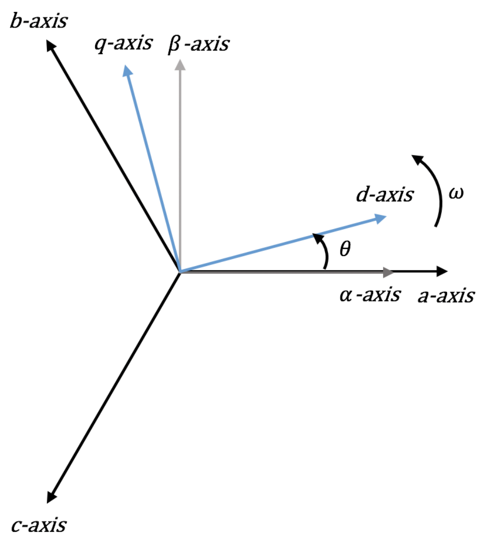

Figure 4.2: Comparison of the reference frames used for VSC control.

The transformation from abc- dq-frame is carried out using the Park transformation, eq. (4.1) and similarly from dq-abc with the inverse Park transformation [15]. When the VSC is connected on the delta side of a transformer, there will be no zero-sequence currents in the circuit, and the zero-sequence component can be let out from the transformation matrix.

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta - \frac{4\pi}{3}) \\ sin(\theta) & sin(\theta - \frac{2\pi}{3}) & sin(\theta - \frac{4\pi}{3} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{4.1}$$

4.2.2 Proportional integral controllers

Proportional integral (PI) controllers are widely used for reference tracking in control systems both in the industry and in research. One of the main benefits of the PI controller is that it can eliminate steady-state error in DC systems. This makes the controller very well suited in the synchronous reference frame since all the control variables are DC quantities. Two equivalent versions of the PI controller transfer function for the are given in eq. (4.2).

$$G_{PI} = K_P \frac{1 + T_i s}{T_i s} = K_p + \frac{K_i}{s} \tag{4.2}$$

The parameters of the controller can be tuned to give the wanted control characteristics of the system. K_p is the proportional part that adjusts the amplitude of the frequency response, and T_i is the time constant of the integral part. By appropriately choosing the combination of K_p and T_i the control can be fast, without overshoot and with sufficient damping of oscillations.

4.2.3 Phase locked loop

A phase-locked loop (PLL) can be used to obtain the reference angle, θ, for the Park transformation. It is used to synchronise or lock-in phase the transformed signal with the grid voltage. In this thesis, the built-in block in PSCAD is used, and therefore the more detailed operation of the PLL is left out of this report. The PLL in PSCAD uses the phase vector technique to generate a ramp signal (θ) between 0° and 360° and is locked in phase with the input voltage given to the block. The PLL is used on the onshore VSC and in the wind farm model. In the offshore VSC, a PLL is not needed since the frequency is predefined from an external reference, and it is not synchronising to an existing grid.

4.3 Control of onshore VSC

First, the control system for the onshore VSC will be derived. It uses vector control in the dq-reference frame as described in [35], which is a very popular control method for a VSC. The outer loop will control the DC voltage and the reactive power, and the inner loop will control the current.

4.3.1 Inner current control loop

The inner loop is derived from the mathematical model of the VSC using Kirchhoff's voltage law on the standard circuit diagram of the VSC given in fig. 3.2. The resistive losses in the converter are neglected, and this gives the very simple dynamic models in eq. (4.3)-eq. (4.5).

$$L\frac{di_a}{dt} = v_{Ga} - V_{conv,a} \tag{4.3}$$

$$L\frac{di_b}{dt} = v_{Gb} - V_{conv,b} \tag{4.4}$$

$$L\frac{di_c}{dt} = v_{Gc} - V_{conv,c} \tag{4.5}$$

Here $\mathbf{v}_{G,abc}$ is the voltage at the grid connection point and $\mathbf{V}_{conv,abc}$ is the average voltage on the converter switching terminals. These equations are transformed into the dq-frame by using the transformation in eq. (4.1), which gives eq. (4.6) and eq. (4.7).

$$L\frac{di_d}{dt} - \omega L i_q = v_{Gd} - V_{conv,d} \tag{4.6}$$

$$L\frac{di_q}{dt} + \omega L i_d = v_{Gq} - V_{conv,q} \tag{4.7}$$

There is a cross-coupling relation between the two current components that make the system nonlinear. These are removed by using a feed-forward loop which removes the coupling and creates separate and linear current loops. The currents in the inner loops are controlled to their reference values, i_d^* and i_q^* by using PI controllers. From this the modulation signals to the PWM generator, $\mathbf{V}_{G,dq}$ are defined, as shown in eq. (4.8) and eq. (4.9).

$$V_{conv,d} = -(K_p\tilde{i_d} + \frac{K_p}{T_i}\int \tilde{i_d}dt) + \omega L i_q + V_{Gd} \tag{4.8}$$

$$V_{conv,q} = -(K_p\tilde{i_q} + \frac{K_p}{T_i}\int \tilde{i_q}dt) - \omega L i_d + V_{Gq} \tag{4.9}$$

In these equations $\tilde{i_{dq}} \triangleq i_{dq}^* - i_{dq}$, K_p is the proportional gain of the PI controller, and T_i is the integral time constant. The same symbol is here used for the PI controller in both the d- and q-component, but in reality, they could be tuned to different values.

When the dynamics are put in closed loop with the controller the equations for the dynamic error is obtained: $L\frac{di_d}{dt} = (K_p\tilde{i_d} + \frac{K_p}{T_i}\int\tilde{i_d}dt)$ and $L\frac{di_q}{dt} = (K_p\tilde{i_q} + \frac{K_p}{T_i}\int\tilde{i_q}dt)$. This proves that the equations in the inner loop are decoupled and can indeed be controlled to the reference by a PI controller. The error model can be written as a first order differential equation, which gives exponential regulation of the $\mathbf{i}_{dq}$ to its reference.

The block diagram of the inner loop is given in fig. 4.3.

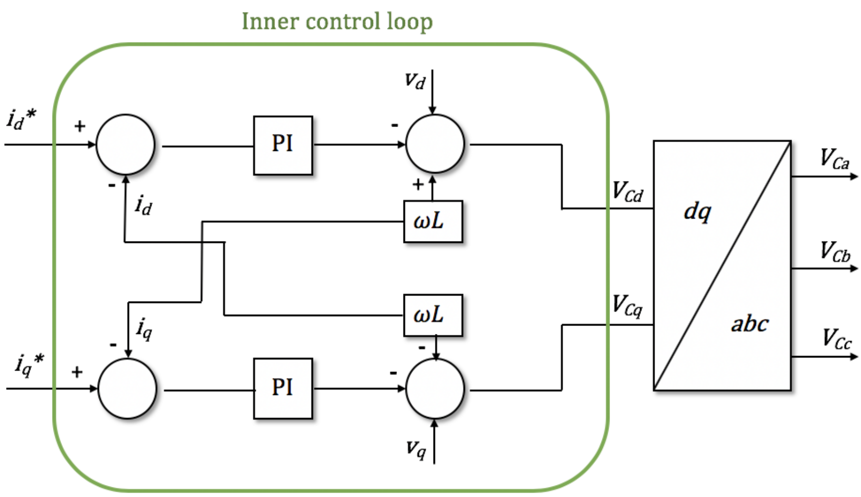

Figure 4.3: Block diagram of the inner current control loop for onshore VSC.

4.3.2 Outer control loop for DC voltage and reactive power

The outer loop is determined from the choice of control modes the converter is operated in, and it provides the suitable reference to the inner loop. Here it will be used to control the DC voltage and the reactive power.

The apparent power injected to the grid is given from eq. (4.10).

$$S = \frac{3}{2}(v_d + jv_q)(i_d + ji_q) \tag{4.10}$$

Since v_d is aligned with $\mathbf{V}_G$, the q-component of the voltage is zero. From this, it follows that the active and reactive power can be decoupled as in eq. (4.11) and eq. (4.12).

$$P = \frac{3}{2} v_d i_d \tag{4.11}$$

$$Q = \frac{3}{2} v_d i_q \tag{4.12}$$

It is clear from eq. (4.12) that reactive power can be controlled by controlling i_q. Here v_d is also constant as it is the voltage of the stiff grid. The proportional relationship between reactive power and i_q allows for a PI controller on $\tilde{Q} \triangleq Q^* - Q$ to provide the i_q reference to the inner loop. Similarly, the DC voltage can be controlled by the d-component since the active power is proportional to i_d and $P = V_{dc} I_{dc}$. If the converter is operated in steady-state and the DC-current is constant, the i_d reference would be given directly from a PI controller on the DC voltage error. However, one of the main characteristics of the wind farm is that the power and thus I_{dc} is constantly changing, so this assumption would in many cases not be valid. Instead, a feed-forward of the DC current impact is added as explained in [21].

If the charging of the DC side capacitor is included and the switches are still assumed to be lossless, the active power balance of the VSC can be written as in eq. (4.13). Moreover, the current in the capacitor is related to a small voltage change across the capacitor by eq. (4.14).

$$\frac{3}{2} v_d i_d + V_{dc} i_{cap} + V_{dc} I_{dc} = 0 \tag{4.13}$$

$$\Delta V_{dc} = \frac{1}{C} \int i_{cap} dt \tag{4.14}$$

The DC voltage is determined from the charging of the DC side capacitor described by eq. (4.14) and the active power balance eq. (4.15). If these equations are combined the dynamics of the DC voltage is obtained in eq. (4.15).

$$\frac{\Delta V_{dc}}{dt} = \frac{-3 v_d}{2 C V_{dc}} (i_d + \frac{2 V_{dc}}{3 v_d} I_{dc}) \tag{4.15}$$

When v_d is constant the i_d-current reference is easily found from eq. (4.15). The i_d-reference is obtained when the DC voltage error, $\tilde{V_{dc}} \triangleq V_{dc}^* - V_{dc}$, is controlled by a PI controller and with a feed-forward term of the DC current. In fig. 4.4 the block diagram of the outer loop in the control system is presented.

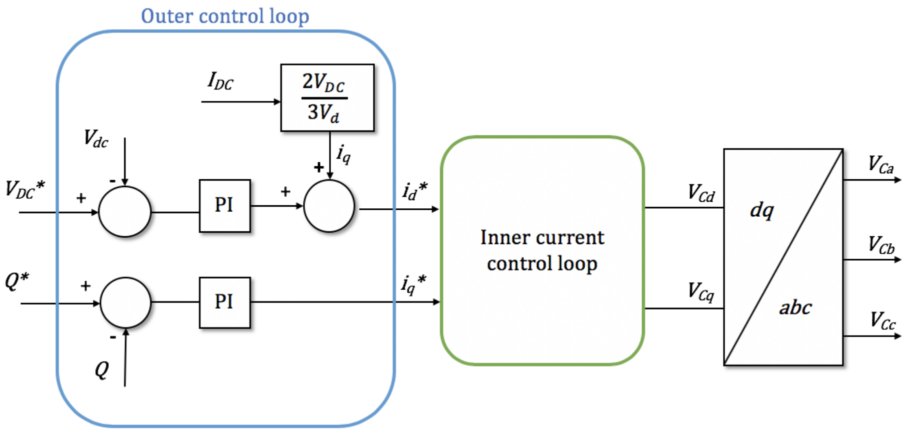

Figure 4.4: Block diagram of the inner and outer control loop for onshore VSC.

4.4 Control of offshore VSC

The control of the offshore VSC in a hybrid converter is the most challenging and no well-established methods exist for this controller in literature. The challenge is that the VSC must be able to control the AC voltage even though the DR is forcing a proportional relationship between the AC and DC voltage. Later, in chapter 5, an active power filter control loop will also be added to the offshore VSC, which further complicates the control system.

The offshore VSC is controlling the AC grid on the offshore side by creating a constant AC voltage at rated frequency. The objective is to control the voltage at the PCC, but here the control is carried out on the converter side of the transformer. The reference voltage to the control system must be determined such that the PCC voltage reaches the rated value. To avoid confusion, the PCC voltage on the converter side of the transformer will be referred to V'_{pcc}. The control system is using the RMS-voltage measurement

Previous research [6, 24, 23, 7, 26] have suggested different approaches to control the AC voltage with the offshore VSC. In this thesis, two different control systems will be tested: First, a direct voltage control method, similar to the method used in [6] and [26]. The second uses a cascaded control with an inner current loop. This cascaded controller is described for a VSC-LCC hybrid system in [12].

4.4.1 Direct voltage controller

The direct voltage controller is the simplest controller of the two options. For convenience, the control is performed in the synchronous reference frame, where the d-component of the voltage is aligned with the AC voltage. The control is performed by directly controlling the $V_{conv,d}$ component feed to the PWM generator. The error term is defined as $\tilde{V'_{pcc}} \triangleq V'^{*}_{pcc} - V_{pcc,d'}$ and a PI controller is used to control the error to zero.

The controller must also establish the AC grid frequency. The controller is open-loop, where an integral of the reference frequency (f*) obtains the transformation angle for the Park transformation. It determined the frequency of the control signals in the PWM, which again determines the frequency in the controlled AC voltage. This method for establishing the frequency is also used for the cascaded controller.

The block diagram for the direct voltage controller is shown in fig. 4.5.

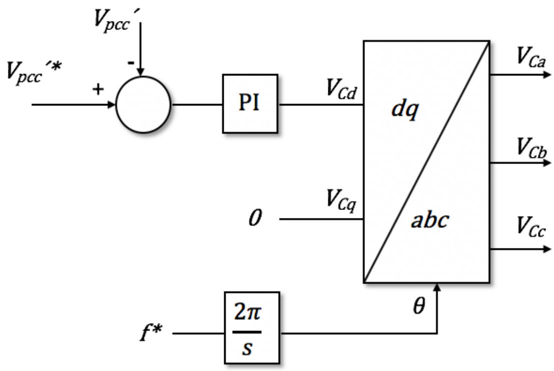

Figure 4.5: Block diagram of direct voltage controller for offshore VSC.

As seen from fig. 4.5 the controller is open-loop for the q-component. The q-component reference is zero, but the controller is not able to correct any deviation as it does not have knowledge of this measurement. Another drawback of using the direct voltage controller is that it only controls the current indirectly [12]. It can therefore not make sure that the current is within the operating limits of the converter and this must be ensured in a different way. Moreover, the controller does not have any information about the input current, and it can respond slowly to current changes. In a wind farm where the power injection is varying a lot, this can be a significant drawback. Although this controller has some drawbacks, it is suitable for many operating scenarios.

4.4.2 Cascaded voltage controller

In the cascaded voltage controller a capacitor is connected in shunt of the converter to provide a reference point for the controller. This is a well-known LCL-filter known used in many applications. The schematic diagram with variable names for the offshore VSC is shown in fig. 4.6.

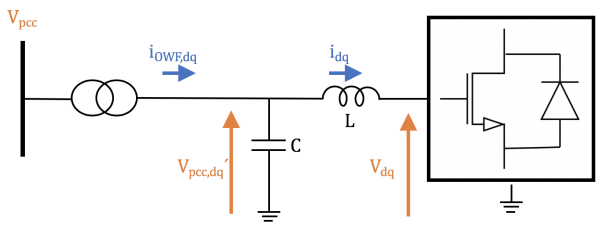

Figure 4.6: Schematic diagram of VSC connected to PCC bus.

The cascaded controller has an inner current loop and an outer voltage loop that controls both the d- and q-components of the voltage. The inner loop is the same as for the offshore VSC and it is given from the dynamics of the inductor. In the synchronous reference frame it is given as:

$$L\frac{di_d}{dt} - \omega L i_q = V'_{pcc,d} - V_{conv,d} \tag{4.16}$$

$$L\frac{di_q}{dt} + \omega L i_d = V'_{pcc,q} - V_{conv,q} \tag{4.17}$$

The rest of the derivation for the inner loop is not rendered here but is explained earlier for the onshore VSC.

The outer loop is derived from the dynamics of the capacitor. By applying Kirchhoff's current law to fig. 4.6 the dynamic model can be obtained in the normal reference frame and on vector form in eq. (4.18).

$$C\frac{d\mathbf{V}'_{pcc}}{dt} = \mathbf{i}_{OWF} - \mathbf{i}_{conv} \tag{4.18}$$

The Park transformation is again used to obtain the equations in the synchronous reference frame. As for the inner current loop, the voltages also have cross-coupling terms in the synchronous frame.

$$C\frac{dV'_{pcc,d}}{dt} - \omega C V_{pcc,q} = i_{OWF,d} - i_{conv,q} \tag{4.19}$$

$$C\frac{dV'_{pcc,q}}{dt} + \omega C V_{pcc,d} = i_{OWF,q} - i_{conv,q} \tag{4.20}$$

Similar as in the inner loop, feed forward terms are used to decouple the components. PI controllers are used to control the V'_{pcc}- components can to their reference values, the d-component to 1.0 pu and the q-component to zero. The current reference signals are found from in eq. (4.21) and eq. (4.22). In the equations the error signal is defined as $\tilde{\mathbf{V}'}_{pcc,dq} \triangleq \mathbf{V}'_{pcc,dq} * - \mathbf{V}'_{pcc,dq}$.

$$i_d* = -(K_p \tilde{V'}_{pcc,d} + \frac{K_p}{T_i}\int \tilde{V'}_{pcc,d} dt) - CV'_{pcc,q} + i_{OWF,d} \tag{4.21}$$

$$i_q* = -(K_p \tilde{V'}_{pcc,q} + \frac{K_p}{T_i}\int \tilde{V'}_{pcc,q} dt) - CV'_{pcc,d} + i_{OWF,q} \tag{4.22}$$

As for the inner current loop, it can be proved that this gives a decoupled system with an exponential regulation of $V'_{pcc,dq}$ to its reference. This is also shown in [12].

The block diagram of the cascaded voltage controller is given in fig. 4.7.

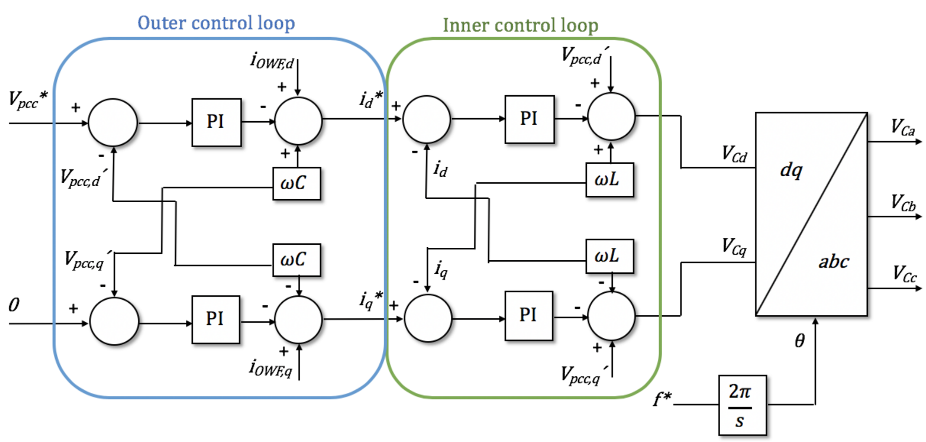

Figure 4.7: Block diagram of cascaded voltage controller for offshore VSC.

4.5 Power balance in hybrid converter

The reduce the size of the offshore VSC, an appropriate power balance in the hybrid converter must be obtained. This implies that the power injected from the wind farm must be divided between the VSC and the DR. The proportional split of the active power is given from the DC voltage balance. The active power of the VSC and the DR can be easily calculated on the DC side when the losses in the converters are neglected: $P = V_{dc}I_{dc}$. The VSC and the DR are series-connected on the DC side, and the same DC current will flow through both the components. As a result, the power balance is determined for the DC voltage balancing.

The DC voltage balance on the offshore side is given from the design of the converter transformers. Since the DC voltage in the HVDC link is controlled by the onshore VSC, the DC voltage of the DR and the VSC in the hybrid converter must equal this voltage (plus the voltage drop across the cable). When the AC voltage is constant, the DC voltage of the DRs is given from the DR characteristic equation in fig. 3.3. The converter transformer can be used to modify the AC voltage on the DR terminals and thus determine the DC voltage of the DR. This will indirectly determine the DC voltage balance and the power balance in the hybrid converter.

The transformer ratio (T_r) needed for the DR converters is given from eq. (4.23) when $P_{vsc,pu}$ is the active power rating of the VSC in per unit.

$$T_r = \frac{1 - P_{vsc,pu}V_{dc}}{1.35V_{ac}} \tag{4.23}$$

The smaller the VSC, the more difficult to obtain a stable and well-performing control system, as the influence of the DR becomes more significant. This can easily be understood from the extreme cases: If the DR rating goes to zero, the system is a conventional VSC-HVDC, and if the DR rating goes to the full rating, the VSC is zero, and the system is a DR-HVDC with no control of the offshore grid. In the design of the control system, the system is designed with VSC is 1/2 and DR is 1/2 of the full active power rating. The sizing of the components in the hybrid converter is a critical factor for determining the success of this system, and it will be further elaborated in Chapter 7.

4.6 Reactive power compensation in offshore grid

One of the control objectives is to ensure reactive power compensation for the diode rectifier. This control objective is automatically fulfilled with both the offshore VSC controllers presented. The reason is that the reactive power is not controlled, but there must still be a balance of reactive power in the system. The reactive power could be delivered either from the offshore VSC or from the turbine converters, where the grid side converter normally controls the DC voltage and reactive power. The decision between which VSCs will provide reactive power is a cost optimisation problem and does not have a great impact on the control system and operation. However, it must be noted that the full apparent power rating of the VSC must include both the active and reactive power of the component. In the simulations, in this thesis, the reactive power compensation is not analysed. The reason is that the simplified wind farm model has a large capacitor in shunt, see section 3.9, which will deliver reactive power to the system.

4.7 Implementation in PSCAD

After the control system was implemented as described in this chapter, some adjustments were made to improve the system performance:

- The DC capacitor values were adjusted to obtain a good balance between DC voltage ripple and response speed.
- The transformer ratios for the DR were adjusted to account for losses in the DR until the correct DC voltage balance was achieved. New transformer ratio was then 33kV:65kV:65kV for the 1/2 VSC - 1/2 DR hybrid converter.
- PI controllers were tuned to achieve good responses for each control variable.
- A start-up sequence was implemented to determine the starting procedure for the system.

4.7.1 Tuning of PI controllers

The PI controllers were tuned to get a good performance of the controllers. The inner loop was first tuned when the reference signals were constants, and then the outer loop was added. It was observed that a wide range of controller parameters gave a good performance of the controllers and very detailed tuning was not needed. The parameters of the PI controllers are given in table 4.1.

Table 4.1: PI controller parameters

Controller			**Ki**	**Ti**
Onshore VSC	Outer loop	d	4.0	0.1
		q	4.0	0.1
	Inner loop	d	2.5	0.01
		q	2.5	0.01
Offshore VSC - direct controller		d	0.1	0.5
Offshore VSC - cascaded controller	Outer loop	d	3.5	0.05
		q	2.5	0.5
	Inner loop	d	0.78	0.01
		q	0.78	0.01

4.7.2 Start-up sequence

A sequential start of the controllers is used to avoid large transients and saturation of the controllers in the beginning. This proved to help very much on the stability and operation of the offshore VSC. This is because this controller is not able to operate until a DC voltage in the correct range is provided to avoid over modulation. The sequence and time delays for the start-up of the system is described in table 4.2.

Table 4.2: Start up sequence for the system

Time	Event
0.0s	Offshore station is disconnected from HVDC-link Onshore VSC starts to control DC voltage
0.4s	DC voltage in HVDC-link reaches reference
0.5s	Offshore station is connected Wind farm start to generate power with a ramp up process
2.5s	Wind farm reaches rated power

Chapter 5

Harmonic control with active power filter

This chapter will focus on the harmonics from the DR in the system and strategies for mitigating the harmonic distortion. The operating principle of an active power filter will be explained and it will be shown how the offshore VSC can be utilised as an active power filter in the system.

5.1 Harmonic distortion

Harmonics are sinusoidal voltages or currents with frequencies that are multiples of the rated system frequency, i.e. the 5th harmonics have a frequency of five times the fundamental frequency [36]. The harmonics in a system are often divided into *characteristic harmonics* and *non-characteristic harmonics* [1], where the first is given from properties of the components in the circuits and the second is related to unwanted behaviours due to faults or unbalanced conditions.

A system that includes a diode rectifier will produce a substantial number of harmonics in the AC current. In systems with DRs, it is almost always necessary to include harmonic filters to improve the power quality and reduce the impact of the harmonics. Some of the negative consequences of harmonic distortion are [36, 30]:

- It can aggravate the control system operation. For example, the Park transformation will produce large ripples, and no steady-state error can not be guaranteed with PI controllers.

- There can be additional losses in lines and utility equipment such as transformers and capacitors
- The lifetime of components can be decreased.
- The harmonic distortion can interfere with communication systems.
- There can be additional noise from components.
- Problems related to voltage amplification from parallel or series resonance can occur.

5.2 Characteristic harmonics of hybrid VSC-DR converter

In the hybrid converter, there are characteristic harmonics from both the DR and the VSC. The harmonics from the VSC are multiples of the modulation frequency and with a high switching frequency they are of very high order. They can easily be filtered by low pass filters and the impact of these harmonics are low. In this chapter only the characteristic harmonics from the DR will be considered.

5.2.1 Harmonics from 12-pulse DR

In this system, the main source of harmonics is the diode rectifier, which produces characteristic harmonics in the current dependent on the number of diodes in the rectifier bridge. These harmonics are given from $Kp \pm 1$, where p is the number of pulses in the system and $K = 1, 2, 3....$

In HVDC systems a 12-pulse diode rectifier connected to a three winding star-star-delta transformer is often utilised because it eliminated many of the harmonics from the 6-pulse bridge [1]. This concept is visualised in fig. 5.1.

It is the low order harmonics in the system that are of most concern because they are most difficult to filter. Therefore the main harmonics of concern in this system are the 11th, 13th, 23rd and 25th in the offshore grid current.

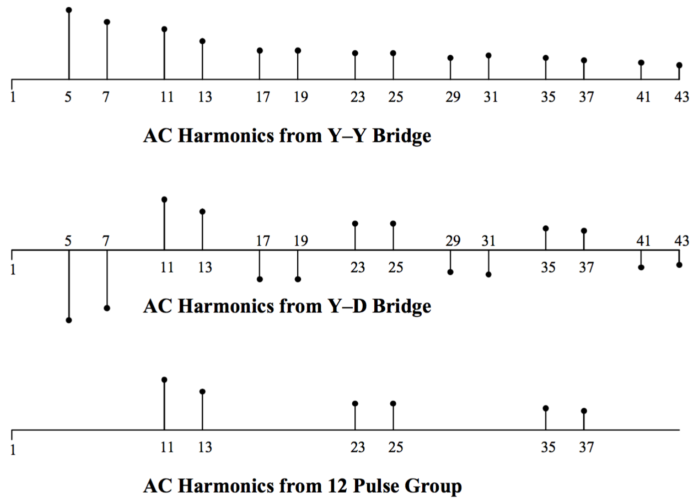

Figure 5.1: Current harmonics of a 12-pulse DR as presented in [1].

5.3 Evaluation of harmonic distortion

5.3.1 Individual harmonic distortion

The individual harmonic distortion (IHD_h) is a measurement of the contribution from the individual harmonic component, h, on the total system current or voltage. The IDH for one specific harmonic h on the system current is given in percentage as:

$$\%IHD_{i,h} = 100\frac{I_{sh}}{I_{s1}} \tag{5.1}$$

In the equation I_{s1} is the fundamental component and I_{sh} is the specific harmonic component of the current. A similar expression can be used for the system voltage.

5.3.2 Total harmonic distortion

The total harmonic distortion(THD) in the voltage or current is a quality indicator of the system voltage or current. The THD for the system current (i_s) is given in percentage as [36]:

$$\%THDi = 100\sqrt{\sum_{h\neq 1}\left(\frac{I_{sh}}{I_{s1}}\right)^2} \tag{5.2}$$

In the equation, I_s is the RMS current, 1 is the fundamental component, and h is the harmonic components which are being added together to get the THD_i. Similarly, THD_v can be calculated using the voltage components in the same equation.

5.4 Methods for harmonic cancellation

The preferred strategy for harmonic cancellation in an application is dependent on several factors such as which harmonics are being cancelled, cost, space, power quality requirements and more. In this section, the three most common strategies for harmonic cancellation will be presented.

5.4.1 System design

In some cases, it is possible to alter the design of the system to eliminate the harmonics from being produced. This will, in many cases, be the most efficient method to increase the power quality, but the design alterations are not always preferable due to other specifications. Examples of this can be to use VSCs or MMCs instead of DRs and LCCs, to use a 12-pulse DR instead of a 6-pulse and to tune the switching frequency of the VSC to generate few and high order harmonics. These choices are rarely determined solely based on harmonic distortion, but harmonic mitigation should be considered when designing the circuit.

5.4.2 Passive filters

Passive filters are different configurations of passive elements such as inductors, capacitors and resistor that are connected in shunt or series with the circuit to filter harmonics. In shunt filters, the filters are tuned to provide a low impedance path for certain harmonics, and similarly, the series filters provide a high impedance path for the harmonics which in both cases prevents the harmonics from entering the system. The filters can be tuned to filter a specific harmonic, or band-pass filters can be used to filter bands of harmonics, from which low pass filters are often used to filter all high order harmonics. Shunt connected passive filters are widely used in HVDC systems to filter current harmonics from DRs and LCCs, where they also act as reactive compensation units.

The advantages of using passive filters are that they are not very complex, the price is relatively low, and they are easy to maintenance [37]. In general HVDC-systems, the main disadvantages of passive filters have been that they are static and cannot adapt to different operating scenarios. However, the main concern for the use of passive filters in offshore wind applications is that they are bulky and therefore not suited to be installed on the offshore platform.

5.4.3 Active power filter

An active power filter (APF) is a dynamic filter that consists of a VSC operating as a controlled voltage or current source eliminate harmonics in the voltage or current. It gives a flexible filter that can adapt to changing conditions and eliminate all the harmonics. The APF is also smaller than passive filters and therefore, more suited offshore. However, this far very few active filters have been installed in high power applications [25], because the cost of high power VSCs is very high compared to the alternatives. In addition, the large size is not a major concern for DRs or LCCs onshore. However, the use of APF can become more relevant as the price of semiconductor devices decreases and harmonic filtering is needed in more advanced systems such as offshore wind integration.

5.5 Harmonic current compensation with shunt active filter

The operating principle of a shunt active power filter which is installed to compensate for harmonics from a nonlinear load is shown in fig. 5.2. The control of the VSC is carried out in two steps:

1. First, the harmonic components of the load current must be measured and separated from the fundamental component.
2. Then the VSC must synthesise a current which is equal to the harmonic current but with opposite sign.

There are different method in which these two steps can be implemented. In this thesis, the synchronous reference frame (SRF) method will be used for the detection step, and PI controllers will be used for the synthesising. This method is often referred to SFR based harmonic controller [26]. An alternative method is by using band-pass filters and proportional resonant controllers, which is explained in [38]. Advantages of the SRF-based APF are:

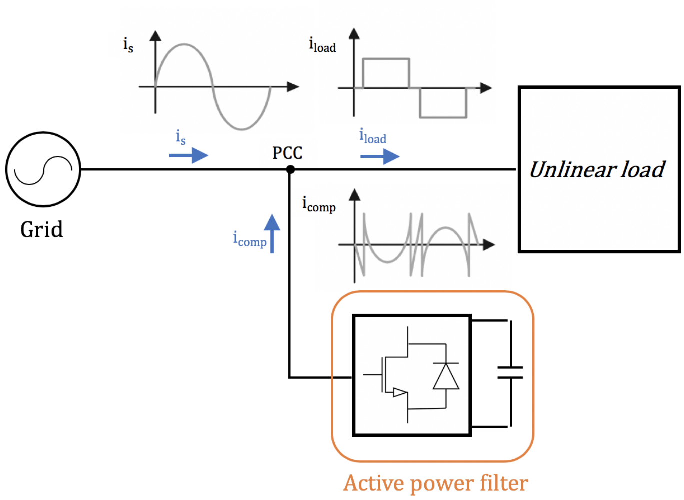

Figure 5.2: Principle of shunt APF.

- The harmonics are measured and controlled using DC signals, and PI controllers can be used. The PI controllers are easier to tune than PR controllers and ensure no steady-state error [39] .
- The controller is not affected by grid variations [39].
- The harmonic components can accurately be separated from the measurements [40].

5.5.1 Detection with SFR based controller

The SFR-based controller uses multiple dq-reference frames to extract the amplitude of the harmonic components in the load current. The concept of the synchronous reference frame was already introduced in chapter 4, where the Park transformation was used to transform the voltages and currents into DC quantities in the dq-frame. For the multiple SFR-controller, this concept is extended to several dq-frames rotating at the frequencies of each of the harmonic components. Each rotating frame is obtained using the Park transformation with the transformation angle obtained from the frequency of the harmonic it is going to compensate. The principle is that the harmonic component becomes DC quantity and all other fundamental and harmonic components become high-frequency ripples. The harmonic component can then be separated by using a low pass filter.

5.5.2 Control of APF in SFR

When the harmonic component is separated from the load current, it consists of two DC current references, namely $i_{hd}*$ and $i_{hq}*$, where h is the number of the harmonic. The compensation current i_{comp} is measured and transformed into the multiple SFR-frames, and PI controllers are used to create the compensation currents: $i_{comp,d} \rightarrow -i_{hd}$ and $i_{comp,q} \rightarrow -i_{hq}$.

In addition to creating the appropriate compensation currents, the VSC must also be controlled to keep a constant DC voltage in the shunt APF. Usually, the shunt APF also has a reactive power control loop to compensate for reactive power at the PCC. The control loops for V_{dc} and Q is the same as described for the onshore VSC in Chapter 4.

The block diagram for the detection and control of the active power filter is shown in fig. 5.3.

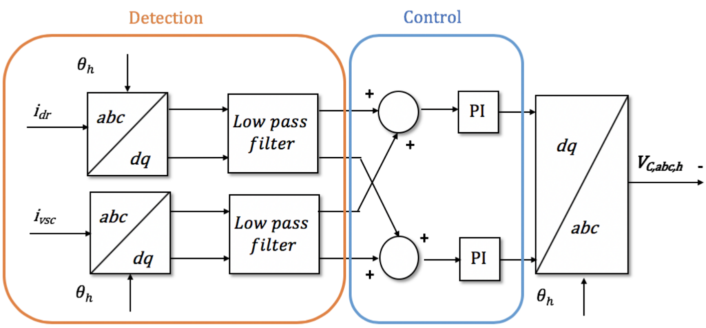

Figure 5.3: Block diagram of SFR based harmonic compensation control loop for component h.

5.6 Offshore VSC with APF capabilities

In the hybrid VSC-DR converter, there is already a VSC connected in parallel to the DR. It is thus possible to use the offshore VSC as an active power filter compensating for harmonic currents in the DR. This is done by adding the control loops developed in the previous section to the control system for the VSC developed in chapter 4. The APF will be used to compensate for selective characteristic harmonic components from the DR. The hybrid converter control system, including the APF, for the offshore VSC is shown in fig. 5.4.

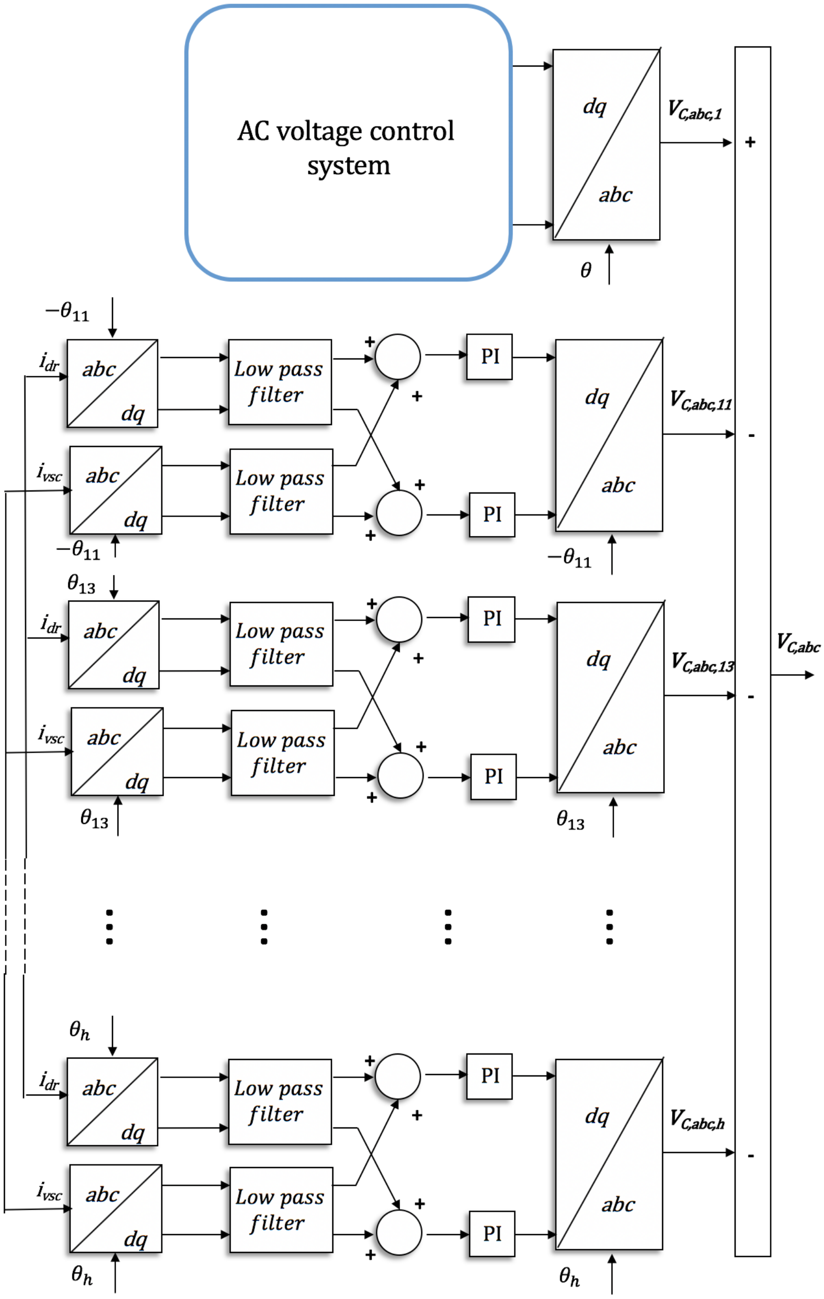

Figure 5.4: Offshore VSC controller with active power filter capablities.

5.7 Implementation of APF in PSCAD

When the active power filter was to be implemented in PSCAD model, some challenges occurred: First, the detection of the DR current became more complicated as the VSC is connected through a star-delta transformer with a phase shift. Second, the measurement capacitor of the VSC cascaded controller provided a path for the VSC generated harmonics. A sketch of the offshore grid is shown in fig. 5.5 to highlight the impact of these challenges. The last problem was related to the harmonic components that were measured in the PCC current, which were not only the expected ones: In addition, the 5th and the 7th harmonics were observed, but they did not originate from the 12-pulse DR. To find the source of the harmonics, the DR was disconnected such that a VSC-HVDC was obtained, but the harmonics were still present. It seems like these harmonic components are generated by the two shunt capacitors in the circuit.

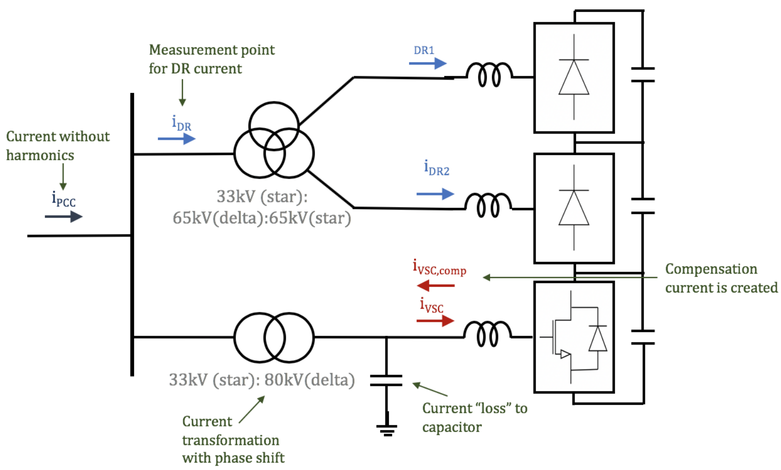

Figure 5.5: Principle of harmonic current reference measurement.

To solve these challenges, it was determined to test the harmonic filter in a more simplified system. The direct voltage controller was used, such that the capacitor could be removed. In addition, the transformer of the VSC converter was neglected. To achieve a good performance of the direct voltage controller, a wind farm model that ramps up to a constant voltage is used. Then the current measurement from the DR can be used directly in the filter, and the unexpected harmonics are removed. The harmonic content in the PCC current without the active power filter is shown in fig. 5.6. It is seen that there are still some uncharacteristic harmonics, but these are of low amplitude, below 0.5% and this is considered satisfactory. It is clear that it is the 11th and 13th harmonic that is most important to filter and only these components will be filtered by the APF.

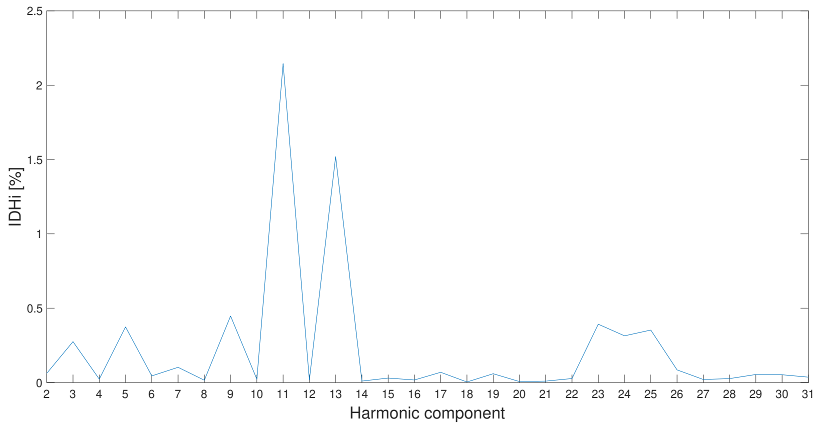

Figure 5.6: Harmonic components with simplified model and direct voltage controller and no APF.

Chapter 6

System performance

In this chapter follows the results from simulations of the transmission system. The performance on the control objectives evaluated in normal operating conditions, including wind power variations. The performance of the active filter is evaluated.

6.1 Performance criteria

In this chapter, the system performance will be evaluated based on simulations. It will be attempted to evaluate the performance on each of the control objectives defined in fig. 4.1. The control objectives are evaluated based on the criteria described below:

1. Operation of control system
   - Is the system stable?
   - Does the parameters go to their references at an acceptable rate?
   - Are there large disturbances or transients?
2. Maximum power transfer to the grid
   - How much of the active power is delivered to the grid?
3. Reactive power to grid:
   - Can the system deliver the requested reactive power to the grid?
4. Harmonic cancellation at offshore PCC

- Is the APF able to cancel harmonics from the DR?

6.2 System performance in an interconnected system

The hybrid VSC-DR transmission system is an interconnected system with several control loops. The control system of each VSC is relying on the other controllers to work properly to perform their tasks. If one of the controllers is performing poorly, i.e. not reaching the reference, having oscillations or creating unbalances, it could result in the other controllers becoming unstable. When implementing a system with several control loops, it is easy to make mistakes that result in the system not working as it is supposed to. One challenge with an interconnected system is that it becomes challenging to find the source of instabilities as the entire system is often affected. To minimise this problem, the controllers were first tested in simplified systems before the full system was tested. In these tests, sources and resistive loads were used to imitate the proper system behaviours. The step responses proved that all the controllers were working as they should. The results from simulations of the full system are presented in the following sections.

6.3 Performance of the hybrid VSC-DR control system

The hybrid VSC-DR HVDC transmission system with the active power filter was verified through simulations in PSCAD/EMTDC. The system was tested for normal operating conditions, including varying wind power production and start-up of the wind farm. Simulation time was set to 5.0s as this gives the controller enough time to reach the reference value and prove the transient stability of the system. The current injected from the wind farm in the simulation period is shown in fig. 6.1 as it impacts the responses for the controllers. In the following sections, the results for each of the controllers will be presented.

6.3.1 AC voltage control in offshore VSC

Two controllers for the AC voltage control was suggested, the direct voltage control and the cascaded voltage controller. The two methods are compared, and the result is shown in fig. 6.2.

The result from fig. 6.2 shows that the cascaded controller is the best-suited controller for the AC voltage this system. The direct voltage controller is affected by the variations in the current, as can be seen from 2.5s-4.5s where the power variations are most apparent. In addition, this controller stabilises on a voltage higher than the reference, which could

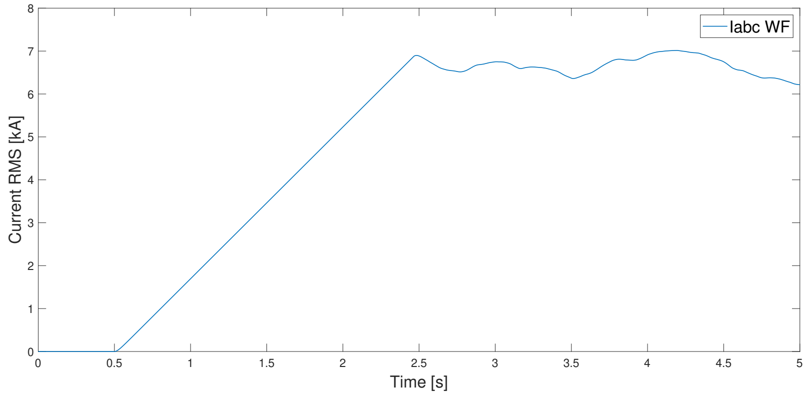

Figure 6.1: Current injected from the wind farm.

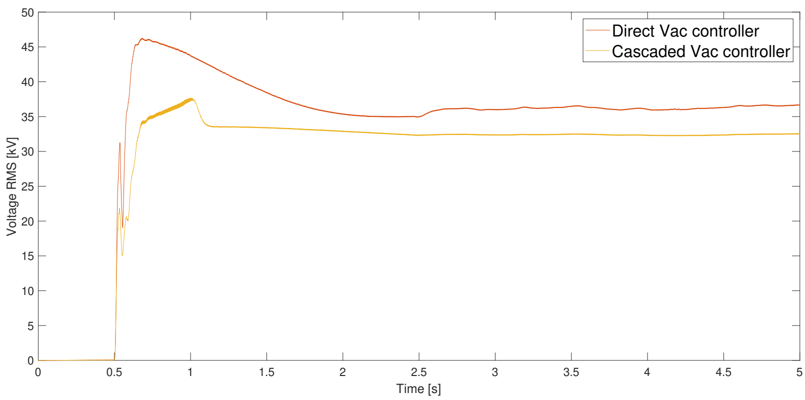

Figure 6.2: AC voltage at offshore PCC

indicate that the q-component of the voltage is not entirely zero as assumed.

The cascaded voltage controller is performing well on the control objective. It reaches the reference after about 0.5s after a transient period due to the start-up of the wind farm. The voltage is constant and not affected by power variations. The waveforms of the voltage are shown in fig. 6.3. The waveforms are balanced and sinusoidal, with few harmonics and have a 50Hz as expected.

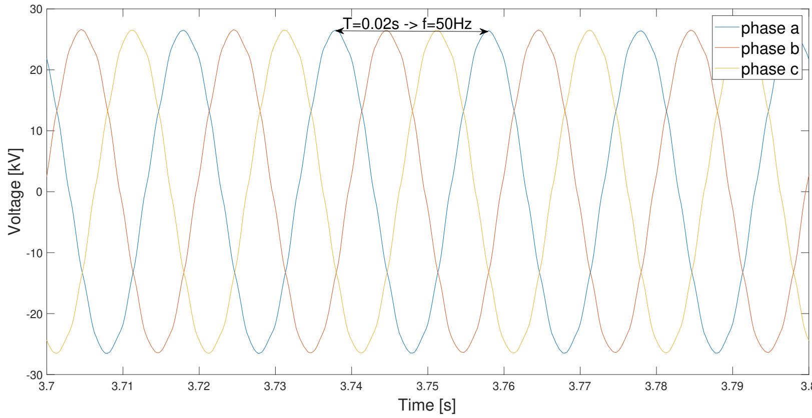

Figure 6.3: AC voltage waveforms at offshore PCC.

6.3.2 DC voltage control

The result from the DC voltage controller in the onshore VSC is shown in fig. 6.4. Here both the sending and receiving end DC voltage is included.

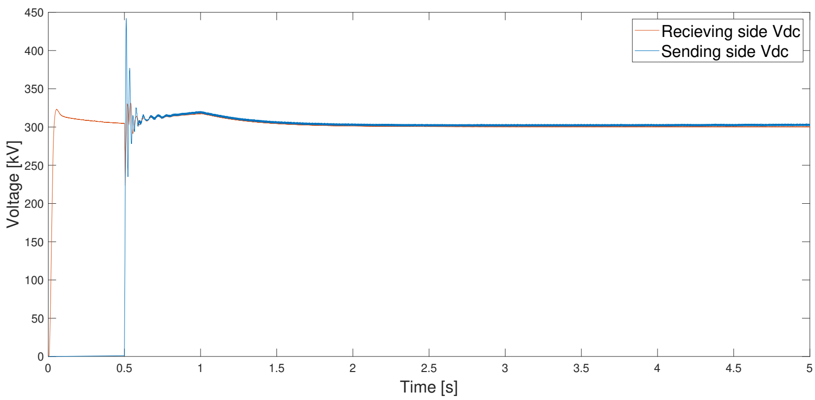

Figure 6.4: DC voltage response

It is seen from fig. 6.4 that the DC voltage is controlled to its reference value. There is a transient in the sending side DC voltage when the offshore side is connected at 0.5s. After this, there is a slight overshoot, most likely related to the increasing current injection, until the voltage settles at the constant reference value. The sending end voltage is slightly higher than the receiving end, to account for losses in the cable and ensure that the current is flowing in the cable. There is also a slight ripple in the voltage of approximately 1 kV.

The overall performance of the controller is satisfactory.

6.3.3 Power balance in hybrid converter

The power balance in the hybrid converter is determined from the proportion of the DC voltage which is across the DR and VSC terminals. The DC voltage balance is seen in fig. 6.5, and the power balance is shown in fig. 6.6.

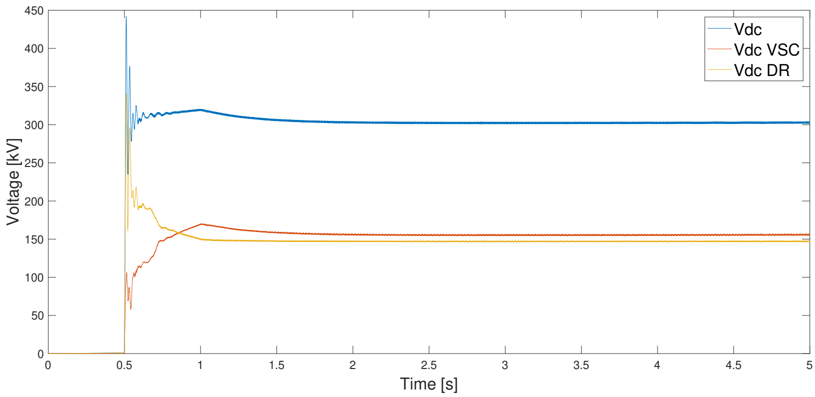

Figure 6.5: DC voltage balance in hybrid converter

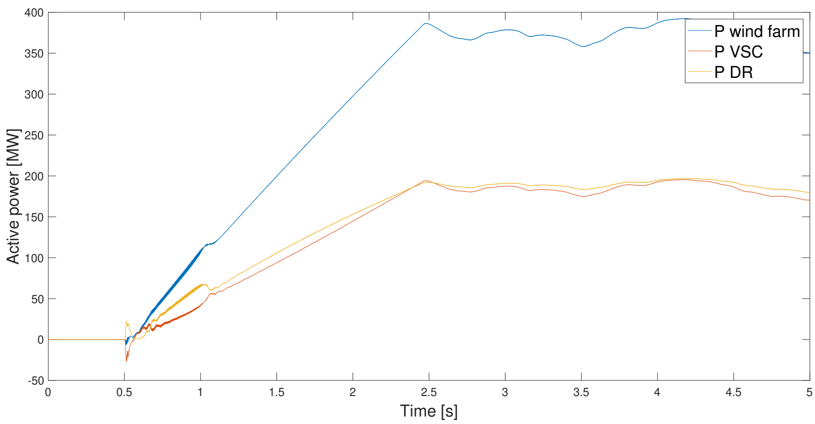

Figure 6.6: Active power balance in hybrid converter

In fig. 6.5 it is seen that the DC voltage is split equally between the VSC and the DR. Similarily, fig. 6.6 shows that the power is split close to equal between the converter components. It shows that it is possible to reduce the size of the VSC to at least 1/2 of the full rating if used together with a DR and that strategy of determining the power balance with the transformer ratio is working.

6.3.4 Maximum power transfer

The active power generated from the wind farm is compared to the active power delivered to the grid to evaluate the power transfer performance of the system. The result is shown in fig. 6.7.

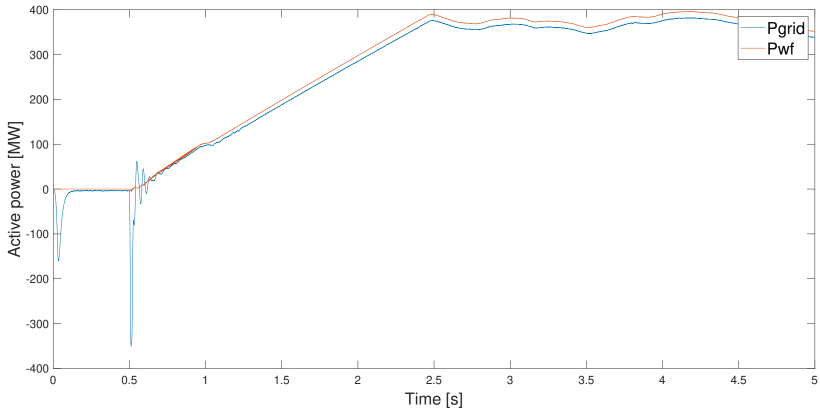

Figure 6.7: Active power generated from wind farm and delivered to grid

The results show that the transmission system is working as intended, and it transfers almost all the generated power to the grid. The estimation of power losses are outside the scope of this thesis, the focus is more to evaluate the control strategy. Since most the components are ideal, these results can not be used to determine the system efficiency.

6.3.5 Reactive power to grid

In fig. 6.8, it is seen that the reactive power delivered to the grid is able to track a reference signal very well. It is also here noticed that the system draws some reactive power from the grid during the start-up. This control system would allow the onshore VSC to help provide reactive power to the grid when needed.

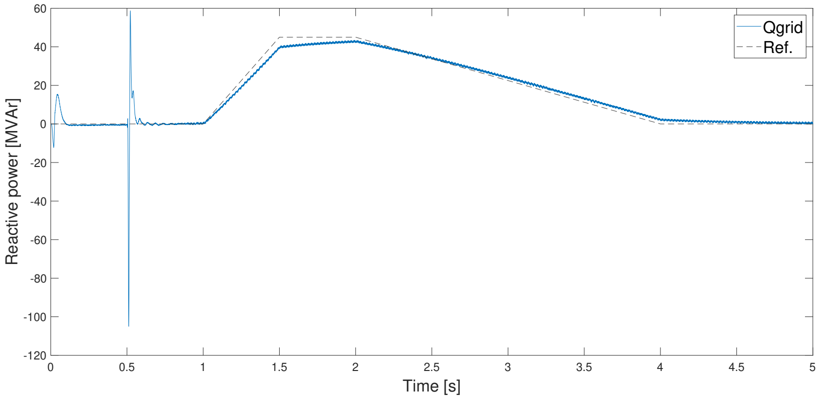

Figure 6.8: Reactive power delivered to grid

6.4 Performance of active power filter

In this section the performance of the active power filter is tested. The simulations are carried out with a simplified system with the direct voltage controller, a constant power wind farm model and no transformer connected to the VSC, as explained in section 5.7. The active power filter is used to filter the 11th and 13th harmonics in fig. 5.6. The result is shown in fig. 6.9. In fig. 6.10 the harmonics generated from the VSC is compared to the harmonics from the DR.

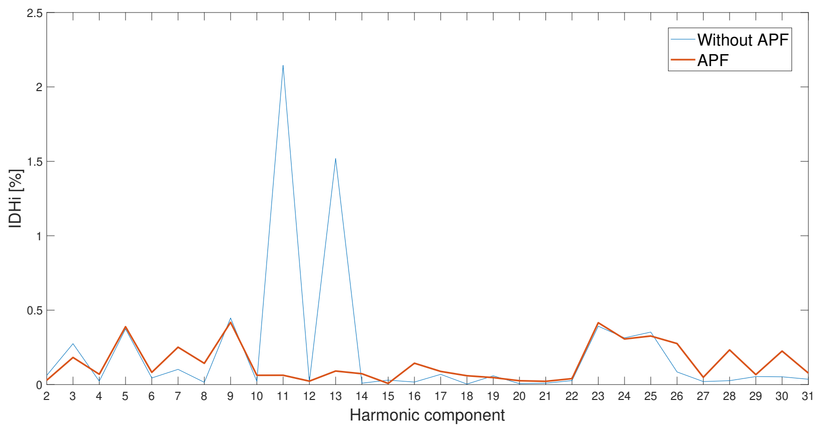

Figure 6.9: Harmonic distortion of PCC current with and without APF.

The result shows that the active power filter is able to very efficiently remove the 11th and

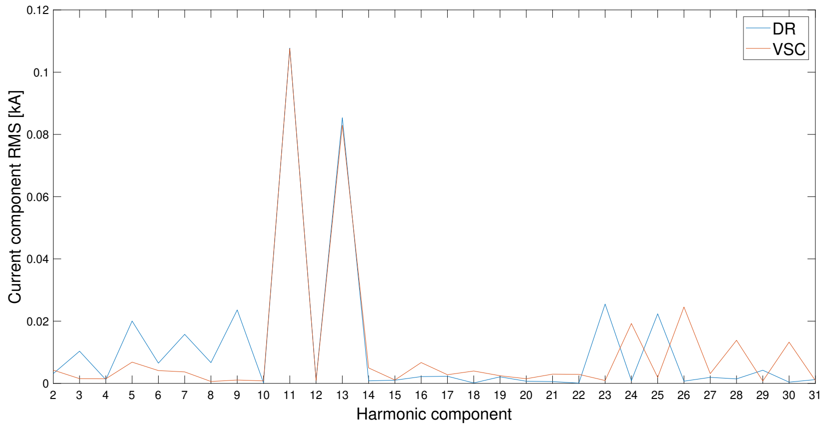

Figure 6.10: Harmonic components in VSC and DR currents at PCC.

13th harmonic components from the current in the PCC. The results above are obtained from around 4.0s into the simulation, such that all the controllers have reached their reference values. During the transient stage in the start-up, the harmonic content is higher. The synthesising of the harmonic current components from the control system are shown in fig. 6.11-fig. 6.14.

The control loop responses show that the controllers have some oscillations in the d-component during the start-up, but that these are damped after approximately 3.0 seconds. The active power filter is working satisfactorily for the 11th and 13th harmonics and manages to significantly reduce the harmonics from the DR.

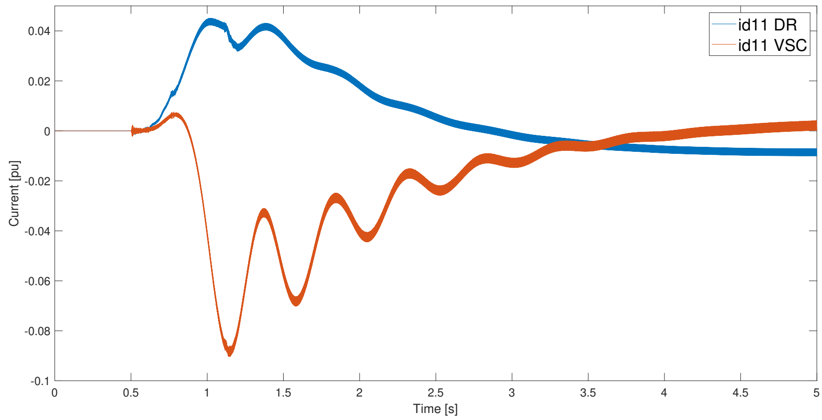

Figure 6.11: APF control of 11th harmonic d-component.

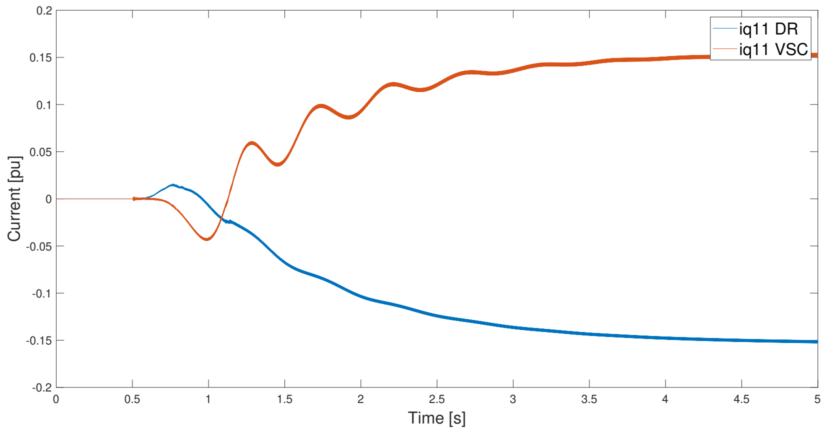

Figure 6.12: APF control of 11th harmonic q-component.

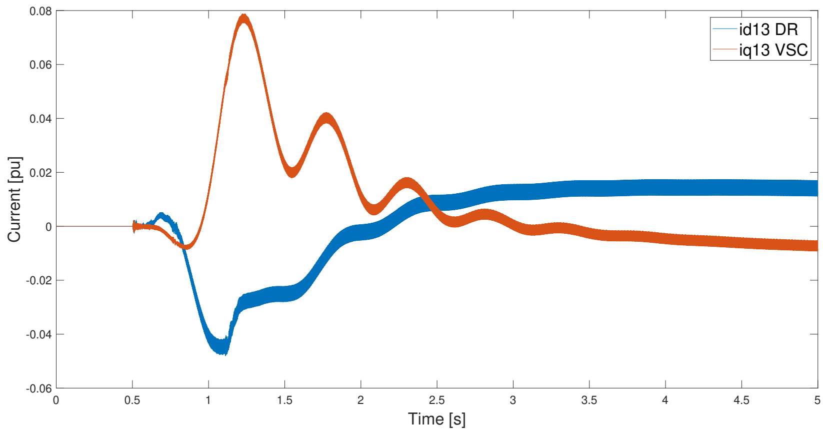

Figure 6.13: APF control of 13th harmonic d-component.

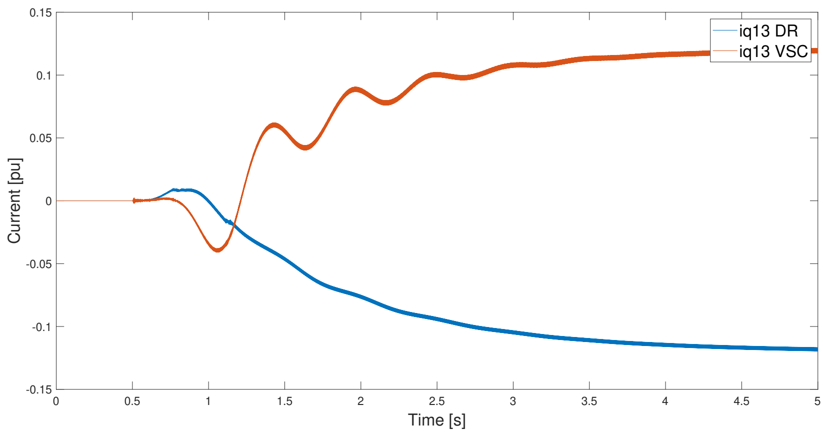

Figure 6.14: APF control of 13th harmonic q-component.

6.5 Evaluation of control system

The control system is able to perform all the defined control objectives that it was tested for. It can control the AC and DC voltage to a reference value, and the system is stable. The AC voltage was best controlled with the cascaded controller, and the anticipated shortcomings of the direct controller were also visible in simulations. The power balance in the hybrid converter was managed adjusting the transformer ratio, but the transformer ratio calculated by eq. (4.23) gives a too low value. In the simulations, the best way to determine the appropriate transformer ratio was by increasing the secondary winding until the correct power balance is observed.

In future work, more effort should be spent on the start-up procedure to see if the large transients can be avoided. The control system is working well in scenarios with variations of the power from the wind farm and during ramp-up of the power in the start. Future work should also include other operating scenarios, including faults and abnormal situations. One expected challenge in these scenarios is that the power balance will be directly affected by AC voltage dips. Since the power balance is not controlled directly, there is no controller stopping the power balance from violating the converter ratings.

The active power filter is working very efficiently on the tuned harmonics. It was necessary to test the active power filter in a simplified system due to time limitations. If the control system is expanded to include the phase shift of the transformer and a converter based wind farm model is used, it is expected that the active power filter performs well in the full system with the cascaded voltage controller. There are also other harmonic components in the PCC current except the 11th and 13th, and more work should find the origin of these components and determine if more components should be filtered by the APF.

Chapter 7

Sizing of the VSC in the hybrid converter

In this chapter, the impact of the sizing of the VSC in the hybrid converter is studied further. It is tested through simulation what are the consequences of decreasing the size from 1/2 of the power rating which was used in the previous simulations.

7.1 VSC size influence on system performance

The internal sizing of the components in the hybrid converter is an essential part of designing the system because it determines the cost and efficiency savings gained from using a hybrid system instead of the conventional VSC-HVDC system. However, finding the optimal sizing is not a straightforward task, and it has not been addressed in detail in earlier studies. The only study found which tries to address this challenge is [27], which proposes a simple optimisation problem for determining the VSC in a similar series hybrid configuration. However, the hybrid converter in the study is used for grid connection to a weak grid and not for integration of an offshore wind farm, and thus the VSC has a different control objective.

In studies of this hybrid converter connected to a wind farm the rating of the converters have been 1/2 VSC-1/2 DR [6] [26] and 1/3 VSC-2/3 DR [23] [7]. The sizing here refers to the proportion of the power which is delivered from each of the components. All these studies show the satisfactory performance of the given ratio and improvement on costs and efficiency compared to the VSC-HVDC system. However, the reasons for choosing these sizes have not been explained. It is therefore interesting to see if it is possible to reduce the size of the VSC further.

7.2 Economic optimisation

Economic considerations are the main motivation for keeping the size of the VSC as small as possible. As earlier stated in chapter 2, the cost of an LCC is on average half the price of the VSC. Since the VSC is considered to be the most expensive component, a simple cost optimisation can be solved where the total size of the VSC is minimised.

The size of the VSC is determined from the maximum active and the reactive power that it should be able to transfer. When considering the power balance between the VSC and the DR, only the active power is of interest since only active power is transmitted to the HVDC link. However the VSC can also provide reactive power to the AC grid. This chapter will try to find an optimal size for the VSC when the reactive power of the DR is compensated from the offshore VSC.

The apparent power (S) is the optimisation parameter, and it is given from eq. (7.1). The active power of the VSC can be written as a function of the nominal active power (P_{nom}), i.e. the full rating of the wind farm, and the active power of the DR as in eq. (7.2).

$$S_{vsc} = \sqrt{P_{vsc}^2 + Q_{vsc}^2} \tag{7.1}$$

$$P_{vsc} = P_{nom} - P_{DR} \tag{7.2}$$

As stated in section 3.4, the DR consumes reactive power equal to approximately 60% of the active power. The apparent power can then be written as a function of the active power in the DR.

$$S_{vsc} = \sqrt{(P_{nom} - P_{DR})^2 + (0.6P_{DR})^2} \tag{7.3}$$

The optimisation is carried out by differentiation with respect to P_{DR} and solving for P_{DR} when the expression is set to zero.

$$\frac{dS_{vsc}}{dP_{DR}} = \frac{1.16P_{DR} - P_{nom}}{\sqrt{P_{nom}^2 - 2P_{nom}P_{DR} + P_{DR}^2}} = 0 \tag{7.4}$$

From this it can be concluded that optimal ratings with respect to costs is $P_{DR} = 294MW$ and $P_{vsc} = (400 - 294)MW = 106MW$. This power balance is very close to VSC - 1/4 and DR - 3/4, which is a smaller VSC than has been suggested in earlier studies.

7.3 Performance of system with reduced size of the VSC

In the following sections, new power balances with reduced size of the VSC is tested with simulations. For the simulation, the cascaded VSC control is used, and the active power is not considered for simplification.

7.3.1 Performance with 1/3 VSC - 2/3 DR

The size of the VSC is first reduced to 1/3 of the full power rating. This is the same power balance as is proved to work in [24, 23, 7]. The transformer ratios used to obtain this balance is 33kV:76kV:76kV for the DR and 33:60kV for the VSC. The DC voltage balance and the power balance is shown in fig. 7.1 and fig. 7.2.

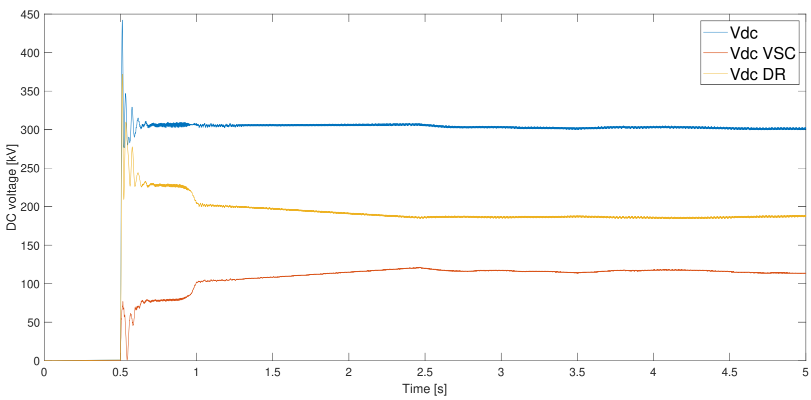

Figure 7.1: DC voltage balance with 1/3-2/3 VSC-DR.

The results show that the DC voltage balance and the power balance is accomplished. The plots also show that the system is stable and that the AC voltage controller is working as intended. This can be concluded since the DC voltage balance is indirectly controller from the AC voltage by the VSC and any instabilities or oscillations would be visible in the DC voltage. These results prove that it is possible to reduce the size of the VSC to 1/3 of the power rating under these conditions.

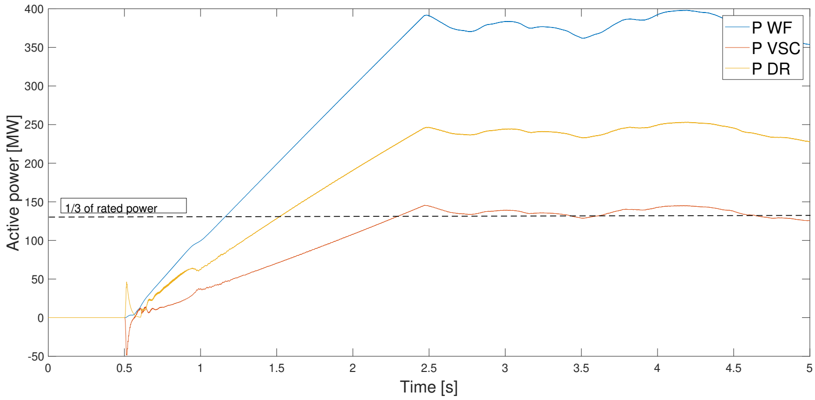

Figure 7.2: Power balance with 1/3-2/3 VSC-DR.

7.3.2 Performance with VSC 1/4 - DR 3/4

The size is now reduced futher such that the VSC is 1/4 and the DR is 3/4 of the total converter rating. The transformer ratio was instead used as 33kV:88kV:88kV for the DRs and 33kV:36kV for the VSC. This power balance is the optimal size considering costs and reactive power compensation from the VSC to the DR, as found in section 7.2. The results are shown in fig. 7.3 and fig. 7.4.

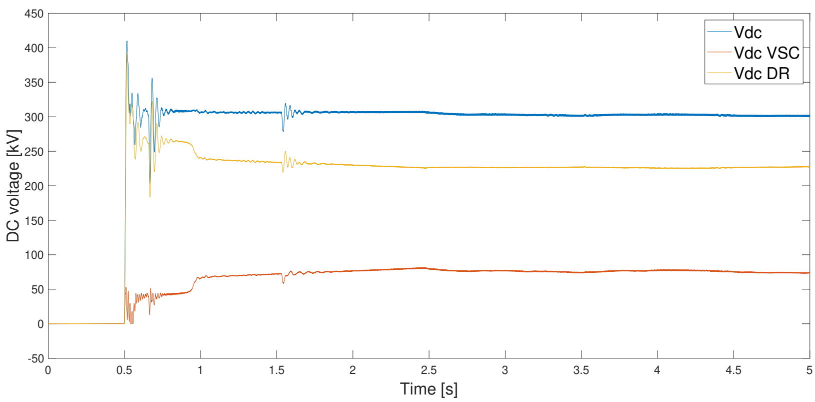

Figure 7.3: DC balance with 1/4 - 3/4 VSC-DR

These results show that is possible to reduce the size of the VSC to 1/4 and still have a stable system. This is a promising result because it indicates that the promising cost-benefit results obtained with 1/3 VSC - 2/3 DR in [7] can be optimised even more by

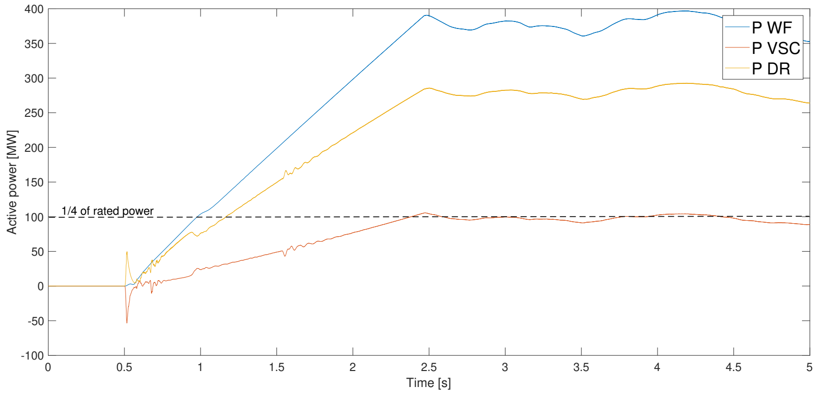

Figure 7.4: Power balance with 1/4 - 3/4 VSC-DR

reducing the size of the VSC to 1/4 of the total converter rating. The total power rating of the VSC would then be 205.9MW (total rating of the system is 400MW) calculated from eq. (7.1). This a reduction of 50% from a fully rated VSC-HVDC. However, it should be noted that the system is here tested without considering the reactive power compensation or harmonic cancellation. The THDi of the system at PCC is here 3.88% when the system has reached steady-state, which is a relatively high level of distortion.

7.3.3 Performance with VSC 1/10 - DR 9/10

To test what happens when the VSC becomes very small, the system is tested with VSC size of only 1/10 of the total system rating. The transformer ratios are then 33kV:100kV:100kV for the DR and 33kV:18kV for the VSC and here the theoretical ratios are used. The result is shown in fig. 7.5 and fig. 7.6.

It is seen that this VSC does not manage to keep the system stable. The AC voltage is not stable, and this impacts the DC voltage balance as well. There are large oscillations in the beginning and large ripples in the DC voltage. Although the DC voltage balance is obtained at certain periods, the large ripple and oscillations make this system considered not satisfactory. It is possible that the system could obtain a satisfactory performance with a VSC below 1/4 of the total power rating, however since 1/4 was calculated to be the optimal size, further attempts to reduce the size were not attempted.

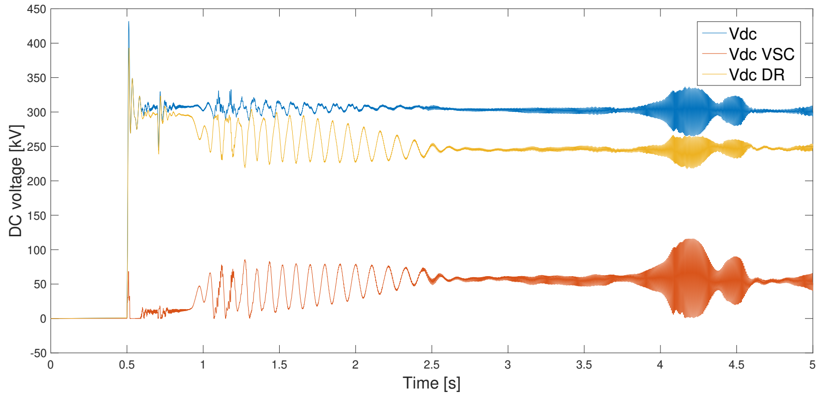

Figure 7.5: DC balance with 1/10 - 9/10 VSC-DR

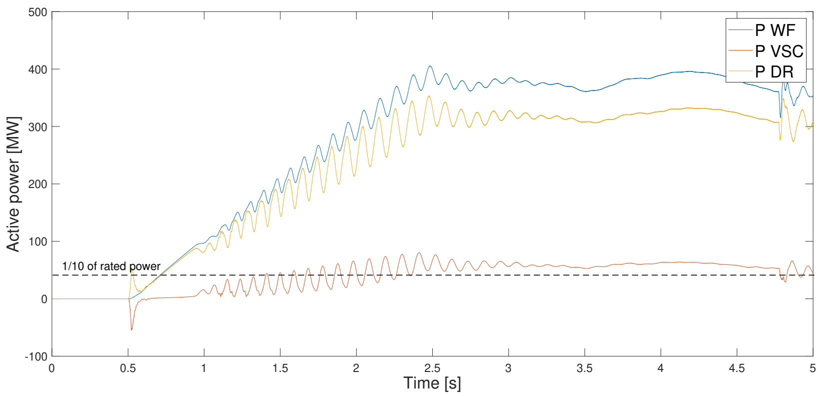

Figure 7.6: Power balance with 1/10 - 9/10 VSC-DR

7.4 Impact of active power filter

In the simulations above the system was tested without the active power filter to test the theoretical limit of the system, and without interference from the stability limits of the APF. However, harmonic compensation becomes more important and more challenging when the size of the harmonic source, the DR, is increased. There are also less current flowing through the VSC, which gives a decreased possibility for compensation. Since the simulations showed a stable and well-performing system with a reduced VSC to 1/4 of the total power rating, it is wanted to verify that the active power filter also works in this case.

When the active power filter was tested in chapter 6, it was necessary to use a simplified system to obtain the correct result as explained in section 5.7. Here it is wanted to keep the cascaded controller as this is the one that proved the best performance for the smaller size VSC and it is accepted that the capacitor in the LCL filter might affect the performance. To keep the system stable, it is also necessary to keep the transformer in the circuit, and it is switched for a star-star transformer to avoid the phase shift. The impact of the transformer is added to the APF control system by multiplying the DR current reference with the transformer ratio. Again only the 11th and 13th harmonics are filtered. The result is shown in fig. 7.7.

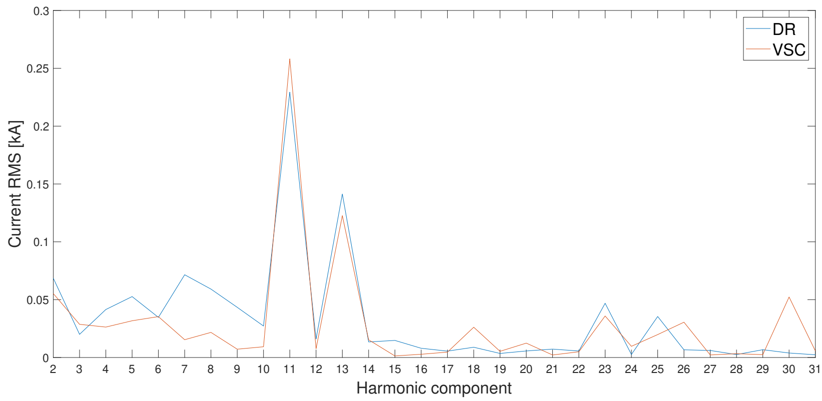

Figure 7.7: Harmonic components in VSC and DR currents at PCC

From fig. 7.7 it is shown that the APF is able to eliminate most of the 11th and 113th harmonics in the PCC current. The result is not as accurate as for the 1/2 VSC - 1/2 DR shown in fig. 6.13, but it is still working very well. The THDi for at the PCC is reduced from 3.88% to 2.80%, when the THDi is measured after the system stabilises around 4.0s. This indicates that the active power filter still able to compensate for the harmonics. It is observed that the VSC compensates the d-component too much and the d-component too little. It should be further analysed if the LCL filter can be a reason for this or if there are limitations in the VSC that prevents the components from reaching the reference.

Chapter 8

Conclusions and final remarks

This chapter concludes this master's thesis. It summarises and concludes on the main findings and presents the contributions of the thesis. Finally, some recommendations for future work are given.

8.1 Performance of control strategy

The control strategy presented in chapter 4 has been verified through simulations. The proposed control system consists of a cascaded AC voltage controller and an active power filter for the offshore VSC and a conventional DC voltage and reactive power controller for the onshore VSC. Both the VSCs are controlled by PI controllers in the synchronous reference frame. The controllers for the offshore VSC is the most challenging, since it in addition to establishing the AC grid also indirectly controls the DC voltage balance and must compensate for harmonics and reactive power from the DR. The simulations showed that the control system is able to perform all the tested control objectives under normal operating scenarios. The reactive power compensation to the DR is not fully addressed in the simulations as the simplified wind farm model delivers some reactive power to the system. However, it is expected that the VSC would be able to deliver this reactive power if needed. The main challenge of the proposed control system is that the power balance in the hybrid converter is only controlled indirectly. The indirect control can cause problems if there is a drop in the AC voltage in the offshore grid, but it is simple and works when the AC voltage control is achieved. It might be necessary to implement an additional control loop for active power or DC voltage to reduce the susceptibility to faults. A simple direct voltage controller is also presented. It is able to keep the system stable, but it has small oscillations due to variations in the power injection from the wind farm and stabilises at a higher voltage than the reference due to the q-component of the voltage not being controlled. Of the two controllers, the cascaded controller is the preferred option, but both are able to operate the system and fulfil the control objectives satisfactorily. The onshore VSC is controlled as in a conventional VSC-HVDC, and it has a compensation loop for DC current variations. This controller performs as expected.

The proposed control system is able to fulfil the control objectives of offshore grid forming, HVDC-link control, power balance control and reactive power compensation to the grid. In addition, it is expected to be able to compensate for the reactive power in the offshore side automatically. The control system that is proposed in this thesis is different from the earlier proposed control systems for this type of transmission system and it has proved to be a well-performing alternative during in the tested operating scenarios.

8.2 Performance of active power filter

The preferred way to compensate for the large characteristic harmonics from the DR is by use of an active power filter as passive filters are large and not well suited for an offshore substation. The active power filter is implemented as extra control loops in the offshore VSC. The detection and the current control are carried out in multiple synchronous reference frames rotating with the frequency of the harmonic components. This gives an effective active filter where the harmonic components are accurately separated and compensated by the use of PI controllers. The APF is tuned to filter the 11th and 13th harmonic components, which are the largest harmonics in the system. When the APF was implemented in PSCAD/EMTDC it was observed that the harmonic distortion of the PCC current was affected by the simplified wind farm model and the LCL filter in the cascaded controller. A reason for this could be resonance interference from the two capacitors, but this will need further investigation. In addition, a phase shift from the star-delta transformer was not included when the APF was implemented due to time limitations. The active filter was therefore tested in a simplified system, where the direct voltage controller and a constant power wind farm model was used. The star-delta transformer for the VSC was neglected. In this set up the APF was able to filter the tuned harmonics very accurately. It could be possible to improve THDi of the system by using the APF to filter more harmonic components and this could be tested in future work. In the system a three winding harmonic cancellation transformer is used to eliminate the 5th and the 7th harmonic, but if wanted the APF could be used instead. The APF is also tested when the size of the VSC is reduced to 1/4 of the total power rating. With this power balance, the DR is larger and the harmonic distortion is increased. Here the cascaded voltage controller is used. The results show that the APF is also able to compensate the harmonics to a good degree, but not as accurately as with the larger VSC and the simplified test set up. The APF over-compensates for the 11th harmonic and under-compensates for the 13th harmonics, which could indicate that it is not the increased harmonic distortion that is causing less accurate compensation.

8.3 Sizing of the VSC in the hybrid converter

A very promising result from this thesis is that the control system and the APF is working well also when the size of the offshore VSC is reduced to 1/4 of the total power rating. The size of 1/4 was found to be the optimal size if the total apparent power of the VSC, including reactive power compensation, is minimised. This is a smaller VSC than what has been suggested in earlier studies, where the smallest have been 1/3 of the total power rating. Although more testing of the system will be needed to conclude on the optimal sizing, this gives a promising indication that the VSC size can be reduced below 1/3. Reduced size of the VSC will increase the benefits from using a hybrid converter, and it is expected to increase both the efficiency and the cost-benefit.

8.4 Evaluation of the hybrid converter

Based on the results and conclusion above the hybrid VSC-DR transmission system is evaluated to have a high potential for improving the cost and efficiency of the VSC-HVDC system that is used today. If the power balance of 1/4 VSC and 3/4 DR is used in the hybrid converter the size of the VSC is reduced significantly. The reduction is by 50% compared to VSC-HVDC if the VSC is used reactive power compensation and 25% if reactive power compensation is delivered from a different source. There is still needed more work to establish the performance of the hybrid VSC-DR transmission system under all operating scenarios and during faults, but the results so far indicate that the topology could be well suited for integration of offshore wind.

8.5 Main contributions

The main contributions of this thesis are:

- A control strategy for a hybrid-VSC-DR HVDC system has been developed. It has a cascaded AC voltage control for the offshore VSC, which can compensate for variations in input current due to power variations for the wind farm. The AC voltage control also indirectly controls the power balancing of the hybrid converter. The onshore converter uses a conventional control method for a VSC. The control system has been verified through simulations in PSCAD/ETMDC.
- It has been shown that the characteristic harmonics in the current from the DR can be eliminated by using the VSC as an active power filter. The IHDi for the filtered harmonics is decreased significantly and is almost zero when the APF is used.
- It has been shown that the control system can, in theory, operate with a VSC smaller than 1/3. Through simulations, the system is stable and fulfilling the control objectives when the VSC is 1/4 of the full rated converters. This result indicates that the size of the VSC can be smaller than 1/3 of the full rating, which would increase the cost-benefit of the converter.
- The optimal size for minimising the apparent power rating of the offshore VSC if reactive power compensation is regarded is calculated to be approximately 1/4 of the total active power rating. It was shown that the control objectives of the transmission system are still fulfilled when this size of the VSC is used. This is the first step towards optimising the hybrid VSC-DR converter.

8.6 Recommendations for future work

The work and results found in this master's thesis are only the primary studies of this system and control system, and it is working as a proof of the concept, which shows promising tendencies. However, a very simplified system is used, and abnormal operating scenarios, such as faults, have not been considered. There are several areas that would benefit from more studies, where some main recommendations are:

- The system should be tested for more operating scenarios, including AC and DC side faults, large wind variations and fault ride-through scenarios.
- The wind farm model should be improved by using a converter interface such that the shunt capacitor can be eliminated. This will allow for more realistic testing of the reactive power compensation and the active power filter capabilities.
- The active power filter control system should be improved by adding the phase shift of the transformer in the measurement of the DR current, such that a star-delta trans-

former does not interfere with the current detection.

- A stability analysis of the system should be carried out to analyse what impact the sizing of the VSC have on the full system.
- The model should be improved to include more realistic components with losses and operating limits.
- A full cost-benefit analysis should be conducted to find out the optimal sizing of the VSC in the hybrid converter, such that the benefits of the hybrid converter can be maximised and evaluated.

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Appendix

Appendix A: Per unit system

Below follows the derivation of the per unit system for a three phase system:

S_{base} is chosen as the rated 3-phase apparent power and V_{base} is chosen as the rated line to line RMS-voltage.

$$S_{base} = S_{base,3\phi} = 3S_{base,1\phi}$$
$$V_{base} = V_{LL,RMS} = \sqrt{3}V_{base,ph}$$

The other base values are derived from these quantities:

$$I_{base} = \frac{S_{base,1\phi}}{V_{base,1\phi}} = \frac{S_{base}/3}{V_{base}/\sqrt{3}} = \frac{S_{base}}{\sqrt{3}V_{base}}$$
$$Z_{base} = \frac{V_{base,1\phi}^2}{S_{base,1\phi}} = \frac{V_{base}^2}{S_{base}}$$

The base system for the dq-reference system is derived based on the single phase peak to peak voltage:

$$V_{dq,base} = \hat{V_\phi} = \sqrt{\frac{2}{3}}V_{base}$$
$$I_{dq,base} = \hat{I_\phi} = \sqrt{2}I_{base}$$
$$S_{dq,base} = \frac{3}{2}V_{dq,base}I_{dq,base}Z_{dq,base} = \frac{V_{dq,base}}{I_{dq,base}}$$

The base values of the system changes for different zones in the system due to transformers and converters. A new V_{base} is found on each side of the transformers. In addition the hybrid converter splits the power between the VSC and the DR and this gives different S_{base} for different part of the system as well. The different zones can be found in section 8.6 and the corresponding base values are found in section 8.6.

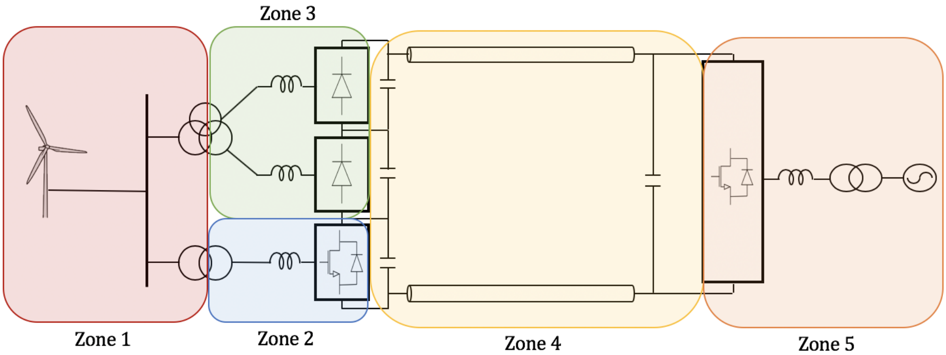

Figure 8.1: Zones in the system with different base values.

Table 8.1: Base values for different per unit zones and different rating of offshore VSC.

	VSC 1/2 - DR 1/2		*VSC 1/3 - DR 2/3*	
Zone	S_{base}	V_{base}	S_{base}	V_{base}
1	400 MVA	33 kV	400 MVA	33 kV
2	200 MVA	80 kV	133 MVA	60 kV
3	100 MVA	65 kV	267 MVA	76 kV
4	400 MW	300 kV	400 MW	300 kV
5	400 MVA	170 kV	400 MVA	170 kV

Appendix B: PSCAD model

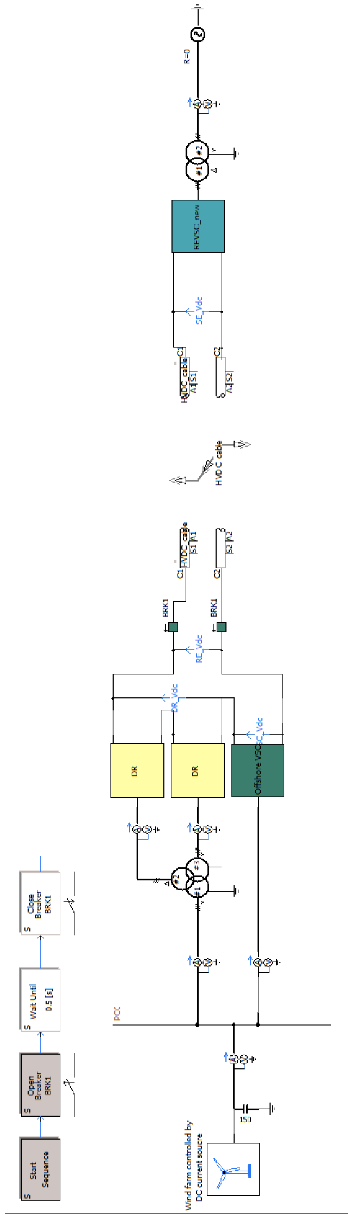

Figure 8.2: PSCAD: Hybrid VSC-DR transmission system

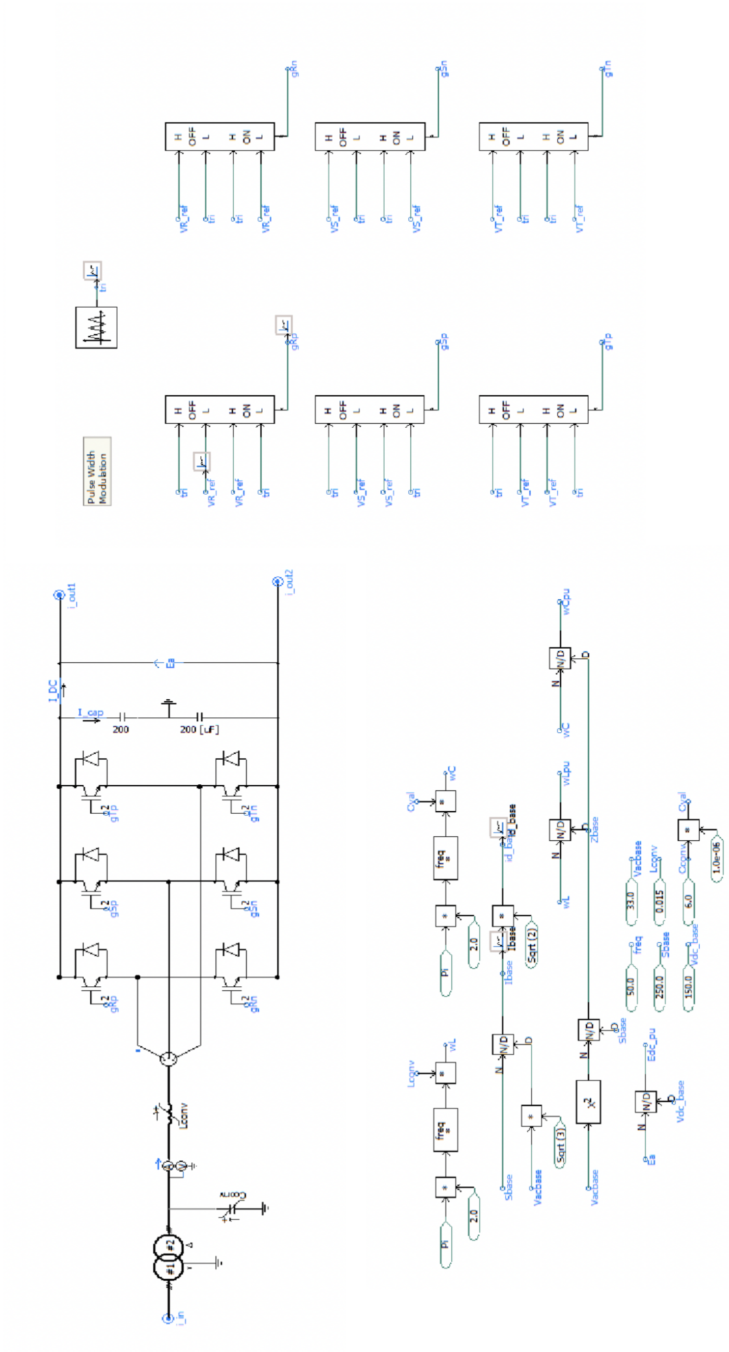

Figure 8.3: PSCAD: VSC, PWM generator and per unit system, similar for offshore and onshore VSC

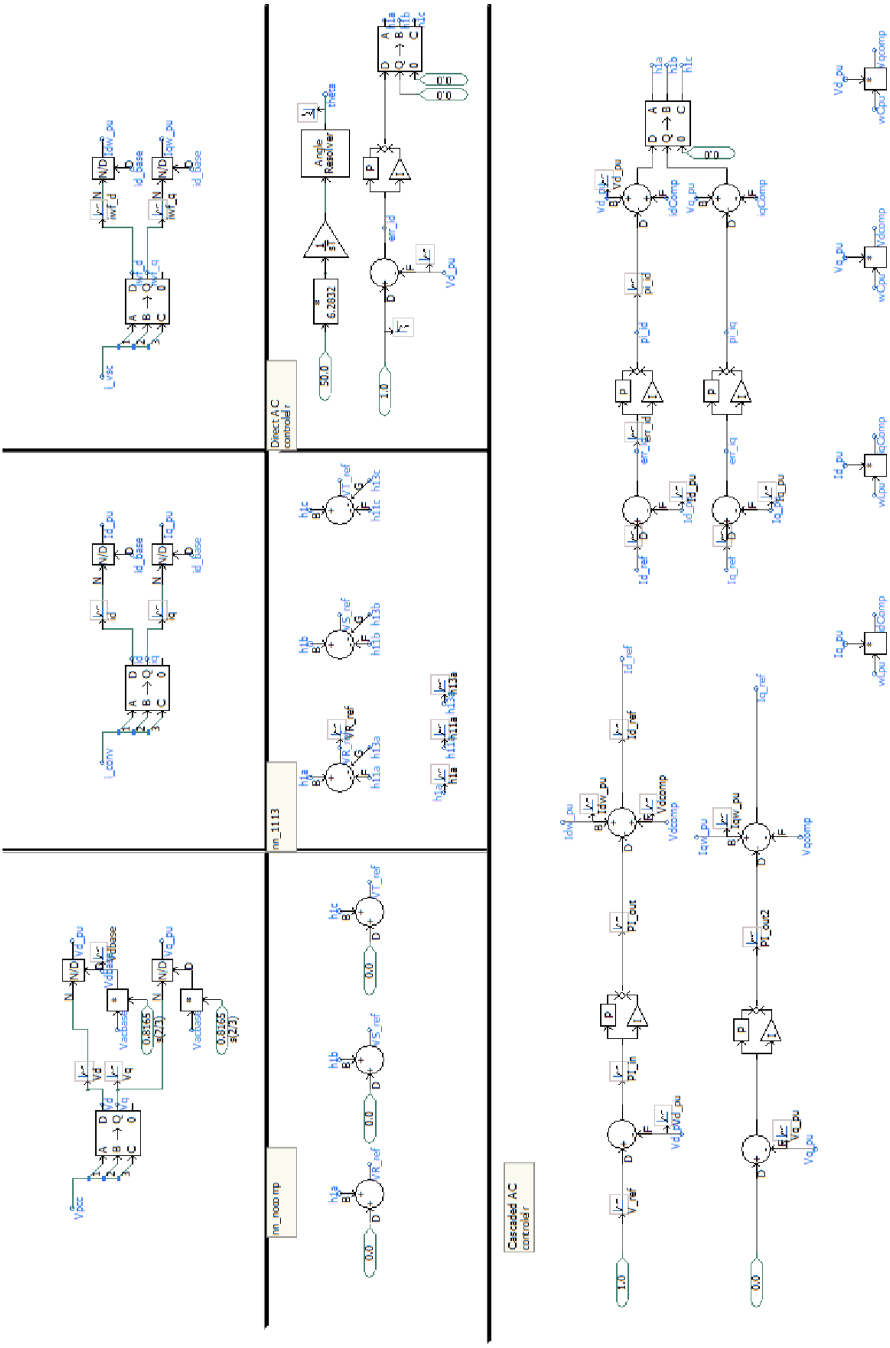

Figure 8.4: PSCAD: Control system for offshore VSC, both direct- and cascaded controller.

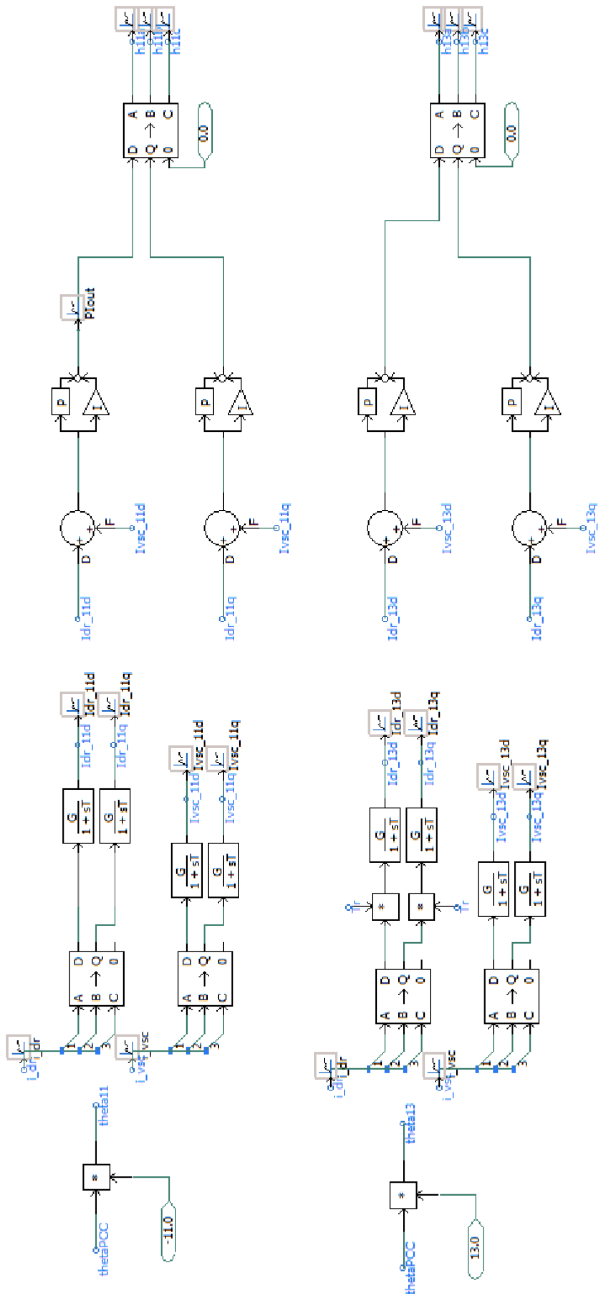

Figure 8.5: PSCAD: Active power filter control loop for offshore VSC.

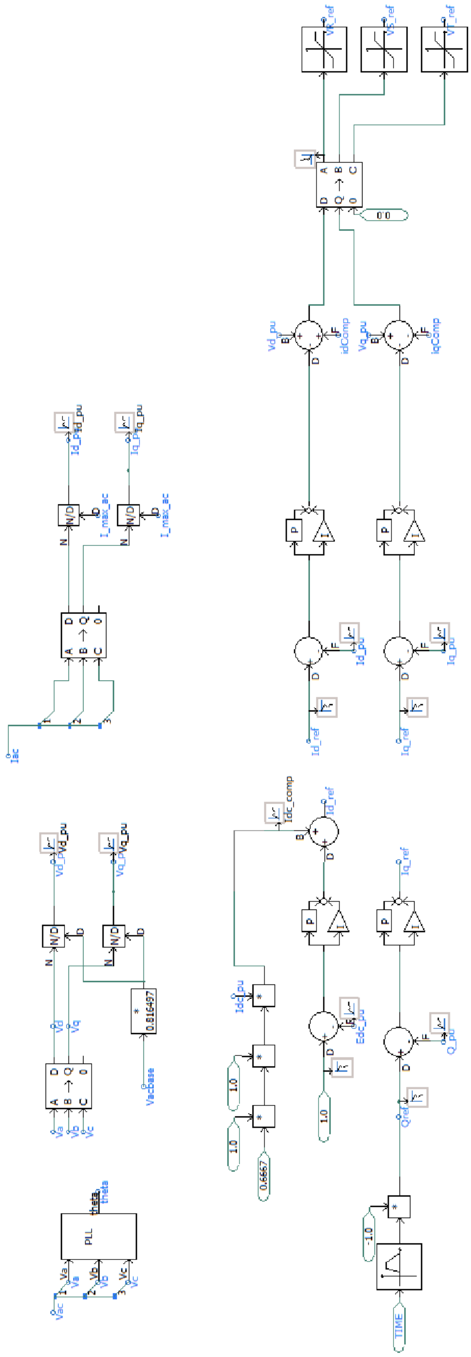

Figure 8.6: PSCAD: Control system for onshore VSC.

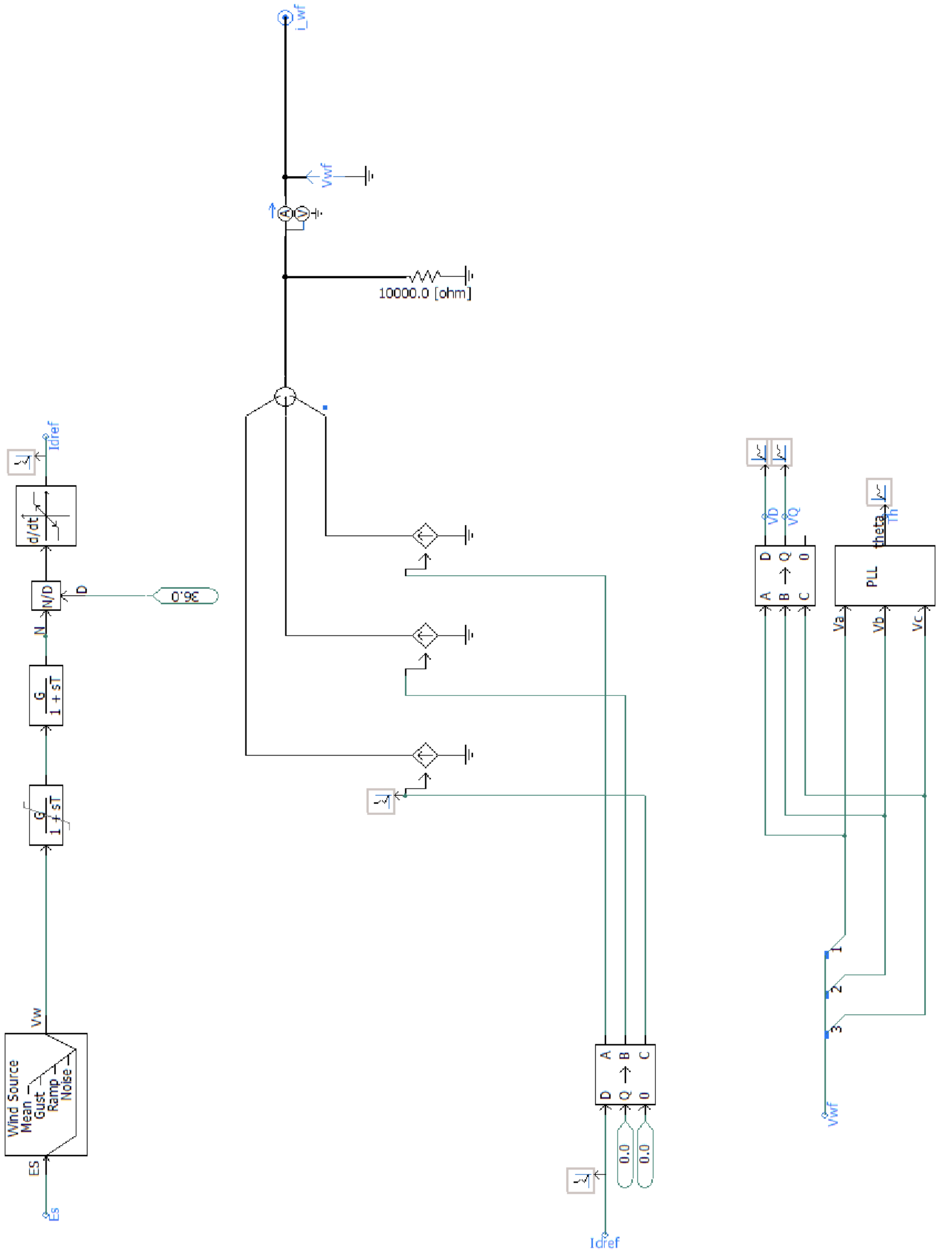

Figure 8.7: PSCAD: Wind farm model.

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Control Design of a Low-Cost Hybrid Converter for HVDC Connection of Offshore Wind Farms

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