Final Degree Project

Control design and simulation of an HVDC-connected Offshore Wind Power Plant

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<tr>
<td>AC</td>
<td>Alternative Current</td>
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<td>DC</td>
<td>Direct Current</td>
<td></td>
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<tr>
<td>DDSRF</td>
<td>Decoupled Double Synchronous Reference Frame</td>
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<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
<td></td>
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<tr>
<td>IGBT</td>
<td>Isolated Gate Bipolar Transistor</td>
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<td>LCC</td>
<td>Line Commutated Converter</td>
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<td>LPF</td>
<td>Low-Pass Filter</td>
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<td>Modular Multilevel Converter</td>
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<td>PCC</td>
<td>Point of Common Coupling</td>
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<td>PI</td>
<td>Proportional Integral</td>
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<td>PLL</td>
<td>Phase-Locked Loop</td>
<td></td>
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<td>PR</td>
<td>Proportional Resonant</td>
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<td>PU</td>
<td>Per Unit</td>
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<td>PWM</td>
<td>Pulse Width Modulation</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>VSC</td>
<td>Voltage Source Converter</td>
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<td>WPP</td>
<td>Wind Power Plant</td>
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Abstract

Offshore wind power is a great opportunity to overcome the problems with which traditional onshore wind power was confronted. The offshore plants can be connected to the shore through an HVDC connection. This technology requires converters that will bring interesting control means.

This thesis aims to model a part of the global system in which an HVDC-connected offshore wind power plant is set, focusing on the transmission part. The DC connection, the two converters and their respective connections to the grid and to the wind power plant will be modelled in Simulink using the PLECS toolbox. The control is designed with the purpose to ensure a proper behaviour of the system under fault conditions. Then, simulations of a grid unbalanced fault and a wind power plant disconnection will be performed.

The analyze of the results will allow to attest the efficiency of the methods used to create a robust system, to identify the weaknesses and issues of the model and to study the sensitivity to various parameters.
Acknowledgments

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It is impossible to forget the circumstances in which this thesis has been written. The person who has been the most in my mind and heart throughout those months is paradoxically the one that cannot cheer me anymore. Those circumstances have made the support of those people I thank more precious than anything in the world.

To the best of my knowledge, a master thesis is not something to be dedicated to anyone. It might be good in this way as, ironically, the person I would like to dedicate it to would have barely understood a word in what follows. Still, I need to say that what has led me all along was the urge to achieve something he could be proud of, wherever he is now, to sign the end of those beautiful years at the University before the beginning of something even more beautiful, because I need, for him, to live beautiful things.

This is why I would like to acknowledge, as it will be the case in everything I will achieve in my life, the mark in this work of my reason for everything, my endless inspiration, my wonderful brother, Hugo Heuveneers.
1 Introduction

Nowadays, nobody questions the necessity of using renewable sources to produce energy. The technologies to reach, canalize and transform the resources such as wind have been developed during decades. The current challenge lies in dealing with the variability inherent to those sources and introducing them in an existing grid that has been relying for years on the strength of conventional production. Currently, the plants are not only asked to produce energy, but also to provide services allowing to ensure the safety and stability of the grid. Wind power is not an exception. If the first wind turbines, implemented in a very straightforward way, were disconnected in case of fault in the grid, the current ones are not only supposed to stay connected but also to provide support if needed.

Onshore wind power is a mature technology. The problems that this technology has to encounter are among other things the limited availability of lands and the public opposition. Offshore wind power is a great opportunity to overcome those problems. In addition, offshore winds have the advantage to present higher strength and stability. But benefits of offshore come along with technological challenges, such as the transmission from the plant to the shore, for which HVDC technology can be used. HVDC implies the use of converters, which require to be implemented and to deal with the technological challenges they bring, but also allow a valuable control of power transmission and system quantities through them.

The methods to control offshore wind power plant through converters and to obtain an appropriate behaviour of the system under fault situations are still a timely subject. This thesis, coming within the scope of it, aims to model part of the global system in which an HVDC-connected offshore wind power plant is set, focusing on the transmission part. The model will be composed of the HVDC connection and of two converters making the link with the grid on one side and with the power plant on the other side. Firstly, the control of the interactions between the different parts and different variables constituting the system will be designed. Afterwards, the model will be simulated in different fault situations to test its behaviour. A grid unbalanced fault and a wind power plant disconnection will be simulated. The analysis of the results will allow to attest the efficiency of the methods used to create a robust system, to identify the weaknesses and issues of the model and to study the sensitivity to various parameters.

The model will be implemented in Simulink, using the PLECS toolbox. The emphasis is put on a maximal extension of the model. For many control elements, different choices of implementation are possible. Those different possibilities could have been presented and discussed, but it is not done for conciseness reasons. Based on the literature, the most suitable implementations for each considered situation are selected. Alternative ways will however be explained if relevant.

For a work based on model building and simulations, reproducibility is important. This report contains then detailed explanations about how each part was built and how they were connected together, as well as all parameters used for the simulations. The main objective of the thesis is to provide a guide to build a model of an HVDC transmission system for offshore wind.
2 Concepts

2.1 HVDC connections

If nowadays, the transmission system is mainly dominated by the AC technology, the advances made in power electronics along the years have allowed an increasing development in DC systems. In the case of long distance transmission, HVDC links, that can be lines or cables, proved to be more efficient and interesting from a commercial point of view than traditional AC connections.

As explained in [21], one of the main applications of HVDC is the submarine power transmission.

It is known, as developed in [19] among others, that AC cables present a higher capacitance than AC overhead lines. This high capacitance limits the power that can be transmitted, as the current circulating in a link is always limited, and the higher the distance, the higher the share of reactive current feeding the capacitive effect, unusable then to transmit active power.

Beyond a certain distance, HVDC is therefore more economical, allowing to transfer efficiently a larger power, as pointed out by [21]. In particular, in the case of offshore wind power plants, it might be more interesting to use HVDC cables to transmit power from the offshore system to the onshore system. That is what is considered in this thesis, following the example of [6], on which the structure of the model is mainly based.

2.2 Types of converters

The use of HVDC connections implies the necessity of specific devices. HVDC is a mode of electricity transport that is not to be used alone but included in an AC system, made on one side of the onshore transmission system, the AC grid, and on the other side of the power plants, that provide AC current. Here comes the need for converters, allowing to transform DC to AC, and the other way around. As the goal of the wind power plant is to produce electricity, the power transfer is considered from offshore to onshore. The offshore converter is then considered as the rectifier, converting the offshore AC voltage to DC, and the onshore converter is considered as the inverter, converting the DC connection voltage to AC voltage, as needed by the transmission grid.

The situation is sketched in Figure 2.1.

Currently, as developed in [21], two converters technologies exist: Line Commutated Converters (LCC) and Voltage Source Converters (VSC). LCC are based on thyristors (acting as controllable diodes) and VSC on Isolated Gate Bipolar Transistors (IGBT).

LCC are current source converters, achieving the conversion by firing the thyristors at a given angle and keeping, in normal operations, the DC current constant. VSC, as the name suggests, are voltage source converters, controlled using Pulse Width Modulation (PWM), and keeping, in normal operations, the DC voltage constant.

This difference in implementation gives them different features, advantages and drawbacks, summarized in Table 2.1.

Voltage Source Converters are the ones suitable for offshore applications, as it does not require to be connected to a strong AC system and has a black start capability, as concludes [21].

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2.3 Voltage Source Converters

2.3.1 Principle

![VSC principle diagram]

Figure 2.2: Illustration of the VSC principle

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<thead>
<tr>
<th>Line Commutated Converter</th>
<th>Voltage Source Converter</th>
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<tbody>
<tr>
<td>Large power ratings</td>
<td>Medium power ratings</td>
</tr>
<tr>
<td>Large harmonic filters needed</td>
<td>Smaller harmonic filters needed</td>
</tr>
<tr>
<td>Active power control, no reactive power control</td>
<td>Independent reactive and active power control</td>
</tr>
<tr>
<td>Strong AC system required</td>
<td>Can be connected to any system</td>
</tr>
<tr>
<td>No black start capability</td>
<td>Black start capability</td>
</tr>
<tr>
<td>Cheaper</td>
<td>More expensive</td>
</tr>
<tr>
<td>Lower losses</td>
<td>Higher losses</td>
</tr>
<tr>
<td>Cheaper</td>
<td>More expensive</td>
</tr>
</tbody>
</table>

Table 2.1: Comparison of LCC and VSC converters
As mentioned above, the VSC rely on IGBTs as switching devices. [21] explains that the IGBTs are associated in modules with other elements, whose goal is to protect them. Those modules are cascaded in series in order to achieve the voltage rating needed, forming what is called valves. The valves can be combined in several ways, which different levels of complexity, which leads to the different implementations possible for the VSC.

The principle of the VSC is to build on the AC side an AC voltage whose frequency, phase and magnitude are controllable, and independent of the load that can be find on the AC side.

Figure 2.2 illustrates the principle, the combination of IGBT valves treated as a black box. The voltage $v_{AC}$ is the AC voltage to build. The capacitor $C_{DC}$ allows to keep the DC voltage $V_{DC}$ constant.

### 2.3.2 Implementations

The most basic implementation, treated as first example in [21], is illustrated in Figure 2.3.

![Basic single phase 2-level converter : Square-wave half-bridge](image)

Only one switch is closed at the same time. When the upper switch is closed, the output voltage $v_{AC}$ is equal to $\frac{V_{DC}}{2}$. When the lower switch is closed, $v_{AC}$ is equal to $-\frac{V_{DC}}{2}$. As the switches open and close, $v_{AC}$ can be drawn as a square wave. That square wave has to be such that when it is appropriately filtered, the result is a waveform that can be considered as a sine wave. In this basic implementation, the square wave has only two possible values. Other implementations allow to have more possible values, and then to get a square wave whose filtering will be simplified, as explained in [21].

The Modular Multilevel Converter (MMC) consists in cells connected in series, and results in a staircase wave. The more levels, the more this staircase wave is similar to a sine wave. This is the implementation that is the most likely to be used in the application developed in this work.
2.3.3 Pulse Width Modulation

As explained previously, the VSC are based on modules of IGBTs that are switched on and off to create an AC voltage. There is then the need for switching orders, to give the switching times. Those orders will allow to build the desired AC voltage. For that, a Pulse Width Modulation (PWM) can be used.

The principle of the PWM, as developed in [21], is to compare a reference sine signal, called the modulation signal, to a triangular signal, called the carrier signal. Those signals are represented in Figure 2.4.

![Figure 2.4: Illustration of the modulation signal (in blue) and the carrier signal (in green)](image)

The switching orders will depend on the relation between the modulation signal and the carrier. When the modulation signal is greater than the carrier, some switches receive the order to close and the others to open. When the modulation signal is smaller than the carrier, the opposite happens.

This results in a signal that has, once filtered, the following expression:

\[ v_{AC} = M \frac{V_{DC}}{2} \cos(\omega t + \phi) \] (1)

Where \( M \) is the amplitude of the modulation signal, \( V_{DC} \) the DC voltage, \( \omega \) the pulsation of the modulation signal and \( \phi \) its phase. The output \( v_{AC} \) is then controllable by choosing the desired \( M \), \( \omega \) and \( \phi \).

Changing the frequency of the carrier will have an impact on the harmonic content.

In the three-phase case, three modulation signals are used, each shifted by \( \frac{2\pi}{3} \), which allows to obtain three shifted sine signals.

The use of several carriers is also possible, in the case of MMC for example.

In this work, the IGBT valves assembly is considered as a black box. This box outputs a sine signal, whose amplitude can be adjusted by varying the modulation index. The feature that has to be retained in what follows is that the VSC can output on its AC side a sine signal with chosen frequency, phase and magnitude, following the expression (1). As explained in [23], forgetting the electronics connecting the AC and DC sides, it leads to the simplified scheme in Figure 2.5. The VSC AC side is represented as three controllable alternative voltage sources, while the DC side is a controllable constant current source across a capacitor.

Tools
2.4 Simulink and PLECS

The model of the system is implemented in Simulink. The additional toolbox PLECS, relevant for power electronics simulations, is used.

All the electrical elements (voltage sources, impedances, ...) are put in the PLECS circuit box. Everything that concerns control is put outside this PLECS box, in a conventional Simulink model.

2.5 Reference frames

Within the framework of three-phase voltage control and grid synchronization, some tools have been developed in order to simplify, or make possible, the processing of voltage. It is important to get familiar with those particular tools and their meaning because they are widely used in the field of this work.

The three-phase voltage is commonly known as three sinusoidal waves of same amplitude and with a $\frac{2\pi}{3}$ phase shift, which is referred to as the abc frame, or natural reference frame. Their well-known expressions are

\[
V_a = \sqrt{2}V\cos(\omega t + \theta) \\
V_b = \sqrt{2}V\cos(\omega t + \theta - \frac{2\pi}{3}) \\
V_c = \sqrt{2}V\cos(\omega t + \theta + \frac{2\pi}{3})
\]
Where $\sqrt{2}V$ is the voltage peak value, $V$ the voltage effective value, $\omega$ the pulsation, related to frequency as $\omega = 2\pi f$ and $\theta$ the angle. They are represented in this way in Figure 2.6.

However, it is really uncomfortable in the operations that are going to be performed in the scope of this work to manipulate the voltage in this form.

There are different ways to transform the basic waves into something more easily manipulable.

### 2.5.1 Clarke transformation

The three-phase voltage can be pictured in a 3D plane as three vectors, each of them attached to one of the main axes x, y and z. Each vector moves with time along the axis it is attached to, the coordinate of its endpoint equalling at each moment the instantaneous value of the phase it represents.

Conceptually, the Clarke transformation consists in changing the viewing point from which the three-phase vectors are seen. The viewing point is placed on one of the phases axis, typical the one of phase c, and the plane perpendicular to this axis is observed. From this perspective, the variations of the vector representing phase c are not visible. The observer only sees phase a and b vectors, which appear in this way as shifted by $\frac{\pi}{2}$.

The transformation results then in two sinusoidal waves shifted by $\frac{\pi}{2}$, referred to as $\alpha$ and $\beta$, and a zero component, referred to simply as 0. The resulting waves when applying the transformation to the waves of Figure 2.6 are displayed in Figure 2.7.

![Figure 2.7: Illustration of the stationary frame](image)

Once values from the abc frame are converted using the Clarke transformation, they are in the $\alpha\beta0$ frame, or stationary reference frame.

The Clarke transformation, or inverse Clarke transformation, is performed applying the Clarke matrix or the inverse Clarke matrix, respectively. Those matrices are given as expressed in (2), based on [6].

\[
C = \frac{2}{3} \begin{pmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{pmatrix}, \quad C^{-1} = \begin{pmatrix}
1 & 0 & 1 \\
-\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\
-\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1
\end{pmatrix}
\]

The advantage of the Clarke transformation is that it allows to describe the system with two components instead of three. The drawback is that the remaining components are still sinusoidal waves.
2.5.2 Park transformation

The Park transformation is based on the Clarke transformation. It consists in applying a rotation to the values in the \(\alpha\beta0\) frame.

After the Park transformation, the 0 value will remain at 0 in that new frame. The two other components become constant values, referred to as the direct component (d) and the quadrature component (q). They are in the dq0 frame, rotating synchronous reference frame.

The resulting waves when applying the transformation to the waves of Figure 2.6 are displayed in Figure 2.7.

![Figure 2.8: Illustration of the rotating synchronous frame](image)

When the correct angle is used to perform the transformation, the quadrature component is supposed to be equal to zero, as it is the case in Figure 2.8. That requirement allows to check if the transformation has been properly made, in other words if the correct angle has been used. When the transformation is applied to balanced quantities, the value of the direct component corresponds to the peak value of the sinusoidal quantities.

The Park transformation is performed applying successively the Clarke matrix and the rotation matrix, whose expressions are given respectively in (2) and (3), based on [6]. The inverse Park transformation is performed applying successively the inverse rotation matrix and the inverse Clark matrix, whose expressions are also given respectively in (3) and (2).

\[
R(\theta) = \begin{pmatrix}
\cos \theta & \sin \theta & 0 \\
-\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{pmatrix} \quad R^{-1}(\theta) = \begin{pmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{pmatrix}
\]  \hspace{1cm} (3)

Such results are ideal for computations, as manipulating constant values is much easier than manipulating sine waves. The difficulty lies in the acquirement of the correct angle to perform the transformation.

In the literature, several conventions on the rotating synchronous components and their meaning exist. The convention used here is the one used in [6].

Both transformations described above will be used in the model, depending on what is relevant. In both cases, the 0 component is neglected as, being equal to 0, it gives no contribution to the system.
2.6 Symmetrical components

The symmetrical components are very useful tools for system analysis under unbalanced conditions. They are known as the positive sequence and the negative sequence.

As explained in [20], the positive sequence consists in three vectors of same magnitude, shifted by $\frac{2\pi}{3}$ and rotating in the order $a \rightarrow b \rightarrow c$. There are actually the balanced three-phase voltage as it is widely represented.

The negative sequence consists as well in three vectors of same magnitude and shifted by $\frac{2\pi}{3}$, but rotating the other way round, in the order $a \rightarrow c \rightarrow b$.

Those rotating vectors are represented in Figure 2.9.

As a general rule, the symmetrical components also include a zero sequence, consisting in three vectors of same magnitude and rotating in phase.

The symmetrical components $V^+, V^-, V^0$ can be transformed into the abc components $V_a, V_b, V_c$ using the Fortescue matrix $F$. Similarly, the abc components can be transformed into the symmetrical components using the inverse Fortescue matrix $F^{-1}$. The expressions of those matrices are given in (4).

$$F = \begin{pmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{pmatrix}, \quad F^{-1} = \frac{1}{3} \begin{pmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{pmatrix} \quad \text{with} \quad a = e^{j\frac{2\pi}{3}} \quad (4)$$

As in the case of three-phase voltage, due to the three-wire connection, the 0 sequence is not present, only positive and negative sequences are considered here.

Three-phase voltage can always be represented as a sum of a positive sequence and a negative sequence. In the case of balanced voltages, the sum contains only the positive sequence. By varying the respective amplitudes and the shifting between the positive and negative sequences, it is possible to represent all unbalanced situations.
This has been explained for voltages, but symmetrical components are also applicable to currents.

### 3 Model

The model that is developed over this thesis is part of the whole system of an HVDC-connected offshore wind power plant. This system spreads from the wind power plant in itself, composed of many wind turbines aggregated in groups and linked through an offshore network, to the connection to the transmission grid, with the whole electrical transport installation in between.

The model developed here focuses on the transport installations allowing to carry the electricity produced offshore to the transmission grid. The scope of the model within the whole system is represented on the drawing in Figure 3.1.

The model can be divided into three distinct parts: the onshore side, with the VSC referred to as the inverter, the offshore part, with the VSC referred to as the rectifier, and the DC connection between the two converters. This division appears throughout the work to structure the description and analysis.

From the implementation perspective, the model can be separated in two parts: the electrical elements and the control elements. The electrical elements are those placed in
the PLECS box and modelling the electrical installations. There are described in Section 4. The control elements are placed in Simulink, outside the PLECS box, and constitute the system giving orders to the electrical part to ensure its proper functioning. They are described in Section 5 and Section 6. Diagrams of the implementation of the different elements in Simulink and PLECS are provided in the Appendices.

In reality, the DC connection is linked to the converters on each side through the IG-BTs assembly, and then through real electrical connections. But based on the simplified scheme in Figure 2.5, the different parts can be decoupled and the three parts are then not connected in the electrical part. The link between them and their variables is done through the control part, using measurements and orders.

Once the model is built, the goal is to simulate fault events, which is done as explained in Section 8. The type of events simulated is different for the different parts. An unbalanced fault will be simulated on the onshore side as a grid fault. Only a wind power plants disconnection is simulated on the offshore side, modelling a failure in the power plant. No faults are simulated in the DC connection in this work, as the converters considered could not handle it. The behaviour of the system under those fault situations is analyzed in Section 9.

4 Electrical Elements

This section aims to explain the electrical elements of the system, those put in the PLECS box. There are three distinct circuits, without any electrical connection between them: the VSC onshore side, the DC connection and the VSC offshore side.

4.1 VSC Onshore Side

Based on [23], this circuit models the VSC placed onshore, the inverter. It is where the connection to the grid is performed. It could be a direct connection to the transmission grid or, more likely, a connection through transformers. The grid is modelled as ideal, as three voltage sources, one for each phase.

On the other side of the circuit is the VSC AC side. It is also modelled as three voltage sources, in accordance with the scheme in Figure 2.5. The sources on both sides are controlled sources, whose waveform is ordered by the control part.

Between the VSC AC side and the connection to the grid are the filters. The filters are modelled as a resistor $R_l$ and an inductor $L_l$ in series, one branch for each phase. Their goal is, as explained in Section 2.3.2, to filter the square signals output by the VSC converter.

The different elements are illustrated in Figure 4.1.

4.2 DC connection

The DC connection is modelled as a simplified version of what is described in [21]. The DC current is carried through two cables. The resistors $R_{DC}$ model the resistance of those cables. At each end of the cables, there are two capacitors, whose value is $\frac{C_{DC}}{2}$, with a
connection to the ground between them. The purpose of those capacitors is to maintain the DC voltage. The model in [21] includes other elements, such as filtering inductors, but they are not included in this model. But in this case, as the faults modelled will be AC faults, an advanced model of the DC cable is not considered.

The left side of the DC connection is the connection to the offshore VSC converter, the rectifier, and the right side is the connection to the onshore VSC converter, the inverter. As shown in the simplified scheme in Figure 2.5, the connection is modelled as a controllable current source. There is then a current source at each side of the circuit, across the capacitors. The voltages of interest are the voltages across the capacitors at each side, $V_{DC}^{rec}$ and $V_{DC}^{inv}$.

The model of the DC connection is provided in Figure 4.2.
4.3 VSC Offshore Side

The offshore side is modelled based on [6]. The right part of the offshore side circuit is the same as the left part of the onshore side. The VSC AC side is modelled as three controllable voltage sources, connected to the filters $R_l-L_l$. The current flowing in the filters is referred to as $I^f_{abc}$. The difference lies in the left side, representing the connection to the offshore wind power plant. Individual wind turbines can be modelled, as done in [6], as current sources, to which are added different elements as parallel capacitor and resistor. As all the wind turbines will them provide current, the wind power plant as a whole is modelled as three current sources, one for each phase. They are connected to the ground in a star configuration as, based on [6], they represent the output of a Δ-Y transformer. Between the connection to the wind and the filters are three capacitors $C$ arranged in three parallel branches connected to the ground, one for each phase. Their goal is to create a voltage with the current that is injected from the wind power plant, as further explained in Section 6.1. The voltages across the capacitors are referred to as $V^pcc_a$, $V^pcc_b$ and $V^pcc_c$, respectively, PCC standing for Point of Common Coupling.

The different elements are illustrated in Figure 4.1.

![Figure 4.3: Model of the offshore electrical circuit](image)

5 Onshore control

5.1 Overall control system

The onshore side of the VSC is destined to be connected to the transmission grid. It is compulsory to produce a voltage compatible with the grid. The whole control performed on the onshore side aims then to create an appropriate voltage in terms of frequency, phase and magnitude, performing what is called grid synchronization. It is done based on [23].

The overall control system block diagram, representing the elements explained below, is given in Figure 5.1.
The first step is to determine the magnitude, frequency and phase of the grid voltage. If the two first parameters are easily determinable, the frequency being known through the pulsation $\omega_0 = 2\pi 50$ and the magnitude obtained by voltage measurements, the phase determination asks for a specific process. This is the task of the PLL block (DDSRF-PLL in Figure 5.1). From the voltage at the grid connection measured in the abc frame, it provides to the other blocks that need them the grid voltage in the dq0 frame and the grid phase angle.

The second step is to control the current flowing to the grid. This is the role of the current controller, constituting the inner loop. The current in the filters is directly dependant on the voltage at the VSC AC side. The current controller will then output the VSC AC side voltage order $V_{vsc}^{abc}$ that is necessary to achieve the desired current. It compares constantly the current measured in the filter $I_{abc}$ to the reference current that gives the desired current.

It is necessary to provide the current controller a reference to follow. This is done by the reference computation block. It will output the reference current $I_{q0}^{+*}$, based on other quantities that need to be controlled or to achieve a certain value (here the DC side voltage and the reactive power).

Before to be provided to the current controller, the reference current passes through the current limitation block. This block aims to check if the reference do not exceed the maximum current and to reduce it if necessary.

The last block of the control system is the DC current order computation. It is drawn
not connected to the rest of the system but still relies on it to provide its inputs, such as the phase angle to perform the Park transformations.

Each block is described in details below.

5.2 Phase-Locked Loop

5.2.1 Basic principle

As explained in [23], the goal of a Phase-Locked Loop (PLL) is to extract the voltage angle of the grid. The knowledge of the actual grid angle is essential to achieve a proper synchronization to the grid. It allows to perform correctly the direct and inverse Park transformations. Indeed, when the Park transformation is applied on the voltage in the abc frame using the actual grid angle, the resulting quantity in the dq0 frame will be constant.

Its functioning is based on a feedback loop on the phase angle. It inputs the measured three-phase voltage in the abc frame and outputs the correct phase angle and the voltage in the dq0 frame.

A basic PLL structure is represented in Figure 5.2.

![Figure 5.2: Structure of a basic PLL](image)

As explained in the section concerning the Park transformation, the quadrature component resulting of a transformation using the correct angle will be equal to 0. The feedback loop relies on that feature by comparing the voltage quadrature component, $V_q$, to 0. The PI controller takes as input the difference between 0 and $V_q$. It outputs the estimated pulsation $\hat{\omega}$. This result is integrated to obtain the estimated angle $\hat{\theta}$. This angle is then given as input to the Park block to perform the Park transformation anew.

The PI controller parameters have to be chosen carefully. The proportional gain $k_p$ and the integral gain $k_i$ will affect the dynamics of the system, which is desired robust but fast. The convergence is faster when adding a reference to the output of the PI controller. This reference is set to the grid pulsation $\omega_0 = 2\pi 50$.

5.2.2 Updated PLL

The weakness of the described basic PLL is that it is unable to track properly the phase angle under unbalanced conditions. Indeed, the voltage $V_{dq0}$ output in that case keeps
oscillating. The advantage of working in the dq0 frame, which allows to manipulate constant values, is then lost.

Several methods have been proposed to overcome that problem, as reviewed in [3]. Following the example of [6], based on the conclusions of [2], a Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL) is integrated in the model. As its name suggests, this updated version of PLL relies on a decoupling network. The block diagram of this decoupling network is given in Figure 5.3.

The decoupling network makes appear the positive and negative sequences constituting the grid voltage $V_{abc}$ and allows to cancel the mutual effect that is the origin of oscillations.

The negative sequence angle $\theta^-$ is taken as $-\theta^+$. The low-pass filter is characterized by the following transfer function

$$H_{LPF}(s) = \frac{\omega_f}{s + \omega_f}$$

The cut-off frequency $\omega_f$ is set to $\frac{\omega_0}{\sqrt{2}}$ rad/s, with $\omega_0 = 2\pi f$ the grid pulsation, as recommended in [2] as a good trade-off between time response and oscillations damping.

To obtain the DDSRF-PLL, a SRF-PLL is added to that decoupling network. The block diagram of this PLL, similar to the basic PLL described above, is given in Figure 5.4.

The estimated grid voltage in the dq0 frame $\tilde{V}_{dq0}^+$ is fed from the decoupling network to the PLL, but only $\tilde{V}_{dq0}^+$ is used. It is input to the PI controller. The PLL output $\theta^+$ is given as input for the decoupling network. The grid pulsation $\omega_0 = 2\pi 50$ is added to the pulsation output by the PI controller to speed up the convergence. The sum is integrated to result in the output $\theta^+$. This output is given as input for the decoupling network, and the control loop is then closed.
5.3 Reference computation

Under unbalanced conditions, many control strategies are possible. The appearance of positive and negative sequences leaves several degrees of freedom, allowing to inject active, reactive, negative or positive sequence current.

The interest of working in the dq0 frame is that it allows to decouple active and reactive power control. The current $I_d$ controls the active power while $I_q$ controls the reactive power.

In this work, the choice is made to inject only positive sequence current. The negative sequence reference current, $I_d^-$ and $I_q^-$, is then set to 0. The positive sequence reference current remains to compute.

The theory on control in HVDC connections from [21] is used here. A HVDC connection implies two stations, a rectifier on one side and an inverter on the other, as explained in Section 2.2. The reactive power is controlled on both sides. The active power control is attributed to one of the terminals, called the slave terminal. The other terminal, called the master terminal, controls the DC voltage across the capacitor, making sure that it remains constant.

In this case, the onshore station will be the master terminal and the offshore station the slave terminal.

The reactive reference current $I_q^{+*}$ ensues from the reactive power that is supposed to be injected or consumed. From the instantaneous power theory developed in [14], transferred in the dq0 plane as explained in [1], the reactive power is expressed based on the synchronous frame components as

$$Q = \frac{3}{2}(V_d^+ I_q^+ - V_q^+ I_d^+)$$

With the assumption that the PLL outputs the correct angle, the quadrature voltage $V_q^+ = 0$. It leads then to the expression

$$Q = \frac{3}{2} V_d^+ I_q^+$$

The positive sequence reactive reference current $I_q^{+*}$ is then computed from the reactive power order $Q^*$ as
This is the open loop calculation. Other methods exist, including a controller on the difference between the reactive power order and the measured reactive power. Those methods allow to overcome the possible error resulting from the filters impedance that is neglected in open loop, as explained in [13]. However, here, the open loop method is preferred for its straightforward implementation.

The active reference current $I_d^{**}$ is obtained by controlling the DC voltage across the capacitor, at the DC side of the inverter. The measured DC voltage $V_{DC}$ is compared to the reference DC voltage $V_{DC}^*$. The difference between the measured voltage and the reference is given as input to a PI controller. The output of the controller gives the active reference current $I_d^{**}$.

The calculations made to obtain the different references can be visualized on the block diagram of the reference calculation, in Figure 5.5.

The PI controller has to be tuned carefully to obtain the desired dynamics on the AC side as well as on the DC side.

The implementation encounters a small problem. Due to DDSRF-PLL, it takes a few milliseconds for $V_d^+$ to rise to its constant value. During this time, the computed
voltage value is very small, which results in huge reference current values. The problem is mitigated by introducing a small delay between the beginning of the simulation and the use of $V_d^+$ for the calculations.

### 5.4 Current limitation

In order not to damage the equipment, as in any electrical installation, the current flowing in the cables must remain under a certain value.

As the chosen control strategy is not to inject any negative sequence current, the computation of the total current is relatively simplified.

It is necessary to respect, at any moment

$$\sqrt{I_d^* + I_q^*} < I_{\text{max}}$$ (9)

It is assumed that in general, the reactive power consumed or produced by the system is small compared to the active power provided, as currently, wind power plants are mainly intended to provide active power, not to act as regulating devices. In (9), the term mainly responsible for reaching the limit will be then $I_d^*$ in most of the cases. The choice is made to limit $I_d^*$ to $\sqrt{I_{\text{max}}^2 - I_q^*}$.

The block diagram of the current limitation is given in Figure 5.6.

![Block diagram of the onshore current limitation](image)

**Figure 5.6: Block diagram of the onshore current limitation**

The norm $\sqrt{I_d^* + I_q^*}$ is computed using the dq components. Once again, the 0 component does not have any contribution. This norm is input to the comparison block, whose output depends on the relative value of the input compared to $I_{\text{max}}$. If $\sqrt{I_d^* + I_q^*}$ is smaller, the $I_{dq^0}^*$ that has been given in input is transferred as output of the current limitation, without modification. If the norm is larger, the output will be the result of the
computations on the upper part of the block. As chosen above, it sets $I_d^+$ to $\sqrt{I_{\text{max}}^2 - I_q^{*2}}$. The value of $I_q^{*}$ is also limited through a saturation block, that will output the value of $I_q^{*}$ if it is in the interval $[-I_{\text{max}}, I_{\text{max}}]$, output $-I_{\text{max}}$ if $I_q^{*}$ is outside the interval and negative, and $I_{\text{max}}$ if it is outside the interval and positive.

The current limitation block is placed between the reference computation and the current controller. It will make sure that the reference current input to the current controller is under the admissible values.

### 5.5 Current controller

The goal of the current controller, as its name suggests, is to control the active and reactive currents flowing in the filters between the VSC converter AC side and the connection to the grid. As mentioned above, the negative sequence current is set to 0. Therefore, only the positive sequence appears in the control scheme.

The measured current is compared to the reference current. The controller outputs the voltage orders to apply at the VSC converter AC side in order to achieve the desired current flow in the filters.

As advised in the additional documentation provided in [23], the values in this block will not be manipulated in the dq0 frame but in the $\alpha\beta0$ frame. The proportional resonant controller explained in this additional documentation, as well as in [2], will be implemented. The advantage of this controller is that it allows to avoid the use of a decoupling network. As explained in [2], the proportional resonant controller is actually the equivalent of a PI controller that can be implemented in the synchronous frame, when transferred in the stationary frame.

The current in the filters is measured in the abc frame. They are converted to the $\alpha\beta0$ frame using the Clarke transformation. In the same way, reference current is provided in the dq0 frame. It is then converted to the $\alpha\beta0$ frame performing an inverse rotation of angle $\theta$.

The block diagram of the current controller is given in Figure 5.7. The voltage $V_{abc}^{\text{ref}}$ refers to the voltage measured at the connection to the grid, while $V_{\text{vsc}}^{abc}$ is the voltage applied to the AC side of the VSC converter.

The transfer function of the controller is the one given in the additional documentation provided in [23]

$$K(s) = \frac{2\omega_c L I s^2 + 2\omega_c R I s}{s^2 + 2as + \omega_0^2}$$

Where $\omega_c$ is the controller bandwidth, $L I$ and $R I$ are the inductance and resistance of the filters, respectively, $a$ is a pole located far from $\omega_c$ and $\omega_0$ is the fundamental pulsation of the current to control, in other words the grid pulsation.

### 5.6 DC current order computation

The voltage on the DC side is supposed to remain constant all the time. If the current injected on the offshore side is greater than the current removed on the onshore side, the difference will be stored in the capacitor, which results in a rise of the DC voltage. The
DC voltage remaining at its nominal value ensures that the amount of current entering the link is leaving it. The reference calculation is adapted to that constraint on the voltage control, as explained previously, and the DC voltage control is then carried out in that part.

It remains to determine the DC current order to inject at the inverter, \( I_{DC}^{inv} \). It is done performing a power balance. Considering a lossless converter, the balance between three-phase active power and DC power must be respected at any time, which is expressed as

\[
P_{AC} = P_{DC} \tag{11}
\]

Developing both sides of (11), it leads to

\[
V_a I_a + V_b I_b + V_c I_c = V_{DC} I_{DC} + C_{DC} V_{DC} \frac{dV_{DC}}{dt} \tag{12}
\]

Considering that the transients do not affect the power balance in a substantial way, the steady state is assumed, which leads to

\[
C_{DC} V_{DC} \frac{dV_{DC}}{dt} = 0 \tag{13}
\]

According to [14], the active power can be expressed using the dq0 frame components as

\[
P = \frac{3}{2} (V_d I_d + V_q I_q) \tag{14}
\]

Using (13) and (14) in (12), the following balance is obtained

\[
V_d I_d + V_q I_q = V_{DC} I_{DC} \tag{15}
\]

The inverter DC current order is then given as

\[
I_{DC}^{inv} = \frac{V_d I_d + V_q I_q}{V_{DC}^{inv}} \tag{16}
\]
Figure 5.8: Block diagram of the onshore DC current order computation

The current order is supposed to be constant, the cable not being designed to carry alternative current. In balanced conditions, the feature of three-phase systems is to provide constant three-phase power. Under unbalanced conditions, the sum $V_a I_a + V_b I_b + V_c I_c$ oscillates with time. This is the interest to use dq0 frame components to compute the AC power. (14) will provide a constant result even under unbalanced conditions. This result is actually the average value of the oscillating AC power.

The use of dq0 frame components instead of the abc components is permitted thanks to the properties of the MMC. Through the MMC, the signal is not transferred from the AC side to the DC side, as the double line frequency component stays within the converter.

The block diagram of the DC current order is provided in Figure 5.8.

The inputs are the voltage measured at the VSC AC side $V_{vsc}^{dq0}$, the current measured in the filters $I_{dq0}^+$ and the DC voltage across the capacitors at the VSC DC side $V_{DC}^{inv}$. The output is the current order $I_{DC}^{inv}$.

$I_{dq0}^+$ is obtained performing the Park transformation using the grid angle $\theta^+$, obtained from the DDSRF-PLL of the grid. $V_{d}^{vsc}$ is obtained from an additional DDSRF-PLL allowing to obtain its own angle. If the Park transformation is performed with the grid angle, the resulting $V_{dq0}^{vsc}$ presents oscillations under fault situation. This unsteady behaviour is detrimental for the DC current computation as well as for the current controller, for which stability is needed, as it will be established in Section 9.

As established below in Section 7.2, the AC and DC sides quantities are converted in per unit based on two different voltage and power bases. An appropriate scaling must then be performed when computing the DC current order.

6 Offshore control

6.1 Overall control system

The approach for the offshore control is different from the onshore one. Onshore, the control is led by the grid synchronization. Offshore, there is no such thing as that strong
AC grid. The objective offshore is to create an equivalent to the grid. As mentioned in Section 4.3 and based on Figure 4.3, this equivalent to the grid is the voltages $V_{pcc}^{abc}$, measured across the capacitors $C$ and fed by the wind power plant current $I_{wpp}^{abc}$. The goal is to perform what is called grid forming.

The block diagram of the overall control is given in Figure 6.1. It is based on what is done on [6].

![Block diagram of the offshore overall control system](image)

No PLL is needed in this part, as the phase is chosen and simply set through integration of the nominal pulsation, $\omega_0 = 2\pi 50$.

The voltage measured across the capacitors at the PCC is first converted to the dq0 frame to be manipulated. This is done by the voltage decoupling block, which allows to separate the negative and positive sequences.

The positive sequence component $V_{dq0}^{pcc}$ is input to the next block, the voltage control. This block compares the measured voltage to the reference voltage, the voltage that is desired for the equivalent to the grid. The PCC voltage is dependant on the current flowing in the filters. The voltage control outputs then the reference filters current $I_{dq}^{++}$ that will allow to achieve the desired PCC voltage.

The current control block, in the manner of the onshore current controller, will compare the current measured in the filters to the reference current and output the voltage to apply at the VSC AC side to achieve this current.
Before to be input to the current control, the reference current is limited through the current limitation.

Eventually, the DC current order to give to the rectifier is computed by the DC current order computation block, as it was done onshore.

### 6.2 Voltage decoupling

If the offshore control does not need a PLL, it still relies on qd0 frame values for its functioning. The goal of this block is to output the voltage in the dq0 and, as its name suggests, to decouple it, obtaining \( V_{\text{pcc}+}^{\text{dq0}} \) and \( V_{\text{pcc}-}^{\text{dq0}} \). It inputs the voltage measured across the capacitors \( V_{\text{abc}}^{\text{pcc}} \).

It is implemented in the same way than the DDSRF-PLL explained in Section 5.2.2, except that the angle \( \theta^+ \) is not obtained through a PLL but simply by integrating the nominal pulsation \( \omega_0 \).

The block diagram of the voltage decoupling is given in Figure 6.2.

![Block diagram of the offshore voltage decoupling](image)

Figure 6.2: Block diagram of the offshore voltage decoupling
6.3 Voltage control

The onshore system did not necessitate an AC voltage control, as the voltage on the other side of the filters was the grid voltage, imposed to the system. Offshore, the voltage on the other side of the filters is $V_{pcc}$, the voltage that is created as an equivalent to the grid. This voltage has to be monitored to make sure it is well what is looking for. The block compares then the measured voltage at the PCC $V_{dq0}$ with the reference voltage. The ideal grid is working at nominal value, which is $V_{RMS} = 1 \text{ pu}$. The control is performed on the dq0 frame components. The d component gives the peak value of the studied voltage, not its RMS value. The reference peak value to achieve nominal voltage is then $V_{peak} = \sqrt{2} \text{ pu}$. The voltage references for the different components are then set to the following values in per unit:

$$
\begin{align*}
V_{d}^{+*} &= \sqrt{2} \text{ pu} \\
V_{q}^{+*} &= 0 \text{ pu} \\
V_{0}^{+*} &= 0 \text{ pu}
\end{align*}
$$

(17)

The block diagram of the voltage control is given in Figure 6.3.

![Block diagram of the offshore voltage control](image)

Figure 6.3: Block diagram of the offshore voltage control

As in many cases, the 0 component does not appear in the system as by definition, it is equal to 0.

For the d and q components, the difference between the reference voltage and the measured voltage is input to a PI controller, whose proportional gain is $K_{pv}$ and integral gain is $k_{iv}$. A decoupling system adds $-\omega CV_{pcc}$ to the d part, and adds $\omega CV_{dq}$ to the q part, the lower part. The capacitance $C$ is the one of the capacitors in Figure 4.3.
Finally, the current injected by the wind power plant, $I^\text{wpp}_d$ and $I^\text{wpp}_q$, is added to the upper and lower parts to comply with the contribution of this current injected from the left.

The system outputs the reference for the current flowing in the filters, allowing to create the desired voltage at the PCC.

### 6.4 Current limitation

As onshore, the current must remain under a certain value to be sure not to provoke overheating which may result in destroying the cables and equipment.

The offshore current limitation is implemented as the onshore current limitation. As only balanced faults are considered on this side, there is not any negative current contribution and the computations are simplified in the same way. The current reference for the currents in the filters must respect the inequation given by (9). The block diagram will be the same than the one given in Figure 5.6.

### 6.5 Current control

The offshore current control principle is similar to the onshore one. From the reference current for the current flowing the filters, the appropriate order on the voltage at the VSC AC side is output.

The block diagram of the current control is given in Figure 6.4.

![Figure 6.4: Block diagram of the offshore current control](image)

For the d and q components, the difference between the reference current and the current measured in the filters is input to a PI controller, whose proportional gain is $K_{pi}$ and integral gain is $k_{ii}$. A decoupling loop is added, in the manner of what was done in [23]. This loop adds $\omega L_i I^f_q$ to the d part of the system, and $\omega L_i I^f_d$ to the q part. The inductance $L_i$ is the one of the inductors in the filters in Figure 4.3.

After those additions, the order for the VSC AC side voltage are obtained in the dq0 frame. It is converted into the abc frame using the inverse Park transformation, with the angle $\theta^+$ that has been set in the voltage decoupling.
6.6 DC current order computation

The DC current order to inject at the rectifier, $I_{DC}^{rec}$, has to be determined. It is done in a similar way that what has been done in Section 5.6 for the onshore side.

As unbalanced situations are not considered offshore, the voltage and current remain balanced all the time. It is then not necessary to use the dq0 frame components as it was done onshore.

The rectifier DC current is given as

$$I_{DC} = \frac{V_aI_a + V_bI_b + V_cI_c}{V_{rec}^{DC}}$$  \hspace{1cm} (18)

It is computed from the current flowing in the filters $I_{abc}^f$ and the VSC AC side voltage $V_{abc}^{vsc}$.

As it was the case on the onshore side, the fact that the AC and DC quantities are converted in per unit in two different bases must be taken into account when performing the calculations.

6.7 Extension to unbalanced faults

In the scope of this work, the offshore faults are limited to balanced faults. In the cases of unbalanced faults, the negative sequence appears. It is managed by creating for the negative sequence the same system than for the positive sequence, in other words to make the voltages $V_{dqdq}^{pcc-}$ go through the same system than $V_{dqdq}^{pcc+}$ in Figure 6.1.

In that case, the current limitation block has to be modified. The inequation 9 is not valid anymore as the negative sequence current has to be taken into account. The computation method explained in [6] or the extended current limitation developed in [7] must be used then.

7 Parameters and values

7.1 Nominal values

7.1.1 AC side

The AC side nominal values, that are the same for both onshore and offshore sides, are displayed in Table 7.1. They are established from [6].

The current limit is chosen as exceeding the nominal current of 20%. The maximum RMS current is then

$$I_{max-RMS} = I_{RMS} + I_{RMS} \times 20\% = 6.93 \text{ kA}$$  \hspace{1cm} (19)

The maximum peak is computed as

$$I_{max-peak} = \sqrt{2}I_{max-RMS} = 9.8 \text{ kA}$$  \hspace{1cm} (20)
### Nominal voltage

<table>
<thead>
<tr>
<th></th>
<th>$U_{RMS}$</th>
<th>400 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase-to-phase RMS voltage</td>
<td>$V_{RMS}$</td>
<td>230.94 kV</td>
</tr>
<tr>
<td>Phase-to-neutral RMS voltage</td>
<td>$\sqrt{3}V_{RMS}$</td>
<td>326.6 kV</td>
</tr>
<tr>
<td>Phase-to-neutral peak voltage</td>
<td>$V_{peak} = \sqrt{2}V_{RMS}$</td>
<td>326.6 kV</td>
</tr>
</tbody>
</table>

### Nominal power

<table>
<thead>
<tr>
<th></th>
<th>$S_{3P}$</th>
<th>4000 MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-phase apparent power</td>
<td>$S_{1P} = \frac{S_{3P}}{3}$</td>
<td>1333.3 MVA</td>
</tr>
</tbody>
</table>

### Nominal current

<table>
<thead>
<tr>
<th></th>
<th>$I_{RMS} = \frac{S_{1P}}{V_{RMS}}$</th>
<th>5.77 kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current</td>
<td>$I_{peak} = \sqrt{2}I_{RMS}$</td>
<td>8.17 kA</td>
</tr>
</tbody>
</table>

**Table 7.1: AC side nominal values**

### 7.1.2 DC side

As only active power is transmitted through the DC cable, the nominal power is expressed in MW. Part of the apparent power on the AC side is reactive power and will then not be transmitted through the DC connection. However, it is quite hard to estimate the part of reactive power, as this one can change over time according to the current requirements in the grid. The DC nominal power is then chosen equal to the AC nominal power, extracted from [6], to make the design relevant for all situations.

The DC connection nominal values are displayed in Table 7.2.

### Nominal voltage

<table>
<thead>
<tr>
<th></th>
<th>$V_{DC}$</th>
<th>500 kV</th>
</tr>
</thead>
</table>

### Nominal power

<table>
<thead>
<tr>
<th></th>
<th>$P_{DC}$</th>
<th>4000 MW</th>
</tr>
</thead>
</table>

### Nominal current

|                          | $I_{DC} = \frac{P_{DC}}{V_{DC}}$ | 8 kA |

**Table 7.2: DC connection nominal values**

### 7.2 Conversion in per unit

#### 7.2.1 AC side

The main base quantities used onshore and offshore are chosen as the nominal values defined in Section 7.1.1. As unbalanced situations, at least for the onshore side, are considered, the base power is the single-phase apparent power, and not the three-phase apparent power as it is the case when considering balanced systems. The other base values are computed from the base quantities.

The conversion in per unit of the AC side values is developed in Table 7.3.
Choice of base

<table>
<thead>
<tr>
<th>Base voltage $V_B = V_{RMS}$</th>
<th>230.94 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base power $S_B = S_{1P}$</td>
<td>1333.3 MVA</td>
</tr>
</tbody>
</table>

Base values

<table>
<thead>
<tr>
<th>Base current $I_B = \frac{S_B}{V_B}$</th>
<th>5.77 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base impedance $Z_B = \frac{V_B}{S_B}$</td>
<td>40 Ω</td>
</tr>
<tr>
<td>Base admittance $Y_B = \frac{I_B}{V_B}$</td>
<td>0.025 S</td>
</tr>
</tbody>
</table>

RMS values in pu

<table>
<thead>
<tr>
<th>Nominal voltage $V_{RMS-\text{pu}} = \frac{V_{RMS}}{V_B}$</th>
<th>1 pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current $I_{RMS-\text{pu}} = \frac{I_{RMS}}{I_B}$</td>
<td>1 pu</td>
</tr>
<tr>
<td>Maximum current $I_{\text{max-RMS-\text{pu}}} = \frac{I_{\text{max-RMS}}}{I_B}$</td>
<td>1.2 pu</td>
</tr>
</tbody>
</table>

Peak values in pu

<table>
<thead>
<tr>
<th>Nominal voltage $V_{RMS-\text{peak}} = \sqrt{2}V_{RMS-\text{pu}}$</th>
<th>1.4 pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current $I_{RMS-\text{peak}} = \sqrt{2}I_{RMS-\text{pu}}$</td>
<td>1.4 pu</td>
</tr>
<tr>
<td>Maximum current $I_{\text{max-RMS-\text{peak}}} = \sqrt{2}I_{\text{max-RMS-\text{pu}}}$</td>
<td>1.7 pu</td>
</tr>
</tbody>
</table>

Table 7.3: Conversion in per unit of the AC side quantities

7.2.2 DC side

The DC main base quantities are chosen as the nominal values defined in Section 7.1.2. The other base values are computed from the base quantities.

The conversion in per unit of the DC side values is developed in Figure 7.4.

<table>
<thead>
<tr>
<th>Choice of base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base voltage $V_B = V_{DC}$</td>
</tr>
<tr>
<td>Base power $P_B = P_{DC}$</td>
</tr>
</tbody>
</table>

Base values

<table>
<thead>
<tr>
<th>Base current $I_B = \frac{P_B}{V_B}$</th>
<th>8 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base impedance $Z_B = \frac{V_B}{S_B}$</td>
<td>62.5 Ω</td>
</tr>
<tr>
<td>Base admittance $Y_B = \frac{I_B}{Z_B}$</td>
<td>0.016 S</td>
</tr>
</tbody>
</table>

Values in pu

<table>
<thead>
<tr>
<th>Nominal voltage $V_{DC-\text{pu}} = \frac{V_{DC}}{V_B}$</th>
<th>1 pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal current $I_{DC-\text{pu}} = \frac{I_{DC}}{I_B}$</td>
<td>1 pu</td>
</tr>
</tbody>
</table>

Table 7.4: Conversion in per unit of the DC side quantities

7.3 Elements parameters

7.3.1 Onshore

Table 7.7 gives the parameters of the elements of the onshore circuit represented in Figure 4.1. They are obtained from [1] in natural units and converted in the base system of this circuit.
7.3.2 DC connection

Table 7.6 gives the parameters of the elements of the DC circuit represented in Figure 4.2.

The cables resistance $R_{DC}$ is deduced from [26], considering a cable length of 50 km. The order of magnitude of the capacitance $C_{DC}$ is obtained from [1]. It is then adjusted empirically, as explained in Section 9.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables resistance</td>
<td>$R_{DC}$</td>
<td>1.75 Ω</td>
</tr>
<tr>
<td>Capacitors capacitance</td>
<td>$C_{DC}$</td>
<td>1600 μF</td>
</tr>
</tbody>
</table>

Table 7.6: Parameters of the DC connection elements

7.3.3 Offshore

The filters parameters $R_l$ and $L_l$ are the same than those of the onshore circuit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters resistance</td>
<td>$R_l$</td>
<td>1.252 Ω</td>
</tr>
<tr>
<td>Filters inductance</td>
<td>$L_l$</td>
<td>13.5 mH</td>
</tr>
<tr>
<td>PCC capacitance</td>
<td>$C$</td>
<td>25 μF</td>
</tr>
</tbody>
</table>

Table 7.7: Parameters of the onshore elements

7.4 Controllers parameters

7.4.1 Onshore

The parameters of the PI controller used in the DDSRF-PLL to obtain the phase angle are determined by trial and error. The final gains are given in Table 7.8.

<table>
<thead>
<tr>
<th>$k_p$</th>
<th>$k_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 7.8: Parameters of the PI controller used in the DDSRF-PLL
The parameters of the PI controller used in the reference computation to control the DC voltage are determined by trial and error. The final gains are given in Table 7.9.

<table>
<thead>
<tr>
<th>$k_p$</th>
<th>$k_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 7.9: Parameters of the PI controller used for the onshore DC voltage control in the reference calculation

The transfer function $K(s)$, given as (10), used in the current controller, has several parameters. The values used for those parameters are displayed in Table 7.10. Their choice is discussed in Section 9.1.3.

<table>
<thead>
<tr>
<th>$\omega_c$</th>
<th>$L_i$</th>
<th>$R_i$</th>
<th>$a$</th>
<th>$\omega_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>$3.375 \times 10^{-4}$</td>
<td>0.0313</td>
<td>0.04</td>
<td>$2\pi 50$</td>
</tr>
</tbody>
</table>

Table 7.10: Values of the parameters of the transfer function of the current controller

### 7.4.2 Offshore

The gains used for the voltage and current controllers are extracted from [6] and converted in per unit to keep the coherence with the system. The voltage controller and current controller gains are given in Table 7.11 and Table 7.12, respectively.

<table>
<thead>
<tr>
<th>$k_{pv}$</th>
<th>$k_{iv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A V$^{-1}$ Computation</td>
<td>0.005 $\times \frac{230.94}{5.77}$</td>
</tr>
<tr>
<td>A V$^{-1}$ Per unit</td>
<td>0.2001</td>
</tr>
</tbody>
</table>

Table 7.11: Gains of the offshore voltage controller

<table>
<thead>
<tr>
<th>$k_{pi}$</th>
<th>$k_{ii}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V A$^{-1}$ Computation</td>
<td>73.7 $\times \frac{5.77}{230.94}$</td>
</tr>
<tr>
<td>V A$^{-1}$ Per unit</td>
<td>1.8414</td>
</tr>
</tbody>
</table>

Table 7.12: Gains of the offshore current controller

### 8 Case study

#### 8.1 Normal operation

Before simulating faults, it is necessary to define a normal situation for the system, that can be used as a reference for comparisons.
The amplitude and phase of the quantities that are imposed to the system by the grid and the wind power plant are set as listed in Table 8.1 to define the normal situation. As explained in [25], the wind turbines rarely function at full capacity. The wind power plant current is then set to a fraction of the nominal value.

<table>
<thead>
<tr>
<th>Grid quantities</th>
<th>WPP quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V^g_+ = \sqrt{2}$</td>
<td>$I^{wpp}_+ = 0.8\sqrt{2}$</td>
</tr>
<tr>
<td>$\theta^g_+ = 0$</td>
<td>$\theta^{wpp}_+ = 0$</td>
</tr>
<tr>
<td>$V^g_- = 0$</td>
<td>$I^{wpp}_- = 0$</td>
</tr>
</tbody>
</table>

Table 8.1: Amplitude and phase of the external quantities defining the normal operation

### 8.2 Fault situations

The decomposition of voltage in positive and negative sequences, as explained in Section 2.6, allows, by varying the amplitude and phase of the sequence, to simulate countless unbalanced situations, from the slightest to the most severe. The shape, duration, gravity of a fault happening at a certain location depend on many factors. Generally, the closer to the source of the fault (a short-circuit for example), the more severe the voltage sag at that studied location. A detailed faults classification is developed in [16].

As defined in Section 3, only a wind power plant disconnection is simulated on the offshore side. This is done by reducing the three-phase current by the same factor. Or, in an equivalent way, to model the wind power plant current only as a positive sequence, without negative sequence contribution.

On the onshore side, as well balanced as unbalanced faults can be simulated. Unbalanced faults are simulated by varying the magnitude of the positive and negative sequences.

Faults in the DC connections could have also been imagined, but this thesis is limited to AC faults.

The simulation of a fault event is divided in three times

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefault</td>
<td>Allows to observe the system in a normal situation, in its steady state, once the transients resulting from the start of the system are cleared.</td>
</tr>
<tr>
<td>During fault</td>
<td>Allows to study the system behaviour when submitted to an abnormal situation.</td>
</tr>
<tr>
<td>Postfault</td>
<td>Allows to study how the system reacts once the fault is cleared, if it goes back to its steady state.</td>
</tr>
</tbody>
</table>

When starting the simulation, important transients appear. It is attributed to several electrical and control factors, such as the presence of capacitors or the time needed for the DDSRF-PLL to converge.
It is assumed than in reality, the start of the system is made following an appropriate process, using mechanisms such as soft-start. Simulating this appropriate process being out of the scope of this work, the system will be observed in most of the cases only once it is in its steady state, ignoring the initial setting up. The time range of the observation will be chosen for each variable following the elements of interest to show.

The simulation is performed during three seconds, in which events and periods are identified in Table 8.2.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Event or period</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Start of the simulation</td>
</tr>
<tr>
<td>[0 1]</td>
<td>Prefault</td>
</tr>
<tr>
<td>1</td>
<td>Fault trigger</td>
</tr>
<tr>
<td>[1 2]</td>
<td>During Fault</td>
</tr>
<tr>
<td>2</td>
<td>Fault clearing</td>
</tr>
<tr>
<td>[2 3]</td>
<td>Postfault</td>
</tr>
</tbody>
</table>

Table 8.2: Identification of the events and periods within the simulation time

8.3 Unbalanced grid fault

The fault simulated affects the three phases. Phase b and c are submitted to a slight sag, while phase a drops to less than half its value. It simulated by setting the symmetrical components as indicated in Table 8.3 during the fault time.

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V^g^+$ = 0.75$\sqrt{2}$</td>
<td>$\theta^g^+ = 0$</td>
</tr>
<tr>
<td>$V^g^-$ = 0.35$\sqrt{2}$</td>
<td>$\theta^g^- = \pi$</td>
</tr>
</tbody>
</table>

Table 8.3: Amplitude and phase of the symmetrical components applied during the unbalanced grid fault

8.4 Wind power plant disconnection

The disconnection simulated will affect the three-phase current.

It will consist in a sag of the three currents to half of their nominal value. The wind power plant current is created by outputting a positive sequence. The disconnection is simulated by keeping the values of Table 8.1 and setting $I^{wpp^+}$ to $0.5\sqrt{2}$ during the disconnection time.

9 Results

9.1 Unbalanced grid fault

As its description can attest, the system comprises several voltages and currents, that are inputs, outputs or intermediate variables. Only those of interest are displayed below.
The outputs of the main blocks of the control systems are presented and analyzed below to attest their good behaviour under the fault situation.

### 9.1.1 Grid voltage

Figure 9.1 illustrates the fault, showing the waveforms few milliseconds before and after the fault.

![Figure 9.1: Representation of the unbalanced fault on the grid voltage](image)

The sag of $V_a^g$ to less than half its value can be observed at $t=1$, as well as the slight sags of phases $b$ and $c$.

### 9.1.2 DDSRF-PLL

The positive sequence grid voltage $V_{d0}^g$, output by the DDSRF-PLL, is displayed in Figure 9.2. It is represented from $t=0$ to show its drawback compared to a basic PLL. In the case of a basic PLL, the $d$ component would have been directly set to its right value. In Figure 9.2, it can be observed that $V_d^{g+}$ rises from 0 before stabilizing at its steady state value. The convergence remains however fast. The steady state value of the $d$ component corresponds to the magnitude of the voltage, in other words $V_d^{g+} = \sqrt{2}$ pu. It is indeed what is expected after the Park transformation, as explained in Section 2.5.2.

An overshoot can be observed on $V_q^{g+}$ before it reaches its steady state value, 0.

When the fault happens, it takes a bit less than 30 ms for $V_d^{g+}$ to reach a steady value. This value is lower than the prefault value, which is consistent with the fact that a voltage sag is simulated. $V_d^{g+}$ does not correspond to the magnitude of any of the
Figure 9.2: Positive sequence grid voltage output by the DDSRF-PLL

phases. Its value is somehow an average of the three magnitudes. A new overshoot can be observed for $V^{g+}_q$ before it stabilizes to 0.

During the fault, once stabilized, all the components remain constant. This is the advantage of updating the PLL, as with a basic PLL, an unbalanced situation results in oscillations on the dq0 components. This stability feature is indispensable for the rest of the system, and compensates for the deteriorated convergence speed.

At t=2, once the fault is cleared, $V^{g+}_d$ jumps to its initial value in about the same time than for the fault event. $V^{g+}_q$ presents once again an overshoot.

As it is supposed to, the 0 component remains equal to 0 during the whole simulation.

In conclusion, the behaviour of this DDSRF-PLL is considered as very satisfactory.

9.1.3 Current controller

The quality of a current controller is determined by its ability to track the reference current. The measured current $I^{+}_{dq0}$ and $I^{++}_{dq0}$ are then simultaneously observed to attest the quality.

The results obtained using the parameters from Table 7.10 are displayed in Figure 9.3.

The 0 components $I^{++}_0$ and $I^{+}_0$ are not represented as they remain as expected at 0.
Figure 9.3: Comparison of the reference current and the current measured in the onshore filters during the whole simulation, perfectly overlapping.

Figure 9.3 attests that the tracking of the reference is a success. For both d and q components, the curves are almost overlapping. In prefault, during fault and postfault steady states, $I_d^+ = I_d^{+\ast}$ and $I_q^+ = I_q^{+\ast}$. The curves are disjointed only during the transients following the fault event or fault clearing and before the setting of the steady state. As it takes longer for $I_d^{+\ast}$ than for $I_q^{+\ast}$ to reach the steady state, the d components curves are disjointed during a longer time lapse.

The behaviour described above results from trial and error on the parameters of the transfer function $K(s)$ given as (10). The parameters $\omega_0$, $R_l$ and $L_l$ being set, it has been observed that the parameters $a$ and $\omega_c$ have a noticeable impact on the behaviour of the system.

The parameter $a$ has an influence on the steady state error. When $a$ is taken small, $I_{dq0}^{+\ast}$ is overlaid on $I_{dq0}^{+\ast}$ in steady state, which means the tracking is good. When $a$ increases, a constant gap appears between the measured current and its reference.

The controller bandwidth $\omega_c$ influences the tracking in steady state and during the transients. When is chosen larger, getting closer to the value $\omega_0$, the measured current $I_{dq0}^{+\ast}$ follows more accurately the reference $I_{dq0}^{+\ast}$.

Figure 9.3 allows to notice that the current limit (1.7 pu in peak value, as established in Section 7.2.1, is not reached within this simulation. As this thesis was mainly focused
on the AC controllers performance, a situation in which the saturation would be hit was not considered.

When the current limit is reached, the current in the filters is limited through the current limitation. It means that the power on the onshore side is then smaller than the power injected from the offshore side. The excess of power has to be dissipated somehow. This can be done by adding a DC chopper. This device, consisting in a resistor connected to the DC cable if the voltage reaches a certain threshold, allows to burn the power produced offshore that cannot be transmitted to the onshore side.

9.1.4 VSC AC side voltage

The VSC AC side voltage is imposed as the output of the current controller. It is expected to follow accurately the grid voltage, as the grid synchronization is the purpose of the onshore control. During fault, it should then continue to follow the fault grid voltage. Once the fault cleared, it is supposed to come back at a balanced situation immediately.

The behaviour of $V_{abc}^{vsc}$ around the fault event is displayed in Figure 9.4a and around the fault clearing in Figure 9.4b.

It can be observed that directly after the fault event, without transient, $V_{abc}^{vsc}$ takes a shape similar to the grid voltage, with an important sag for phase a and slight sags for phases b and c.

Once the fault cleared, $V_{abc}^{vsc}$ comes back to its initial shape, without transients once again.

The behaviour of the VSC AC voltage is then the one expected under a fault situation.

9.1.5 Filters current

The current flowing in the filters allows to achieve, among other things, the desired power exchange with the grid. When the voltage sags, the current will logically increase in order to keep the power exchange constant. This increase must however remain under the admissible values.

It is valuable that the current in the filters could remain balanced during the fault, even if the voltage at its terminals are not. It avoids a current overload in only one of the conductors, and simplifies the monitoring of the current.

The behaviour of $I_{abc}$ around the fault event is displayed in Figure 9.4a and around the fault clearing in Figure 9.4b.

After the fault event, the magnitude of the current starts to increase progressively, and then decrease to finally stabilize around $t=1.3$. It remains balanced throughout the rise and descent, which is the desired behaviour.

Once the fault is cleared, the current has the opposite behaviour. It decreases and then increases slightly before stabilizing, remaining balanced.
Figure 9.4: Onshore VSC AC side voltage under the unbalanced fault situation
Figure 9.5: Current in the onshore filters under the unbalanced fault situation
The steady state peak value of the current is then higher during the fault, as expected to continue to ensure the same power transfer. This fault value remains however under the limit.

In conclusion, the convergence to steady state values could be faster, but the behaviour of the current in the filters remains satisfactory for its magnitude and balance.

9.1.6 DC connection

The effects of the fault on the DC side are studied here. They reflect directly the quality of the DC voltage control performed by the reference calculation.

The DC voltage at the inverter is given in Figure 9.6. It can be noticed that before the fault, the voltage $V_{inv}^{DC}$ is constant and set at $V_{inv}^{DC} = 1$ pu, attesting the good convergence of the controller in normal operation. After the fault event, the voltage presents an overshoot of less than 10% of its nominal value, before converging to 1 pu. Once the fault is cleared, the voltage presents a sag similar to the fault event overshoot and converges to 1 afterwards.

![Figure 9.6: Inverter DC voltage under the unbalanced fault situation](image)

The DC currents across the DC connection, as defined in Figure 4.2 are displayed in Figure 9.7. Similarly to the DC voltage, the fault event or clearing result in sag or overshoot. Those are quite important compared to the steady state value of the current. Afterwards, the currents converge slowly to a stable steady state value. The transients are more substantial for $I_{inv}^{DC}$, whose order comes from the onshore side, smaller for $I_{DC}$.
and even smaller for $I_{DC}^{rec}$. In other words, they decrease in amplitude when moving away from the inverter.

![Figure 9.7: DC currents under the unbalanced fault situation](image)

If an overshoot is admissible, it should be cleared as fast as possible. The behaviour of the system remains intrinsically linked to the choice of gains and to the capacitance of the offshore capacitors.

Changing the proportional and integral gains result in change in stability, making appear more or less oscillations, and in the amplitude of the overshoots. Choosing them too large or too small might prevent the system to converge, or make it converge to a wrong value.

Increasing the value of $C$ allows to reduce the magnitude of the overshoot when an event happens. But this induces a more oscillating behaviour, especially during the fault.

Although many combinations of parameters have been tried, it was not possible to improve the speed while keeping stability.

It illustrates that well-known fact in the control world, that it is most of the time impossible to obtain a perfect system. It is always a trade-off between robustness, stability and velocity.

It can be highlighted than once the overshoot cleared, the DC quantities remain constant during the faults. The speed of convergence should however be improved, using a technique that might not have been tested here.
The fact that the DC voltage could stabilize at a constant value during the fault shows that the balance between the current entering and leaving the DC cable was respected. If the current limit was reached on the onshore side, it would have not been possible to impose \( I_{DC}^{\text{inv}} \) as large as needed, leading to an inevitable increase in the DC voltage. This problem, not considered here, could however be addressed as suggested in Section 9.1.3, by adding a DC chopper allowing to burn the excess power that cannot be transferred to the onshore side.

### 9.1.7 Use of a second DDSRF-PLL

As mentioned in Section 5.6, when explaining the DC current order computation, the VSC AC side voltage needed in the dq0 frame is obtained from its own DDSRF-PLL. This section aims to show the necessity to proceed this way, while the most straightforward method would be to perform the Park transformation using the grid angle.

Firstly, Figure 9.8 shows the different \( V_{vsc}^{\text{dq0}} \) obtained following the method used. Figure 9.8a is the result of the use of a second DDSRF-PLL, while Figure 9.8b is obtained from the Park transformation with the grid angle.

It can be observed in Figure 9.8a that despite the non zero q component and a relatively slow convergence, the values remain stable even during the fault. On the other hand, Figure 9.8b indicates an oscillatory behaviour all the fault long for \( V_d^{\text{vsc}} \) and \( V_q^{\text{vsc}} \). In the case of the grid voltage, it is precisely that kind of behaviour that was supposed to be avoided using the DDSRF-PLL.

Figure 9.9 shows the impact of the use of the Park transformation with grid angle on several variables.

In the case represented in 9.8b, the power computation will result in oscillations during the fault as \( V_{\text{dq0}}^{\text{vsc}} \) is not constant. This leads to an oscillating current order, resulting in oscillations for the current flowing in the DC cables \( I_{DC} \), as shown in Figure 9.9a. The DC voltage is affected by those oscillations, as attested by Figure 9.9b. The reference current \( I_d^* \) is obtained by controlling the DC voltage and will then also be affected by the oscillations. The current in the filters, following the reference, is slightly unbalanced, as it can be noticed in Figure 9.9d.

In conclusion, the use of a second DDSRF-PLL in order to output \( V_{\text{dq0}}^{\text{vsc}} \) is necessary, especially to avoid the substantial oscillations on the DC current that might be harmful for the cables.

### 9.1.8 Influence on the offshore side

When observing the quantities on the offshore side during the fault time, it can be noticed that none of them is affected by the grid fault.

This is due to the choice of implementation. It could have been chosen to make the offshore side participate to mitigate the grid fault by providing some support.

Here, it illustrates one of the features of HVDC connections, not valued in this work but still an advantage for some applications, that is to isolate two systems.
Figure 9.8: Onshore VSC AC side voltage in the dq0 frame

(a) Using its own DDSRF-PLL

(b) Using the Park transformation with the grid angle
Figure 9.9: Effect of using the grid angle to compute the onshore VSC AC side voltage on several variables during the unbalanced fault.
9.2 Wind power plant disconnection

9.2.1 Wind power plant currents

Figure 9.1 illustrates the disconnection on the wind power plant current, showing the waveforms few milliseconds before and after the disconnection. The current drops to half of its nominal value at t=1.

![Figure 9.10: Representation of the disconnection on the wind power plant current](image)

9.2.2 Voltage decoupling

The voltage decoupling is the first element of the system on which the other elements relies. Its correct functioning must be attested to provide a good base to the rest of the system.

The output of the voltage decoupling is given in Figure 9.11.

It can be observed that it globally outputs the desired value, $V_{pcc+}^d$ as a positive constant value, corresponding to the peak value of $V_{abc+}^{pcc}$, $V_{q}^{pcc+}$ as 0, and $V_{0}^{pcc+}$ as 0 as well, by definition.

At the beginning of the simulation, an overshoot followed by few oscillations can be noticed. This can be explained by the fact that the voltage across the capacitors $C$ is initially 0. Some time is then needed to reach steady state. This behaviour might be overcome by appropriate control changes, but it is not severe and then left as it is.
When the disconnection occurs, small oscillations appear on the d and q components but they are rapidly cleared. The same observation is made after the reconnection.

In conclusion, the voltage decoupling fulfills its role, that is to say outputting the positive sequence of the PCC voltage in the dq0 frame as constant values.

### 9.2.3 Current control

As onshore, the goal of the current control is to track the reference current. The measured filters current $I_{dq}^+$ and the reference $I_{dq}^{ref}$ are observed simultaneously in Figure 9.12. The 0 components are not represented as they remain at 0 during the whole simulation.

It can be attested that the tracking is very good. The two curves are overlapping most of the time, being disjointed only during the transients, that are only substantial at the beginning of the simulation.

### 9.2.4 Point of Common Coupling voltage

The PCC voltage is a quantity of great interest as the offshore goal, as explained in Section 6.1, is to create an equivalent to the grid. Its stability, the desired feature for a grid, has to be attested, attesting in the same time the good functioning of the control loop composed of the voltage and current controls.
The behaviour of the PCC voltage around the disconnection is displayed in Figure 9.13.

It can be observed that $V_{\text{pcc}}^{\text{abc}}$ remains steady and balanced all along, except for a small sag when the disconnection occurs and a small peak when the wind power plant is reconnected, but they are considered as negligible.

The results are very satisfactory, as the PCC voltage is kept stable during the whole simulation, even with the disconnection. The purpose, creating a equivalent to the grid, is reached.

9.2.5 Filters current

The current produced by the wind power plant is carried to the rectifier through the filters. The filters current is then directly proportional and obviously expected to decrease when the WPP current does. What has to be attested is the absence of transients that might be harmful.

The behaviour of the filters current around the disconnection is displayed in Figure 9.13.

It can be observed that when the disconnection happens, the filters current decreases directly. When the WPP is reconnected, it directly goes back to the initial values.

The transitions are then made softly, which was the desired result.
Figure 9.13: PCC voltage under the WPP disconnection
Figure 9.14: Current in the offshore filters under the WPP disconnection

(a) Before disconnection - During disconnection

(b) During disconnection - After reconnection
9.2.6 DC connection

The behaviour of the DC quantities under the WPP disconnection are attested in what follows. Ideally, their values should remain as steady as possible.

The DC currents are supposed to drop during the disconnection, as less current is injected from the offshore side. This is confirmed in Figure 9.15, showing the different DC currents of Figure 4.2 dropping during the disconnection.

Figure 9.15: DC currents under the WPP disconnection

The rectifier DC current presents important peaks at disconnection event and clearing. As it is extremely brief, it is considered as not worrying.

The shape of the currents is smoother when moving from the rectifier to the inverter. The few oscillations during the transients are deeper for $I_{\text{DC}}^{\text{rec}}$ and $I_{\text{DC}}^{\text{inv}}$ than for $I_{\text{DC}}$.

When the current injected in the DC connection decreases, the inverter DC voltage, attesting the balance between the current going in and out, will first decrease. The onshore DC voltage controller reacts then to bring $V_{\text{DC}}^{\text{inv}}$ to its nominal value, 1 pu.

The inverter DC voltage is represented in Figure 9.16. The voltage decrease following the disconnection can be observed, and then the slow convergence to the steady nominal value.

The rectifier DC voltage, unlike the inverter DC voltage, is not controlled. It depends on the inverter DC voltage and of the current flowing between the two stations. $V_{\text{DC}}^{\text{rec}}$ will then present the same overshoots and sags than $V_{\text{DC}}^{\text{inv}}$. During the disconnection, the DC
current flowing in the cables is reduced, which induces a decrease in the voltage difference between the terminals. As $V_{\text{inv}}^{\text{DC}}$ is kept to its nominal value by the DC voltage controller, in the absence of a same mechanism for $V_{\text{rec}}^{\text{DC}}$, the rectifier DC voltage will stabilize to a value smaller than its nominal value.

Those statements about $V_{\text{rec}}^{\text{DC}}$ can be visualized in Figure 9.17.

The behaviour of the quantities on the DC is then satisfactory, except for the speed of convergence to steady values, but this is due to the DC voltage control performed on the onshore side and is not impacted by the offshore side.

### 9.2.7 Influence on the onshore side

The onshore VSC AC side voltage is not influenced by the wind power plant disconnection, remaining synchronized to the grid during the whole simulation.

The onshore filters current $I_{\text{abc}}$ is influenced. When the disconnection occurs, as the current injected from the wind power plant decreases, the DC voltage at the inverter first decreases as well, as the onshore side is taking more current than what is injected by the offshore side. The inverter DC voltage controller fulfills then its role and $V_{\text{inv}}^{\text{DC}}$ increases to its nominal value. This is done by modifying the reference current. The filters current decreases then, adapting to the decrease of injected current.

The filters current can be visualized in Figure 9.18.
Figure 9.17: Rectifier DC voltage under the WPP disconnection

Figure 9.18: Onshore filters current under the WPP disconnection
10 Conclusion

The aim of this thesis was to investigate the control of HVDC-connected offshore wind power plants, a field still subjected to discussions on the strategies to use in order to overcome problems resulting from faults and to provide support to the grid.

Over this thesis, a model has been developed with Simulink, using the PLECS toolbox. The model represents a part of the global system of an HVDC-connected offshore wind power plant, focusing on the transmission part. It is composed of the HVDC connection and of the two converters, the rectifier and the inverter, making the link with the wind power plant on the offshore side and with the grid on the onshore side.

The first part of the report contains the descriptions of the modelled circuit and of the control design, with all the elements composing it. The choices of implementation were presented and explained, and the parameters used carefully reported.

Once the model built, its behaviour was tested by simulating fault situations. A grid unbalanced fault and a wind power plant disconnection were simulated using the symmetrical components. The behaviours of the relevant system quantities and of the outputs of the main control blocks under the fault or disconnection were analyzed. It was confirmed that the quantities had the desired shapes, remaining under the admissible limits, and that the control outputs the desired results. The analysis attested the necessity of some types of implementation, such as the DDSRF-PLL that is preferred to a basic PLL, and of some choices, as the use of a second DDSRF-PLL in the onshore control. It showed that the goal of the control on each side was fulfilled, namely to perform grid synchronization on the onshore side and to create an equivalent to the grid on the offshore side. The study of the system emphasized the fact that the choice of the controller gains are primordial. The system stability, robustness, speed of convergence, correctness of the convergence are based on them. For example, the influence of transfer function parameters of the onshore current controller was highlighted. The weaknesses of the model were also demonstrated. In particular, even tuning the parameters of the DC voltage controller, the speed of convergence remained unsatisfying, which led to important transients on the quantities of the DC connection. The global functioning of the system however fulfilled the expectations.

This work leaves room for improvements. Further research could have been undertaken to improve the DC voltage control. The model could have been extended. For example, the wind power plant could have been modelled in more details, with several groups of wind turbines, with the cables and transformers forming the offshore network and connecting the turbines to the rectifier, instead of current sources representing the whole production. The offshore side could also have been modelled to behave properly when subject to unbalanced conditions. A DC chopper could have been added to deal with saturation situations.

This thesis was of course unable to state all the perspectives and challenges that represents the control of an HDVC-connected offshore wind power plant submitted to unbalanced conditions. But this insight in the complex world of offshore control was undoubtedly enriching and valuable for an electrical engineer-to-be.
Figure 11.1: Global control system in Simulink
Figure 11.2: AC grid in Simulink

Figure 11.3: Wind power plant in Simulink
Figure 11.4: Onshore control in Simulink

Figure 11.5: Onshore DDSRF-PLL in Simulink
Figure 11.6: Onshore reference calculation in Simulink

Figure 11.7: Onshore current limitation in Simulink
Figure 11.8: Onshore current control in Simulink

Figure 11.9: Onshore DC current order computation in Simulink

Figure 11.10: Offshore control in Simulink
Figure 11.11: Offshore voltage decoupling in Simulink

Figure 11.12: Offshore voltage control in Simulink
Figure 11.13: Offshore current limitation in Simulink

Figure 11.14: Offshore current control in Simulink

Figure 11.15: Offshore DC current order computation in Simulink
Figure 11.16: Onshore circuit in PLECS

Figure 11.17: DC circuit in PLECS
Figure 11.18: Offshore circuit in PLECS
References


