Dynamic Modeling and Control of VSC-based Multi-terminal DC Networks

Sílvia Miguel Fragoso Rodrigues

Dissertação para a obtenção de Grau de Mestre em Engenharia Electrotécnica e de Computadores

Júri
Presidente:  Prof. Doutor Paulo José da Costa Branco
Coorientador:  Prof. Doutor Rui Manuel Gameiro de Castro
Vogal:  Prof. Doutora Sónia Maria Nunes dos Santos Paulo Ferreira Pinto

December 2011
Dynamic Modeling and Control of VSC-based Multi-terminal DC Networks

Sílvio Miguel Fragoso Rodrigues

Dissertação para a obtenção de Grau de Mestre em Engenharia Electrotécnica e de Computadores

Dissertação realizada sob a orientação de:

Orientador: Prof.dr.ir. P. Bauer
Coorientador: Eng. Rodrigo Teixeira Pinto
Coorientador: Prof. Doutor Rui Manuel Gameiro de Castro

December 2011
This document was prepared using \LaTeX.
Acknowledgments

First of all I want to express my gratefulness to Eng. Rodrigo Teixeira Pinto and to Prof. Paul Bauer for the opportunity of finishing my study at TUDelft. I am grateful for the vote of trust, and for all the support and comprehension through the development of this thesis.

A word to my Portuguese coordinator Prof. Rui Castro who has been a very kind and supportive person since the beginning. He also trusted me and my capabilities while the development of this dissertation.

An enormous and generous thank to all my friends that have been by my side all this years. A special thanks to Henrique Silva, Ricardo Grizonic, Pedro Carreira, João Falcão, Ricardo Batista, Joana Botelho, Paulo Chainho, Duarte Martins, André Grilo and João Bastos. There are a lot more and despite the fact that their names are not here they were not forgotten.

I would also like to mention all the friendships that I have done during my staying in the Netherlands, special my friends from JvB27 and my house-mates at JvB89. They always made me feel at home and were, and will continue to be, very good friends of mine.

Last but not least I would like to thank my parents. They have supported me during my entire life and worked hard to keep me in school. To them a special thank you.
Resumo

Com o aumento da procura por energia elétrica por todo o mundo devido não só à cada vez maior dependência energética dos países industrializados como também devido ao grande desenvolvimento de países como a Índia e a China, a produção de energia elétrica tem indubitavelmente que acompanhar essa subida [1]. Neste momento, fontes de energia renovável são uma forte aposta na Europa [2]. Uma destas fontes é a energia eólica cuja tecnologia, bastante amadurecida, já consegue rivalizar a nível económico com as fontes de energia de origem não renovável [3]. Por outro lado a energia eólica offshore apenas agora começa a dar os seus primeiros passos como tecnologia de escolha para o transporte em corrente contínua de energia proveniente dos parques eólicos mais distantes da costa. No entanto, em 2020, é esperado que os parques eólicos offshore produzam um terço de toda a energia eólica [4].

Atualmente existem mais de 100 sistemas de transmissão em corrente contínua mas no entanto apenas 3 deles têm 3 terminais sendo os restantes sistemas ponto a ponto [5]. Com os recentes avanços na tecnologia CFT (conversores de fonte de tensão), redes multi-terminal em corrente contínua poderão ser criadas com maior facilidade. O espaço ocupado por estes equipamentos é mais reduzido quando comparado com o espaço utilizado pelos CFC (conversores de fonte de corrente) o que traz grandes vantagens a nível offshore pois os custos de instalação e manutenção são bastante elevados [6][7].

Nos próximos anos serão instalados dezenas de parques eólicos offshore por toda a Europa [4]. Devido às vantagens que a tecnologia CFT apresenta face às restantes opções, existe uma forte possibilidade que seja essa a tecnologia escolhida para estar presente nos parques [8]. Tal situação serve de mote para que sejam estudados os métodos de simulação e controlo deste tipo de sistemas. Como tal, esta tese tem como objetivo o estudo de modelos que sejam capazes de simular com detalhe necessário os sistemas elétricos de parques eólicos offshore, os conversores e a rede multi-terminal. Os métodos de controlo de todo o sistema também serão estudados e serão apresentadas várias técnicas para controlar a tensão dentro da rede. Deste modo será possível aos vários países ligados à rede multi-terminal não só receber energia, proveniente dos parques eólicos offshore segundo um certo critério de partilha, como também transaccionar energia entre si.

Palavras-Chave: VSC-HVDC, Rede Multi-terminal, Offshore, Modelo Equivalente, Estratégias de Controlo.
Abstract

With the increased need for electric energy all over the world, not only because of the higher energetic dependency of the industrialized countries, but also due to the enormous development of countries such as India and China, the production of electric energy has, without question, to increase as well [1]. Nowadays, renewable energy sources are being installed at a huge rate in Europe [2]. One of these renewable sources is the onshore wind energy, whose technology, already developed, is able to compete in an economic way with the non-renewable energy sources [3]. On the other hand, the offshore wind energy is now giving its first steps as the technology of choice for the power transmission in direct current from the distant offshore wind farms. However, in 2020, it is expected that one third of all the wind energy will be transmitted from offshore wind farms [4].

Nowadays, there are more than 100 transmission systems in direct current. However, only 3 of them have 3 terminals, while all the others are point-to-point systems [5]. With the recent developments in the VSC technology, MTDC grids may be more easily created. The space required by the equipments of this technology is smaller when compared to the space used by the CSCs. Therefore, the installation and maintenance costs are reduced [6][7].

In the next years, dozens of offshore wind farms will be installed all over Europe [4]. Due to the technologic advantages that VSCs have when compared to the other options, there is a strong possibility that it will be the technology chosen to connect the offshore wind farms [8]. Such assumption intensifies the need of studying and simulating the control methods for these systems. Therefore, the purpose of the present thesis is the study of models that are able to simulate with the necessary detail, the electric systems of the offshore wind farms, the converters and the DC grid. The control methods of the system will also be studied and several methods to control the DC voltage will be presented. This way, it will be possible for the several countries connected to the multiterminal DC grid not only to receive energy from the offshore wind farms, according a certain criteria, but also to trade energy with each other.

Keywords: VSC-HVDC, Multi-terminal Network, Offshore, Equivalent Model, Control strategies.
Contents

Acknowledgments ................................................................. i
Resumo .................................................................................. ii
Abstract .................................................................................. iii
Contents .................................................................................. vi
List of Tables ........................................................................ vii
List of Figures .......................................................................... x
List of Acronyms ....................................................................... xi
List of Symbols ......................................................................... xiv

1 Introduction ........................................................................... 1
  1.1 Motivation ......................................................................... 1
  1.2 Thesis objective and contributions .................................. 2
  1.3 Publications ....................................................................... 2
  1.4 Thesis layout ....................................................................... 2
  1.5 State of the Art ................................................................. 3
  1.6 Current Status of Offshore Wind Energy ......................... 4
  1.7 Offshore Transmission technologies .............................. 5
    1.7.1 HVAC ......................................................................... 5
    1.7.2 LCC-HVDC ................................................................. 6
    1.7.3 VSC-HVDC ................................................................. 6
  1.8 Comparison of transmission systems: HVAC vs HVDC .... 7
  1.9 Comparison of DC transmission systems: LCC- vs VSC-HVDC 8
  1.10 Transmission cables ........................................................ 9
  1.11 Wind Energy in Portugal ................................................ 11
# VSC-HVDC Equivalent Model and Controllers

## 2.1 Introduction

## 2.2 VSC-HVDC Transmission System

- **2.2.1 AC Breakers**
- **2.2.2 AC Filters**
- **2.2.3 Transformer**
- **2.2.4 Phase Reactor**
- **2.2.5 Voltage Source Converter**
- **2.2.6 DC Capacitor**
- **2.2.7 DC Cable**
- **2.2.8 DC Chopper**

## 2.3 Voltage Source Converter’s equivalent model

- **2.3.1 Equivalent model of the VSC AC side**
- **2.3.2 Equivalent model of the VSC DC side**

## 2.4 The control system of the VSC-HVDC

- **2.4.1 Inner Current Controller**
- **2.4.2 Outer Controllers**
- **2.4.3 VSC Controllers Bandwidth**
- **2.4.4 Current Limiter**

# Multi-Terminal DC Networks

## 3.1 Introduction

- **3.1.1 The need for a MTDC Grid**
- **3.1.2 Applications of a MTDC grid**

## 3.2 State-space model of MTDC grids

- **3.2.1 Meshed MTDC grid**
- **3.2.2 Radial MTDC grid**
- **3.2.3 Generic MTDC grid**

# DC Voltage Control Methods

## 4.1 Introduction

## 4.2 Market dispatch schemes

## 4.3 DC voltage control methods
List of Tables

1.1 AC and DC submarine cable parameters. ........................................ 10

2.1 Controllers’ gains. ................................................................. 28

5.1 MTDC system parameters. .......................................................... 58

5.2 Order of events in the offshore wind farms. ................................. 59

5.3 Order of events in the offshore wind farms (fault scenario). ............ 59

5.4 Power ratios and maximum value of $V_{DC}$ of the onshore station 2. .... 63

5.5 Capability of the DC voltage control methods to perform the dispatch schemes. .... 80

5.6 Comparison of the different DC voltage control methods. ............... 80
List of Figures

1.1 Offshore wind power installed in Europe up to 2010 [9]. 4
1.2 Map of operational offshore wind farms in Europe up to 2010 [10]. 4
1.3 European wind resources over open sea [11]. 5
1.4 Actual and future planned offshore wind farms in the North Sea [3]. 5
1.5 Layout of a real VSC-HVDC station: ABB HVDC Light and SIEMENS HVDC Plus, respectively [12][13]. 7
1.6 Connection technologies depending on the power and transmission distance for underground or submarine cables [14]. 9
1.7 Cost Comparison between AC and DC transmission systems for underground or submarine cables. 9
1.8 Comparison between AC and DC submarine transmission cables. 10
1.9 Different types of offshore wind towers [15]. 11
1.10 Wave farm installed at Aguçadoura [16]. 12
1.11 Portuguese offshore seabed’s slope. 12
1.12 Portuguese offshore potential [17]. 12
1.13 Possible MTDC grid in the Portuguese shore. 12
2.1 Typical layout of a VSC-HVDC transmission system. 13
2.2 Conventional 2-level VSC three-phase topology. 15
2.3 Main circuit of a Modular Multilevel Converter (M2C) [18]. 16
2.4 PWM for different converter topologies. (a): two-level converter. (b): three-level converter. (c): M2C with five modules [19]. 16
2.5 Equivalent circuit for the AC side of a VSC-HVDC station disregarding losses. 19
2.6 Phasor diagram of a VSC station providing active and reactive power to its AC network. 20
2.7 Real (P,Q) diagram of a VSC-HVDC station 21
2.8 Equivalent circuit for AC and DC sides of a VSC-HVDC station. 22
2.9 VSC-HVDC Control Scheme. 23
2.10 Block diagrams of the phase reactor and the ICC. ........................................ 24
2.11 Active and reactive power outer controller diagrams. .................................. 25
2.12 DC voltage controller diagram. ................................................................. 26
2.13 AC Voltage outer controller diagram. ....................................................... 27
2.14 Current limiting strategies. ........................................................................... 28

3.1 MTDC Network classification scheme. ............................................................ 29
3.2 Transnational “Supergrid” proposed by Airtricity [20]. ................................... 30
3.3 Wave energy in Europe in kW/m width of oncoming wave. ............................ 32
3.4 Applications for a Multi-Terminal DC grid. .................................................... 33
3.5 Example of a meshed-connected VSC-HVDC MTDC network with three terminals. 34
3.6 Example of a radially-connected VSC-HVDC MTDC network with four terminals. 37

4.1 MTDC grid with two DC voltage controlling stations. ....................................... 46
4.2 DC voltage droop characteristic. ................................................................. 47
4.3 $V_{DC}(I_{DC})$ characteristics for the Droop controller - Priority Power Sharing. ...... 48
4.4 DC voltage droop characteristics of terminals 1 and 2. ................................... 49
4.5 $V_{DC}(P)$ characteristic of terminal 1 and DC voltage droop characteristic of terminal 2. 51
4.6 DC voltage controller and limiter present in the Voltage Margin Method. .......... 52
4.7 One-stage DC voltage controller. ................................................................. 53
4.8 $V_{DC}(P)$ characteristic of the one-stage DC voltage controller. ...................... 53
4.9 $V_{DC}(P)$ characteristics for two one-stage DC voltage controlling converters and the resulting operating point (P). ......................................................... 54
4.10 Two-stage DC voltage controller. ............................................................... 55
4.11 $V_{DC}(P)$ characteristic of a station composed by two stages. ......................... 55
4.12 $V_{DC}(P)$ characteristics for two DC voltage controlling converters and the resulting operating point (P). ................................................................. 55
4.13 $V_{DC}(P)$ characteristics of the stations performing fixed power sharing. .......... 56
4.14 $V_{DC}(P)$ characteristics of the stations performing priority power sharing. ....... 56
4.15 $V_{DC}(P)$ characteristics of the stations performing proportional power sharing. ... 56

5.1 4 terminal radial MTDC network used in the simulations. ............................. 58
5.2 $V_{DC}(I_{DC})$ characteristics for the droop controller - Priority Power Sharing. .... 60
5.3 Simulation results using the DC Voltage Droop Method - Priority Power Sharing. 62
5.4 $V_{DC}(I_{DC})$ characteristics for the Ratio controller. ............................................. 63
5.5 $V_{DC}(P)$ characteristics for the Priority controller. .................................................. 64
5.6 Simulation results using the Ratio Control - Proportional Power Sharing. .................. 65
5.7 Simulation results using the Priority Control - Priority Power Sharing. ...................... 66
5.8 $V_{DC}(P)$ characteristics for the Voltage Margin Method - Fixed Power Sharing. ......... 67
5.9 Simulation results using the Voltage Margin Method - Fixed Power Sharing. ............... 68
5.10 $V_{DC}(P)$ characteristics for the Voltage Margin Method - Priority Power Sharing. ...... 69
5.11 Simulation results using the Voltage Margin Method - Priority Power Sharing. .......... 70
5.12 $V_{DC}(P)$ characteristics for the Voltage Margin Method - Proportional Power Sharing. 71
5.13 Simulation results using the Voltage Margin Method - Proportional Power Sharing. .... 72
5.14 $V_{DC}(P)$ characteristics for the DC voltage controllers. ........................................ 73
5.15 Simulation results of a onshore three-phase AC fault. ............................................. 75
5.16 Simulation results of a onshore one-phase AC fault. .............................................. 77
5.17 Simulation results of a offshore three-phase AC fault. ............................................. 79

6.1 Relationship between the ($\alpha\beta$) and ($dq$) frames. ........................................... 90
6.2 General control scheme with saturation. ................................................................. 91
6.3 Anti-windup implemented: Integrator clamping. ..................................................... 91
## List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternate Current</td>
</tr>
<tr>
<td>CFC</td>
<td>Conversores Fonte de Corrente</td>
</tr>
<tr>
<td>CFT</td>
<td>Conversores Fonte de Tensão</td>
</tr>
<tr>
<td>CSC</td>
<td>Current Source Converter</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EDP</td>
<td>Energias de Portugal</td>
</tr>
<tr>
<td>GTO</td>
<td>Gate Turn Off Thyristor</td>
</tr>
<tr>
<td>HVAC</td>
<td>High Voltage Alternating Current</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>ICC</td>
<td>Inner Current Controller</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>KCL</td>
<td>Kirchhoff’s Current Law</td>
</tr>
<tr>
<td>KVL</td>
<td>Kirchhoff’s Voltage Law</td>
</tr>
<tr>
<td>LCC</td>
<td>Line Commutated Converter</td>
</tr>
<tr>
<td>M2C</td>
<td>Modular Multilevel Converter</td>
</tr>
<tr>
<td>MTDC</td>
<td>Multi-Terminal Direct Current</td>
</tr>
<tr>
<td>NSTG</td>
<td>North Sea Transnational Grid</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional-Integral</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional-Integral-Derivative</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-Locked Loop</td>
</tr>
<tr>
<td>pu</td>
<td>per unit</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Static Compensator</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>VMM</td>
<td>Voltage Margin Method</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
</tr>
<tr>
<td>WF</td>
<td>Wind Farm</td>
</tr>
<tr>
<td>XLPE</td>
<td>Cross Linked Polyethylene</td>
</tr>
</tbody>
</table>
# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>α&lt;sub&gt;c&lt;/sub&gt;</td>
<td>ICC closed-loop bandwidth</td>
</tr>
<tr>
<td>α&lt;sub&gt;oc&lt;/sub&gt;</td>
<td>Outer controllers closed-loop bandwidth</td>
</tr>
<tr>
<td>δ</td>
<td>Converter voltage phasor angle or power angle</td>
</tr>
<tr>
<td>τ</td>
<td>DC capacitor’s time constant</td>
</tr>
<tr>
<td>ω</td>
<td>AC system’s angular frequency</td>
</tr>
<tr>
<td>ω&lt;sub&gt;sw&lt;/sub&gt;</td>
<td>Angular switching frequency</td>
</tr>
<tr>
<td>θ</td>
<td>Angle of the AC voltage at the PCC</td>
</tr>
<tr>
<td>(abc)</td>
<td>Three-phase quantities frame</td>
</tr>
<tr>
<td>(αβ)</td>
<td>Alpha-beta fixed frame</td>
</tr>
<tr>
<td>(dq)</td>
<td>Direct-quadrature rotating frame</td>
</tr>
<tr>
<td>A</td>
<td>State Matrix</td>
</tr>
<tr>
<td>B</td>
<td>Input Matrix</td>
</tr>
<tr>
<td>C</td>
<td>Station DC capacitor or Output Matrix</td>
</tr>
<tr>
<td>C&lt;sub&gt;cable&lt;/sub&gt;</td>
<td>Capacitance of the DC cable</td>
</tr>
<tr>
<td>D</td>
<td>Direct Transition Matrix</td>
</tr>
<tr>
<td>e&lt;sub&gt;dq&lt;/sub&gt;</td>
<td>Voltage at the PCC in the (dq) frame in pu</td>
</tr>
<tr>
<td>e&lt;sub&gt;dq&lt;/sub&gt;&lt;sup&gt;*&lt;/sup&gt;</td>
<td>Reference of the voltage at the PCC in the (dq) frame in pu</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>e&lt;sub&gt;dq&lt;/sub&gt;&lt;sup&gt;∗&lt;/sup&gt;</td>
<td>Magnitude reference of the voltage at the PCC in the (dq) frame in pu</td>
</tr>
<tr>
<td>e&lt;sub&gt;S&lt;/sub&gt;</td>
<td>AC voltage at the PCC in pu (phasor)</td>
</tr>
<tr>
<td>E&lt;sub&gt;S&lt;/sub&gt;</td>
<td>AC voltage at the PCC (phasor)</td>
</tr>
<tr>
<td>e&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Magnitude of the AC voltage at the PCC in pu</td>
</tr>
<tr>
<td>f</td>
<td>AC system’s frequency</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$I_N$</td>
<td>DC cable’s nominal current</td>
</tr>
<tr>
<td>$I_P$</td>
<td>Active current capacity of the DC cable</td>
</tr>
<tr>
<td>$i^*$</td>
<td>Reference for the q-axis of the converter’s current in pu</td>
</tr>
<tr>
<td>$i_{q,lower}$</td>
<td>Current Limiter’s lower limit</td>
</tr>
<tr>
<td>$i_{q,upper}$</td>
<td>Current Limiter’s upper limit</td>
</tr>
<tr>
<td>$k$</td>
<td>Droop of the DC voltage characteristic</td>
</tr>
<tr>
<td>$K_d$</td>
<td>Derivative coefficient of a PID controller</td>
</tr>
<tr>
<td>$k_i$</td>
<td>Integral gain in pu</td>
</tr>
<tr>
<td>$k_p$</td>
<td>Proportional gain in pu</td>
</tr>
<tr>
<td>$K_{i,p}$</td>
<td>Integral gain of the Active Power PI regulator</td>
</tr>
<tr>
<td>$K_{i,q}$</td>
<td>Integral gain of the Reactive Power PI regulator</td>
</tr>
<tr>
<td>$K_{i,v}$</td>
<td>Integral gain of the AC Voltage PI regulator</td>
</tr>
<tr>
<td>$K_{i,w}$</td>
<td>Integral gain of the DC Voltage PI regulator</td>
</tr>
<tr>
<td>$K_{p,p}$</td>
<td>Proportional gain of the Active Power PI regulator</td>
</tr>
<tr>
<td>$K_{p,q}$</td>
<td>Proportional gain of the Reactive Power PI regulator</td>
</tr>
<tr>
<td>$K_{p,v}$</td>
<td>Proportional gain of the AC Voltage PI regulator</td>
</tr>
<tr>
<td>$K_{p,w}$</td>
<td>Proportional gain of the DC Voltage PI regulator</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of the DC cable</td>
</tr>
<tr>
<td>$L$</td>
<td>Number of cables of the MTDC grid</td>
</tr>
<tr>
<td>$L_{cable}$</td>
<td>Reactance of the DC cable</td>
</tr>
<tr>
<td>$L_T$</td>
<td>Total inductance between the VSC and the PCC</td>
</tr>
<tr>
<td>$m_a$</td>
<td>PWM modulation index</td>
</tr>
<tr>
<td>$n$</td>
<td>Power ratio</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of nodes of the MTDC grid</td>
</tr>
<tr>
<td>$P$</td>
<td>Active power</td>
</tr>
<tr>
<td>$p_{ac}$</td>
<td>Active power at the AC side of the converter in pu</td>
</tr>
<tr>
<td>$p_{ac}^*$</td>
<td>Reference of the Active power at the AC side of the converter in pu</td>
</tr>
<tr>
<td>$P_{AC}$</td>
<td>Active power at the AC side of the converter</td>
</tr>
<tr>
<td>$P_{AC}^*$</td>
<td>Active power reference</td>
</tr>
<tr>
<td>$P_C$</td>
<td>Active Power in the DC capacitor</td>
</tr>
<tr>
<td>$P_{DC}$</td>
<td>Active power at the DC side of the converter</td>
</tr>
<tr>
<td>$P_{lower,1}$</td>
<td>Converter’s inversion limit of the 1-stage PI controller</td>
</tr>
<tr>
<td>$P_{lower,2}$</td>
<td>Converter’s inversion limit of the 2-stage PI controller</td>
</tr>
<tr>
<td>$P_{upper,1}$</td>
<td>Converter’s rectification limit of the 1-stage PI controller</td>
</tr>
<tr>
<td>$P_{upper,2}$</td>
<td>Converter’s rectification limit of the 2-stage PI controller</td>
</tr>
<tr>
<td>$Q$</td>
<td>Reactive power</td>
</tr>
<tr>
<td>$q_{ac}$</td>
<td>Reactive power at the AC side of the converter in pu</td>
</tr>
<tr>
<td>$q_{ac}^*$</td>
<td>Reference of the Reactive power at the AC side of the converter in pu</td>
</tr>
<tr>
<td>$Q_{AC}$</td>
<td>Reactive power at the AC side of the converter</td>
</tr>
<tr>
<td>$Q_{AC}^*$</td>
<td>Reactive power reference</td>
</tr>
<tr>
<td>$\Re$</td>
<td>Real axis</td>
</tr>
<tr>
<td>$R(\theta)$</td>
<td>Rotation transformation matrix</td>
</tr>
<tr>
<td>$R_{cable}$</td>
<td>Resistance of the DC cable</td>
</tr>
<tr>
<td>$R_T$</td>
<td>Total resistance between the VSC and the PCC</td>
</tr>
<tr>
<td>$S_b$</td>
<td>Apparent Power base</td>
</tr>
<tr>
<td>$S_k$</td>
<td>Short-circuit power</td>
</tr>
<tr>
<td>$S_n$</td>
<td>Nominal apparent power</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>$u_{abc}^*$</td>
<td>Converter’s voltage reference in the $(abc)$ frame in pu</td>
</tr>
<tr>
<td>$u_{dq}^*$</td>
<td>Converter’s voltage reference in the $(dq)$ frame in pu</td>
</tr>
<tr>
<td>$</td>
<td>V_{AC}</td>
</tr>
<tr>
<td>$</td>
<td>V_{AC}</td>
</tr>
<tr>
<td>$V_{acb}$</td>
<td>AC voltage base</td>
</tr>
<tr>
<td>$v_c$</td>
<td>AC voltage of the converter in pu</td>
</tr>
<tr>
<td>$V_C$</td>
<td>AC voltage at the AC side of the converter</td>
</tr>
<tr>
<td>$\bar{V}_c$</td>
<td>AC voltage of the converter in pu (phasor)</td>
</tr>
<tr>
<td>$V_{AC}$</td>
<td>AC voltage at the AC side of the converter (phasor)</td>
</tr>
<tr>
<td>$V_{DC}$</td>
<td>DC voltage at the DC side of the converter</td>
</tr>
<tr>
<td>$V_{DC,H}^*$</td>
<td>DC voltage reference of the 2-stage PI controller</td>
</tr>
<tr>
<td>$w^*$</td>
<td>DC energy reference in pu</td>
</tr>
<tr>
<td>$W_b$</td>
<td>DC energy base</td>
</tr>
<tr>
<td>$W_C$</td>
<td>Energy stored in the DC capacitor</td>
</tr>
<tr>
<td>$W_C^*$</td>
<td>DC capacitor’s energy reference</td>
</tr>
<tr>
<td>$\dot{x}$</td>
<td>State vector</td>
</tr>
<tr>
<td>$x^2$</td>
<td>square function</td>
</tr>
<tr>
<td>$x_T$</td>
<td>Total reactance between the VSC and the PCC in pu</td>
</tr>
<tr>
<td>$X_T$</td>
<td>Total reactance between the VSC and the PCC</td>
</tr>
<tr>
<td>$\mathbb{Z}$</td>
<td>Cable impedance</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Motivation

Nowadays, more than ever, there is a serious concern about the environment and the footprint made by all sorts of humankind activities. Europe has set as goals the reduction of its primary energy consumption and greenhouse gas emissions by 20% and to have 20% of its primary energy coming from renewable electricity sources by 2020 [4]. At the same time the need for electric energy is increasing with time, since it is a key component to modern societies and in developing countries is one of the most important tools for promoting welfare and development [21].

In 2010, power plants using gas, coal or fuel oil represented 56% of all Europe’s installed power [22]. However they have two major problems: they are not renewable in the human time scale and are highly pollutant. Moreover, countries are trying to become oil independent and, thus, there is now a strong investment in renewable energies, such as: wind power, solar thermal, solar photovoltaic, biomass, tidal and wave power and biofuels, among others.

One of the most utilized renewable energy sources is wind energy [22]. In Europe, onshore wind energy technology is already a mature technology, since it has been largely installed throughout in the last years. Indeed, the onshore wind energy market has grown in Europe in the past decade at an average pace of 33% [9], while worldwide the growth rate was of around 25%, with the total installed power reaching 159 GW in the end of 2009 [1]. However, suitable places onshore are becoming rare. Therefore, countries are now starting to install wind turbines offshore, where space is more abundant and the wind has higher speeds, since there are no obstacles in the open sea (see Figure 1.3).

When the distance of offshore wind farms to the shore is over 50-80 km, the electricity transmission should be done in direct current (DC), otherwise, a large amount of the energy would be lost in the transport itself [23][24]. Regarding DC transmission systems, there are two possible technologies: LCC-HVDC (HVDC classic) or VSC-HVDC technology.

The VSC-HVDC technology has a higher control capability when compared with the classic alternative, since it can independently control the active and the reactive power exchanged with the connected AC network. Additionally, the footprint of a VSC station is smaller, since the filters needed are smaller - due to the use of PWM techniques - and this is a key factor, since building large structures offshore tends to be expensive. Furthermore, with VSCs there is no need for reactive power compensation and the necessary communication between stations is smaller making this technology more attractive for offshore purposes [25][26].
1.2 Thesis objective and contributions

One of the main purposes of this thesis is to model VSC-HVDC systems for dynamic simulation analysis of multi-terminal direct current (MTDC) networks. In fact, the proposed models are independent of the DC grid configuration, and therefore, they can be used to simulate any multi-terminal system. The model of MTDC networks is also concerned in this thesis.

Another major contribution is the comparison of several DC voltage control methods for VSC-HVDC stations inside MTDC networks. The following methods will be studied: Voltage Droop Method, Priority Control, Ratio Control, and Voltage Margin Method. They will be compared in terms of steady-state and dynamic behavior, expansibility, flexibility, reliability, controllability, and fault handling capability.

In the present work all the equivalent models are implemented in the MATLAB/Simulink software in order to represent, as realistically as possible, the entire MTDC transmission system.

1.3 Publications

The present thesis has resulted in the following publications:


1.4 Thesis layout

This thesis is structured in six chapters. In Chapter 1, an introduction to the current status of the offshore wind energy is made. An overview on the existing wind energy capacity and its distribution in Europe is done. A comparison between transmission systems, HVDC (LCC and VSC) and HVAC, is made. In Chapter 2, a typical VSC-HVDC station is presented and a description about its components is done. Further on, the VSC equivalent model and its controllers are explained in detail. In Chapter 3, the MTDC grid is modeled and its characteristics are described. The different DC voltage control methods implemented are described and explained in Chapter 4. In Chapter 5, simulations are carried out and the results are shown and interpreted. In Chapter 6, conclusions and recommendations for future work are presented.
1.5 State of the Art

In order to build an offshore electrical power transmission system there are three different possibilities available: HVAC, LCC-HVDC and VSC-HVDC. Comparisons between these transmission technologies regarding power efficiency and economical aspects can be found in the literature [6][8][26][27][28]. The cost of submarine transmission systems for the different technologies can be found at [24].

Recent advances in HVDC power transmission systems and a list of projects that make use of the VSC technology can be found at [29]. The VSC multilevel (M2C) is explained in detail at [30], while the study and development of its model is presented at [31].

Different VSC topologies and the description of the components normally present in a VSC transmission system can be found in the literature at [32][33]. The AC and DC models of the VSC are achieved and implemented in [19][34]. The inner current controller and the outer controllers for the VSC technology are described in the previous references of the present paragraph and also at [25][35]. The capability curve of a VSC is explained in detail at [36].

Information about anti-wind up strategies, e.g. back-calculation and conditional integration, is possible to be found at [37][38].

The need for MTDC grids and their applications can be found in the literature at [39]. The use of State-Space Models to derive a model of a VSC and a point-to-point transmission system is presented at [40]. The model of a MTDC grid, also making use of State-Space Model, is achieved at [41].

Several DC voltage control methods have been presented in the literature. The Ratio Control and the Priority Control can be found at [42]. The Priority Control strategy and its behavior when a wind farm is lost is presented at [43]. The Voltage Droop is explained at [44]. The Voltage Margin method with 2 DC voltage stages is presented and explained in detail at [45][46]. A 3-stage VMM and its dynamic response when a onshore station is disconnected from the MTDC grid is described at [34].

Models of DC choppers are presented and described in [34][47]. Fault Ride Through methods are presented in the literature at [48][49]. The study about AC faults and its consequences can be found at [19][33][34].
1.6 Current Status of Offshore Wind Energy

Among the renewable sources exploited by man, one of the most promising for the coming years is offshore wind power [3][50]. In the last decade, the growth of wind energy production and its share in the total electricity production rapidly increased. Figure 1.1 shows the accumulated offshore power installed in Europe up to 2010. In Figure 1.2, it is possible to see the distribution of the operational offshore wind farms in Europe up to 2010.

![Figure 1.1: Offshore wind power installed in Europe up to 2010 [9].](image1)

The predictions for the offshore wind energy are that 150 GW of offshore wind power will be in operation, by 2030, from more than 100 installed offshore wind farms only in the North Sea [4][50]. Hence, to meet the predictions, an enormous amount of wind turbines will have to be installed every year for the next coming years. Figure 1.4 depicts not only the offshore wind farms already in operation but also those which are under construction, approved or planned to be build in the future in the North Sea. A list with all the wind parks in operation, approved and in approval process in the North Sea and in the Baltic Sea can be found in the European Wind Energy Association report Oceans of Opportunity [9].

![Figure 1.2: Map of operational offshore wind farms in Europe up to 2010 [10].](image2)

Since the Baltic and North Sea have a very good wind resource over open sea (see Figure 1.3), most of the offshore energy in Europe is planned to be installed there. Therefore, integration aspects of this offshore power to the different national electricity grids constitute a very important challenge since no project with the possible dimensions and impact of the transnational grid has previously been carried out.

Consequently, the North Sea Transnational Grid project (NSTG) was created with the objective to
identify and study the technical and economic aspects with regard to the development of a transnational electricity network in the North Sea for the connection of offshore wind power and trade between European countries [4].

1.7 Offshore Transmission technologies

One of the challenges is to find the most suitable technology to connect the offshore wind farms to shore, having different power ratings and different distances from the onshore connection point. This selection should be done by taking into consideration power efficiency and economical aspects. In order to build an offshore electrical power transmission system there are three different possibilities available: HVAC, LCC-HVDC and VSC-HVDC. In this section these three technologies are going to be present, explained and compared.

1.7.1 HVAC

Most of the existing offshore transmission systems use HVAC for the transport of electrical power between mainland and stations located offshore. The reasons for choosing this technology are: lower station costs, no power converters needed, and a simpler layout for the offshore wind farm is possible. HVAC systems contain the following main components: an AC collecting system in the platform, an offshore transforming substation with transformers and reactive power compensation, three-phase submarine cable (generally XLPE three-core cable) and an onshore transforming substation with transformers and reactive power compensation.

Depending on the distance to the connection point and on the power that has to be transmitted, there are different solutions that can be engaged. For a shorter distance and smaller power a direct connection
over middle voltage can be used and therefore, collecting transformer and high voltage transmission can be avoided. For a higher power or a longer distance the use of high voltage for transmission and collecting transformers is inevitable. When the voltage of the transmission cable and the grid voltage are equal the onshore transformer is not necessary.

Due to their construction, distributed capacitance in submarine cables is much higher than in overhead lines. This implies that the maximum feasible length and power transmission capacity of HVAC cables is limited. The reactive power that is inherently generated in HVAC cables increases with both the square of the voltage level and the cable length. Thus, for distant transmission distances and high voltage levels, reactive power compensation will be required at both cable ends.

### 1.7.2 LCC-HVDC

Classical HVDC transmission systems are based on current source converters (CSC) with naturally commutated thyristors, also known as line-commutated converters (LCC) since the applied thyristors need an AC voltage source in order to commutate and, thus, only can transfer power between two active AC networks. Therefore, an auxiliary start-up system would be necessary in the offshore wind farm. Due to line-commutation, this converter operates with line switching frequency (50 or 60 Hz) and the power losses are around 1-2% at full power [24].

The first ever built LCC-HVDC system, which included a submarine cable, was built, in 1954, between the island of Gotland and Sweden mainland with a 100 kV submarine cable and with a transmission system of 96 km [14]. The application of LCC-HVDC submarine transmission has only been used for connection of high voltage grids and there is no single converter station located in the sea. For shorter distances and smaller power, LCC-HVDC is too expensive because of the high costs of the converter stations.

A LCC-HVDC system usually has the following main components at each end of the transmission line: transformers, converter based on thyristors, AC and DC filters, DC current filtering reactance, a capacitor bank or a STATCOM for reactive power compensation, and a DC cable.

Based on the overall system economics, the LCC-HVDC technology becomes only interesting for transmission capacities above approximately 600 MW [14], as shown in Figure 1.6.

### 1.7.3 VSC-HVDC

The VSC-based HVDC technology makes use of insulated gate bipolar transistors (IGBT) and pulse width modulation (PWM). High power IGBT development allows the use of VSC technology in HVDC systems in the frequency range of 1-2 kHz [8]. Higher frequencies would reduce the filter size but the switching power losses would be excessive. Multilevel converters are very well suited in this application due to their high voltage capacity and lower harmonic content. Nowadays, two manufacturers, ABB and Siemens, have commercially available VSC-HVDC systems. ABB uses the trade mark HVDC Light [51], while the system from Siemens is called HVDC Plus [13]. These commercial systems are available with power ratings between 50 and 1.100 MW and with voltages up to ±320 kV and their real layout is shown in the Figure 1.5.

The first VSC-HVDC system was installed in Hellsjön by ABB, in 1997. The system had a power rating of 3 MW and 10 kV voltage and was built with the goal of studying the viability of the technology [24]. During the last ten years several systems have been built, including some that make use of submarine transmission cables.
A VSC-HVDC system has the following main components: AC breakers, AC filters, a transformer, a phase reactor, a voltage source converter, a DC capacitor, and a DC cable to connect it to another station or grid.

1.8 Comparison of transmission systems: HVAC vs HVDC

HVAC systems are widely used and have lower costs than the HVDC technology in underground or submarine short-transmission distances (distances up to 50-80 km, although this distance may be reduced soon). A major drawback of HVAC systems is the limited transmission distance. On the other hand, HVDC technology have no practical transmission distance limitation and needs less cabling than equivalent HVAC, generating a considerable cable and installation cost reduction, and the maintenance, environmental impact and fault rate are also reduced. HVDC technology (either LCC or VSC) has many technical advantages when compared to HVAC technology which can be very important if the contribution of offshore power generation is expected to be a major player in the electrical energy generation and the grid stability. These advantages are [26][52]:

- The losses in a DC cable are lower than in an AC cable for long distances;
- Asynchronous connections of the offshore farms and the onshore grids are only possible with HVDC technology. The frequency and phase of both transmitting ends do not have to be synchronized because the DC link decouples them. Grid voltage dips and other faults do not have a direct effect in the generators of the offshore farm, and therefore, there is a higher flexibility in the design of these units;
- HVDC technology allows almost instantaneous control over the transmitted power and the system can contribute to the frequency control of the grid;
- The VSC-HVDC technology can control active and reactive power independently. Thus, it is possible to control both AC and DC voltages of the converter. This feature is very helpful if the connected grid is weak;
- Unlike HVAC, the HVDC technology does not increase the short-circuit level of the connected AC system.
1.9 Comparison of DC transmission systems: LCC- vs VSC-HVDC

The main difference between LCC-HVDC and VSC-HVDC is the higher controllability of the latter, due to its self-commutating capability and the use of PWM techniques. Some more important differences are listed below [8][24]:

- VSC-HVDC systems are able to start a collapsed grid from the DC voltage bus (black start capability). LCC-HVDC technology requires an operating grid at both ends of the DC line;
- Power losses in the LCC technology are lower (1 − 2%) than VSC systems (2 − 3%);
- The HVDC classic is line commutated (50 or 60 Hz), while VSC-HVDC systems have switching frequencies of 1-2 kHz. Therefore, the necessary filter size is reduced;
- LCC-HVDC converters demand reactive power according to the thyristors’ firing angle. The use of capacitors banks or STATCOMs to supply reactive power compensation is necessary. VSC-HVDC systems can control the active and reactive power at both ends (4-quadrant power control) and it can help to control the grid’s voltage and enhance power quality;
- The VSC converters are suitable for creating DC grids with several nodes since little coordination is needed between them;
- LCC technology handles better DC side faults due to control characteristics. The VSCs have no way of limiting DC fault currents (due to free-wheeling diodes) and therefore DC breakers could be necessary for multi-terminal purposes;
- The power ratings for the LCC technology are still much higher than those for VSC, making the first one the current choice for bulk transmission;
- The LCC-HVDC requires large onshore and offshore converter stations, and auxiliary service at the offshore converter station for the operation of the line-commutated converters during wind still periods and power failures.

Looking at the overall system economics, submarine-VSC-based HVDC transmission systems are most competitive at transmission distances over 100 km or power levels of between 200 to 900 MW, as shown in Figure 1.6.

From Figure 1.7 it is possible to see that the initial cost, for the construction of the terminal itself, is much higher with DC technology. On the other hand, the losses on the AC transmission cables are superior leading to a higher variable cost. HVAC technology is the most economic alternative when transmission distances are low and, thus, the losses in the cables are within affordable limits. According to previous assertions [53], HVAC systems are estimated to be cost effective for submarine or underground transmission distances up to 50-80 km.

Another factor is the evolution in component cost. The cost of HVAC equipment is not expected to be reduced. On the other hand, the cost of semiconductors (the main cost in HVDC stations) has a tendency to be reduced with time [54]. Therefore, it is expected the break-even point to decrease, making the HVDC technology also attractive for shorter transmission distances.
1.10 Transmission cables

In AC systems the cable must carry not only the load current but also the reactive current claimed by the cable’s capacitance. Hence, the active power rating of the cable is reduced. The capacitive current, $I_{cap}$, is obtained as:

$$I_{cap} = 2\pi fCIV$$

(1.1)

where $f$ is the frequency of the system, $C$ the capacitance per km, $V$ the cable voltage and $I$ is the cable length in km.

The active current capacity of the cable, $I_P$, is given by:

$$I_P = \sqrt{I_N^2 - I_{cap}^2}$$

(1.2)

where $I_N$ is the cable’s nominal current. Although for short-transmission distances the capacitive current is not high, when distances longer than 50-80 km are considered, the capacitive current may become equal to the cable rated current. The effective transmission distance of HVAC submarine or underground cables is lower than overhead lines because the capacitance and circulating reactive currents are higher [24].

In HVAC systems, reactive compensators can be placed at both ends of the cable offshore and onshore in order to reduce the produced capacitive currents, and this way lower losses can be obtained. On the other hand, the reactive compensator would increase the total transmission costs. In HVDC applications, in steady state, there is no capacitive current.

In Table 1.1 a comparison between AC and DC submarine transmission cables is shown [51][55]. In the table it is possible to observe that, for the 400 kV AC cable with a cross-section of 1200 mm$^2$, at a distance of 50 km, the produced reactive power would be of 452 MVar, leaving 798 MW (86.98%) of active power left to be transmitted at full-load current. If the distance increases to 100 km, the produced reactive power would increase to 905 MVar, leaving in that case only 149 MW (16.27%) left available for transmission of active power.

With the increase of the voltage the cable rated power also increases but on the other hand, the cable reactive power generation grows with the square of the voltage, since:
Table 1.1: AC and DC submarine cable parameters.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>$AC\ 220\text{kV}$</th>
<th>$AC\ 400\text{kV}$</th>
<th>$DC\ \pm 150\text{kV}$</th>
<th>$DC\ \pm 320\text{kV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section [mm$^2$]</td>
<td>1000</td>
<td>1200</td>
<td>2800</td>
<td>2800</td>
</tr>
<tr>
<td>Rated Power [MW]</td>
<td>400</td>
<td>915</td>
<td>575</td>
<td>1225</td>
</tr>
<tr>
<td>Capacitance per phase [µF/km]</td>
<td>0.18</td>
<td>0.18</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Reactive Power [pu] @50 km</td>
<td>34.04%</td>
<td>49.33%</td>
<td>N/D</td>
<td>N/D</td>
</tr>
<tr>
<td>Reactive Power [pu] @100 km</td>
<td>68.08%</td>
<td>98.67%</td>
<td>N/D</td>
<td>N/D</td>
</tr>
<tr>
<td>Active Power [pu] @50 km</td>
<td>94.03%</td>
<td>86.98%</td>
<td>96.18%</td>
<td>96.44%</td>
</tr>
<tr>
<td>Active Power [pu] @100 km</td>
<td>73.24%</td>
<td>16.27%</td>
<td>95.75%</td>
<td>96.22%</td>
</tr>
</tbody>
</table>

*N/A - Data not available; N/D - Field not defined.

\[ Q = 3VI_C \Rightarrow Q = 6\pi fCIV^2 \quad (1.3) \]

From Figure 1.8, it is possible to conclude that with the state-of-the-art technology, and without providing reactive power compensation, for offshore wind farms with power ratings above 400 MW and for transmission distances higher than circa 50 km, AC transmission starts to be less competitive than HVDC for the connection of offshore wind farms.

Future offshore wind farms will be built further away from the shore and will have higher rated power. Therefore, HVDC transmission will become the most attractive technology even though it presents a higher capital expenditure cost for its implementation [21].

![Figure 1.8: Comparison between AC and DC submarine transmission cables.](image)

It is important to refer that the maximum transmittable power of the DC systems at zero distance is not 1 pu, since the losses in the converters are taken into consideration. Without the converters it would be impossible to transfer DC power. Thus they have to be considered for the overall losses of the transmission system.

Losses in submarine cables are generated due to the following reasons [24]:

- Dielectric losses.
- Losses in the core. These are the most significant losses in submarine cables.
- Losses in the metallic sheath, generated by induction of the main core current. This loss can be up to one third of the core losses.
• losses in the steel armature, also generated by induction of the main core current. This loss can be up to one third of the core losses as well.

1.11 Wind Energy in Portugal

Portugal in terms of electricity’s percentage that comes from wind farms is, nowadays, only surpassed by Denmark. The electricity that comes from this energy source is 14.8% of all the electricity consumed. At the end of 2010, there were about 4 GW of onshore wind energy capacity installed in Portugal - all onshore. By 2020, Portugal aims to have around 7 GW of wind energy capacity, providing 23% of all the electricity needed.

The power grid is a limiting factor for many countries, but is a particularly problem for Portugal given its position on the periphery of Europe. The Iberian Peninsula is notoriously poorly linked to the rest of Europe. This means that nearly all the power produced in Portugal stays there.

Portugal has plenty of onshore wind energy installed but none offshore. The major reason for this are the geographical characteristics of the Atlantic Ocean which, unlike Europe’s northern waters, becomes deep extremely quickly. This makes it difficult to put up today’s standard offshore wind turbines, whose foundations rest on the seabed. Another difficulty is that, on average, the wave height on the Atlantic ocean is twice that of the North Sea [56].

However, progress has been made in offshore wind turbines. As it can be seen in Figure 1.9 there is already the possibility to install wind turbines in deep places. Through a project called Windfloat, started in 2009, EDP and other partners – including Vestas – hope to find a solution to the problem by building a new type of floating platform. Windfloat is based on designs from the oil industry: it is a triangle, with the wind turbine fitted onto one of the corners (fourth turbine in Figure 1.9). The platform is semisubmersible, with water inside the platform as a ballast to weigh it down and provide stability.

One wind turbine was placed at 6 km offshore from Aguçadoura, in the north of Portugal. The project partners will then carry out tests on the system for no less than 12 months. The Windfloat platform could be commercially available between 2015 and 2020 and will be suitable for water depths greater than 50 meters [57].

In this same local, in 2008, the world’s first wave farm was installed. It was located 5 km from the shore and it had 3 Pelami machines (Figure 1.10), with a maximum power of 2.25 MW, that convert the kinetic wave’s energy into electric energy. However, the machines were brought to the shore after a few months due to technical problems.

After 40 meters offshore the seabed’s slope is low (see Figure 1.11) and this way it is possible to install
500 MW of offshore wind power in the north of Portugal and 700 MW more in the center [17]. The productivity could reach 3400 hours per year as it can be seen in Figure 1.12.

Figure 1.10: Wave farm installed at Aguçadoura [16].

In Figure 1.13 it is shown a possible MTDC grid installation for the Portuguese shore. With this grid it would be possible to connect all the Portuguese offshore wind farms and also the wave farms, if available.

Figure 1.11: Portuguese offshore seabed’s slope.

Figure 1.12: Portuguese offshore potential [17].

Figure 1.13: Possible MTDC grid in the Portuguese shore.
Chapter 2

VSC-HVDC Equivalent Model and Controllers

2.1 Introduction

The main objective of the present chapter is to achieve an equivalent model of a VSC-HVDC station and its control system. Firstly, the components of a typical VSC-HVDC transmission system are presented and described. Further on, the equivalent models of the AC and DC sides of the VSC station are derived. In the last part of the chapter the entire control system is presented and explained.

2.2 VSC-HVDC Transmission System

A typical VSC transmission system consists of: AC breakers, AC filters, a transformer, a phase reactor, a voltage source converter, a DC capacitor, a DC chopper with a dump resistor, and a DC cable to connect it to another station or grid. The layout of a typical VSC-HVDC transmission system is shown in Figure 2.1 and its components are described in detail below.

![Figure 2.1: Typical layout of a VSC-HVDC transmission system.](image-url)
2.2.1 AC Breakers

The presence of an AC circuit breaker (located in the AC switchyard) is needed in a VSC-HVDC station due to several reasons [32]:

- to have the ability of disconnecting the station from the AC system for maintenance;
- to connect the AC system to the VSC link when the DC capacitor needs to be charged at the start-up of the VSC-HVDC transmission system;
- to disconnect the VSC link from the AC system during DC-side fault, since differently from the HVDC classic (LCC-HVDC), the 2- or 3-level VSC transmission system has no mechanism to clear DC-side faults.

2.2.2 AC Filters

The presence of harmonics in the VSC-HVDC system may be very prejudicial to the transmission system and to the connected AC network. Some phenomena that may occur due to the presence of harmonics are:

- Higher losses and overheating in the system;
- Over-voltages, due to the existence of resonance;
- Interference, inaccuracy or instability in the control systems;
- Noise on voice-frequency telephone lines and radio.

Because of all the phenomena above, the presence of AC filters is important. Nevertheless, PWM operation reduces significantly the harmonic content. Therefore, AC filters in a VSC link will be smaller and cheaper than in HVDC classic.

The AC filter acts as a high-pass filter, tuned so that the high-frequency signals are given an easier path to earth (lower resistance). The filter is installed between the transformer and the converter and it prevents harmonics from entering the AC system, and filters high-frequency components so that the transformer is not exposed to high-frequency stress. Additionally, sinusoidal currents and voltages can be obtained at the secondary side of the transformer due to the presence of the AC filters.

The design of the filter is, in most of the cases, made for the AC grid that is going to be connect to the VSC station. For this reason it is necessary to know the AC network impedance seen from the connection point. However, this information is difficult to be obtained and usually project related [33][58].

2.2.3 Transformer

The converters are connected to the AC system, in most cases, via transformers. The most important function of the transformers is to change the voltage of the AC network to a voltage level that is appropriate for the converter. The transformer also acts as a galvanic barrier between AC and DC sides. This is important since some faults in the AC system give overvoltages in the healthy phases. Furthermore, the reactance of the transformer will reduce short circuit currents.

Standard two-winding transformers can be used since for VSC-HVDC applications since there is no need to block DC components. The transformer can be represented by a combination of a π equivalent and an ideal transformer. Alternatively, it can be represented simply by its leakage reactance.
### 2.2.4 Phase Reactor

The phase reactor is one of the most important elements installed on the AC side of the VSC station. The phase reactor has several purposes: it reduces the high-frequency harmonic content of the AC current (it acts as a low-pass filter), prevents changes in the current polarity in the IGBT valves (due to switching). Additionally, it allows to control active and reactive power independently by adjusting the current that flows through it and it also limits the short-circuit currents. Usually the chosen value to the phase reactor impedance is kept between 0.10-0.25 pu and is selected as a compromise between harmonic attenuation and voltage droop on the reactance [51].

### 2.2.5 Voltage Source Converter

Voltage source converters employ self-commutating switches, e.g., gate turn off thyristors (GTOs) or IGBTs, which can be turned on or off freely. Therefore, a VSC can produce its own sinusoidal voltage waveform using PWM technology independent of the interconnected AC system.

The 2-level bridge is the simplest topology (see Figure 2.2) that can be used in order to build up a three-phase forced-commutated VSC bridge. The bridge consists of six valves and each valve consists of a self-commutating switch device and an anti-parallel diode.

![Figure 2.2: Conventional 2-level VSC three-phase topology.](image)

The operation principle of the 2-level bridge is simple. Each phase of the VSC can be connected either to the positive or the negative DC terminal. By adjusting the width of the pulses, the reference voltage can be reproduced, as shown in Figure 2.4 (a). AC filters are mandatory for reducing the harmonic content due to the switching operation of the IGBTs in order to prevent disturbances in the AC system.

 Almost all the VSC-HVDC transmission systems implemented so far employ 2- or 3-level (Figure 2.4 (b)) PWM converters. However, some years ago, an alternative VSC-HVDC, commonly referred to as Modular Multilevel Converter (M2C), was suggested [31]. This solution is based on series-connection of sub-modules containing a semiconductor half-bridge and a DC capacitor (see Figure 2.3). Siemens was the first company to win an order of an HVDC link using M2C technology. The Trans Bay HVDC Link in the San Francisco area entered into operation in 2010. The HVDC link is rated at ±200 kV and the rated power is 400 MW [59].

Each arm of the VSC is composed of a series-connection of sub-modules. The function of the half-bridge is to insert or bypass the sub-module capacitor in the chain of series-connected sub-modules. The control system keeps the average of the sum of the number of inserted sub-modules in the upper and the lower arm at a constant level in order to balance the applied DC voltage. The AC voltage is obtained by changing the number of inserted sub-modules in the upper and the lower arms.
In the M2C technology, contrary to the switching operations in the 2-level converter, each step in the output waveform results from switching only of one sub-module in each arm. Therefore, the average switching frequency per device is highly reduced, being around 150 Hz, when compared to the one of the 2-level converter (up to 2 kHz). Moreover, the harmonic content of the produced waveform is low, thus small filters are necessary.

The number of semiconductors in a M2C is higher than in a 2-level converter. However, the total silicon area does not differ significantly [30]. Due to the reduced switching frequency the total loss per converter is approximately 1.0% at full load. The stress of the inductors in a M2C circuit is much smaller than in the 2-level converter due to the smaller step-heights Figure 2.4 (c)).

The most important control problem in the M2C is to make sure that the capacitor voltages in all the sub-modules are strictly controlled in order to avoid overvoltages.

Figure 2.4: PWM for different converter topologies. (a): two-level converter. (b): three-level converter. (c): M2C with five modules [19].
2.2.6 DC Capacitor

The DC capacitor is one of the most important elements in a VSC transmission system and usually is placed inside the converter station. The DC capacitor acts as a DC voltage source since it helps to keep the DC voltage constant within close limits. By increasing the DC capacitor’s size the transient response is enhanced, and the DC voltage stiffness and control bandwidth are increased. However, it is expensive to augment the size of the capacitor.

The design of the DC capacitor has to be carefully carried out due to its importance in a HVDC system. Because of the PWM switching action in the VSC-HVDC, the current flowing to the DC side of the converter contains harmonics which will result in a ripple on the DC side voltage. Since large power imbalances may occur during disturbances between the AC and DC side, such as faults or switching maneuvers while changing the operating point, the size of the capacitor cannot be only determined by steady-state operation because that would lead to DC over-voltages that may stress or damage the converter’s valves. So it is extremely important to take into consideration the transient voltage constrain when the DC capacitor is to be chosen [32].

A time constant, $\tau$, characterizes the DC capacitor and it is defined as the ratio between the energy stored in the capacitor when the nominal DC voltage, $V_{DC}$, is applied to the converter at nominal apparent power ($S_n$):

$$\tau = \frac{1}{2} C V_{DC}^2 \frac{1}{S_n} [s]$$  \hspace{1cm} (2.1)

The time constant, $\tau$, defines the time that is necessary to completely charge the DC capacitor (starting with from zero DC voltage) at nominal power.

2.2.7 DC Cable

The cable used in the VSC-HVDC applications can be designed to use extruded polymeric insulation, which is particularly resistant to the DC voltage, as a substitute to the conventional oil-impregnated paper insulation.

AC XLPE cables cannot be directly used for DC transmission due to a phenomenon called space charges. The DC voltage creates an electric field, which would cause space charges to move and accumulate in certain spots of the insulation, resulting in its degradation. Special XLPE cables have been developed in order to prevent space charge problems to happen. A precondition for such cables is that the voltage polarity does not change rapidly, as this causes high stresses in the insulation. Since in the VSC-HVDC power flow reversal does not require the inversion of the DC voltage polarity, XLPE cables can be used. This results in lighter and more flexible cables with no risk of oil leakage, since the insulator is solid, and the installation of these cables is easier and faster. A special type of XLPE cables are submarine cables, which face harsh environmental conditions and because of that they are armored with galvanized steel wire for mechanical sturdiness [58].

All VSC-HVDC systems in operation are equipped with XLPE cables. Cables with voltages up to $\pm 320$ kV DC are presently available [51].

The risk of a DC fault is reduced when using cables. This is an important aspect since no DC breakers are present in VSC-HVDC systems as previously explained. The conductors for HVDC transmission system can be modeled by a $\pi$ circuit, which is sufficiently accurate for short to middle-long distances.
2.2.8 DC Chopper

The DC chopper consists of voltage-triggered power electronic switches and resistors. When the DC voltage rises above a predefined threshold value, the power electronic components start switching and part of the DC current is dissipated in the resistors. The amount of current dissipated depends on the duty ratio of the switches and therefore, it depends on the value of the DC voltage. The amount of power dissipated is, however, limited to the rated capacity of the DC chopper [47].

During an onshore fault, the onshore stations are unable to deliver active power to the onshore grid, which causes the DC voltage to increase due to the power imbalance. Therefore, the active power being transmitted from the offshore wind farms has to be reduced. The DC chopper requires a simple control and can be triggered directly by using a hysteresis function based on the DC voltage. The main advantage of this technique is that the wind farms stay unaffected by the fault i.e., the output power of the wind farms remain constant during the fault. Moreover, there is no impact on the mechanical drive train and thus, the wind farms do not speed up during the fault [49].

2.3 Voltage Source Converter’s equivalent model

2.3.1 Equivalent model of the VSC AC side

It is possible to consider the AC side of a VSC-HVDC station as a controllable voltage source since a converter using PWM techniques is able to control independently the frequency, the phase and the amplitude of its AC voltage. This voltage source can be described as:

\[ V_C(t) = \sqrt{2} \cdot V_C \cdot \sin(\omega t + \delta) + \text{harmonics} \quad \text{with} \quad V_C = m_a \cdot \frac{V_{DC}}{2} \quad (2.2) \]

where \( m_a \) stands for the PWM modulation index, \( \omega \) is the angular frequency of the voltage fundamental component, and \( \delta \) is the phase angle difference between the AC network and the converter fundamental voltage [60].

In a VSC-HVDC station, as discussed in section 2.2, a phase reactor, AC filters and a transformer are usually present. Thus, it is possible to disregard the switching harmonics, and assume that the voltage of the converter is equal to the modulator (PWM) reference voltage, as long as the modulator reference voltage does not exceed the linear region [61].

The equivalent diagram of a VSC link connected to an AC system is shown in Figure 2.5. As shown in the figure, the AC system and the controllable voltage source are connected via series reactors \( X_T \), since the transformer and the phase reactor resistances can be neglected when compared to the sum of the inductive reactances. The AC voltages represented in Figure 2.5 are line voltages: \( E_S = E_{ST \omega} \) and \( V_C = V_{Ce}^\delta \).

If the transformer and reactor resistances are disregarded (i.e. lossless), the active power flow between the AC network and the VSC can be formulated, in pu, as [29][51]:

\[ p_{ac} = \frac{e_s V_C}{x_T} \sin(\delta) \quad (2.3) \]

From the above equation it is possible to realize that the control of the active power flow is accomplished by changing the VSC voltage output phase angle, \( \delta \), while maintaining all the other variables unchanged.
This is achieved through PWM technique by controlling the switching instant of the converter’s valves.

\[
\begin{align*}
\delta < 0 & \implies \bar{v}_c \text{ lagging } \bar{v}_s \implies p_{ac} < 0 \text{ (Inversion)} \\
\delta > 0 & \implies \bar{v}_c \text{ leading } \bar{v}_s \implies p_{ac} > 0 \text{ (Rectification)}
\end{align*}
\]

(2.4)

If the voltages of the AC network of the VSC are in phase, i.e. \( \delta = 0 \), there will be no transfer of active power (disregarding losses) and the VSC will operate as a reactive power compensator, absorbing or providing reactive power as needed. Under such cases the VSC operates as a STATCOM [5].

The reactive power flow between the AC network and the VSC station can be calculated as [29][51]:

\[ q_{ac} = \frac{e_s}{X_T} (e_s - v_c \cos(\delta)) \]  

(2.5)

From the equation (2.5) it is possible to observe that if the real component of the VSC output voltage \( (v_c \cos(\delta)) \) has a smaller magnitude than the voltage of the AC system, the converter will consume reactive power from the AC network. Otherwise the converter will provide reactive power to the network.

\[
\begin{align*}
v_c \cos(\delta) > e_s & \implies q_{ac} < 0 \text{ (Production)} \\
v_c \cos(\delta) < e_s & \implies q_{ac} > 0 \text{ (Absorption)}
\end{align*}
\]

(2.6)

The amplitude of the VSC output voltage is controlled by the modulation ratio, \( m_a \), as shown in equation (2.2).

By varying \( \delta \), the influence on the active power is substantial, but its account on the reactive power is negligible, since \( \delta \) is rather small \( (\delta \approx 0) \). On the other hand, the magnitude of the converter voltage when compared to the voltage of the AC network has a large influence on the reactive power but negligible effects on the active power. Therefore, active and reactive power controls can be achieved practically independent of each other.

Figure 2.6 shows the phasor diagram for the AC side of a VSC-HVDC station.

**VSC Capability Chart**

Due to the fact that active and reactive power controls are independent, the VSC is able to operate, theoretically, at any point of the \( (P,Q) \) diagram. The \( (P,Q) \) characteristic will be a circle, due to the possibility of operation in all four quadrants. However, the operation range of a VSC-HVDC system
Figure 2.6: Phasor diagram of a VSC station providing active and reactive power to its AC network.

will in practice be limited by two factors: the current flowing through the converter’s valves and the DC voltage value [36].

The first limitation is that the current flowing through the converter needs to be limited to protect the switching valves. Therefore, the VSC will be able to operate within its rated current, which corresponds to a circle with radius of 1 pu.

Another limitation which determines the reactive power capability of the VSC is the voltage magnitude of the VSC (modulation index limitation). The over-voltage limitation is imposed by the DC voltage level. As shown in equation (2.5), the reactive power depends on the difference between the AC network voltage and the VSC output voltage, which depends on the DC voltage as it can be seen in equation (2.2).

Rearranging the active and reactive power equations in equations (2.3) and (2.5), respectively, and eliminating \( \cos(\delta) \) and \( \sin(\delta) \), yields:

\[
\sin^2(\delta) + \cos^2(\delta) = 1 = \left( \frac{P_{ac}x_T}{e_s v_c} \right)^2 + \left[ \left( \frac{q_{ac} + \frac{e_s^2}{x_T}}{e_s v_c} \right) \frac{x_T}{e_s v_c} \right]^2
\]  
(2.7)

After rearranging, an equation of a circle in the (P,Q) diagram with its center in \( \left( 0, -\frac{e_s^2}{x_T} \right) \) and radius of \( \frac{e_s v_c}{x_T} \) is obtained:

\[
\left( \frac{e_s v_c}{x_T} \right)^2 = p_{ac}^2 + \left( q_{ac} + \frac{e_s^2}{x_T} \right)^2
\]  
(2.8)

The under-voltage limit, however, is limited by the main circuit design and the active power transfer capability, which requires a minimum voltage magnitude to be transmitted [19].

In Figure 2.7 the limits explained above are depicted.

The capability chart differs in steady state and dynamic operation since all the parameters that constrain the (P,Q) diagram change during the VSC operation.

It is possible to create an analogy between capability charts for synchronous generators and VSCs. The maximum current that flows through the converter valves corresponds to the maximum armature current, the converter voltage limit corresponds to the maximum field current and, finally the maximum power through the DC cable represents the maximum turbine output. Therefore, the capability charts of synchronous generators and VSCs are very similar [58].
Figure 2.7: Real (P,Q) diagram of a VSC-HVDC station
2.3.2 Equivalent model of the VSC DC side

The DC side of the converter is modeled as a controllable DC current source. The DC current can be calculated based on the power balance between the AC and DC sides of the converter (disregarding converter losses):

\[ P_{AC} = P_{DC} = V_{DC} \cdot I_{DC} \Rightarrow I_{DC} = \frac{P_{DC}}{V_{DC}} \]  

(2.9)

If conversion losses are to be considered, the efficiency of the converter station needs to be present at equation (2.9). With PWM and multi-level technology for the VSC-HVDC, the efficiency of each station is around 98%, this meaning that there are circa 2% losses per station at full power. However, losses are not linear and obtaining the value of the efficiency with different operating points is not straight-forward [62].

The equivalent circuit for AC and DC sides of a VSC-HVDC station is presented in the Figure 2.8.

![Figure 2.8: Equivalent circuit for AC and DC sides of a VSC-HVDC station.](image)

2.4 The control system of the VSC-HVDC

The objective of the VSC control is to set all the controllable parameters of equation (2.2), i.e. the PWM modulation index, \( m_a \), the angular frequency, \( \omega \), and the phase angle, \( \delta \). The VSC-HVDC using PWM technique can control the active and reactive power independently through two independent channels.

The reactive power can be controlled by the required AC voltage or set manually. In the manual control mode, the converter PWM modulation index is controlled directly to make the converter absorb or generate the desired amount of reactive power. If the reactive power exchange is to be used for AC voltage control, the measured AC network voltage is compared to a given AC voltage reference and a signal will be provided to the reactive power controller. If the AC voltage is to be lifted up, the converter will increase its AC voltage by increasing the modulation index, sending reactive power to the AC network. On the other hand, if the AC voltage is to be lowered, the converter will lower its AC voltage and absorb reactive power from the AC grid.

The active power flow can be used to control the DC voltage (or the energy stored in the DC capacitor), the variation of the frequency at the AC side or set manually. In order to achieve manual control of the active power it is necessary to set the phase angle, \( \delta \). The active power flowing through the link must be always balanced, i.e. the active power in the VSC-HVDC transmission system must be equal to the active power delivered by the system plus the system’s losses. The task of balancing the active power flow is achieved by controlling the DC voltage, since any active power flow unbalance would cause the DC voltage of the VSC-HVDC station to rapidly change. Therefore, in a VSC-HVDC multi-terminal transmission
system it is necessary that at least one station operates in DC voltage control mode, regulating the amount of active power needed to charge or discharge the DC capacitor in order to sustain the required DC voltage level. This way, the DC voltage controller will guarantee active power balance at all instants.

The frequency control is possible when the VSC is connected to weak networks or passive loads, i.e. the VSC is the main source of power. The frequency control in such case is obtained by varying the frequency of the valve pulse firing sequence.

Another important control in the VSC-HVDC is the AC current control. The VSC-HVDC control system has an inner current control (ICC) that will receive the references of the currents from the outer controllers and will generate the voltages’ references and provide them to the PWM control of the VSC. Figure 2.9 shows the control structure for the VSC-HVDC station.

2.4.1 Inner Current Controller

In the VSC-HVDC control system there is an inner current control that evaluates the necessary voltage drop over the series reactance \( X_T \) to produce the required AC current without exceeding the converter maximum current \([51]\).

Usually in the inner current controller, the converter currents and the AC three-phase voltages are transformed to the rotating direct-quadrature (\(dq\)) coordinate system, which will be synchronized with the AC network voltage through a phase-locked loop (PLL). The control system will determinate the converter voltage reference in the (\(dq\)) axis and this signal will be transformed to the three-phase (\(abc\)) coordinate system before being provided to the converter’s PWM control.

Figure 2.9: VSC-HVDC Control Scheme.
For the VSC-HVDC equivalent circuit represented in the Figure 2.5 it is possible to write (considering the phase reactor and transformer losses):

\[ e_s - v_c = R_T \cdot i_c + L_T \cdot \frac{d}{dt} (i_c) \]  

(2.10)

The above equation can be rewritten in the \((dq)\) reference frame by performing the Park Transformation (see Appendix A):

\[
\begin{align*}
    e_d - v_d &= R_T \cdot i_d + L_T \cdot \frac{d}{dt} (i_d) - \omega L_T \cdot i_q \\
    e_q - v_q &= R_T \cdot i_q + L_T \cdot \frac{d}{dt} (i_q) + \omega L_T \cdot i_d
\end{align*}
\]

(2.11)

where \(R_T\) and \(L_T\) represent, respectively, the total resistance and inductance between the converter and the point of common coupling (PCC) with the AC network.

The VSC equations, after application of the Laplace transformation, can be represented by the left block diagram depicted in Figure 2.10. The Inner Current Controller is shown on the right side of the Figure 2.10.

![Figure 2.10: Block diagrams of the phase reactor and the ICC.](image)

### 2.4.2 Outer Controllers

The outer controllers are responsible for generating and providing the reference currents \((i_d^*\) and \(i_q^*)\) to the inner current controller. These controllers can be categorized in two distinguished groups: active power channel and reactive power channel.

In this thesis for each group there will be two different controllers: for the active power channel the active power and DC voltage controllers will be applied and they will provide the current reference for the \(q\)-axis. For the reactive power channel, the reactive power and AC voltage controllers will be implemented and these will be ones responsible of generating the current reference of the \(d\)-axis. In every controller a proportional-integral (PI) regulator is employed to annul steady state errors. An anti-windup method was implemented in the PI regulators (see Appendix B).
Active and Reactive Power Outer Controllers

The active and reactive powers at the PCC in the \((abc)\) frame can be calculated as [63]:

\[
\begin{align*}
    p_{ac} &= v_a i_a + v_b i_b + v_c i_c \\
    q_{ac} &= \frac{1}{\sqrt{3}} (v_a b i_c + v_b c i_a + v_c a i_b)
\end{align*}
\] (2.12)

If the Park-Transformation that conserves power from \((abc)\) to \((dq)\) frame is used and if the three-phase system is balanced, the expressions above in the \((dq)\) frame are given by:

\[
\begin{align*}
    p_{ac} &= e_d i_d + e_q i_q \\
    q_{ac} &= e_q i_d - e_d i_q
\end{align*}
\] (2.13)

Moreover, it is assumed that the q-axis of the \((dq)\) frame is aligned with the AC network voltage phasor through a PLL, i.e. \(e_d = 0\), and the following expressions are obtained:

\[
\begin{align*}
    p_{ac} &= e_q \cdot i_q \\
    q_{ac} &= e_q \cdot i_d
\end{align*}
\] (2.14)

The above equations show that an independent control of the active and reactive power is possible through the converter currents. The control diagrams are mathematically expressed in equation (2.15) and in diagram form in Figure 2.11.

\[
\begin{align*}
    i_d^* &= (q_{ac}^* - q_{ac}) \cdot \left( K_{p,q} + \frac{K_{i,q}}{s} \right) \\
    i_q^* &= (p_{ac}^* - p_{ac}) \cdot \left( K_{p,p} + \frac{K_{i,p}}{s} \right)
\end{align*}
\] (2.15)

**Figure 2.11:** Active and reactive power outer controller diagrams.

DC Voltage Outer Controller

The objective of the DC voltage controller is to maintain the DC voltage at its reference value by regulating the active power exchanged with the AC grid by regulating \(i_q^*\).

A DC voltage controller that operates on the error between the DC voltage and its reference value \(\Delta V_{DC} = V_{DC}^* - V_{DC}\) could be applied, in an analogous way as in the active and reactive power outer controllers. However, if the controller is to operate linearly on the DC voltage, the closed-loop dynamics will be dependent on the operating point [61].
The power in the capacitor is \( P_C = V_{DC} \cdot I_{Cap} \) and the current flowing through it can be obtained since: \( I_{Cap}(s) = sCV_{DC}(s) \).

Thus, \( P_C \) can be obtained as:

\[
P_C = sCV_{DC}^2
\]  

(2.16)

So it is possible to observe that the power through the capacitor is proportional to the square of the DC voltage \( (P_C \propto V_{DC}^2) \). As an alternative, the DC voltage outer controller is made to operate on the energy, \( W_c \), stored in the VSC-HVDC station capacitor.

\[
W_C = \frac{1}{2}CV_{DC}^2
\]  

(2.17)

Thus, as previously mentioned, the DC voltage outer controller is made to operate on the error proportional to the square of the DC voltage, \( \Delta W_C = W_C^* - W_C \), instead of directly on the DC voltage. This is done to avoid nonlinearities in the DC voltage controller since \( W_{DC} \propto V_{DC}^2 \).

The control diagram is mathematically expressed in equation (2.18) and in diagram form in Figure 2.12.

\[
i_q^* = (W_c^* - W_c) \cdot \left( K_{p,w} + \frac{K_{i,w}}{s} \right)
\]  

(2.18)

Figure 2.12: DC voltage controller diagram.

**AC Voltage Outer Controller**

The objective of the AC voltage controller is to regulate the amplitude of the AC voltage at the PCC at a given reference value by modifying the current reference of the d-axis, \( i_d^* \). This implies that the controller commands the converter to transmit an amount of reactive power (up to the limit of the converter rated power) so that the AC voltage at the PCC matches the given reference value.

The control diagram is mathematically expressed in equation (2.19) and in diagram form in Figure 2.13.

\[
i_d^* = (|e_d^*| - |e_d|) \cdot \left( K_{p,v} + \frac{K_{i,v}}{s} \right)
\]  

(2.19)

**2.4.3 VSC Controllers Bandwidth**

**Inner Current Controller**

When PWM modulation is used, in order to achieve a satisfactory performance, the ICC closed-loop bandwidth should not be higher than 5 times the angular switching frequency \( (\omega_{sw}) \), i.e. [61]:
If a switching frequency of 2kHz is used ($\omega_{sw} = 12.56 \text{ krad/s}$) the maximum system bandwidth would be $\alpha_c \approx 2.5 \text{ krad/s}$. In this thesis a value of $\alpha_c = 2 \text{ kHz}$ has been chosen in order to accommodate safety margins.

**Outer Controllers**

According to [61] in order to obtain a closed-loop system without an oscillatory response, the proportional gain of the outer controllers, in pu, must be set as:

$$k_p \leq \frac{1}{8} \cdot \frac{\alpha_c}{C} \Rightarrow \alpha_{oc} \leq 0.125\alpha_c \quad (2.21)$$

The above analysis leads to a maximum theoretical value for the proportional outer controller gain, which can be related to the inner current controller bandwidth. In practice, the limit of the outer controller bandwidth will be lower than this value, since some simplifications were made, e.g. the cross-coupling effect between the d-axis and q-axis, and the converter switching behavior were neglected. Therefore, the value $\alpha_{oc} = 0.075\alpha_c$ will be used as the maximum value to account for these simplifications. Thus, the outer controllers loops will be sufficiently slower than the AC current control loop, to help achieving stability.

For the integral gain, it can be shown that a reasonable controller gain value, in pu, is [61]:

$$k_i \approx \alpha_{oc}^2 C \quad (2.22)$$

Table 2.1 presents the formulas that were used to tune the gains of the PI controllers.

### 2.4.4 Current Limiter

The converter valves have a maximum current carrying capability and they may be destroyed by excessive overcurrent. This way, a current limiter is always present in the VSC control system. The current limiter compares the magnitude of the reference current value (2.23), generated by the outer controllers, with the permitted maximum value. If it exceeds the rated current of the converter, the magnitude of the reference current is limited.

$$|i| = \sqrt{(i_d^*)^2 + (i_q^*)^2} \quad (2.23)$$
When $|i|$ exceeds the maximum permitted value there are three different possible strategies to limit the current (see Figure 2.14). Priority can be given to voltage restoration (reactive power priority) and therefore, the d-axis current will be maintained and q-axis will be reduced. This strategy is normally chosen if the converter is connected to a weak grid or used to supply an industrial plant.

If the converter is connected to a strong grid the priority is usually given to the delivery of active power (q-axis current will stay unchanged and the d-axis current will be reduced). The last method is to proportionally limit the current in both axis, maintaining then the power factor constant.
Chapter 3

Multi-Terminal DC Networks

3.1 Introduction

There are more than 100 HVDC transmission systems installed all over the world, but only three have more than two terminals: the Hydro-Quebec/New England system, in Canada [5]; the SACOI-2, connecting Italy and France [21], and a back-to-back scheme using VSC technology at the Shin-Shinano substation, in Japan [45]. All the aforementioned systems have 3 terminals.

In order to create a multi-terminal grid, the stations can be either connected in series or in parallel. When connected in series all the stations share the same current. On the other hand, for the parallel connection the stations share the same DC transmission voltage [21]. There are several possibilities for the grid’s topology: shore-to-shore, radial, meshed, cluster with multi-way interconnector, a combination of interconnectors and meshed grids, etc.. In Figure 3.1 it is shown the network topologies that are possible according to the HVDC technology implemented.

![MTDC Network classification scheme](image)

Figure 3.1: MTDC Network classification scheme.

The VSC technology created the possibility of building true MTDC grids which has been difficult with the use of CSC technology. Some of the main reasons for this are: the limitations of thyristor based HVDC to 2-quadrant operation while used in multiterminal topology, the need for supply of reactive power at each terminal, and the difficult control structure (see Chapter 1).
One of the earliest proposals for a transnational grid using VSC technology was the “Supergrid” concept by Airtricity (Figure 3.2). The grid was planned to connect offshore wind power plants to onshore transmission systems in the North and Baltic Sea regions, the Atlantic coast and the Mediterranean sea. As a first element of the Supergrid, Airtricity proposed the “10 GW Foundation Project,” which consisted of several wind power plants situated in the North Sea, connected with the UK, Germany and the Netherlands onshore grids. Other proposals for transnational grids can be found in [64].

![Figure 3.2: Transnational “Supergrid” proposed by Airtricity [20].](image)

### 3.1.1 The need for a MTDC Grid

An increasing interest can be observed in Europe towards the establishment of transnational electricity grids which is driven by two developments. Firstly, in order to reach the European Union’s targets on renewable energy generation, large-scale offshore wind power might be a key technology. Secondly, due to the deregulation of the energy sector in Europe, there exists an increasing demand for cross-border exchange capacity.

Due to the fact that correlation among wind speeds decays exponentially with the distance between locations, several initiatives funded by environmental agencies, TSOs and the European Commission, have pointed the importance of international electricity markets and of an adequate pan-European transmission system [64]. The existence of a transnational grid would enable the trade of power imbalances (unscheduled surpluses or deficits of wind energy) and a decrease in variability in wind power production when aggregated over large areas.

Like the development of AC networks at the end of the XVIII century, the HVDC grids will most likely start as simple grids and then their complexity will increase. Standardization is necessary to make it possible for early built DC transmissions to be part of a future HVDC grid. For the offshore HVDC grid the types of HVDC converter and DC voltage must be standardized.

The most important standardization is the MTDC network voltage. Technically, an offshore grid based on same voltage is not necessary. Intermediate stations could perform a DC-AC-DC transformation in order to change the DC voltage to an adequate value, and this way a grid with several DC voltages would be possible. However, such solution has two important drawbacks: installation cost and losses. The cost of a HVDC converter and especially an offshore HVDC converter with platform contributes greatly to the total investment that the technical-economical optimum will be with fewest possible converters. In addition, the extra converter will have losses which increases the operational costs [65].
Reliability and Redundancy

All the offshore wind power plants built until now use a single cable as a connection to the shore. Thus, this type of connection has no redundancy. The reliability of the connection critically relies on some of its main components, most importantly the cable circuit connecting the wind power plant to the onshore grid. When malfunctioning, these components will take the complete installation out of service.

With the expected increase of the offshore wind power capacity in the future, this situation will probably change. TSOs may start putting requirements on the availability of the connection and then the loss of production due to an offshore transmission outage will become a manageable risk.

Transnational offshore grids are expected to improve reliability. They will have several connection points to the onshore grids and in that way there will be always an alternative path along which the power, or part of it, can be evacuated.

Flexibility, Standardization, and Modularity

The development of offshore wind power and offshore transmission system will probably take over a decade. Thus, it is difficult, in the present, to determinate a detailed blueprint of such infrastructure. The evolution of offshore infrastructure is a gradual process that constantly needs to adapt to new developments in the industry and society as a whole. However, since the nodes in this offshore network, i.e. substations located on offshore platforms, will be difficult to modify or extend once installed, it is crucial for the success of such network to consider future expansion plans right from the beginning. For optimal results, such offshore grid expansion plans should be the result of coordinated efforts among the responsible authorities.

Controllability of Power Flows

Due to the fact that an offshore transnational grid will likely be based on HVDC technology, it will have higher controllability of power flows than onshore AC grids, where the distribution of power flows results from the dispatch of generators and the impedance of the transmission lines. However, the power flow can be influenced indirectly e.g. via additional equipment such as phase-shifting transformers. HVDC technology inherently enables forcing a predefined power flow along a certain transmission cable. This feature will have an impact on the rules for congestion management for such grid. Nowadays, there are different rules among the European electrical markets for the priority dispatch of renewable energy sources, including onshore and offshore wind. Some markets, such as the German one, always give precedence to generation from renewable sources, whereas others, e.g. the Dutch market, renewables have an equal status as any other generation source. The creation of a transnational offshore grid would create a coupling of these markets and, hence, it will be necessary a harmonization of market and operation rules.

3.1.2 Applications of a MTDC grid

Beyond the time horizon of 2020, offshore wind power plants are expected to have higher power ratings and to be situated further from the shore. This implies that the costs of the electrical infrastructure will constitute a higher share in the total investment costs. Therefore, methods to increase the utilization of the connection are attractive.
An increased need for interconnection capacity between European countries is leaded by market coupling and balancing of the variable output of renewables. Offshore wind power plant connections can be combined with interconnectors between countries to increase the utilization of the electrical infrastructure and, hence, to reduce costs. Cost-effective networks demand an overall optimized grid design that avoids suboptimal solutions based on individual and national projects. To achieve an optimal solution cooperation among countries is also recommended: harmonization of legal rules, simplification of authorization procedures and international spatial maritime planning.

An interconnection between offshore wind farms, oil and gas platforms and onshore grids can result in reduced operational costs, increased reliability and reduced \( CO_2 \) emissions. In most offshore installations, power supply generators and large compressors are driven by onboard gas turbines or diesel engines. Many of these power sources have efficiencies around 20-25% under the best assumptions. The result is the emission of large amounts of \( CO_2 \) emission and unnecessary high fuel consumption. If the electrical power can be supplied from the DC grid, \( CO_2 \) emissions from offshore installations are eliminated. This leads to a significant cost savings for oil companies. In addition, transmission of electrical energy from the DC grid involves less maintenance, longer lifetime and higher availability than gas turbines and diesel engines. If the transmission equipment can be located on decommissioned offshore installations, the postponed removal cost for the installation can be an important factor as well [66].

The offshore potential in Europe consists both of wind energy and ocean energy. The term ocean energy includes wave energy, tidal current, tidal range, osmotic energy and ocean thermal energy. West European coasts have high wave energy potential (see Figure 3.3). Nonetheless, in areas with low wave energy potential such as the North Sea, wave energy converters can produce 10-75 TWh/y [27].

![Figure 3.3: Wave energy in Europe in kW/m width of oncoming wave.](image)

The wave and tidal energy converters are located on the sea surface or below it, whereas offshore wind turbines use their respective resource tens of meters above the sea level. Therefore, wave and tidal energy converters can be deployed between offshore wind turbines since there has to be a certain distance among the turbines to avoid shadow effects. Placed together, they can share the same offshore grid. Therefore, installation costs would be reduced since the cable costing is not a linear function of the number of the cables as the same route and laying procedure might be applied for more than one cable.

A combination of the power output of both resources would result in smoother variations of the generated power, better predictability and higher capacity credit, since wave energy peaks generally occurs 6-8 h later than wind energy peaks, and because wave energy has greater predictability and less variability when compared to wind energy [27].

Differently from an AC system, with a DC grid it is possible to collect power from multiple non-
synchronized generators. It also allows the interconnection of asynchronous systems (the UK and Continental Europe are not united into a single synchronous network) since AC grids, adjacent to each others but running asynchronously, cannot exchange power. If there is a surplus of generating capacity in one of the grids power cannot be transmitted to others. Every network must have its own capacity of peak power generation, usually in the form of older, inefficient fuel fossil plants, or diesel or gas turbine units. Thus, peak power generation is often a source of substantial pollution, and their fuel economy is frequently bad. The power exchange between the networks is also very easy to measure accurately and asynchronous HVDC links act as an effective protection against propagation of cascading outages in one network from passing to another. With a DC grid the reinforcing of existing AC grids it is also a possibility [27]. In Figure 5.1 the applications and advantages of a MTDC grid are depicted.

Figure 3.4: Applications for a Multi-Terminal DC grid.
3.2 State-space model of MTDC grids

3.2.1 Meshed MTDC grid

In this section a state-space model for a grid composed of 3 VSC stations will be derived. The grid considered is shown in Figure 3.5. Each station is connected through a DC cable to the others nodes in the network, thus forming a meshed grid.

The incidence matrix, $I_M$, which contains the information about the existing DC cables in the grid considered, is given by:

$$I_M = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix}_{L \times N} \quad (3.1)$$

where the value 1 means that the current is flowing from the node, and -1 means that the current is flowing to the node. The letter N stands for the number of nodes and L for the number of cables of the MTDC grid.

The application of Kirchhoff's current law (KCL) on each node, yields:

- $I_{DC1} = I_{C11} + I_{C21} + I_{L1} + I_{L2} \Leftrightarrow$

  $$I_{DC1} = sC_{11}V_{DC1} + sC_{21}V_{DC1} + I_{L1} + I_{L2} \Leftrightarrow$$

  $$sV_{DC1} = \frac{I_{DC1} - I_{L1} - I_{L2}}{C_{11} + C_{21}} \quad (3.2)$$

- $I_{DC2} = I_{C12} + I_{C31} - I_{L1} + I_{L3} \Leftrightarrow$

  $$I_{DC2} = sC_{12}V_{DC2} + sC_{31}V_{DC2} - I_{L1} + I_{L3} \Leftrightarrow$$

  $$sV_{DC2} = \frac{I_{DC2} + I_{L1} - I_{L3}}{C_{12} + C_{31}} \quad (3.3)$$

- $I_{DC3} = I_{C22} + I_{C32} - I_{L2} - I_{L3} \Leftrightarrow$

  $$I_{DC3} = sC_{22}V_{DC3} + sC_{32}V_{DC3} - I_{L2} - I_{L3} \Leftrightarrow$$

  $$sV_{DC3} = \frac{I_{DC3} + I_{L2} + I_{L3}}{C_{22} + C_{32}} \quad (3.4)$$
And from the application of Kirchhoff’s voltage law (KVL) on each cable, it is obtained:

\[
\begin{align*}
\bullet & \quad I_{L1} = \frac{V_{DC1} - V_{DC2}}{R_1 + sL_1} \iff sI_{L1} = \frac{V_{DC1}}{L_1} - \frac{V_{DC2}}{L_1} - I_{L1} \frac{R_1}{L_1} \\
\bullet & \quad I_{L2} = \frac{V_{DC1} - V_{DC3}}{R_2 + sL_2} \iff sI_{L2} = \frac{V_{DC1}}{L_2} - \frac{V_{DC3}}{L_2} - I_{L2} \frac{R_2}{L_2} \\
\bullet & \quad I_{L3} = \frac{V_{DC2} - V_{DC3}}{R_3 + sL_3} \iff sI_{L3} = \frac{V_{DC2}}{L_3} - \frac{V_{DC3}}{L_3} - I_{L3} \frac{R_3}{L_3}
\end{align*}
\]

(3.5) – (3.7)

Rearranging the equations derived from Kirchhoff’s laws, it is possible to express the system through a state space model representation (see Appendix C):

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}
\]

(3.8)

One equation per each energy-storage element (capacitors and reactances) of the system was derived. Thus, the state vector is given by:

\[
\dot{x} = \begin{bmatrix} \dot{V}_{DC1} \\ \dot{V}_{DC2} \\ \dot{V}_{DC3} \\ \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{I}_{L3} \end{bmatrix}
\]

(3.9)

The input vector is equal to:

\[
u = \begin{bmatrix} I_{DC1} \\ I_{DC2} \\ I_{DC3} \end{bmatrix}
\]

(3.10)

The state equation of the system becomes:

\[
\begin{bmatrix} \dot{V}_{DC1} \\ \dot{V}_{DC2} \\ \dot{V}_{DC3} \\ \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{I}_{L3} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{C_1} & -\frac{1}{C_1} & 0 \\ 0 & 0 & 0 & \frac{1}{C_2} & 0 & -\frac{1}{C_2} \\ 0 & 0 & 0 & 0 & \frac{1}{C_3} & \frac{1}{C_3} \\ \frac{1}{L_1} & \frac{1}{L_1} & 0 & -\frac{R_1}{L_1} & 0 & 0 \\ \frac{1}{L_2} & \frac{1}{L_2} & 0 & 0 & -\frac{R_2}{L_2} & 0 \\ 0 & \frac{1}{L_3} & \frac{1}{L_3} & 0 & 0 & -\frac{R_3}{L_3} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 \\ 0 & 0 & \frac{1}{C_3} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{DC1} \\ V_{DC2} \\ V_{DC3} \\ I_{L1} \\ I_{L2} \\ I_{L3} \end{bmatrix}
\]

(3.11)

where \( \frac{1}{C_1} \), \( \frac{1}{C_2} \), and \( \frac{1}{C_3} \) represent the sum of the capacitances connected to each node.

The state matrix, \( A \), is composed by 4 distinctive sub-matrices:

\[
A = \begin{bmatrix} A^{11}_{N \times N} & A^{12}_{N \times L} \\ A^{21}_{L \times N} & A^{22}_{L \times L} \end{bmatrix}_{(N+L) \times (N+L)}
\]

(3.12)

After inspection of the matrix system presented above, it is possible to derive formulas using the incidence matrix to obtain each matrix that compose the state matrix.

\[
\bullet A^{11} = [0]_{N \times N}
\]

(3.13)
\( A_{12}^T = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix}_{L \times N} \times \begin{bmatrix} \frac{1}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 \\ 0 & 0 & \frac{1}{C_3} \end{bmatrix}_{N \times N} = \begin{bmatrix} \frac{1}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 \\ 0 & 0 & \frac{1}{C_3} \end{bmatrix}_{L \times N} \)  

\( \Rightarrow A_{12}^2 = \begin{bmatrix} -\frac{1}{C_1} & \frac{1}{C_2} & 0 \\ \frac{1}{C_1} & -\frac{1}{C_2} & 0 \\ 0 & \frac{1}{C_2} & \frac{1}{C_3} \end{bmatrix}_{N \times L} \)  

\( A_{21} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{L_2} & 0 \\ 0 & 0 & \frac{1}{L_3} \end{bmatrix}_{L \times L} \times \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix}_{L \times N} = \begin{bmatrix} \frac{1}{L_1} & 0 & 0 \\ \frac{1}{L_2} & 0 & -\frac{1}{L_3} \\ 0 & 1 & -\frac{1}{L_3} \end{bmatrix}_{L \times N} \)  

\( A_{22} = \begin{bmatrix} -R_1 & 0 & 0 \\ 0 & -\frac{R_2}{L_2} & 0 \\ 0 & 0 & -\frac{R_3}{L_3} \end{bmatrix}_{L \times L} \)  

The input matrix, \( B \), is also composed by 2 different sub-matrixes.

\( B = \begin{bmatrix} B_{11} & B_{21} \end{bmatrix}_{(N+L) \times N} \)  

\( B_{11} = \begin{bmatrix} \frac{1}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 \\ 0 & 0 & \frac{1}{C_3} \end{bmatrix}_{N \times N} \)  

\( B_{21} = [0]_{L \times N} \)  

It is possible to observe that all the matrixes derived above are dependent of the grid configuration, but the necessary information is obtained from the incidence matrix, \( I_M \).

The output equation is given by:

\[
\begin{bmatrix}
V_{DC1} \\
V_{DC2} \\
V_{DC3} \\
I_{L1} \\
I_{L2} \\
I_{L3}
\end{bmatrix} = \frac{1}{C} \cdot \begin{bmatrix}
V_{DC1} \\
V_{DC2} \\
V_{DC3} \\
I_{L1} \\
I_{L2} \\
I_{L3}
\end{bmatrix} + \frac{0}{D} \cdot \begin{bmatrix}
I_{DC1} \\
I_{DC2} \\
I_{DC3}
\end{bmatrix}
\]  

\( \text{(3.20)} \)
The output matrix, $C$, is an identity matrix since there is no need for combinations of state variables in the output.

$$ C = [I]_{(N+L) \times (N+L)} \quad (3.21) $$

Given the fact that there are no current sources present in the grid, the direct transition matrix, $D$, is only filled with zeros.

$$ D = [0]_{(N+L) \times N} \quad (3.22) $$

### 3.2.2 Radial MTDC grid

In this section a state-space model for a grid composed by 4 stations will be derived. The grid considered is shown in Figure 3.6. Each station is connected to a central point, forming this way a radial grid.

![Figure 3.6: Example of a radially-connected VSC-HVDC MTDC network with four terminals.](image)

The incidence matrix, $I_M$, for this grid is given by:

$$ I_M = \begin{bmatrix} 1 & 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix}_{L \times N} \quad (3.23) $$

Once again the Kirchhoff's laws are applied. The application of KCL on each node, yields:

- $I_{DC1} = I_{C11} + I_{L1} \iff I_{DC1} = sC_{11}V_{DC1} + I_{L1} \iff sV_{DC1} = \frac{I_{DC1} - I_{L1}}{C_{11}} \quad (3.24)$

- $I_{DC2} = I_{C21} + I_{L2} \iff I_{DC2} = sC_{21}V_{DC2} + I_{L2} \iff sV_{DC2} = \frac{I_{DC2} - I_{L2}}{C_{21}} \quad (3.25)$

- $I_{DC3} = I_{C31} + I_{L3} \iff I_{DC3} = sC_{31}V_{DC3} + I_{L3} \iff sV_{DC3} = \frac{I_{DC3} - I_{L3}}{C_{31}} \quad (3.26)$

- $I_{DC4} = I_{C41} + I_{L4} \iff I_{DC4} = sC_{41}V_{DC4} + I_{L4} \iff sV_{DC4} = \frac{I_{DC4} - I_{L4}}{C_{41}} \quad (3.27)$
\[ I_{DC5} = -I_{L1} - I_{L2} - I_{L3} - I_{L4} + I_{C12} + I_{C22} + I_{C32} + I_{C42} \]
\[ I_{DC5} = -I_{L1} - I_{L2} - I_{L3} - I_{L4} + sC_{12}V_{DC5} + sC_{22}V_{DC5} + sC_{32}V_{DC5} + sC_{42}V_{DC5} \]
\[ sV_{DC5} = \frac{I_{DC5} + I_{L1} + I_{L2} + I_{L3} + I_{L4}}{C_{12} + C_{22} + C_{32} + C_{42}} \]

And from the application of KVL on each cable, it is obtained:

- \[ I_{L1} = \frac{V_{DC1} - V_{DC5}}{R_1 + sL_1} \]
- \[ sI_{L1} = \frac{V_{DC1}}{L_1} - I_{L1} \frac{R_1}{L_1} \]
- \[ I_{L2} = \frac{V_{DC2} - V_{DC5}}{R_2 + sL_2} \]
- \[ sI_{L2} = \frac{V_{DC2}}{L_2} - I_{L2} \frac{R_2}{L_2} \]
- \[ I_{L3} = \frac{V_{DC3} - V_{DC5}}{R_3 + sL_3} \]
- \[ sI_{L3} = \frac{V_{DC3}}{L_3} - I_{L3} \frac{R_3}{L_3} \]
- \[ I_{L4} = \frac{V_{DC4} - V_{DC5}}{R_4 + sL_4} \]
- \[ sI_{L4} = \frac{V_{DC4}}{L_4} - I_{L4} \frac{R_4}{L_4} \]

As for the previous MTDC grid, one equation per each energy-storage element (capacitors and reactances) of the system was derived. Therefore, the state vector is given by:

\[
\dot{x} = \begin{bmatrix} \dot{V}_{DC1} & \dot{V}_{DC2} & \dot{V}_{DC3} & \dot{V}_{DC4} & \dot{V}_{DC5} & \dot{I}_{L1} & \dot{I}_{L2} & \dot{I}_{L3} & \dot{I}_{L4} \end{bmatrix} \]

The input vector is equal to:

\[
u = \begin{bmatrix} I_{DC1} & I_{DC2} & I_{DC3} & I_{DC4} & I_{DC5} \end{bmatrix}
\]

Rearranging the equations derived from Kirchhoff’s laws, it is possible to express the system through a state space model representation:

\[
\begin{bmatrix} \dot{V}_{DC1} \\ \dot{V}_{DC2} \\ \dot{V}_{DC3} \\ \dot{V}_{DC4} \\ \dot{V}_{DC5} \\ \dot{I}_{L1} \\ \dot{I}_{L2} \\ \dot{I}_{L3} \\ \dot{I}_{L4} \end{bmatrix} = A \cdot \begin{bmatrix} V_{DC1} \\ V_{DC2} \\ V_{DC3} \\ V_{DC4} \\ V_{DC5} \\ I_{L1} \\ I_{L2} \\ I_{L3} \\ I_{L4} \end{bmatrix} + B \cdot \begin{bmatrix} I_{DC1} \\ I_{DC2} \\ I_{DC3} \\ I_{DC4} \\ I_{DC5} \end{bmatrix}
\]

(3.35)
where \( A \) is given by:

\[
A = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & -\frac{1}{C_1} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{C_2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{C_3} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{C_4} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{1}{L_1} & 0 & 0 & 0 & -\frac{1}{L_1} & 0 & 0 & 0 & 0 \\
0 & \frac{1}{L_2} & 0 & 0 & -\frac{1}{L_2} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{L_3} & 0 & -\frac{1}{L_3} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{L_4} & -\frac{1}{L_4} & 0 & 0 & 0 & 0 \\
\end{bmatrix}_{(N+L) \times (N+L)}
\]

\[ (3.36) \]

and \( B \) by:

\[
B = \begin{bmatrix}
\frac{1}{C_1} & 0 & 0 & 0 & 0 \\
0 & \frac{1}{C_2} & 0 & 0 & 0 \\
0 & 0 & \frac{1}{C_3} & 0 & 0 \\
0 & 0 & 0 & \frac{1}{C_4} & 0 \\
0 & 0 & 0 & 0 & \frac{1}{C_5} \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}_{(N+L) \times N}
\]

\[ (3.37) \]

Once again the state matrix, \( A \), is composed by 4 distinctive sub-matrixes:

\[
A = \begin{bmatrix}
A_{11}^{1} & A_{12}^{1} \\
A_{21}^{1} & A_{22}^{1} \\
\end{bmatrix}_{(N+L) \times (N+L)}
\]

\[ (3.38) \]

Using the same approach as before the formulas to obtain the sub-matrixes that constitute the state matrix were derived:

\[ \bullet \ A_{11}^{1} = [0]_{N \times N} \]

\[ (3.39) \]
\[
\begin{align*}
\mathbf{A}_{12}^T &= \begin{bmatrix}
1 & 0 & 0 & 0 & -1 \\
0 & 1 & 0 & 0 & -1 \\
0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 1 & -1
\end{bmatrix}_{\mathbf{L} \times \mathbf{N}} \times \begin{bmatrix}
\frac{1}{\mathbf{C}_1} & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\mathbf{C}_2} & 0 & 0 & 0 \\
0 & 0 & \frac{1}{\mathbf{C}_3} & 0 & 0 \\
0 & 0 & 0 & \frac{1}{\mathbf{C}_4} & 0 \\
0 & 0 & 0 & 0 & \frac{1}{\mathbf{C}_5}
\end{bmatrix}_{\mathbf{N} \times \mathbf{N}} = \begin{bmatrix}
\frac{1}{\mathbf{C}_1} & 0 & 0 & 0 & \frac{1}{\mathbf{C}_5} \\
0 & \frac{1}{\mathbf{C}_2} & 0 & 0 & \frac{1}{\mathbf{C}_5} \\
0 & 0 & \frac{1}{\mathbf{C}_3} & 0 & \frac{1}{\mathbf{C}_5} \\
0 & 0 & 0 & \frac{1}{\mathbf{C}_4} & 0 \\
0 & 0 & 0 & 0 & \frac{1}{\mathbf{C}_5}
\end{bmatrix}_{\mathbf{L} \times \mathbf{N}} \quad (3.40)
\end{align*}
\]

\[
\begin{align*}
\Rightarrow \mathbf{A}_{12}^T &= \begin{bmatrix}
\frac{1}{\mathbf{C}_1} & 0 & 0 & 0 \\
0 & \frac{1}{\mathbf{C}_2} & 0 & 0 \\
0 & 0 & \frac{1}{\mathbf{C}_3} & 0 \\
\frac{1}{\mathbf{C}_5} & \frac{1}{\mathbf{C}_5} & \frac{1}{\mathbf{C}_5} & \frac{1}{\mathbf{C}_5}
\end{bmatrix}_{\mathbf{N} \times \mathbf{L}}
\end{align*}
\]

\[
\begin{align*}
\mathbf{A}_{21} &= \begin{bmatrix}
\frac{1}{\mathbf{L}_1} & 0 & 0 & 0 \\
0 & \frac{1}{\mathbf{L}_2} & 0 & 0 \\
0 & 0 & \frac{1}{\mathbf{L}_3} & 0 \\
0 & 0 & 0 & \frac{1}{\mathbf{L}_4}
\end{bmatrix}_{\mathbf{L} \times \mathbf{L}} \times \begin{bmatrix}
1 & 0 & 0 & 0 & -1 \\
0 & 1 & 0 & 0 & -1 \\
0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 1 & -1
\end{bmatrix}_{\mathbf{L} \times \mathbf{N}} = \begin{bmatrix}
\frac{1}{\mathbf{L}_1} & 0 & 0 & 0 & -\frac{1}{\mathbf{L}_1} \\
0 & \frac{1}{\mathbf{L}_2} & 0 & 0 & -\frac{1}{\mathbf{L}_2} \\
0 & 0 & \frac{1}{\mathbf{L}_3} & 0 & -\frac{1}{\mathbf{L}_3} \\
0 & 0 & 0 & \frac{1}{\mathbf{L}_4} & -\frac{1}{\mathbf{L}_4}
\end{bmatrix}_{\mathbf{L} \times \mathbf{N}} \quad (3.41)
\end{align*}
\]

\[
\begin{align*}
\mathbf{A}_{22} &= \begin{bmatrix}
-\frac{\mathbf{R}_1}{\mathbf{L}_1} & 0 & 0 & 0 \\
0 & -\frac{\mathbf{R}_2}{\mathbf{L}_2} & 0 & 0 \\
0 & 0 & -\frac{\mathbf{R}_3}{\mathbf{L}_3} & 0 \\
0 & 0 & 0 & -\frac{\mathbf{R}_4}{\mathbf{L}_4}
\end{bmatrix}_{\mathbf{L} \times \mathbf{L}} \quad (3.42)
\end{align*}
\]

The input matrix, \( \mathbf{B} \), can be decomposed in 2 different sub-matrixes.

\[
\mathbf{B} = \begin{bmatrix}
\mathbf{B}_{11}^{11} & \mathbf{B}_{21}^{21}
\end{bmatrix}_{\mathbf{(N+L)} \times \mathbf{N}} \quad (3.43)
\]

\[
\begin{align*}
\mathbf{B}_{11}^{11} &= \begin{bmatrix}
\frac{1}{\mathbf{C}_1} & 0 & 0 & 0 \\
0 & \frac{1}{\mathbf{C}_2} & 0 & 0 \\
0 & 0 & \frac{1}{\mathbf{C}_3} & 0 \\
0 & 0 & 0 & \frac{1}{\mathbf{C}_5}
\end{bmatrix}_{\mathbf{N} \times \mathbf{N}} \quad (3.44)
\end{align*}
\]

\[
\begin{align*}
\mathbf{B}_{21}^{21} &= \begin{bmatrix}
0
\end{bmatrix}_{\mathbf{L} \times \mathbf{N}} \quad (3.45)
\end{align*}
\]
The output equation is given by:

\[
\begin{bmatrix}
V_{DC1} \\
V_{DC2} \\
V_{DC3} \\
V_{DC4} \\
V_{DC5} \\
I_{L1} \\
I_{L2} \\
I_{L3} \\
I_{L4}
\end{bmatrix}
= \begin{bmatrix}
I_{DC1} \\
I_{DC2} \\
I_{DC3} \\
I_{DC4} \\
I_{DC5}
\end{bmatrix}
\cdot \begin{bmatrix}
I_{C1} \\
I_{C2} \\
I_{C3} \\
I_{C4} \\
I_{C5}
\end{bmatrix}
\]

(3.46)

As before, the output matrix, \( C \), is an identity matrix since there is no need for combinations of state variables in the output, and the direct transition matrix, \( D \), is only filled with zeros because there are no current sources present in the grid.

\[C = [I]_{(N+L) \times (N+L)} \quad (3.47)\]

\[D = [0]_{(N+L) \times N} \quad (3.48)\]

Both examples lead to the conclusion that the approach used is general. Due to the fact that the formulas derived in the examples are independent of the type of connection between stations it is possible to achieve a state-space model for any given DC network.

### 3.2.3 Generic MTDC grid

From inspection of the previous examples, it is possible to achieve general equations using the Kirchhoff’s laws (KVL and KCL) for a generic MTDC grid composed of \( i \) cables and \( j \) nodes:

- \[ I_{Li} = \frac{V_{DCi} - V_{DCj}}{R_i + sL_i} \Leftrightarrow sI_{Li} = \frac{V_{DCi}}{L_i} - \frac{V_{DCj}}{L_i} + I_{Li} \frac{R_i}{L_i} \quad (3.49) \]

- \[ sV_{DCj} = \frac{1}{C_j} \left( I_{DCj} - \sum_{i=1}^{L} I_{Mij} \cdot I_{Li} \right) \quad (3.50) \]

where \( I_{Li} \) is the current flowing through the cable \( i \), \( C_j \) is the sum of the capacitances of the node \( j \), and \( I_{M} \) is the incidence matrix.

It is also possible to conclude, from the previous examples, that all the matrixes of the state-space model equation (3.51) can be obtained with the same formulas, independently of the grid configuration.

Rearranging the equations derived from Kirchhoff’s laws, it is possible to express the system through a state space model representation (see Appendix C):

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}
\quad (3.51)
\]
One equation per each energy-storage element (capacitors and reactances) of the system has to be derived. Therefore, the state vector will be given by:

\[
\dot{x} = \begin{bmatrix} \dot{V}_{DC1} & \dot{V}_{DC2} & \cdots & \dot{V}_{DCj} & \dot{i}_{L1} & \dot{i}_{L2} & \cdots & \dot{i}_{Li} \end{bmatrix}_{1 \times (N+L)}
\] (3.52)

The input vector is equal to:

\[
u = \begin{bmatrix} I_{DC1} & I_{DC2} & \cdots & I_{DCj} \end{bmatrix}_{1 \times N}
\] (3.53)

The state equation of the system becomes:

\[
\begin{bmatrix} \dot{V}_{DC1} \\ \dot{V}_{DC2} \\ \vdots \\ \dot{V}_{DCj} \\ \dot{i}_{L1} \\ \dot{i}_{L2} \\ \vdots \\ \dot{i}_{Li} \end{bmatrix} = A \cdot \begin{bmatrix} V_{DC1} \\ V_{DC2} \\ \vdots \\ V_{DCj} \\ i_{L1} \\ i_{L2} \\ \vdots \\ i_{Li} \end{bmatrix} + B \cdot \begin{bmatrix} I_{DC1} \\ I_{DC2} \\ \vdots \\ I_{DCj} \end{bmatrix}
\] (3.54)

The state matrix, A, is composed of 4 sub-matrixes:

\[
A = \begin{bmatrix} A^{11}_{N \times N} & A^{12}_{N \times L} \\ A^{21}_{L \times N} & A^{22}_{L \times L} \end{bmatrix}_{(N+L) \times (N+L)}
\] (3.55)

Which can be obtained by:

\[A^{11} = [0]_{N \times N}
\] (3.56)

\[
A^{12} = -I_M \cdot \begin{bmatrix} \frac{1}{C_1} & 0 & \cdots & 0 \\ 0 & \frac{1}{C_2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \frac{1}{C_j} \end{bmatrix}_{N \times L}
\] (3.57)

\[
A^{21} = \begin{bmatrix} \frac{1}{L_1} & 0 & \cdots & 0 \\ 0 & \frac{1}{L_2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \frac{1}{L_i} \end{bmatrix}_{L \times N} \cdot I_M
\] (3.58)
The input matrix, $B$, which is constituted by 2 sub-matrixes, can be calculated as:

\[ B = \begin{bmatrix} B^{11} & B^{21} \end{bmatrix}_{(N+L) \times N} \]  
\[ B^{11} = \begin{bmatrix} \frac{1}{C_1} & 0 & \ldots & 0 \\ 0 & \frac{1}{C_2} & \ldots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \ldots & 0 & \frac{1}{C_j} \end{bmatrix}_{N \times N} \]  
\[ B^{21} = \begin{bmatrix} 0 \end{bmatrix}_{L \times N} \]  

Finally, the output matrix, $C$, and the direct transition matrix, $D$, from the output equation are given by:

\[ C = \begin{bmatrix} I \end{bmatrix}_{(N+L) \times (N+L)} \]  
\[ D = \begin{bmatrix} 0 \end{bmatrix}_{(N+L) \times N} \]  

With the method derived it is possible to obtain a state-space model for a general DC grid. Due to the fact that the matrixes are derived from the information contained in the incidence matrix, this approach allows to easily change the grid topology.
Chapter 4

DC Voltage Control Methods

4.1 Introduction

When a MTDC system is concerned, the DC voltage control is indubitably one of the most important tasks of the VSC-HVDC transmission system. The DC voltage must be well controlled within stiff limits under all conditions in order to guarantee power balance between all transmission terminals inside the MTDC network. If the DC voltage increases excessively, it may trigger protection equipment (e.g. DC choppers plus resistors). Low DC voltage values can give rise to non-linear phenomena of PWM modulation and negatively affecting the linear stability of the control systems. Furthermore, a relatively large DC voltage drop might, temporarily, limit the capability of the AC voltage controller [67].

In most cases, in a point-to-point HVDC transmission system, one of the terminals controls the DC voltage of the transmission link while the other terminal controls the active power sent to the interconnection. However, when a MTDC network is considered, it may be very difficult to operate the system with just one converter station controlling the DC voltage, as in the previous case. This is due to mainly two reasons: limited power rating of the VSC station controlling the DC voltage and the possibility of faults in the AC network connected to that station which could trigger protection equipment within only a few cycles of the AC network. Therefore, giving the DC voltage control to more than one VSC station seems to be a better option to operate a MTDC system.

In future transnational offshore networks, several offshore wind farms and countries will be interconnected and different market dispatch schemes may be applied among the onshore stations to share the power from the wind farms as well as to perform power trade among them. There are three dispatch possibilities that may be applied: fixed power sharing, priority power sharing and proportional power sharing.

In order to have such dispatch possibilities, control strategies capable of performing different market dispatch schemes in the future transnational network are required. Besides the capability of performing different market dispatch schemes during normal operation, the control strategies have to be capable of acceptably performing during and after disturbances, e.g. voltage dip at an onshore grid or disconnection of an onshore station. Moreover, it is also required that the control scheme must be independent of the network topology to avoid unsuitable operation points upon changes in the network, e.g. expansion of the DC grid and subsequently addition of new transmission cables or temporary disconnection of an existing cable for maintenance purposes. Furthermore, if the control system requires communication, in order to perform the dispatch schemes, with an outer remote controller, such as a transmission system operator (TSO), it is important that the control strategy should be capable of performing acceptable operation during communication delays or failure.
4.2 Market dispatch schemes

In this section the market dispatch schemes are explained in detail. These schemes will be, most certainly, implemented in a future offshore transnational MTDC grid.

Fixed power sharing

When in fixed power sharing, one onshore station receives a fixed amount of active power and the other stations will balance the power generation variability of the offshore wind farms. The active power transmitted to the priority station may be generated at the offshore wind farms, come from the others onshore stations, or part of the power may be generated at the offshore wind farms and the rest of the power will be transmitted from the others onshore stations.

Priority power sharing

In priority power sharing, one station has priority in terms of transmitting the power generated by the offshore wind farms over the others onshore stations. Thus, it obtains all the offshore generated power up to a particular limit set by the system operators while the other stations receive the excess power to balance the DC voltage inside the grid.

Therefore, while the power delivered to the priority station does not reach the limit, the other onshore stations will not receive power from the wind farms.

Proportional power sharing

If a proportional power sharing scheme is implemented, the onshore stations share the power in a proportion set by the system operator. The supervisory controller measures the offshore power being generated and then calculates the amount of power that each station will receive according to the ratio defined, which may be changed from time to time.
4.3 DC voltage control methods

A number of control strategies have already been proposed in the literature to operate a multi-terminal VSC-HVDC network, such as a future transnational offshore network. In this thesis different DC voltage control methods will be analyzed and compared according to their capability of performing different market dispatch schemes.

- The first one is the voltage droop method. It uses a droop mechanism to control the DC voltage. Although, this method was initially developed for controlling MTDC networks using HVDC classic technology, it can also be applied for MTDC networks with voltage-source converters [44];

- The second control method is the ratio control. A power ratio between the rectifier stations is established and the converters will then share the power generated by the wind farms according to this ratio. The power transmission ratio between the stations can be set and varied by the system operators from time to time [42];

- The third strategy is the priority control. One onshore terminal has priority in terms of transmitting the power generated offshore over the others. Under this arrangement, the other onshore terminals will not transmit any power until the capability or the active power limit of the first terminal has been reached [43];

- The last analyzed control method is the so-called voltage margin method. In this method, each converter station in the system is given a DC voltage reference marginally offset, generating the voltage margin [34][45][46].

In the following sections of the present chapter, the DC voltage control methods will be explained and analyzed, considering, for the sake of simplicity, that there are only two DC voltage controlling stations as shown in Figure 4.1.

Figure 4.1: MTDC grid with two DC voltage controlling stations.
4.3.1 Voltage Droop Method

The voltage droop method was initially developed for controlling MTDC networks using HVDC classic technology. However, it can also be applied for grids composed by terminals using VSC technology. The droop control scheme for MTDC networks works in a similar way when compared to the one implemented in traditional AC systems, where the frequency droop is used for the control system to adjust the power of all generators in the network.

In order to guarantee power balance, the method employs a proportional controller which represents a droop characteristic describing a unique relation between the DC voltage and the converter’s current as shown in Figure 4.2. However, the droop characteristic is valid only for the network topology considered when the droop characteristics were established. Due to this fact the desired operation of the control strategy cannot be achieved using the same droop characteristic if the network topology is changed.

A margin of 3% was given between the minimum and maximum values of the DC voltage in the droop characteristics to prevent the control gain, $k_p$, from reaching excessive values. This because the droop of the characteristic is the inverse of the controller’s gain, and if an excessive value is chosen, instability may emerge in the DC voltage.

![Figure 4.2: DC voltage droop characteristic.](image)

Differently from the controllers presented in the Chapter 2, where a proportional-integral (PI) regulator is used to annul steady state errors, thus maintaining the DC voltage at its reference value, this method does not have the ability to keep the DC voltage at a predefined value. If the network DC voltage starts to increase, there will be a power surplus in the system and the DC voltage regulating stations should start to increase inversion operation to reestablish power balance. On the other hand, if the DC voltage starts to decrease, that means that there is a lack of power in the system and the DC voltage regulating stations should start to increase rectification.

The droop regulator is implemented so that the maximum and minimum values of the DC voltage occur at the maximum converter’s current. Although, the method provides the current reference for the q-axis, $i_q^*$, it actually tries to indirectly regulate the DC current, since:

\[
p_{ac} = e_di_d + e_qi_q \approx p_{dc} = v_{dc}i_{dc} \quad \text{if} \quad e_d \approx 0 \text{ pu}; e_d \approx 1 \text{ pu} \quad \text{and} \quad v_{dc} \approx 1 \text{ pu} \quad \Rightarrow \quad i_q^* \approx i_{dc}^* \quad (4.1)
\]
Fixed power sharing

With the voltage droop method it is difficult to perform fixed power sharing. Since with this strategy the controller adjusts the power delivered by the converter according to the value of the DC voltage, it is difficult to perform constant power control required by the fixed power sharing control scheme. This way, it would be impossible for a country connected to a transnational multiterminal grid to demand a certain amount of power during a certain period of time.

Priority power sharing

The voltage droop method is capable of performing priority power sharing dispatch scheme by implementing different droop characteristics among the onshore converter stations. The capability of the voltage droop method to perform such dispatch scheme as well as to perform acceptable operation during and after voltage dip at an onshore station and disconnection of a DC voltage controlling converter has been explored and shown in [43][68].

Since it is necessary to give higher DC voltage values to the terminals with less priority, if a priority scheme among the onshore stations is to be implemented, there is a limit of the amount of terminals that can be interconnected before the DC voltage values become excessively high.

In Figure 4.3 it is possible to see the droop characteristics of both onshore terminals. In order to perform priority power sharing (priority being given to station 1) the system operators have to set the minimum DC voltage value of the second station the same or higher than the maximum DC voltage of the first station \( V_{DC2}^{min} \geq V_{DC1}^{max} \).

\[
\begin{align*}
V_{DC1}^{max} & \quad \text{Rectifier} & \quad 0 & \quad \text{Inverter} & \quad -I_{DC}^{min} & \quad I_{DC} \\
+I_{DC} & \quad 0 & \quad -I_{DC} & \quad I_{DC}
\end{align*}
\]

\[
\begin{align*}
V_{DC2}^{max} & \quad \text{Rectifier} & \quad 0 & \quad \text{Inverter} & \quad -I_{DC}^{min} & \quad I_{DC} \\
+I_{DC} & \quad 0 & \quad -I_{DC} & \quad I_{DC}
\end{align*}
\]

Figure 4.3: \( V_{DC}(I_{DC}) \) characteristics for the Droop controller - Priority Power Sharing.

Proportional power sharing

With two static droop characteristics it is not possible for the TSO to change the power ratio between the DC voltage controlling stations. The next DC voltage control method, Ratio Control, employs a fixed droop characteristic for one of the onshore stations, while the other station is provided with a variable droop characteristic.
4.3.2 Ratio Control

In this control method the DC voltage controlling stations share the power being generated by the wind farms according to a certain ratio. The shared amount (ratio) between the two terminals can be set and varied by the system operators.

The difference between the ratio control method and the voltage droop method is that by changing the slope of one of the droop characteristics, while the other one is kept constant, the system operator can vary the power ratio between the two DC voltage controlling terminals [42]. In Figure 4.4 it is possible to see the DC voltage droop characteristics of both terminals.

![DC voltage droop characteristics of terminals 1 and 2.](image)

Figure 4.4: DC voltage droop characteristics of terminals 1 and 2.

As presented in Chapter 2, the DC power can be obtained according to:

\[ P_{DC} = V_{DC}I_{DC} \]  \hspace{1cm} (4.2)

Since, under normal operation, \( V_{DC} \) is approximately equal to its nominal value, it is possible to consider that the DC power is proportional to the DC current (\( P_{DC} \propto I_{DC} \)).

Then the transmitted power ratio, \( n \), between the two VSC stations is given by:

\[ \frac{P_1}{P_2} \approx \frac{I_{DC1}}{I_{DC2}} = n \]  \hspace{1cm} (4.3)

In steady-state operation, the following relation between the two DC voltages of the onshore stations is valid (see Figure 4.1):

\[ V_{DC2} = V_{DC1} + R_1I_{DC1} - R_2I_{DC2} \]  \hspace{1cm} (4.4)

where \( R_1 \) and \( R_2 \) are the resistances of the cables that are connected to the onshore stations 1 and 2, respectively.
However, in reality the values of $R_1$ and $R_2$ are not constant due to cable temperature variation. Thus, the accuracy of the power distribution may be affected. Nevertheless, in this thesis this phenomenon is not considered.

According to Figure 4.4, the DC droop characteristics are given by:

$$\begin{cases} 
I_{DC1} = k_1 \Delta V_{DC1} = k_1 (V_{DC1} - V_{DC1}^{min}) \\
I_{DC2} = k_2 \Delta V_{DC2} = k_2 (V_{DC2} - V_{DC2}^{min})
\end{cases} \tag{4.5}$$

where $k_1$ and $k_2$ are the slopes of the DC voltage characteristics.

It is possible to rearrange the equation (4.4) in order to obtain:

$$(V_{DC2} - V_{DC2}^{min}) - (V_{DC1} - V_{DC1}^{min}) = R_1 I_{DC1} - R_2 I_{DC2} \tag{4.6}$$

Substituting the DC voltages from equations (4.5) into (4.6), yields:

$$\frac{I_{DC2}}{k_2} - \frac{I_{DC1}}{k_1} = R_1 I_{DC1} - R_2 I_{DC2} \tag{4.7}$$

Finally, in order to guarantee that the transmitted power ratio, $n$, meets the one set by the operator, the relationship between the two droop characteristics under steady-state operation is given by:

$$\frac{I_{DC1}}{I_{DC2}} = \frac{R_2 + \frac{1}{k_2}}{R_1 + \frac{1}{k_1}} = n \Leftrightarrow k_2 = \frac{1}{\frac{n}{k_1} + n \cdot R_1 - R_2} \tag{4.8}$$

A disadvantage of this method is that it requires communication to perform power ratio among more than two DC voltage controlling stations. In order to accomplish power ratio, the system supervisor would require the amount of power being generated at the offshore stations, at all times, so to set the droop characteristics of each DC voltage controlling station.
4.3.3 Priority Control

The priority control is a modified way of using DC voltage droop controllers to perform priority power sharing. In this control strategy, one onshore terminal will have priority in terms of transmitting the power generated by the offshore wind farms over the other terminal. The terminal with the highest priority will control the DC voltage, by means of a PI regulator (see Chapter 2), until it reaches its rated capacity or a maximum power set point established by system operators. On the other hand, the second terminal employs a fixed DC voltage droop controller and it will receive the power surplus that could not be transmitted to the first terminal [42]. The DC voltage controllers are depicted in Figure 4.5.

If the total generated power by the offshore wind farms is lower than the rated power of the priority terminal, the DC voltage will be controlled at the predefined value and no power will flow through the second onshore station. However, if the total generated active power exceeds the power limit of the first terminal, it will no longer be capable of controlling the DC voltage in the MTDC network. As a consequence of the power unbalance, the DC voltage inside the system will start to increase.

Under such condition, the terminal using the droop control method is designed to transmit the extra power. To perform such dispatch scheme, the system operators need to set $V_{DC1}^{\text{min}}$ the same or higher than the peak value of station 1 during changes of operating point. The values for the DC voltage droop control have to take into account the grid characteristics, e.g. DC cable resistance variation and DC voltage dynamic peak values, in order to assure that the second terminal will only transmit power when the limit is reached in the first one. Moreover, system design rules, such as the DC voltage ratings of the VSC stations and of the DC cables have also to be taken into consideration [43].

Figure 4.5: $V_{DC}(P)$ characteristic of terminal 1 and DC voltage droop characteristic of terminal 2.
4.3.4 Voltage Margin Method

The basic control strategy of the voltage margin method consists of a DC voltage controller with a limiter at its output as shown in Figure 4.6. The DC voltage controller employs a PI controller (see Chapter 2). The limiter is applied to limit the q-axis current reference value to an upper value and a lower value, in order to prevent overcurrents in the converter valves. Thus, the active power flowing through the converter is also limited to an upper and a lower value. This way, the DC voltage controller will be able to keep the DC voltage equal to the reference value as long as the active power flowing through the converter is between the predefined limits.

![Figure 4.6: DC voltage controller and limiter present in the Voltage Margin Method.](image)

As previously presented in Chapter 2, the active power flowing through the converter can be obtained by:

\[ p_{ac} = e_d i_d + e_q i_q \]  \hspace{1cm} (4.9)

Therefore, the relationship between the lower limit of the q-axis current reference value and the converter’s inversion limit is given by:

\[ i_{q,\text{lower}}^* = \frac{P_{\text{lower}} - e_d \cdot i_d^*}{e_q} \]  \hspace{1cm} (4.10)

On the other hand, the upper limit of the q-axis current reference value is calculated as:

\[ i_{q,\text{upper}}^* = \frac{P_{\text{upper}} - e_d \cdot i_d^*}{e_q} \]  \hspace{1cm} (4.11)

where \(i_d^*\) is the d-axis current reference value provided by the reactive channel outer controllers; \(e_d\) and \(e_q\) are the PCC voltages in the \((dq)\) frame; and \(P_{\text{lower}}\) and \(P_{\text{upper}}\) are, respectively, the converter’s inversion and rectification limits. In Figure 4.7 it is shown the complete one-stage DC voltage controller.

The lower and upper values of the limiter are adjustable and may be set directly at the converter station or sent from a remote supervisory dispatch controller. By adjusting the lower and upper limits to the same value, the converter can perform constant power control and therefore, act as a passive constant load [46]. It is important to notice that the converter will not be able to control the DC voltage when the active power flowing through the converter exceeds the limits. Thus, if the converter is performing rectification and the active power exceeds \(P_{\text{max}}\) (see Figure 4.8) the DC voltage will drop since the converter has reached its rated power. On the other hand, if inversion is being performed at the station and if the power surpasses \(P_{\text{min}}\) the DC voltage will increase, since the converter will no longer be able to remove the required amount of energy from the system.

The characteristic presented in Figure 4.8 shows that the converter will keep the DC voltage equal to the reference value (B-C-D part of the presented voltage characteristic) as long as the active power flowing through the converter is kept between the limits. The converter will perform inversion when the operation point is in the B-C line and rectification when the operation point is in the C-D line.
However, when the active power flowing through the converter is equal to the lower limit, the controller will no longer be able to control the DC voltage and while the active power is maintained constant, the DC voltage will increase following the B-A line. On the other hand, when the active power flowing through the converter is equal to the upper limit, the control of the DC voltage will be lost and it will drop following the D-E line [45].

In a MTDC grid, the $V_{DC}(P)$ characteristic may be implemented in two or more DC voltage controlling converters. The DC voltage reference value of each converter can differ from the others by a voltage margin. In this way, the control of the DC voltage will be transferred from one station to another in a cascading effect. The DC voltage will start being controlled at the station with the lowest DC voltage reference and will be controlled, lastly, in the station with the highest DC voltage reference.

An example of the $V_{DC}(P)$ characteristics of two converters operating with a voltage margin is shown in Figure 4.9. Firstly, the converter 1 will be receiving power ($P_{1,lower}$) and the converter 2 will control the DC voltage inside the network. Thus, the operating point is the one represented in the figure as P. This is equivalent as a fixed power sharing, where the first station receives a fixed amount of active power.

However, if the offshore power production is higher than the one requested by station 1, the converter 2 will receive this extra power and the operation point will move to the left of P. If the maximum inversion is reached in the converter 2, the DC voltage control will be lost since both DC voltage controlling stations have reached their power limits. In such case the power output of the offshore wind farms has to be decreased. This may be done by dissipating the extra power in breaking resistors via a DC chopper, or
through fast reduction of the wind farms output power [48].

The voltage margin method is the only control strategy capable of performing fixed, priority and proportional power sharing, making this method a versatile and powerful control scheme [34]. However, in order to perform the different power schemes, it is necessary to implement a voltage margin method that employs more than one DC voltage stage.

**Two-stages DC voltage controller**

In order to achieve a more versatile and robust voltage margin method, a two-stage DC voltage controller may be applied. In this approach, as shown in Figure 4.10, two proportional-integral controllers are used [34][46].

When the VSC terminal tries to control the DC voltage at the first stage the DC voltage controller 1 is used. On the other hand, when the station is controlling the DC voltage at the second stage a new PI controller is employed (DC voltage controller 2). In Figure 4.10 it is possible to observe how these PI controllers are interconnected and Figure 4.11 shows the $V_{DC}(P)$ characteristic of the station and how it is achieved.

Figure 4.12 shows an example of a station using the two-stage voltage margin method. This controller is helpful when the second converter has reached its inversion limit. In this way, the DC voltage will start to increase due to the power imbalance (G-H line). Converter 1 will control the DC voltage using the second PI controller at $V_{DC1,H}$. The DC reference value of the second PI controller is set higher than the one of the first controller. Thus, the first controller will maintain the DC voltage equal to its reference value and perform operation in the first stage (D-E line) and when the DC voltage rises above the reference value of the second controller, it will automatically increase its inversion capability and will start controlling the DC voltage at the second stage. The operation point will then be situated in the B-C line.

**Fixed power sharing**

When in a fixed power sharing dispatch scheme, the $V_{DC}(P)$ characteristics of the stations have to be set by the TSO as presented in Figure 4.13. With such DC voltage controller, station 1 will act as a constant passive load absorbing a certain amount of active power, $P_{1,lower,1}$. On the other hand, station 2 will be responsible for controlling the DC voltage inside the MTDC grid.
Figure 4.10: Two-stage DC voltage controller.

Figure 4.11: $V_{DC}(P)$ characteristic of a station composed by two stages.

Figure 4.12: $V_{DC}(P)$ characteristics for two DC voltage controlling converters and the resulting operating point (P).
Priority power sharing

In order to perform priority power sharing the $V_{DC}(P)$ characteristics of the converters have to be the same as shown in Figure 4.14. In this way, the priority in receiving the active power generated offshore is given to station 1. Once station 1 reaches its inversion limit, $P_{1,lower}$, it will act as a constant passive load and station 2 will be responsible for controlling the DC voltage inside the MTDC grid.

Proportional power sharing

Differently from the ratio control method previously presented, even when there are only two DC voltage controlling stations, in order to perform proportional power sharing with the VMM, communication between the stations and a remote supervisory controller is required. The TSO measures the offshore power being generated and then calculates the amount of power that each station will receive according to the defined ratio. Then, the station with the lowest DC voltage reference will use that information to adjust its lower value of the limiter, $P_{2,lower}$. The $V_{DC}(P)$ characteristics of two stations performing proportional power sharing are shown in Figure 4.15.
Chapter 5

Simulation Results and Discussion

5.1 Introduction

In this chapter the results of the computer simulations performed using the software MATLAB/Simulink are presented and discussed in order to evaluate and validate the developed models and control structures. The VSC control system (i.e. inner current controller and outer controllers) is analyzed and tested in order to see if the performance of the system is as expected. Simulations using the implemented DC voltage control strategies are presented and discussed. It is shown the capability of the different DC voltage control strategies of performing different market dispatch schemes (fixed, priority and proportional power sharing) during normal operation. The developed model for the MTDC grid shown in Chapter 3 is used for all the simulations.

It is important to refer that, the outer controllers chosen for the onshore converters were the DC voltage controller for the active channel and the reactive power controller for the reactive channel. On the other hand, the offshore converter stations were set to control the active power and the amplitude of the PCC voltage.

For every simulation it is shown a chart with the DC voltage, active power, module of the voltage at the PCC, reactive power, module of the converter’s voltage, and the module of the converter’s current. All the mentioned AC quantities are presented in the \((dq)\) frame. The charts display the information for all the converter stations and the results are shown in pu.

All the results are plotted using the same axis values for the analyzed dispatch schemes and DC voltage control strategies. This may not be the better solution for a particular study case but it provides an important tool to easily and quickly compare the results obtained from the different case scenarios.

In the last part of the present chapter, the VSC-HVDC transmission model and control system are analyzed by submitting them to AC fault situations. The most common and demanding fault scenarios, the single-line-to-ground fault and the three-phase fault are simulated in order to test the capability of the VSC-HVDC model to return to the previous steady-state time shortly after the fault is cleared.
5.2 Case Study

In order to fairly compare the several control strategies, all the simulations were performed using the same DC grid. The 4 terminal DC grid used is shown in Figure 5.1. This grid is composed of two offshore wind farms and two onshore AC networks that could represent, for instance, two different countries. The grid is radially connected since the 4 stations are interconnected through a central point, A. In Table 5.1 all the system’s parameters used during the simulations are presented. It is important to refer that the chosen system base is the nominal power of the offshore VSC-HVDC, i.e. 500 MVA.

![Figure 5.1: 4 terminal radial MTDC network used in the simulations.](image)

<table>
<thead>
<tr>
<th>Model</th>
<th>Rated Voltage</th>
<th>Impedance</th>
<th>Rated Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Network 1</td>
<td>220 kV</td>
<td>0.002 + j0.235 pu</td>
<td>3500 MVA</td>
</tr>
<tr>
<td>AC Network 2</td>
<td>220 kV</td>
<td>0.002 + j0.235 pu</td>
<td>3500 MVA</td>
</tr>
<tr>
<td>Wind Farm 1</td>
<td>33 kV</td>
<td>0.005 + j0.1 pu</td>
<td>500 MVA</td>
</tr>
<tr>
<td>Wind Farm 2</td>
<td>33 kV</td>
<td>0.005 + j0.1 pu</td>
<td>500 MVA</td>
</tr>
<tr>
<td>Transformer (Onshore)</td>
<td>220 / 180 kV</td>
<td>0.005 + j0.1 pu</td>
<td>500 MVA</td>
</tr>
<tr>
<td>Transformer (Offshore)</td>
<td>33 / 180 kV</td>
<td>0.005 + j0.1 pu</td>
<td>500 MVA</td>
</tr>
<tr>
<td>Phase Reactors</td>
<td>180 kV</td>
<td>0.005 + j0.15 pu</td>
<td>N/D</td>
</tr>
<tr>
<td>Converters</td>
<td>AC Side: 180 kV</td>
<td>N/D</td>
<td>500 MVA</td>
</tr>
<tr>
<td></td>
<td>DC side: 400 kV</td>
<td>N/D</td>
<td></td>
</tr>
<tr>
<td>DC Capacitor</td>
<td>400 kV</td>
<td>N/D</td>
<td>N/D</td>
</tr>
<tr>
<td>DC Cable</td>
<td>± 200 kV</td>
<td>0.02 + j0.06 [Ω/km]</td>
<td>220 nF/km</td>
</tr>
<tr>
<td>DC Chopper</td>
<td>460 kV</td>
<td>N/D</td>
<td>500 MW</td>
</tr>
</tbody>
</table>

\(N/D\) - Field not defined.

In Table 5.2 it is possible to see the order of events used in the offshore wind farms during the simulations for the several DC voltage controlling strategies implemented. As it can be seen in the table no active power is produced before \(t=0.2\) s. At \(t=0.2\) s, the power production, at the first offshore wind farm, increases from 0 pu to 0.6 pu. At \(t=0.4\) s, the active power rises to 0.8 pu, while at \(t=0.8\) s, the production decreases to 0.5 pu. At the second offshore wind farm, the power production only starts at \(t=0.4\) s. At this instant the wind farm will start increasing its production to 0.4 pu. At \(t=0.6\) s, the generation will rise to 0.6 pu and it will be maintained at this value for the rest of the simulation. All the simulations are carried out for one second.
Table 5.2: Order of events in the offshore wind farms.

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>WF 1 Power [pu]</td>
<td>0</td>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>WF 2 Power [pu]</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

AC faults

AC faults will be simulated at onshore and offshore stations. Firstly, a three-phase AC fault at one of the DC voltage controlling stations will be simulated, presented and analyzed. Secondly, an one-phase AC fault will be simulated, once again, at one of the onshore stations. Lastly, a three-phase AC fault will be simulated at one of the offshore wind farms.

In Table 5.3 it is possible to see the order of events used in the offshore wind farms during these simulations. As it can be seen in the table, no active power is produced before t=0.1 s. At t=0.1 s, the power production, at both offshore wind farms, increases from 0 pu to 0.6 pu. At t=0.4 s, the active power being generated at the offshore wind farms is reduced by means of a fast reduction control method to 0.3 pu [48]. However, at t=0.6 s, the production is reestablish to the same value it had before the fault, being 0.6 pu generated at each wind farm, and it will be maintained at this value for the rest of the simulation. All the simulations are carried out for one second. The simulated faults occur at t=0.3 s and are cleared at t=0.5 s.

Table 5.3: Order of events in the offshore wind farms (fault scenario).

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>0</th>
<th>0.1</th>
<th>0.4</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>WF 1 Power [pu]</td>
<td>0</td>
<td>0.6</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>WF 2 Power [pu]</td>
<td>0</td>
<td>0.6</td>
<td>0.3</td>
<td>0.6</td>
</tr>
</tbody>
</table>
5.3 Simulation Results

In these simulations the controllers described in Chapter 2 were applied for the inner current controller and the outer controllers. However, the DC voltage controller is different for each simulation in order to compare the performance and capability of the several developed DC voltage controllers to perform the different market dispatch schemes.

5.3.1 Voltage Droop Method

In this simulation the voltage droop method with fixed droop characteristics will be employed in both onshore stations. With this control method, as previously explained, it is possible to implement the priority power sharing dispatch scheme.

Priority Power Sharing

In order to perform this dispatch scheme the DC voltage controllers displayed in Figure 5.2 were employed. Priority in receiving the power generated offshore was given to station 1. Therefore, station 1 will start receiving power when its DC voltage is higher than 1 pu and it will reach its rated power when its DC voltage is 1.03 pu. On the other hand, the second station will only start to transmit power when \( V_{DC2} = 1.04 \) pu and, therefore, station 1 will have already reached its rated power. Station 2 will reach its rated power when it has a DC voltage of 1.07 pu.

A margin of 3% was given between the minimum and maximum values of the DC voltage in the droop characteristics to prevent the control gain, \( k_p \), from reaching excessive values. This is because the slope of the characteristic is the inverse of the controller’s gain and if an excessive value is chosen, instability may arise in the DC voltage.

The simulation results in Figure 5.3 show that a priority scheme is applied among the onshore stations as desired. Initially there is no active power being generated at the offshore wind farms. However, at \( t = 0.2 \) s the wind farm 1 starts to transmit power to the grid. Therefore, the DC voltage inside the grid starts to increase. As it can be seen in the DC voltage chart (Figure 5.3 (a)), the first station starts to transmit power to reestablish the power balance. When station 1 reaches its rated power, around \( t = 0.4 \) s, station 2 starts to receive power. From \( t = 0.4 \) s until the end of the simulation, station 1 keeps its transmission in 1 pu and station 2 is the one responsible to keep the power balance inside the grid. This way it will deal with the variability in the power generation at the offshore wind farms. The stations are not able
to keep the DC voltage at its nominal value since DC voltage droop characteristics, i.e. proportional control, were employed.

In the AC voltage at PCC chart (Figure 5.3 (c)) it is possible to observe that at the wind farms this value is kept equal to its reference, 1 pu, while at the onshore stations this value varies with time since the converter stations are not controlling the AC voltage. Thus, the PCC voltage changes due to the fact that the stations are controlling the power factor at unity. In order to perform this control the onshore stations need to change the PCC voltage of the converters to values that annul the reactive power exchanged with their AC network. This way it is possible to see in the forth chart (Figure 5.3 (d)) that the reactive power is controlled at 0 pu in the onshore stations, while at the wind farms that does not occur. However, as it can be seen the reactive power exchanged is always lower than 0.1 pu during the complete simulation time.

One additional remark is that in the converter’s current chart (Figure 5.3 (f)) station 1 is receiving 1 pu of power but its converter’s current is slightly higher than 1 pu. This is due to the fact that the power is being controlled at the PCC and this voltage is not being controlled (the converter’s reactive power is being controlled instead) and as it can be seen in Figure 5.3 (c) it is lower than 1 pu. On the other hand, the power being received is 1 pu and so the converter’s current has to compensate for this difference. However, the overcurrent is less than 0.05 pu, which, momentarily, do not pose a threat to the converter IGBT valves.
Figure 5.3: Simulation results using the DC Voltage Droop Method - Priority Power Sharing.
5.3.2 Ratio Control

The ratio control method allows the system supervisor to change the power ratio between two onshore DC voltage controlling stations. In Figure 5.4 the $V_{DC} (I_{DC})$ characteristics implemented for this DC voltage control method are presented. These characteristics are similar to the ones implemented in the voltage droop control. As it can be seen, the voltage limits in the first station are set by the system operator and they may be fixed. On the other hand, the upper limit of the DC voltage of station 2 has to vary in order to change the slope of the characteristic, and therefore, the power ratio between the onshore stations.

![Figure 5.4: $V_{DC} (I_{DC})$ characteristics for the Ratio controller.](image)

In Table 5.4 the power ratios set by the system supervisor during the simulation are given. At $t=0.2$ s, it is defined that 30% of the power will be transmitted to onshore station 1 and the other 70% to the second station. At the instant $t=0.4$ s, the ratio changes to 50/50 which means that the power is equitably divided among the onshore stations. At $t=0.6$ s, the first station starts to receive 60% of the DC power. Thus, for the first time in the simulation, station 1 will receive more power than the second station. Finally, at $t=0.8$ s, the power ratio is set, once again, to 50/50.

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>30/70</td>
<td>50/50</td>
<td>60/40</td>
<td>50/50</td>
</tr>
<tr>
<td>$V_{max}^{DC2}$ [pu]</td>
<td>1.012</td>
<td>1.040</td>
<td>1.065</td>
<td>1.040</td>
</tr>
</tbody>
</table>

In Table 5.4 are also present the values, in pu, of the inversion limit of the second onshore station. It is possible to observe that when it is desired to transmit more power to the second station its inversion limit is set lower (1.012 pu) than the one of the first station (1.040 pu). However, $V_{max}^{DC2}$ is set higher, 1.065 pu, when the station is receiving only 40 of the total power generated offshore. Finally, when a 50/50 ratio is set, the limit of the second station is the same as the one in the first station, 1.040 pu.

It is worth mentioning that this power ratio is obtained with these voltage droop characteristics because the DC cables that connect both onshore stations to the central point of the MTDC grid have similar characteristics and length. Otherwise, the limits of the voltage droops would have to be different in a way that they would compensate the difference in the DC cables and therefore the difference in the power conduction.

In the active power chart of Figure 5.6 (b) it is possible to observe that the desired power ratio, $n$, is achieved during the simulation. However, the power division is not exactly equal to the value established by the power ratio coefficient, having a precision above 95%. This phenomenon is due to fact that the
MTDC grid has power losses.

At the instants where $V_{\text{max}}^{\text{DC}}$ is changed, there are transients in the responses, specially at the PCC voltages and, thus also the converter voltages. However, these transients do not last long (less than 50 ms) and the VSC is able to achieve a new operating point that allows the desired power ratio set by the system operator.

### 5.3.3 Priority Control

As it can be observed in Figure 5.5, the DC voltage reference set for the first onshore station is 1 pu. On the other hand, the second station starts transmitting power only when its DC voltage reaches 1.04 pu. A margin between the DC voltage references is given in order to guarantee that the first station has priority over the generated power and that the second station only starts to transmit power after the first one has reached its inversion power limit.

![Figure 5.5: $V_{\text{DC}}(P)$ characteristics for the Priority controller.](image)

In the DC voltage chart (Figure 5.7 (a)) it is shown that, when the station that employs the PI controller is controlling the DC voltage inside the grid, the steady state error is null. At t=0.2 s the DC voltage has an overshoot of 4% higher than its reference, but it is brought back by the onshore station 1 to its reference of 1 pu after 200 ms.

At t=0.4 s the priority station reaches its rated power limit and consequently loses the control over the DC voltage. Thus, the DC voltage starts to increase due to the power imbalance. When the DC voltage of onshore station 2 reaches 1.04 pu, that station starts to control the DC voltage and power starts to be transmitted to it. However, the DC voltage is not kept at its nominal value anymore due to the fact that a DC voltage droop is implemented in this station and it does not have the same capacity as a PI regulator to control the DC voltage at a fixed level.

Once more, the converter’s current of station 1 is slightly higher than 1 pu when 1 pu of power is being transmitted to it. This is due to the fact that the power is being controlled at the PCC with unity power factor. It can be seen in Figure 5.7 (f) that the PCC voltage is lower than 1 pu and therefore, the converter’s current has to compensate for this difference. However, this overplus in the current is lower than 0.05 pu, which, momentarily, do not pose a threat to the converter IGBT valves.
Figure 5.6: Simulation results using the Ratio Control - Proportional Power Sharing.
Figure 5.7: Simulation results using the Priority Control - Priority Power Sharing.
5.3.4 Voltage Margin Method

Fixed Power Sharing

In fixed power sharing dispatch scheme, the first onshore station receives a constant active power during the entire simulation time, which means it is not helping to control the DC voltage of the MTDC. The active power may be generated at the offshore wind farms, be transferred from the other onshore station, or a combination of both. In order to achieve such dispatch scheme, the $V_{DC}(P)$ characteristics displayed in Figure 5.8 are employed.

The limits $P_{1,lower,1}$ and $P_{1,upper,2}$ are set the same and equal to 0.5 pu. Therefore the first station will receive 0.5 pu of active power. The onshore station 1 only starts to receive active power at $t=0.1$ s. However, if station 2, which is controlling the DC voltage inside the grid, saturates, the first station will start receiving more active power. Such situation is possible due to the presence of the second-stage PI controller employed in the DC voltage controller of the first converter station.

In the DC voltage chart (Figure 5.9 (a)), it is shown that the steady state error is null since both station employ PI controllers. However, only the second onshore station is controlling the DC voltage since the first one is operating as a fixed load.

In Figure 5.9 (b) it is possible to observe that the first station receives 0.5 pu of power and the second station is the one responsible for keeping the power balance inside the MTDC grid. Therefore, the second station deals with the power variations from the offshore wind farms. At the beginning since no active power is being produced offshore, station 2 generates 0.5 pu plus the system losses to keep the power balance. However, at $t=0.2$ s, WF 1 starts to produce 0.6 pu. Therefore, the second station alters its operation point and it starts to operate in inversion mode.

Figure 5.8: $V_{DC}(P)$ characteristics for the Voltage Margin Method - Fixed Power Sharing. 
Figure 5.9: Simulation results using the Voltage Margin Method - Fixed Power Sharing.
Priority Power Sharing

In this dispatch scheme station 1 has priority in transmitting 0.6 pu \( P_{1,lower,2} \) of active power (see Figure 5.10). Therefore, the first station will transmit all the offshore generated power until it reaches its inversion limit. Then, the second onshore station will start to control the DC voltage inside the grid and, therefore, it will be the one to deal with the power variations offshore. In Figure 5.10 it is shown that when no power is being produced at the wind farms, both onshore stations will not transmit any active power.

\[
P_{1,lower,2} = P_{1,upper,2} = P_{max}
\]

Figure 5.10: \( V_{DC}(P) \) characteristics for the Voltage Margin Method - Priority Power Sharing.

In the active power chart (Figure 5.11 (b)) it is shown that, at \( t=0.2 \) s, the commanded power flow is achieved after 30 ms. It is worth mentioning that at \( t=0.3 \) s, station 2 starts to transmit power in order to reduce the DC voltage to its reference \( V_{DC2,H} \) of 1.01 pu (see Figure 5.10). However, when the power balance is achieved, station 2 stops receiving power because station 1 has priority in receiving the power being generated offshore.

At \( t=0.4 \) s, more power starts being generated offshore and, because of that, the DC voltage has a peak of ca. 8% higher than its nominal value. This value is the double of the value observed with priority control method. Since with the VMM the PI controllers are in cascade the second PI controller bandwidth gets reduced and, therefore, this leads to a slower response.
Figure 5.11: Simulation results using the Voltage Margin Method - Priority Power Sharing.
Proportional Power Sharing

In proportional power sharing, the second onshore station has priority in transmitting a certain amount of active power generated offshore. The value, \( P_{2,\text{lower}} \), can be the rated power of the station and it may be changed by the system supervisor during normal operation (see Figure 5.12). Therefore, the first station will control the DC voltage and it will transmit the power that exceeds the one requested by the other station minus the system’s losses. When no power is being produced at the wind farms, \( P_{2,\text{lower}} \) is set to 0 pu, thus both onshore stations will not transmit any active power. Such situation is depicted in Figure 5.12. The power ratios during the simulation are the same as the ones presented in Table 5.4.

![Converter 1 and Converter 2](image)

Figure 5.12: \( V_{DC}(P) \) characteristics for the Voltage Margin Method - Proportional Power Sharing.

In the DC voltage chart (Figure 5.13 (a)) it is possible to observe that the maximum DC voltage peak is less than 3% the nominal value. The DC voltage reference is the one of the first station, 1 pu. Although the second station has a smaller DC voltage reference, it is always working at its inversion limit. Therefore, station 1 has to balance the power inside the grid. Since station 1 employs PI controllers for the DC voltage, there are small overshoots in its active power chart. This is due to the fact that the converter is controlling the DC voltage in such a way that the steady state error is annulled.

It is possible to see that the active power chart is similar to the one obtained with the ratio control method, meaning that, once again, the power ratios were followed during the simulation.

The voltage margin method needs communication with a system supervisor since the value \( P_{2,\text{lower}} \) needs to be set when there is the desire to alter the power ratio or when the generated offshore power changes.
Figure 5.13: Simulation results using the Voltage Margin Method - Proportional Power Sharing.
5.3.5 Onshore AC faults

Three-phase AC fault

The DC voltage controllers presented in Figure 5.14 were employed at the onshore stations. Therefore, they will control the DC voltage inside the MTDC grid at 1 pu, annulling the steady state error while the active power generated at the offshore wind farms does not surpass the inversion limits of the onshore stations. Since the DC voltage references and the DC cables that connected both onshore stations to the central point of the MTDC grid are the same and have the same length (see Figure 5.1), a proportional power sharing will be applied, going 50% of the active power generated offshore to each DC voltage controlling station.

\[
\begin{align*}
V_{DC1} & = V_{DC1}^* \\
V_{DC2} & = V_{DC2}^*
\end{align*}
\]

Figure 5.14: \(V_{DC}(P)\) characteristics for the DC voltage controllers.

It is possible to observe in the active power chart (Figure 5.15 (b)) that while the AC fault occurs in the onshore station 1, between \(t=0.3\) s and \(t=0.5\) s, no active power is transmitted to that station. A total of 1.2 pu of active power is being generated at the offshore wind farms when the fault occurs. Therefore the onshore station 2 is not able to receive all the power (it saturates in 1 pu), and as it can be seen in the DC voltage chart (Figure 5.15 (a)) a voltage peak of 10% higher than its nominal value occurs around \(t=0.35\) s. After the fault is cleared, at \(t=0.5\) s, the onshore station 1 is able to receive active power once again.

The DC chopper present at the onshore station 1 was set to start to dissipate active power in the resistors when its DC voltage reached the value of 1.10 pu. Therefore, when the DC voltage of the station 1 reaches 1.10 pu, around \(t=0.35\) s, the DC chopper’s current starts to increase as it can be seen in Figure 5.15 (h). The DC chopper receives active power during 50 ms in order to bring the DC voltage inside the MTDC grid to its reference of 1 pu.

In Figure 5.15 (c) the voltage at the PCC is presented. It is observable that during the fault its value drops to 0.1 pu. On the other hand, the AC voltage of the converter also drops, however, the converter is able to maintain it’s AC voltage at 0.2 pu (Figure 5.15 (e)). Therefore, during the AC fault the converters sends reactive power to the PCC in order to help to restore the voltage. This is shown in the reactive power chart, 5.15 ((d), since the reactive power is negative during the fault in the station 1. This means that reactive power is being generated at the converter and sent to the PCC.

In the AC converter’s current chart (Figure 5.15 (f)) it is shown that after the fault is detected the control system reduces the fault current to half of the maximum load current in order to minimize the short-circuit current contribution to the AC system and to protect the valves of the converter from overcurrents. During the fault the priority is given to the d component of the current in order to support voltage restoration.
In Figure 5.15 (g) it is shown the DC current provided by the converter. As it can be seen the DC chopper’s current it is not present in the chart. Therefore, the current that flows through the DC chopper does not come from the converter but from the MTDC grid as observable in the DC cable current’s chart (Figure 5.15 (i)).

In the last chart (Figure 5.15 (j)) it is shown the grid’s AC voltage in pu in the converter’s base. Both components of the voltage are 0 pu during the AC fault since a three-phase fault was simulated.
Figure 5.15: Simulation results of a onshore three-phase AC fault.
One-phase AC fault

The DC voltage controllers presented in Figure 5.14 were employed at the onshore stations. In this simulation a one-phase AC fault was applied to the AC grid of the onshore station 1. Once again, the fault started at t=0.3 s and it was cleared at t=0.5 s. The simulation results are shown in Figure 5.16.

In the active power chart (Figure 5.16 (b)) it is possible to see that, oppositely to what was observed in the three-phase fault, the onshore station 1 does not stop receiving active power during the fault.

Important to refer that the charts of Figures 5.16 (c) and (e) show the average of the amplitude of the voltages at the PCC and of the converter, respectively. As it is observable in Figure 5.16 (e), the voltage at the PCC drops to approximately 0.7 pu. This result was expected since the system maintains two healthy phases. In reality the voltage at the PCC is oscillatory. Therefore, the AC voltage of the converter and the active and reactive powers are also oscillatory. This phenomenon occurs due to the fact that it is not possible to achieve a synchronous rotative frame with the AC grid’s voltage since one the phases is zero during the fault. However, the PCC and converter’s voltages do not drop as much as they did in the three-phase AC fault simulation.

At t=0.5 s, after the fault’s clearance, the oscillatory response at the PCC voltage stops. Therefore, the active and reactive power are no longer oscillatory.

Due to the fact that the onshore station 1 continues to receive active power during the fault, the DC voltage inside the grid does not increase as much as it would be necessary to make the DC chopper to start dissipating active power in the resistors.

Once again the control system, as soon as the fault is detected, set the converter’s current limit to 0.5 pu. Therefore, the converter valves are protected against overcurrents and the short-circuit current contribution to the AC system is minimized. During the fault the priority is given to the d component of the current in order to give priority to voltage restoration.
Figure 5.16: Simulation results of a onshore one-phase AC fault.
5.3.6 Offshore AC faults

Three-phase AC fault

The DC voltage controllers presented in Figure 5.14 were employed, once again, at the onshore stations in this simulation.

A three-phase AC fault was applied to offshore wind farm 1. The simulation results are shown in Figure 5.17.

As it can be seen in the active power chart (Figure 5.17 (b)) the offshore wind farm 1 does not produce any active power between $t=0.3$ s and $t=0.5$ s. However, when the three-phase is cleared at $t=0.5$ s, the wind farm starts to transmit power once again to the MTDC grid.

A proportional power sharing of 50% was applied among the onshore stations during the simulation, thus half of the active power being generated offshore is transmitted to each DC voltage controlling station.

In Figure 5.17 (c) the voltage at the PCC is presented. It is observable that during the fault it drops to 0.05 pu. On the other hand, the AC voltage of the converter also drops, however, the converter is able to maintain it’s AC voltage around 0.2 pu. Therefore, during the AC fault the converters sends reactive power to the PCC in order to help to restore the voltage. This can be seen in the reactive power chart (Figure 5.17 (d)) since the reactive power is negative during the fault, meaning that reactive power is being generated at the converter and sent to the PCC.

Once again, as soon as the fault is detected, the control system set the converter’s current limit to 0.5 pu. Therefore, the converter valves are protected against overcurrents and the short-circuit current contribution to the wind farm is minimized. During the fault the priority is given to the $d$ component of the current in order to support voltage restoration.
Figure 5.17: Simulation results of a offshore three-phase AC fault.
5.4 Comparison of the DC voltage control methods

In this section a comparison between the several DC voltage control methods implemented is presented. In Table 5.5 the capability of the control method to perform the different dispatch schemes is shown.

It is important to refer that the Ratio Control is able to perform proportional power sharing without communication if there are only two onshore DC voltage controlling stations connected to the MTDC grid. However, as presented in Table 5.5, it is considered that the method actually requires communication. Since future MTDC networks will most likely have more than two DC voltage controlling stations, the method will require communication between them to share the total amount of offshore power being produced at all times. On the other hand, the VMM requires communication to perform proportional power sharing independently of the number of onshore stations.

<table>
<thead>
<tr>
<th>Onshore station</th>
<th>1st</th>
<th>2nd</th>
<th>1st</th>
<th>2nd</th>
<th>1st</th>
<th>2nd</th>
<th>1st</th>
<th>2nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controllers</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Fixed</td>
<td>Variable</td>
<td>Fixed</td>
<td>2-stage</td>
<td>Fixed</td>
<td>2-stage</td>
</tr>
<tr>
<td>Control Method</td>
<td>Droop</td>
<td>Ratio</td>
<td>Priority</td>
<td>Voltage Margin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Priority</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportional</td>
<td>−</td>
<td>+∗</td>
<td>−</td>
<td>+∗</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(+) - The DC voltage control method is able to perform the dispatch scheme. 
(−) - The DC voltage control method is not able to perform the dispatch scheme. 
(∗) - needs communication to perform that particular dispatch scheme.

In Table 5.6, the main characteristics of each method are presented. The methods are compared accordingly to their dynamic response, expandability, flexibility, and the communication requirement.

The dynamic response reflects the speed with which the control method is able to minimize the transient response of the DC voltage inside the MTDC grid with regard to the power variability from the onshore wind farms. The expandability represents the possibility of controlling the DC voltage in MTDC grids with a considerable number of nodes, while the flexibility characterizes the capability of each DC voltage control strategy to perform the dispatch schemes. Finally, the communication requirement reflects the need of each method for external data input to perform the dispatch schemes.

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Dynamic Response</th>
<th>Expandability</th>
<th>Flexibility</th>
<th>Communication Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droop</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Ratio</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Priority</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Voltage Margin</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Conclusions

Europe will benefit from the development of offshore wind power in many aspects. Firstly, the dependency of the fossil fuel in the electricity production will decrease. Secondly, this offshore development will reduce the \( CO_2 \) emissions which meets the international engagements face to the climate changes.

The offshore development in the North Sea will include a DC interconnection between several countries. Therefore, standardization is necessary to make it possible for early built DC transmissions to be part of a future HVDC grid. For the offshore HVDC grid the types of HVDC converter and DC voltage must be standardized.

This thesis presented a four terminal MTDC network linking two onshore grids and two offshore wind farms through a radial DC grid. The main focuses were the development of a control system for the stations, the creation of a model for the DC grid and the implementation of several strategies to control the DC voltage of the stations that would allow the trade of energy accordingly different criteria between the interconnected countries. The system was simulated in order to evaluate the model’s legitimacy and accuracy. Simulink/MATLAB was the simulation tool employed.

When DC connections are concerned, two technologies are available: LCC-HVDC and VSC-HVDC. When VSC technology is used, active power ratings are relatively lower when compared with those that are possible to achieve with HVDC classic. This is the main reason why the latter is still preferred over the first for bulk DC transmissions. On the other hand, VSC technology is suited for the offshore transmission because of the smaller size of the converter which allows an easier and cheaper installation on an offshore platform. Furthermore, this technology offers a significant advantage: the control of the active power independently of the reactive power.

With the use of different modulation techniques the VSC can independently control the active power flowing through the transmission system as well as the reactive power being exchanged with the connected AC network. Therefore, different types of controllers and strategies can be used depending on the environment chosen for the VSC-HVDC to operate. In this thesis, for the onshore stations the DC voltage control was set for the active channel and the reactive power exchanged with the connected AC network was the control chosen for the reactive channel. On the other hand, at the offshore stations, the controls used were the active power generated at the wind farms for the active channel and the module of the AC voltage at the PCC of the stations for the reactive channel.

The AC side of the VSC station was modeled as a controllable voltage source (where frequency, phase angle and amplitude can be controlled independently) connected to an AC transmission network through series reactors (transformer and phase reactor). On the other side, the DC part of the VSC link was
modeled as a controllable current source, controlled by instantaneous power balancing between the AC and the DC side.

The VSC-HVDC control system structure was based on an inner current loop in combination with different outer controllers. The purpose of the inner current controller is to guarantee that the AC current flowing through the series reactance corresponds to the AC current reference without exceeding the converter maximum current. The outer controllers are responsible for giving the inner current controller the AC current reference values. The outer controllers include the already mentioned controls: reactive power controller, the AC voltage controller, the active power controller, and the DC voltage controller.

The results of the simulations show that the system response is fast and the controls implemented accurate. Active and reactive power can be controlled independently and flow bi-directionally: from the AC network to the DC grid or the opposite.

The harmonic distortion caused by the switching of the converter valves has been neglected. This assumption is possible since as explained in this thesis, the harmonic content of the VSC-HVDC voltages, and therefore also of its currents, can be kept really low by the use of PWM techniques as well as AC filters. Furthermore, the presence of series reactance between the station and the connected AC network also contributes to the minimization of the harmonic distortion.

In this thesis several controllers for the DC voltage were implemented with the objective of studying their performance and capability to perform several market dispatch schemes: fixed, priority, and proportional power sharing.

The voltage droop control method is able to perform priority power sharing dispatch scheme. In order to give priority to one of the onshore stations it is necessary to set the droop characteristic of the other onshore station higher. Therefore, the priority station will transmit all the offshore generated power until it reaches its limit. Then, the second onshore station starts to control the DC voltage inside the grid. The extension of the voltage droop method to MTDC networks with more than two onshore stations should be straightforward. The disadvantage of this control method as presented, is that it is not able to perform fixed power sharing, i.e. the transmission of a constant power to a particular station in the network is not possible.

Since the slope of the voltage droop characteristic is equivalent to a proportional control, the dynamic behavior of the active power is given by the inner current controller loop, which has fast dynamics. Therefore, the changes in the DC voltage occur almost instantaneously.

If the ratio control is employed, a static droop characteristic is set to one of the stations and a dynamic one to the other onshore station. In the case study, the power ratio (n) between the onshore stations varied during the simulation. The simulation results show that the power division is not exactly equal to the value established by the power ratio coefficient, however, the precision is high and above 95%. This phenomenon is due to the fact that the DC grid has losses. In addition, the analytic expression depends on the resistance of the DC cables, which may vary, further affecting the method’s accuracy. It is possible to perform the desired power ratio without the need for communication if one of the two onshore stations employs a fixed voltage droop characteristic. However, expandability is a downside of the ratio control method since it is difficult to achieve an analytic expression for the power ratio when more than two DC voltage control stations are connected to the DC grid.

In the priority control method the first onshore terminal will control the DC voltage at a reference value until it reaches its rectification limit. The DC voltage steady-state error is null when the station that employs a PI controller is in charge of controlling the grid voltage. When the first terminal saturates, the second terminal starts receiving the exceeding power from the wind farms and the DC voltage varies according to the droop characteristic of the second terminal. The priority control strategy is interesting
for small MTDC networks where a specific country wishes to have precedence over the power produced by its wind farms and is willing to sell the exceeding power to neighbor countries connected to the DC grid.

The last control strategy considered in this thesis was the voltage margin method. Among the methods compared it is the one with highest flexibility since it is possible to implement all the dispatch schemes, thus emulating the other DC voltage control strategies presented. The VMM is capable of performing fixed power sharing and priority power sharing without depending on communication. However, in order to perform proportional power sharing the control strategy requires communication with a supervisory controller that will set the inversion limit of one of the onshore stations, accordingly.

While the other DC voltage control strategies have shown maximum DC voltage transients up to 4% higher than the nominal voltage, for the VMM these transients were somehow higher, with the highest overvoltage being of 8% higher than the nominal value in case of power imbalances inside the MTDC grid. The reason for the worse transient response of the VMM could be because this method employs cascaded PI controllers.

Although, the voltage droop control was dependent on the grid typology, the voltage margin method is capable of performing DC voltage control interchangeably among the assigned converters and may work without necessarily depending on the topology of the network [46].

Extending the voltage margin method to MTDC networks with a higher number of terminals should be easier to accomplish than for the Ratio or Priority controllers. However, with a limited DC voltage normal operating range, e.g. ±5% the nominal voltage, the maximum number of terminals that can be controlled by the VMM may be limited to prevent adverse interaction between the controllers of each terminal due to possible too low voltage margins.

In every DC voltage controller with a droop characteristic, margins were given between the minimum and maximum values of the DC voltage to prevent the control gain from reaching excessive values. Otherwise, the DC voltage can display an oscillatory or even have an unstable behavior.

It is important to notice that during the simulations, some of the generated active power is lost in the DC cables due to their resistance. Thus, the power received onshore does not match the active power generated offshore.

The most common and demanding AC fault scenarios, one-phase and three-phase faults, were also simulated in order to test the capability of the VSC-HVDC model to maintain the link properly functioning throughout the whole simulation time without disturbing the voltages on the non-faulted station and to observe if the system returns to the previous steady-state condition shortly after the fault is solved.

Independently of the type of fault considered the VSC demonstrated its capability of recovering from the fault, returning to the previous operating point shortly after the disturbance was cleared.

The DC choppers were installed in the DC voltage controlling stations since it is cheaper to install them onshore. The DC chopper did not work for longer than 50 ms each time in order to avoid over-heating the resistors.

Wind energy is a mature technology yet it is still increasing all over the world. As the onshore wind power locations are becoming scarcer, countries are now starting to install offshore wind turbines, where space is more abundant and the wind has higher speeds. The perspective of an offshore DC grid connecting several countries in the North Sea has been in active consideration in the last years. Therefore, most probably, a MTDC offshore grid will be built in the next decade.
Future work

Some aspects related with the VSC-HVDC technology that were not taken into consideration in this thesis and could be subject for future work are:

- Implementation of a frequency control system. The frequency control is possible when the VSC is connect to weak networks or passive loads, i.e. the VSC is the main source of power. The frequency control in this case is obtained by varying the frequency of the valve pulse firing sequence in the PWM technique;

- The standard 2- or 3-level VSC technology has no way of limiting DC fault currents due to the presence of the free-wheeling diodes. Therefore, the presence of DC breakers in the model is needed if DC faults are to be simulated;

- In order to perform proportional power sharing with more than two stations, the control strategy requires a supervisor that sends information to the onshore stations. In this thesis, communication delay was not considered. Therefore the capability of the control strategy to perform proportional power sharing under a communication delay demands further exploration;

- Combination of the MTDC model with more realistic model of wind farms with different turbine technologies;

- Test the capability of the MTDC on performing black-starts;

- The VSC capability chart was not implemented. However, its presence is very important since it prevents the stations from working in overloaded operation points;

- In order to validate the control system developed in this thesis, an experimental setup should be implemented.
Bibliography


Appendix

Appendix A - Park Transformation

\[ e_s - v_c = R_T \cdot i_c + L_T \cdot \frac{d}{dt} (i_c) \]  \hspace{1cm} (6.1)

The above equation describes the current flowing through the series reactors in the AC side of the converter and can be rewritten in the \((\alpha\beta_o)\) reference frame by performing the Clark Transformation [63]:

\[ x_{\alpha\beta_o} = T \cdot x_{abc} \hspace{1cm} with \hspace{1cm} T = \begin{pmatrix} \frac{\sqrt{2}}{3} & -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \]  \hspace{1cm} (6.2)

Since the Clark transformation does not involve time dependent variables, the equation (6.1) can be formally re-written in the new reference frame:

\[ e_{\alpha\beta_o} - v_{\alpha\beta_o} = R_T \cdot i_{\alpha\beta_o} + L_T \cdot \frac{d}{dt} (i_{\alpha\beta_o}) \]  \hspace{1cm} (6.3)

However, in order to simplify the control, another transformation is performed to a new synchronously rotating coordinate system, which will remove the rotation of the voltage and current vectors to make them constant in steady-state. The rotation transformation is defined as:

\[ x_{dqo} = R(\theta) \cdot x_{\alpha\beta_o} \hspace{1cm} with \hspace{1cm} R(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta & 1 \\ \sin \theta & \cos \theta & 1 \\ 1 & 1 & 1 \end{pmatrix} \]  \hspace{1cm} (6.4)

\[ R^{-1}(\theta) = R^T(\theta) = R(-\theta) \]  \hspace{1cm} (6.5)

where \(\theta\) is the AC network voltage angle, provided by a PLL. The 0 subscript indicates the homopolar sequence, which generally is not present since in VSC-HVDC transformers isolated-star connections on the secondary side are usually made. In Figure 6.1 it is depicted the relationship between the \((\alpha\beta)\) and \((dq)\) frames.

In this transformation, \(R(\theta)\) is time dependent because \(\theta\) is time dependent. Since the \((dq)\) frame is rotating with respect to the fixed \((\alpha\beta)\) frame, electromotive forces terms of motional nature will emerge. This way the VSC equation (6.1) cannot be the same in the new \((dq)\) frame as happened in the \((\alpha\beta)\) frame. The VSC equation then becomes:
The difference between the VSC equation in the $(dq)$ frame is the last term, which concerns the derivative of the converter’s current. Evaluating this last term yields:

\[
L_T \cdot R(\theta) \left( \frac{d}{dt} \left( R^{-1}(\theta) \cdot i_{dq} \right) \right) = L_T \cdot R(\theta) \cdot \frac{d}{dt} \left( R(-\theta) \cdot i_{dq} + L_T \cdot R(\theta) \cdot R(-\theta) \frac{d}{dt} (i_{dq}) \right)
\]

\[
\Rightarrow L_T \cdot \left( \begin{array}{cc} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{array} \right) \cdot \frac{d}{d\theta} \left[ \left( \begin{array}{cc} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{array} \right) \right] \cdot \frac{d}{dt} (-\theta) \cdot i_{dq} + L_T \cdot \frac{d}{dt} (i_{dq})
\]

\[
\Rightarrow L_T \cdot \left( \begin{array}{cc} 0 & 1 \\ -1 & 0 \end{array} \right) - \omega \cdot i_{dq} + L_T \cdot \frac{d}{dt} (i_{dq}) = + j\omega L_T \cdot i_{dq} + L_T \cdot \frac{d}{dt} (i_{dq})
\]

Finally, the VSC equations, one for the $d$-axis and one for the $q$-axis, in the $(dq)$ frame, to include the new developed terms are:

\[
\begin{cases}
e_d - v_d = R_T \cdot i_d + L_T \cdot \frac{d}{dt} (i_d) - \omega L_T \cdot i_q \\
e_q - v_q = R_T \cdot i_q + L_T \cdot \frac{d}{dt} (i_q) + \omega L_T \cdot i_d
\end{cases}
\]
Appendix B - Anti-Windup

In practical applications, proportional-integral-derivative (PID) controllers are among the most commonly applied control structures. PID controllers are often the controller of choice due to their simplicity in tuning for their performance and robustness requirements. In addition they have the ability to achieve zero steady state error in the presence of disturbances. A PID is described by the following transfer function in the s-domain:

\[ G(s) = P + I + D = K_p + \frac{K_i}{s} + K_d \cdot s \]  

(6.9)

where \( K_p \) is the proportional gain, \( K_i \) is the integration coefficient, and \( K_d \) is the derivative coefficient.

The performance of PID controllers can be highly limited in practical cases by the presence of saturation of the system input (see Figure 6.2), which causes integrator windup, giving rise to closed-loop instability, longer settling of the output signal and overshoots.

When a reference change is applied, the output of the PID controller might attain the limits during the transient response. In this case the system operates as in the open-loop case, since the system's input is at its maximum (or minimum) limit, independently of the system output value. The error decreases slower than the ideal case (without saturation) and therefore the integral term becomes large (it winds up). Thus, even when the system variable is equal to the reference signal, the controller will still be saturated due to the integral term.

The typical method to deal with the integrator windup problem is to tune the PID controller to ignore the saturation and subsequently to add an anti-windup compensator to prevent the degradation of performance. In this context, several techniques have been developed to design the compensator [38]. They can be distinguished in two different approaches: conditional integration in which the value of the integrator is kept constant when certain conditions are verified, and back-calculation where the difference between the PID output and the actual system input is fed back to the integral term.

With the conditional integration approach, as explained above, the integral term is only increased when certain conditions are satisfied, otherwise it is kept constant (for this reason this method is also called integrator clamping). The different options are described in the literature [37]. The implemented method is depicted in Figure 6.3.

---

*Figure 6.2: General control scheme with saturation.*

*Figure 6.3: Anti-windup implemented: Integrator clamping.*
Appendix C - State-space model

The differential equations of a linear system can be written in the form:

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}
\]  
(6.10)

This system of first-order differential equations is known as the state equation of the system, where \(x(t)\) is the state vector and \(u(t)\) is the input vector. The second equation is referred to as the output equation. \(A\) is called the state matrix, \(B\) the input matrix, \(C\) the output matrix and \(D\) the direct transition matrix.

One advantage of the state-space method is that the form lends itself easily to the digital and/or analog computer methods of solution. Further, the state-space method can be easily extended for the analysis of nonlinear systems. State equations may be obtained from an nth-order differential equation or directly from the system model by identifying appropriate state variables [69].

To illustrate how is the selection of a set of state variables, an nth-order linear model described by a differential equation is considered:

\[
\frac{d^n y}{dt^n} + a_{n-1} \frac{d^{n-1} y}{dt^{n-1}} + \cdots + a_1 \frac{dy}{dt} + a_0 y = u(t) 
\]  
(6.11)

where \(u(t)\) is the input and \(y(t)\) is the output. A state model for this system is not unique but depends on the choice of a set of state variables. A useful set of state variables, referred to as phase variables, is defined as:

\[
x_1 = y, \ x_2 = \dot{y}, \ x_3 = \ddot{y}, \ \cdots, \ x_n = y^{n-1} 
\]  
(6.12)

Taking the derivatives, yields:

\[
\dot{x}_1 = x_2, \ \dot{x}_2 = x_3, \ \dot{x}_3 = x_4, \ \cdots, \ \dot{x}_n = -a_0 x_1 - a_1 x_2 - \cdots - a_{n-1} x_n + u(t) 
\]  
(6.13)

or in matrix form:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\vdots \\
\dot{x}_{n-1} \\
\dot{x}_n
\end{bmatrix} = 
\begin{bmatrix}
0 & 1 & 0 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 1 \\
-a_0 & -a_1 & -a_2 & \cdots & -a_{n-1}
\end{bmatrix} 
\begin{bmatrix}
x_1 \\
x_2 \\
\vdots \\
x_{n-1} \\
x_n
\end{bmatrix} + 
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
1
\end{bmatrix} u(t) 
\]  
(6.14)

The output equation is given by:

\[
y = \begin{bmatrix}
1 & 0 & 0 & \cdots & 0
\end{bmatrix} x 
\]  
(6.15)

For electrical networks, the state variables are directly related to the energy-storage elements of the system. Therefore, the number of independent initial conditions is equal to the number of energy-storing elements.