OPERATION AND CONTROL OF MULTI-TERMINAL DC (MTDC) GRIDS

AALBORG UNIVERSITY
STUDENT REPORT

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Master Thesis
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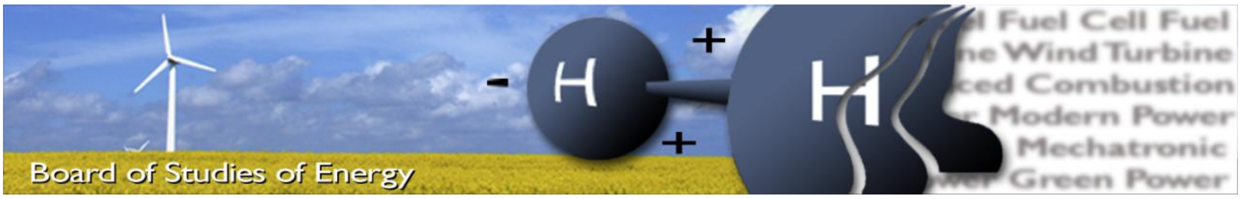

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SYNOPSIS: Europe has many possibilities to generate renewable energy. A great example is wind power. Wind power plants are changing from point-to-point connection to multi-terminal network. The multi-terminal connection will make easier the transmission between different countries, having different grids. This improvement will also help the transmission from offshore wind power plants. To get the multi-terminal grid it will be used the VSC-HVDC system, which is more efficient in long distances and it has lower power losses than other systems. This project aims at developing the power sharing control in an MTDC transmission system.

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Abstract

Europe has many possibilities to generate renewable energy. A great example is wind power, which is a green and efficient resource and, for this reason, the wind power plants are growing constantly. Wind power plants are changing from point-to-point connection to multi-terminal network. The multi-terminal connection will make easier the transmission between different countries, having different grids. This improvement will help the transmission from offshore wind power plants too. To get the multi-terminal grid it will be used the VSC-HVDC system, which is more efficient in long distances and it has lower power losses than other systems.

This project aims at developing the power sharing control in an MTDC transmission system under normal conditions. The multi-terminal network, the control system and the simulation studies are modelled in MATLAB/Simulink environment.

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Abbreviations

AC	Alternative Current
CSC	Current Source Converter
DC	Direct Current
HVAC	High Voltage Alternative Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
LCC	Line Commutated Converter
MTDC	Multi-Terminal Direct Current
NPC	Neutral-Phase Clamped converter
OPWM	Optimized Pulse Width Modulation
PLL	Phase Locked Loop
PI	Proportional Integrator
PWM	Pulse Width Modulation
SCC	Self Commutated Converter
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
VSC	Voltage Source Converter
WPP	Wind Power Plant

1 Introduction

1.1 Background

Population is increasing, therefore the electricity demand grows too. The depletion of primary energy sources and the research on renewable energies improvements make these grow every year. Besides being clean energies, they have little environmental impact. Furthermore, they are endless sources of energy and they work with free resources, such as wind and sun. Another advantage of renewable energies is their geographical situation, they can be installed in much more places than petroleum, for instance, which exists only in few countries that control the market. Therefore, thanks to renewable energies some countries will not depend on other countries in an energy way [1].

An important green energy is wind power, which can generate GW of energy. Wind energy spread through EU twenty years ago and, although the financial crisis has affected to its growth, its installations increase annually, as the Figure 1.1 shows.

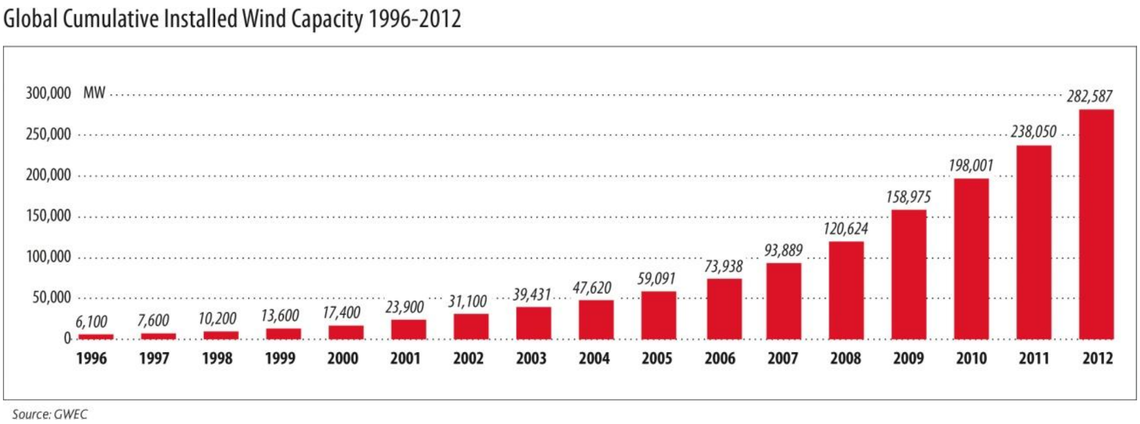

Figure 1.1 Global Cumulative Installed Wind Capacity 1996-2012 [2].

Nowadays, the 7% of Europe’s electricity demand is produced by wind energy. Two years ago, in 2011, this percentage was 6.3% and in 2009 it was 4.8%. It can be seen with this information how this renewable is expanding. Another fact is that wind energy means 26% of all EU power capacity installed in 2012 [2].

The future of wind power depends on the continued investigation of progress, because wind is unpredictable, frequently changing and unclear [3].

A great definition of wind power plant could be a wind energy installation, which has a large number of turbines and converts the kinetic energy of the wind into electrical energy. It can difference between two types of wind power plants, the first, which is the most developed in EU, is onshore and the other one is offshore, which is flourishing more every year and it is expected to equalize the capacity of onshore parks in some years.

Figure 1.2 represents the forecast of European Wind Energy Association (EWEA) for the next years, where is observed that it is predicted a continued increase of offshore wind power. Although offshore plants have high costs, they are being reduced and it causes a positive prediction for this parks.

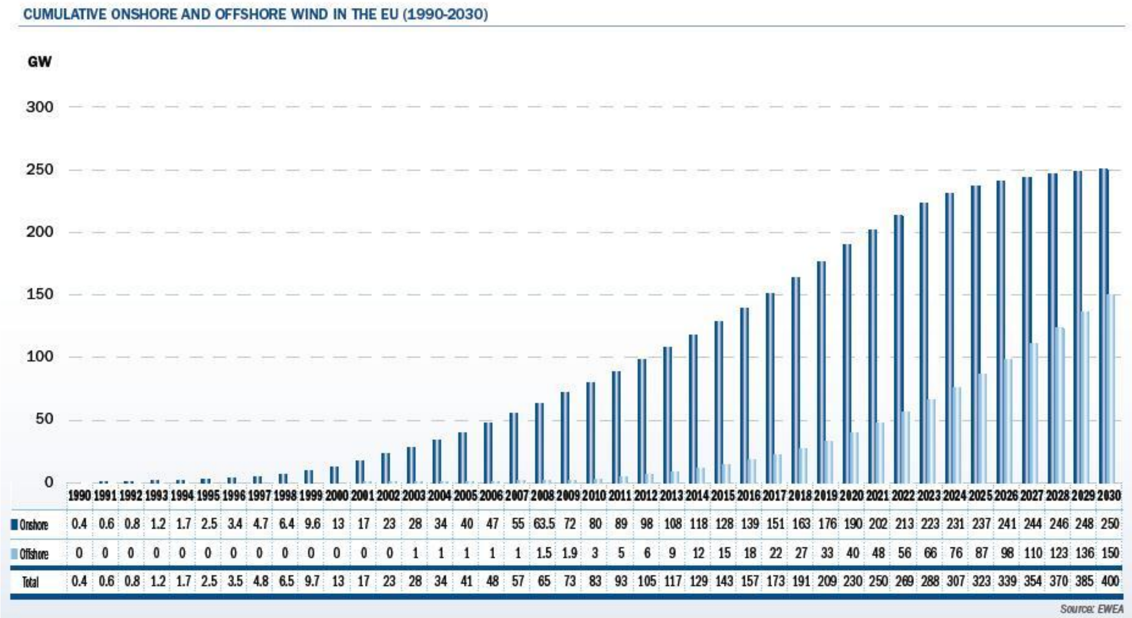

Figure 1.2. Cumulative onshore and offshore wind in the EU (1990-2030) [3].

The first offshore wind farm in the world was installed in 1991, months later, the first electricity was exported onshore from Vindeby offshore wind farm. It was about 5 MW. These days, this number is multiplying by 1000, which means 2% of the total wind power capacity installed in the world. Most of the offshore wind parks, 90%, are situated in the North, Baltic and Irish Seas and the English Channel. There is a big interest too in Asia and North America [2].

Offshore parks are growing constantly because they have some advantages over onshore plants. They have an important disadvantage, which is the cost of the development. Obviously, the maintenance of offshore plants will cost much more because of their situation, but the different costs are being studied for their decrease. However, there have many advantages too. The clearest one is that speed of the offshore wind is higher and steadier than on land. They have less environmental constraints than onshore. Another advantage is that offshore plants have typically less turbulence than onshore ones [2].

In the following section, the explanation about the suitable system to carry out this task is discussed.

1.2 State-of-the-Art

HVDC and HVAC are the responsible for transmitting high amounts of energy. It is discussed in the next paragraphs which is more appropriate.

Although HVDC is not economical for short distances, due to the high cost of the converter stations, it is more suitable for long distances than HVAC. It is shown in Figure 1.3 the HVDC and HVAC cost comparison. In this figure, it is observed that HVDC has low costs than HVAC from a break-even-distance. This distance is, approximately, 600 km, but it is much smaller for submarine cables, it is less than 100 km [4].

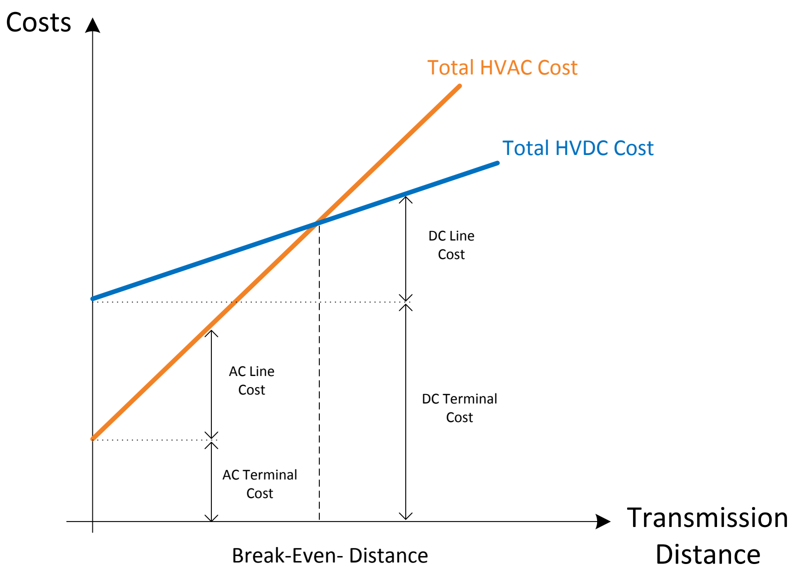

Figure 1.3 HVDC-HVAC costs [5].

Another possible comparison between these systems is showed in Figure 1.4. It is observed that HVAC system has no converter losses when the distance is minimum, however it increases when the length grows [5]. The break-even distance is the same as in the previous comparison.

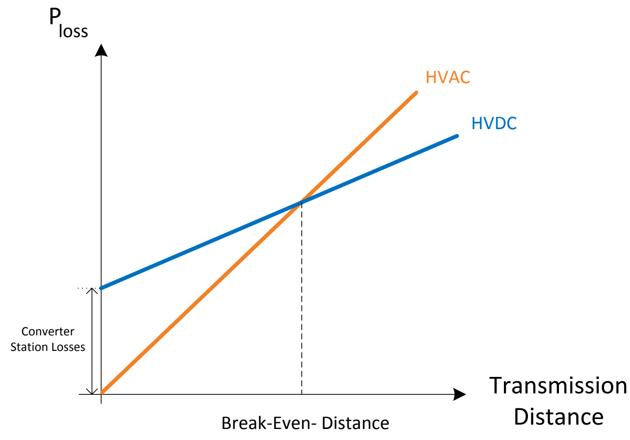

Figure 1.4 HVDC-HVAC losses.

In addition to have low losses than AC system in long distances, HVDC with bipolar configuration can transmit the energy using two cables instead the needed three of AC. This fact means that HVDC costs less than HVAC when the length is important. Another important advantage over HVAC is that HVDC system is able to connect asynchronous AC network.

Even though HVDC system has some disadvantages comparing it with the traditional HVAC, the main advantages to choose this DC system are having neither reactance, nor stability problem and therefore no distance limitation. Being HVDC perfect for transmitting electricity over great distances [4].

In conclusion, today the more appropriate system to transmit this amount of energy from offshore to onshore is HVDC system. It presents many advantages and is the reason why is used in more projects every year.

1.2.1 HVDC Technology

Otherwise, the main component of HVDC system is its converter. Depending on the type of the converter HVDC system can be classified as HVDC Classic or Light.

On the one hand, HVDC Classic works with conventional Line Commutated Converter (LCC), in other words, conventional HVDC uses Line Commutated Current Source Converter (CSC). Thyristor valves are utilized in this transmission. This system has lower cost and less station losses than VSC HVDC [7].

A back-to-back LCC scheme is showed in Figure 1.5.

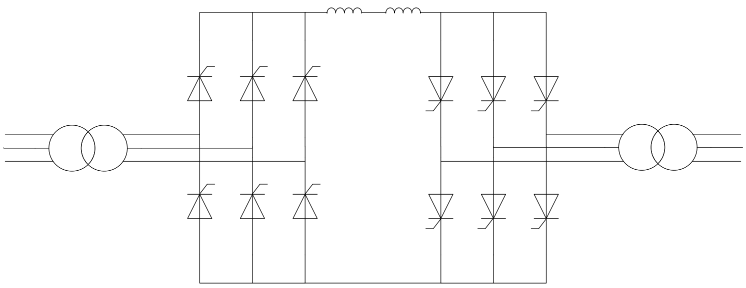

Figure 1.5 LCC HVDC.

On the other hand, HVDC Light works with Self Commutated Converter (SCC), that is, Voltage Source Converter (VSC) with PWM. VSC HVDC utilizes self-commutated transistors, IGBT, instead thyristors. An important characteristic which should be considered is the ease of incorporating new VSC-HVDC terminals to an existing MTDC system. Furthermore, VSC systems have the benefit that the DC voltage polarity remains the same when there is a power reversal. VSC-HVDC is presented in Figure 1.6.

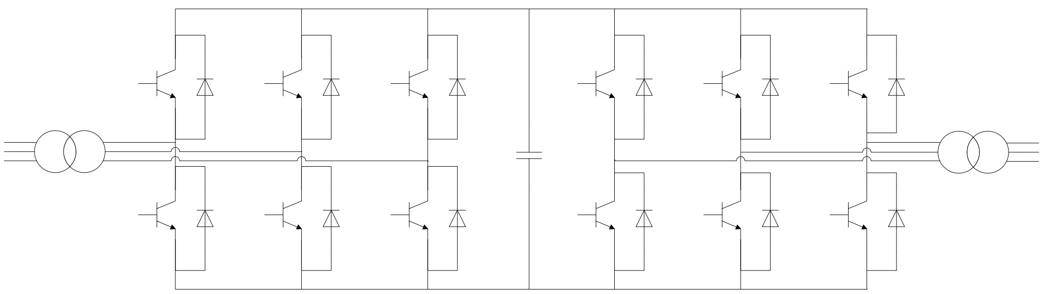

Figure 1.6 VSC HVDC.

The IGBTs has the advantage, over using thyristors, of turn off capability, giving the converter another degree of freedom and making the VSC self-commutated. The IGBT devices could be controlled at any moment unlike thyristors.

Both systems have advantages and disadvantages over the other one, but, in this case, VSC will be the choice, due to the previous mentioned advantages and the fact that VSC-HVDC can control independently the active and reactive power, while CSC cannot do that [8].

1.2.2 MTDC

Another important point in HVDC systems is their connection. Most projects about HVDC systems are two terminals, point to point connection, but the term of supergrid exists. It would be a large network that transmits high amounts of renewable energy to different places, located at a great distance.

There are many reasons to build a Multi-terminal HVDC, instead having several separate point to point transmissions. The main advantage is that MTDC will improve the functionality and reliability of the network, decreasing conversion losses and with less cost [9].

MTDC is more efficient than a point-to-point connection. It allows having multiple AC grids and in case that one AC link breaks, MTDC will have other grids to deliver the energy, unlike point-to-point, which only has one AC grid and if some problem happens it will make that all the network fails.

MTDC is interesting for offshore wind transmission, considering that VSCs have a limited transmission capacity and offshore wind farms have separate locations in the wind area, because MTDC can take out and deliver power from and to different terminals [10].

Some projects like the Kriegers Flak (the Baltic Sea) and the Tres Amigas (USA) are being developed. These two projects have the same purpose, working in different environments. The first one is working with offshore wind power and the Tres Amigas project works with onshore wind power, apart from solar and geothermal. This is a great example to show that MTDC, based in VSC, is suitable for any condition.

The objectives of Kriegers Flak are connecting the new offshore wind turbines to the power network and interconnect the power grids of Denmark and Germany. The benefits of an offshore power grid are, among others, improving renewable energy utilization and national economies, because although when the wind turbines deliver limited power, the power grid can be used. In this project, HVDC is used due to the German and Danish systems are not synchronous, to make a connection between them DC is needed [11].

Kriegers Flak is the step before a greater project in the North Sea, where a much larger MTDC offshore power grid is planned. This could help to the fossil fuel independence in Europe.

In Germany is planned another example of MTDC. It consists of transmit the offshore energy of the Baltic Sea across the country and delivering electricity in the south, which depends more on nuclear energy. In this manner, the rest nuclear reactors of this country could be closed, having an energy alternative [12].

These projects will be the predecessors of the European Supergrid, which is explained in the following paragraph.

Another project proposal is shown in Figure 1.7. It is based on a supergrid, consisting of VSC-MTDC, connecting and integrating different separated wind farms across Europe. This project would provide many benefits to the EU members, being a great improvement in the energy needs of Europe. The energy could be delivered where it would be needed through the internal network, transmitting it from the offshore grid to the continental Europe. This proposal is extensively described in literature [13].

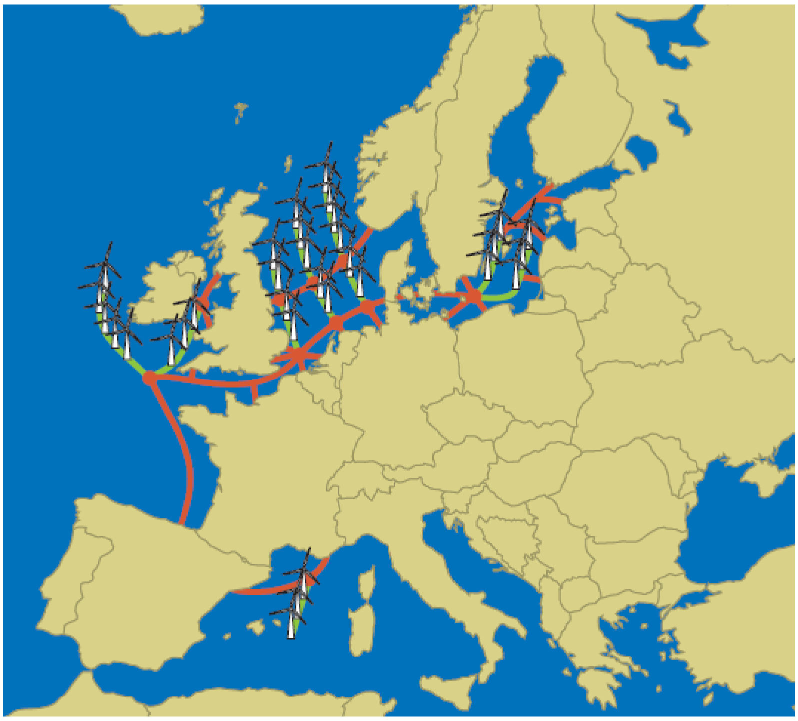

Figure 1.7 HVDC Supergrid proposal for Europe [13].

1.3 Motivation

The North Sea, the Baltic and the seas around United Kingdom and Ireland has a huge potential for the offshore wind power generation. Similarly, the southern Europe and northern Africa has a large potential for the solar power generation. It is proposed that a Multi-Terminal DC Supergrid overlay could be developed to facilitate GWs of power throughout the European Grid from the offshore wind parks to the continental Europe.

In this project it is intended to simulate a three-terminal HVDC, trying to find how this system works and hence, having an idea of how the future MTDC supergrid would work.

1.4 Problem definition

A multi-terminal DC with three terminals is designed to its simulation and control. The model can be seen in the Figure 1.8.

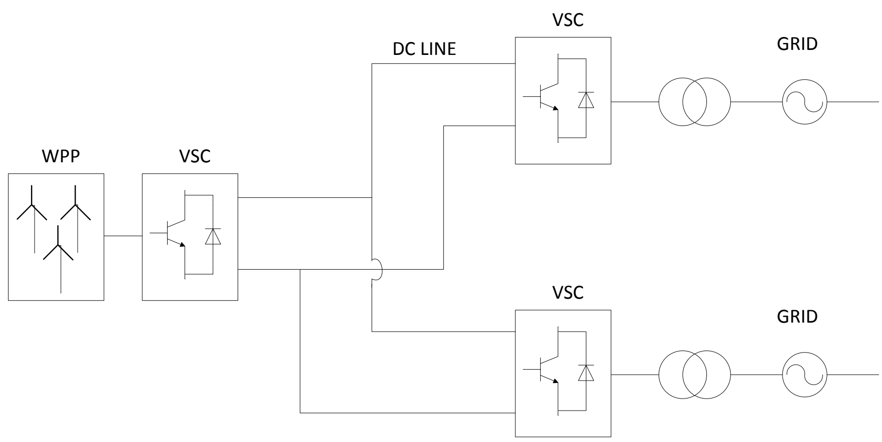

Figure 1.8 MTDC.

The scheme consists of two onshore terminals, which are connected to the grid, being responsible to transmit the alternative current to other load centers, and the third terminal, which receives the energy from the wind power plant. The three terminals are communicated by a DC line. Otherwise, there is a converter in each terminal, it transforms the current from DC to AC in the onshore terminals or AC to DC in the offshore.

On the other hand, this MTDC will be controlled by Voltage and Power Controllers.

Once the system is controlled, it will be simulated, obtaining the final results.

1.5 Methodology

The first step carried out was reading literature. Many documents have been read to make this project. Some of them are reports of important institutions, power systems books, papers of other projects and publications of IEEE.

MATLAB/Simulink, was used for modeling and simulation. The system was developed from the beginning, solving different errors, simplifying the parts that were not too important and focusing on the scope, which was to get the correct running of a three terminal MTDC.

Subsequently, the control for this system was designed. Firstly, two different regulators were separately implemented in two terminals. After their proper operation, they were replaced for a more complete droop controller.

Lastly, the simulation of the entire system was tested by Simulink tool, obtaining some results, which were compared with the expectations.

2 VSC-HVDC and MTDC System

The selected system to get across the energy from offshore to onshore is HVDC. It has several features for carrying out this task. First of all, it is appropriate for long distances, which is perfect to transmit energy from an offshore park to land or from onshore to load centers, for instance. It can use overhead lines and subsea or underground cables, being environmentally friendly. Another quality is that this system tolerates large amounts of electrical power and asynchronous interconnections. Apart from the previous features, it has low losses in long distances than other systems, HVAC for example. All these characteristics are the reasons why HVDC projects are increasing every time [14][15].

HVDC system can have different configurations. When this configuration consists of more than two terminals, it is called Multi-Terminal DC (MTDC). Figure 2.1 shows a Bipolar HVDC configuration and Figure 2.2 a Bipolar MTDC.

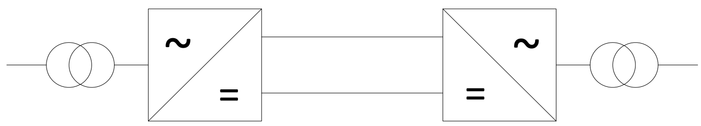

Figure 2.1. Bipolar HVDC.

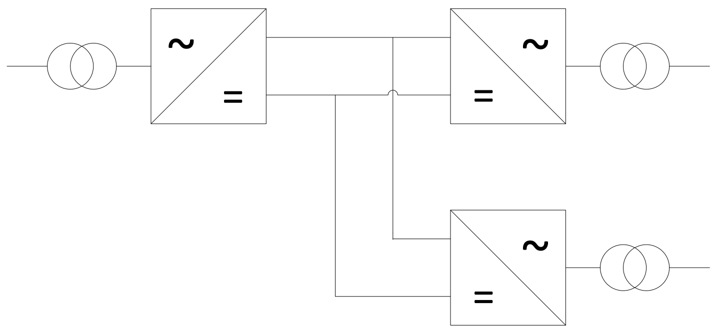

Figure 2.2. Multi-terminal HVDC.

Multi-terminal HVDC system have more than two converter stations, in this example there are three converter stations, which are interconnected in the DC side of the transmission system.

2.1 Voltage Source Converter

This converter transforms the direct current in alternative current. If the conversion is DC to AC is called inverter and rectifier when the transformation is AC to DC.

Figure 2.3 represents a two-level, three-phase Voltage Source Converter. As we can observe it is formed by two transistors per phase with an anti-parallel diode.

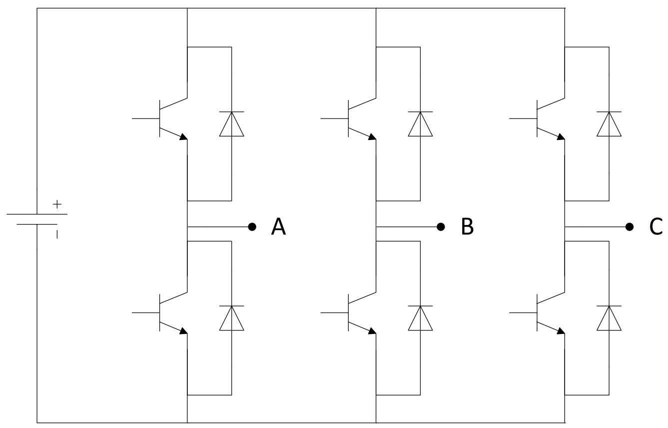

Figure 2.3 2-level VSC

2.1.1 PWM

It is usually used to control the input of electrical devices, in this case, the input signal of the IGBTs. There are different types of PWM used for the IGBTs of the VSC, like Optimized PWM (OPWM), Space Vector PWM (SVPWM) and the simplest Sinusoidal PWM (SPWM) [16].

Sinusoidal PWM is a modulation technique that forms the width pulse of a signal by comparing a triangle waveform with the modular signal. This PWM is used in this project.

2.1.2 Multilevel

Apart from the 2-level VSC presented before, there are different multi-level converters, which are suitable to HVDC system too. A known 3-level VSC is showed in Figure 2.4.

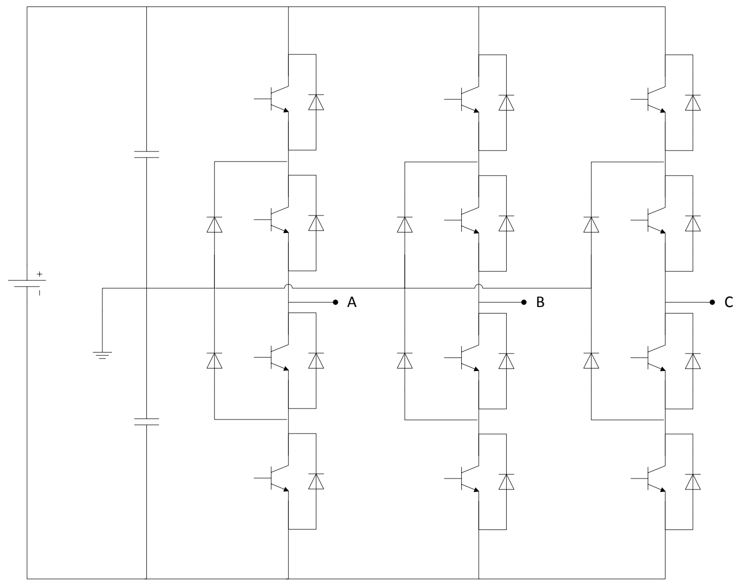

Figure 2.4. 3-level VSC

This three-level VSC is called Neutral-Point Clamped (NPC). The number of series-connected switches is reduced by NPC. Each switch cell of this system has to resist half of the DC voltage, hence it can be reduced the switches in series. Furthermore, comparing the two-level VSC with this NPC, the three-level system can produce a three-phase AC voltage with a lower harmonic distortion. It is explained extensively in literature [17].

2.2 Filter

The filter is situated after the converter and before the grid. Its main function is to diminish the high frequency harmonics.

The voltage of the grid is measured in this filter.

2.3 DC Cable

DC cable will connect the different parts that belong to direct current. It has usually a resistance in its line.

We can compare HVDC cable with traditional AC cable and we will notice that it has many advantages. DC cable has lower losses, it does not need an intermediate station, it neither has increasing of the capacitance in the AC network, nor limit on the cable length. AC cable does have limit in the length because of the cable capacitance and AC transmission needs an intermediate station to compensate the reactive power [15].

2.4 DC Capacitor

DC voltage has small ripples when a DC capacitor is implemented. This ripple is produced by the switching actions of the converter. The DC capacitor has to be a medium size to be able to diminish the ripple and to permit normal speed responses.

3 Modelling and Control of MTDC System

A three-terminal MTDC will be design in this project. Two terminals are the onshore plants, with grid connection. The other terminal is the offshore plant. It can be observed the described system in Figure 3.1.

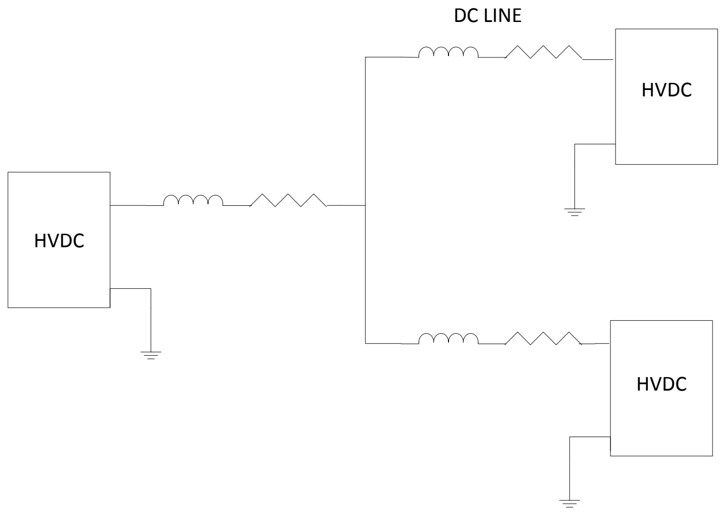

Figure 3.1 MTDC.

Bipolar HVDC system is used, this means that one line is for positive and the other one for negative. In the model it is represented only by one line and ground. In this project, it is used ground, because the DC line has the double value of inductance and resistance, instead having two single values in positive and negative lines.

3.1 Voltage Source Converter

The VSC of this project is three-phase, two-level converter. First of all, it is created the gate pulse for the IGBTs. The chosen PWM between those described in the previous chapter is pure Sinusoidal PWM.

Figure 3.2 shows the comparison of the sinusoidal reference with the triangular wave, obtaining the switching pulse of Figure 3.3. This pulse is different depending on the chosen three-phase sinusoidal wave, they are 120º phase-shifted. Using the different signal pulses in the gates of the IGBTs, in the Figure 2.3, it can get the output of the converter, it is represented in Figure 3.4.

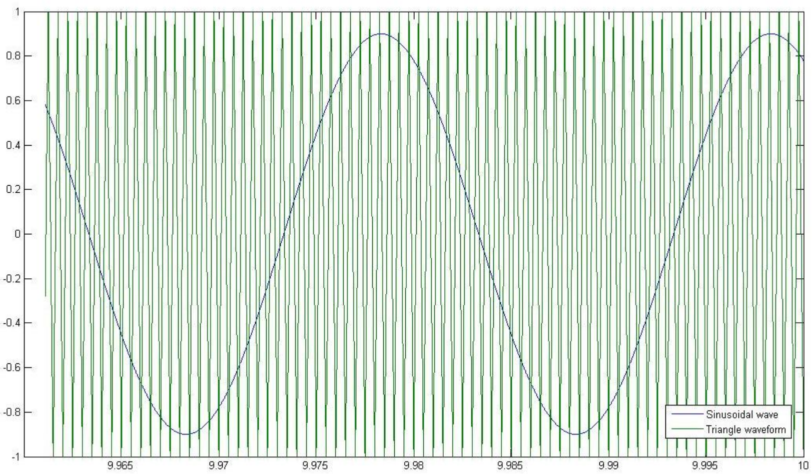

Figure 3.2. Comparison.

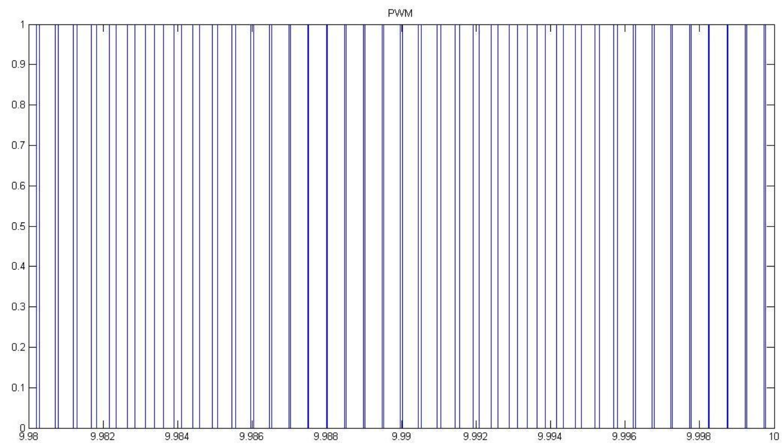

Figure 3.3 PWM.

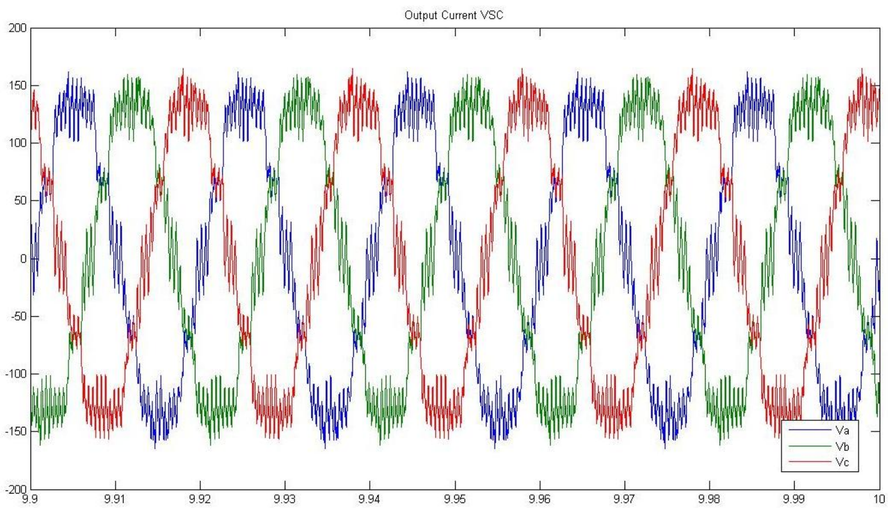

Figure 3.4 Output VSC Current.

The scope of this project is not this VSC, hence it is simplified the circuit replacing the VSC and the PWM for three current sources, which have the same output as the previous converter.

3.2 Transformer

The objective of the transformer is adapting the signal of the converter to the grid, besides giving galvanic isolation. In this project the transformer is considered ideal, there are no losses, therefore in its place an inductance in series with a resistance are put.

3.3 DC Cable

In the description it is written that the DC cable connects the DC parts, in this project these are the output of the rectifier, in the offshore plant, and the input of the inverters, which are part of the onshore park.

To simulate the DC cable resistance, the DC line has a resistance in series with an inductance.

3.4 Control

In this chapter the different utilized controllers for VSC-HVDC are explained.

3.4.1 Vector control

Vector control is the most basic and the most used control for VSC. This control transforms the currents and the voltages into d-q reference frame, it will be synchronized by the PLL [18].

The Figure 3.5 represents the three phase voltage transformations.

The transformation can be done by Clarke method. It turn abc into $\alpha\beta$ and then $\alpha\beta$ into dq. Otherwise, the abc-to-dq transformation and vice versa could be done directly by the transformation of Park.

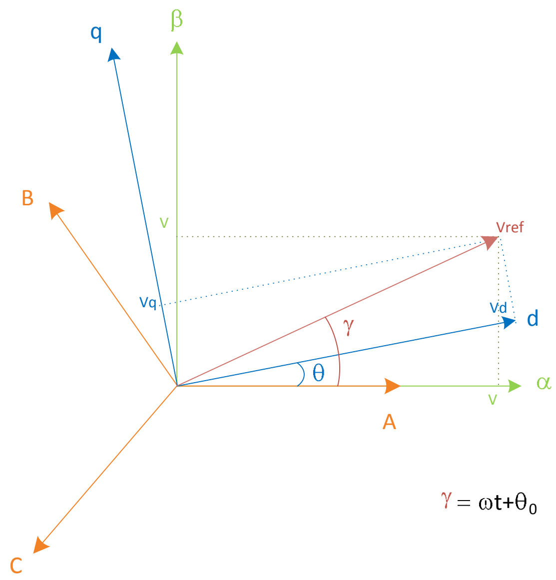

Figure 3.5 Three-phase Voltages Transformations.

The AC voltages are defined in the following equations (1).

$$V_a = V_m \cos \omega t$$
$$V_b = V_m \cos\left(\omega t - \frac{2\pi}{3}\right)$$
$$V_c = V_m \cos\left(\omega t + \frac{2\pi}{3}\right) \tag{1}$$

Calculating the $\vec{V}_{ref}$ it can be seen that Clarke gives the components along $\alpha\beta$-axes (2) and Park along the synchronously rotating dq-axes (3).

$$\vec{V}_{ref} = \frac{2}{3}\left(V_a(t) + V_b(t)e^{j\frac{2\pi}{3}} + V_c(t)e^{-j\frac{2\pi}{3}}\right) \tag{2}$$

$$\vec{V}_{ref} = \frac{2}{3}\left(V_a(t)e^{-j\omega t} + V_b(t)e^{j\left(\frac{2\pi}{3}-\omega t\right)} + V_c(t)e^{j\left(\frac{4\pi}{3}-\omega t\right)}\right) \tag{3}$$

In this control, it is aligned the dq-axis in such direction that the d-axis is in phase with the AC grid. Hence, it is achieved the following statement (4).

$$\theta = \gamma = \omega \boldsymbol{t} \qquad \begin{cases} Vd = \vec{V}_{ref} \\ \\ Vq = 0 \end{cases}$$

(4)

The transformation of Park is done in this project to turn AC currents and voltages into dq components, i.e. abc-to-dq. To achieve that, the next operation is done (5), knowing that $\theta = \omega \boldsymbol{t}$.

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

(5)

To obtain the dq-abc transformation, the inverse transformation of Park is carried out by (6).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}$$

(6)

3.4.2 Phase Lock Loop

Frequency is measured by the PLL, obtaining the angular frequency, which will be used in the dq-to-abc and the abc-to-dq transformation as the reference. The PLL synchronize the output voltage of the converter with the grid.

Figure 3.6 shows the scheme of PLL.

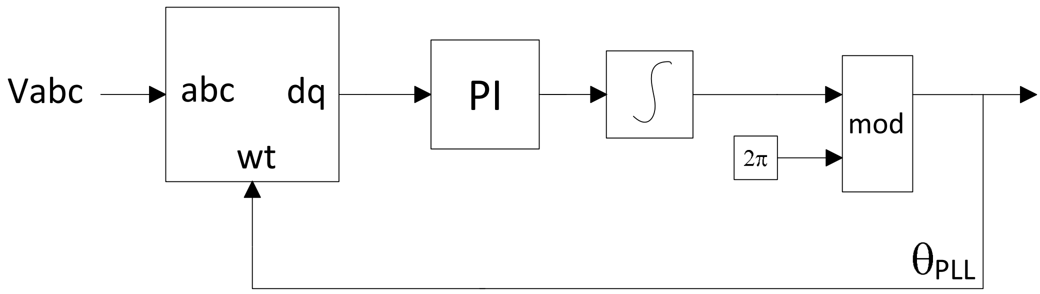

Figure 3.6 PLL.

3.4.3 Voltage control

Observing the Figure 3.7 it can be seen that the error of voltage is calculated by $V_{DC}^{*} - V_{DC}$, that is, the difference between the voltage reference and the voltage of the DC side, measured in the DC capacitor. This error is passed through a proportional integrator (PI) and the result is id^{*}, the reference of the d-axis current component [19].

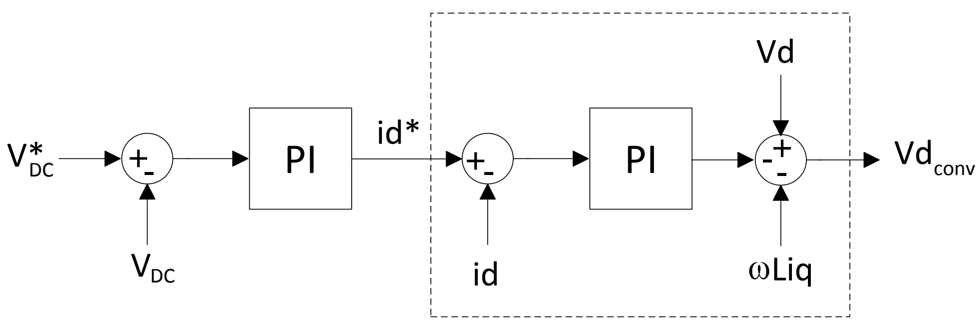

Figure 3.7 Voltage controller.

Otherwise, id and Vd are the d-axis components of current and voltage, respectively, of the AC side. iq is the q-axis current component of the grid.

Furthermore, ωL is the converter transformer reactance.

The model of the Figure 3.7 is simplified, due to the inner control loop in this project is considered ideal. The result, which is built in the project, is represented in Figure 3.8.

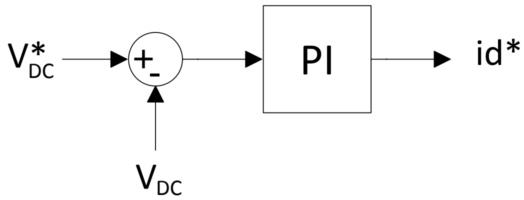

Figure 3.8 Simplified Voltage Controller.

Figure ***3.9*** Voltage Regulator Curve ***[20]***Figure 3.9 shows the characteristic curve of the DC voltage regulation of VSC-HVDC. The DC voltage controller maintains the DC voltage constant.

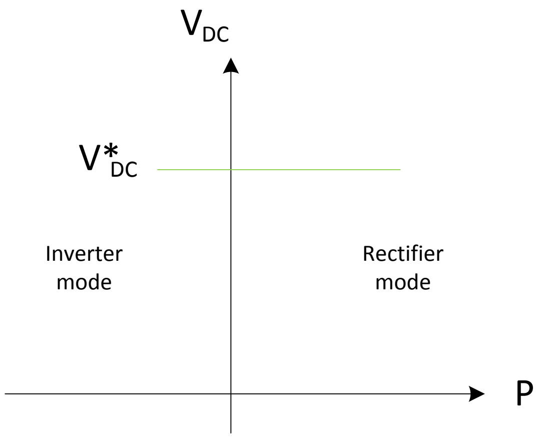

Figure 3.9 Voltage Regulator Curve [20].

3.4.4 Power control

The Figure 3.10 resembles Figure 3.7. They follow the same process, although in this case the power error is calculated by $P^* - P$, the difference between the active power reference and the active power of the system. Active power is calculated as follows (7).

$$P = \frac{3}{2} V_d i_d \tag{7}$$

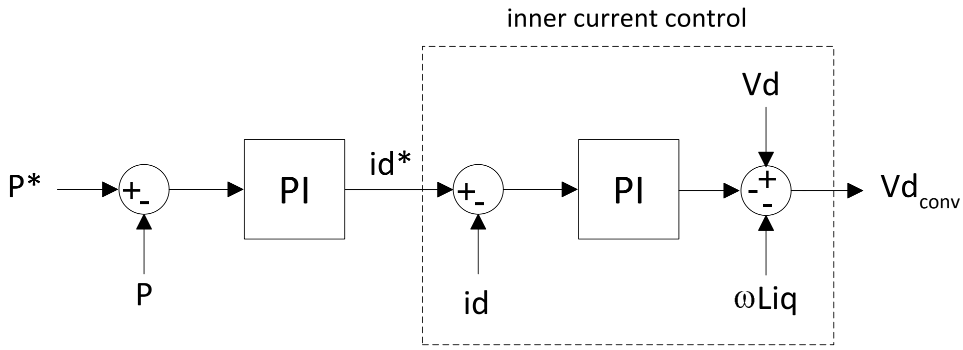

Figure 3.10 Active Power Controller.

The inner current control, as it was mentioned earlier, is considered ideal. Therefore, the simplified and designed power regulator is the same as the one represented in Figure 3.11.

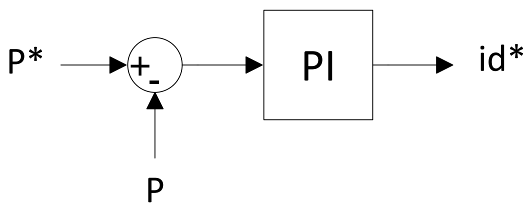

Figure 3.11 Simplified Active Power Regulator.

The power regulator curve is represented in Figure 3.12, it shows the relation between the DC voltage and the power. It can be seen that the power keeps constant.

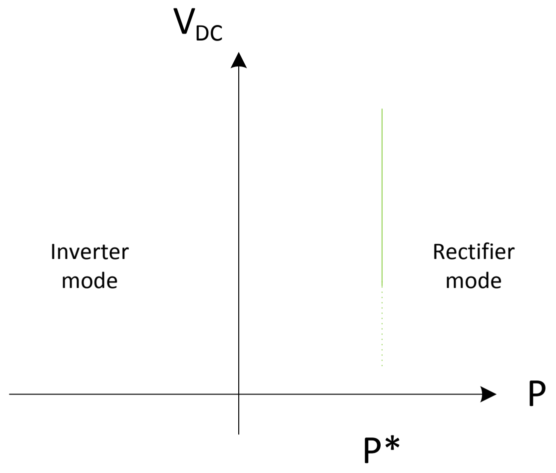

Figure 3.12 Active Power Controller Curve.

In this project reactive power becomes zero, therefore $iq = 0$. However, if a reactive power controller is designed, it would be the demonstrated in Figure 3.13. The Q^* would be the reactive power reference and Q would be the calculated reactive power, its value is calculated by the following equation (8).

$$Q = -\frac{3}{2} V_q i_q \tag{8}$$

Another difference is Vq, which are the q-axis component of voltage of the AC side.

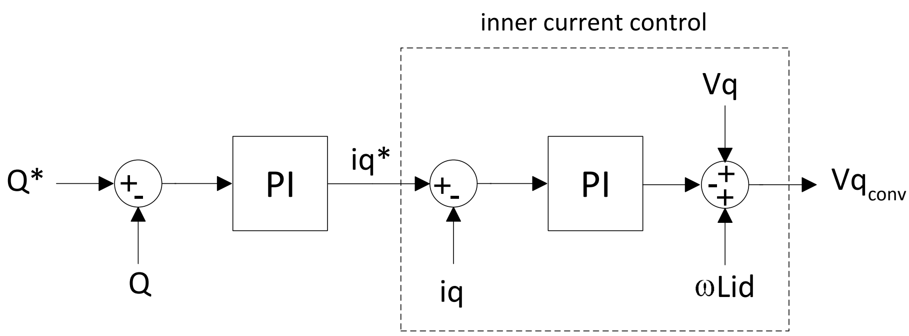

Figure 3.13 Reactive Power Regulator.

The regulator is simplified as the Figure 3.14 shows.

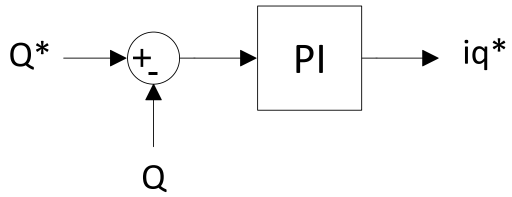

Figure 3.14 Simplified Reactive Power Regulator.

3.4.5 Droop control

Once the power and voltage controllers worked, they were changed for the droop control, which regulate both power and voltage. There was a power controller in one terminal and a voltage controller in other, but it is not desirable. It is not appropriate that only one terminal regulate the voltage in a MTDC. The reason for this change is that fact.

The droop regulator is a combination of the previous controllers, getting a droop balance between voltage and power.

The scheme of the droop regulator is represented in Figure 3.15.

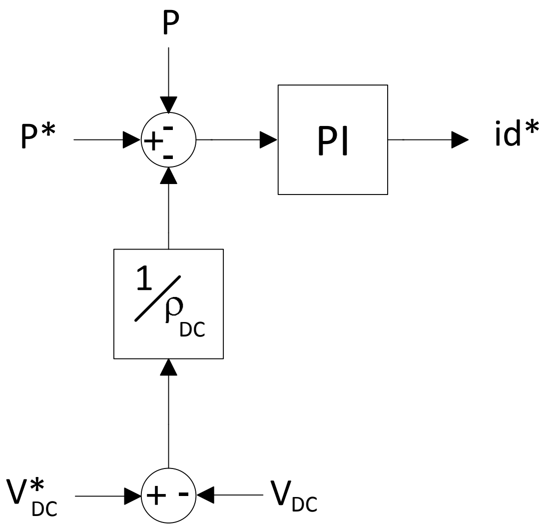

Figure 3.15 Voltage Droop Controller [19].

The gain of this regulator is $1/\rho_{dc}$, the next equation is used to calculate it (9).

$$V_{DC} = V_{DC\,ref} + \rho_{DC}(P - P_{ref})$$
$$\rho_{DC} = \frac{V_{DC} - V_{DC\,ref}}{P - P_{ref}}$$
$$\rho_{DC} = \frac{\Delta V_{DC}}{\Delta P}$$

(9)

This gain will be the reference to obtain the slope in the relation between voltage and active power. There are different slopes, depending on the sign of the ρ_{DC}. These options are represented in Figure 3.16 and Figure 3.17.

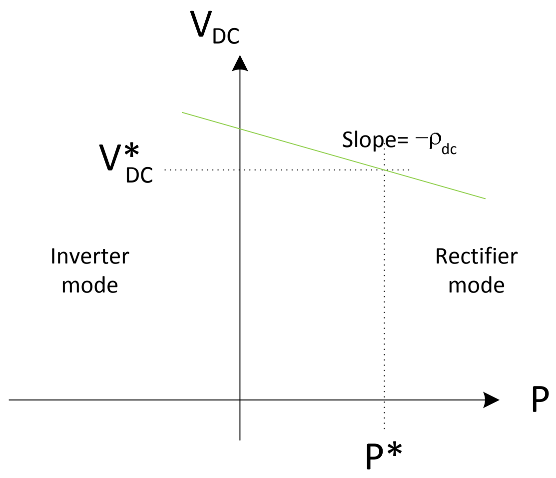

Figure 3.16 Droop Controller [19].

In this project, Figure 3.16 represents how the system works and Figure 3.17 is the droop controller designed for the system. The regulator gets that when the power is decreasing the voltage will diminish its value too and if the power increases, the voltage will grow too.

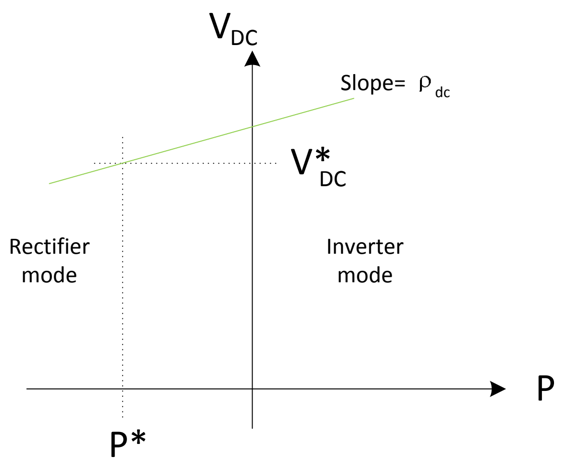

Figure 3.17 Droop Controller.

4 Simulation and results

The MTDC model designed before is testing in this chapter. Its simulation will be carried out with different regulators.

First of all, voltage and active power controllers were designed and tested. To improve the control of the MTDC they were replaced for voltage droop control. This new regulator was installed in each terminal to control both active power and voltage at the same time.

As the wind is not constant, it usually changes during time and it has different amplitudes, a pulse generator is included in the offshore stations, in the left side of the schemes. In this manner, the wind variations can be simulated. This pulse generator changes every 5 seconds with an amplitude of 0.2. In the case of MTDC of four and five terminals there are two pulses blocks, the second one is delayed 2.5 seconds in relation to the first offshore station and the wind has 0.1 more amplitude.

Moreover, to simulate the different MTDC systems the voltage and power references are determined. They are needed to the proper operation of the controllers. The voltage reference is $640\ KV$ and the active power reference is $400\ MW$. Depending on the station the power reference will change, having 0.5, 0.8 or $0.1\ pu$.

Some results are expected. The power control should maintain constant the power value in its reference, independently of the offshore station changes. Otherwise, the voltage control should get the reference as the final voltage value, although there are some increases or decreases in the delivery station. On the other hand, the droop control should get the power sharing between the different onshore stations.

To verify the awaited results there will be some study cases. The first case is three MTDC with separated voltage and power control, the next is three MTDC with droop control. And the last study cases are three and four terminal MTDC with droop control. In each study case, the DC line length, the power reference and the gain of the droop control, when it is implemented, change to different values to observe how the response of the system is.

4.1 Three terminal MTDC

The first simulated model is the three-terminal MTDC with separated voltage and power control. Terminal 1, HVDC1 in Figure 4.1, has the voltage controller of this model, while Terminal 2, HVDC2, controls the active power.

In the second case, HVDC1 and HVDC2 have the same regulator, voltage droop controller.

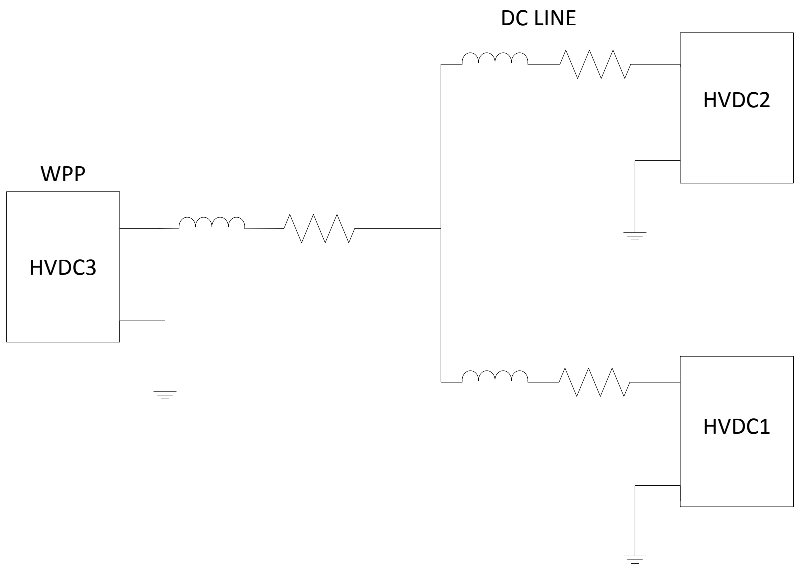

Figure 4.1 Three MTDC.

After the explanation of both systems and their graphic results, they are compared with each other to verify that droop control improves the response of the system.

4.1.1 MTDC with Voltage and Power control

Figure 4.2 show the DC current, the DC voltage and the power of this system. Voltage and current are measured in the DC capacitor of each HVDC.

The legend of the figures has three terminals. HVDC1 and HVDC2 are the onshore stations, while HVDC3 is the offshore plant, where the wind is varying.

HVDC3 has some DC line impedance, HVDC1 has the double of this impedance and HVDC2 the triple. Furthermore, HVDC3 has $0.8\ pu$ power reference, HVDC2 has in its power reference $0.5\ pu$ and HVDC1 $640\ KV$ voltage reference.

It is observed in Figure 4.2 that the HVDC1 voltage reacts to the power change, but after some seconds the system achieve the reference voltage value that it had again. That means that the voltage regulator is working properly in this station. Otherwise, the voltage value of HVDC2 changes, the reason is that it has no voltage controller. However, HVDC2 maintain its reference power value. When the power is steady, it has no changes. This fact shows that the active power control helps to keep it constant. The same situation than before is occurring, HVDC1 has no power control, therefore its value is modified when the wind changes.

HVDC3 power is in its reference. It vary 0.2 in amplitude, when it is in its higher value, 1 pu, has $400\ MW$ and the lower value, 0.8 is $320\ MW$.

On the other hand, if the DC Current is observed, it is confirmed that the system is doing its work. The waveforms are the same as the power responses and its values fulfill the division of power over voltage.

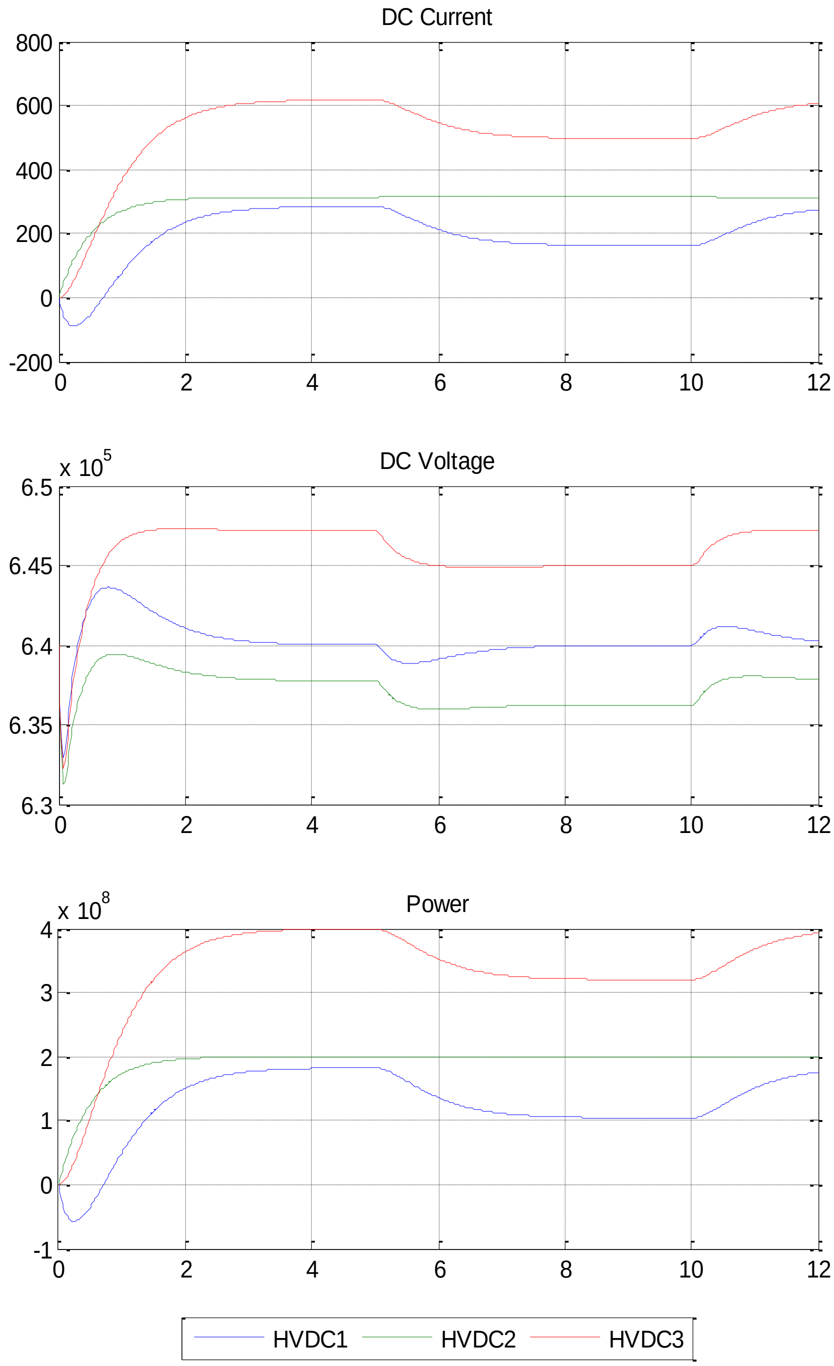

Figure 4.2 Three MTDC with Voltage and Power Control.

If the DC line is changed, making it longer, the results are similar to the ones in Figure 4.2. The voltage decreases $5\ KV$ and it is compensated with the power. The system would have more losses, but HVDC1 maintains its voltage reference value and HVDC2 its power reference. This fact shows that the controllers are working properly.

It is observed in Figure 4.3 what happen if the reference values change. Voltage reference in HVDC1 was increased to $840\ KV$, while power reference in HVDC2 changed to 0.8.

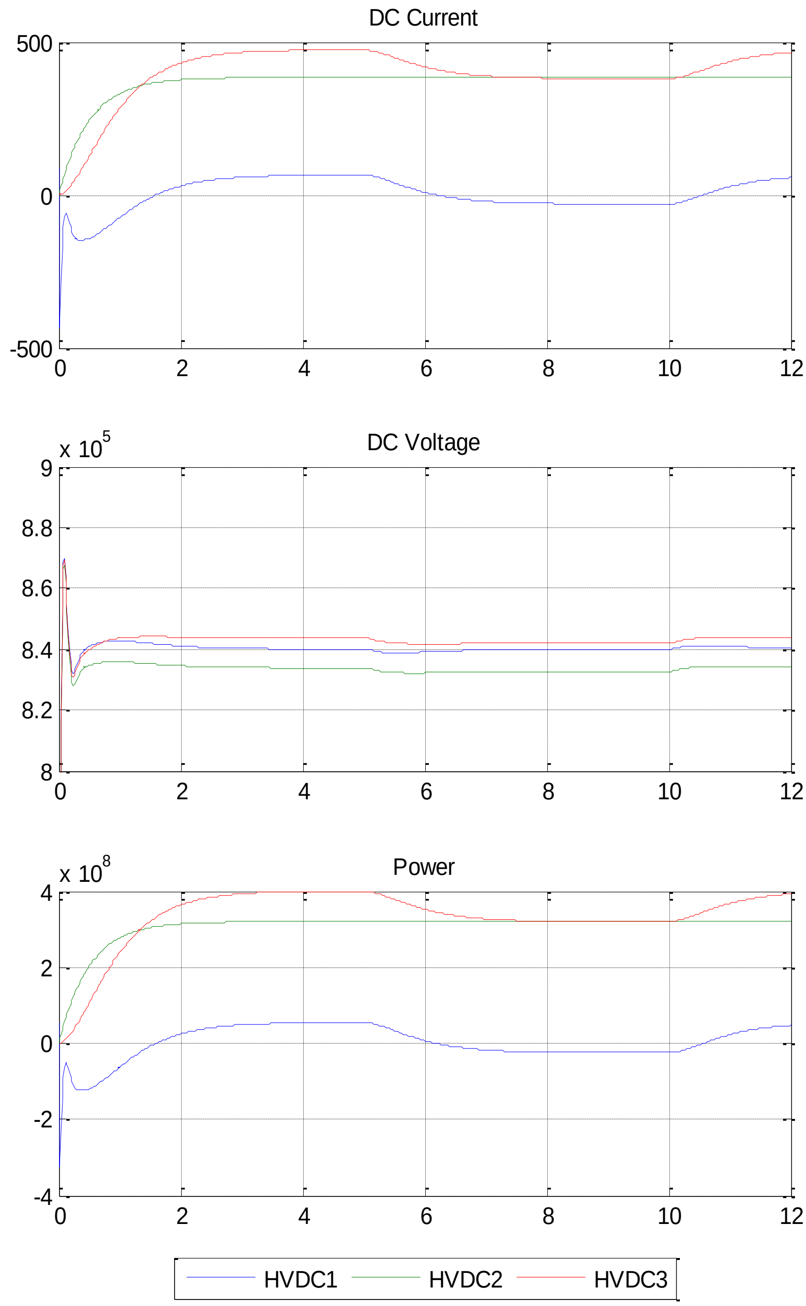

Figure 4.3 Three MTDC with changed Voltage and Power Control references.

The controllers maintain the reference value of power, in the case of HVDC2, and the voltage reference value in HVDC1.

It can be seen in Figure 4.3 that the HVDC1 power decreases, the reason is that HVDC1 compensates the power increase of HVDC2. The same is happening with the current. Otherwise, the voltage grows, HVDC1 keep constant its voltage in its reference value.

In the 7 second it is observed that the power reference value of HVDC2 and HVDC3 are the same, it means that there is no power for HVDC1, which is represents by its near 0 value.

In conclusion, both regulators are working correctly.

4.1.2 MTDC with Voltage Droop Control

The next simulated scheme is three-terminal MTDC, but it has droop control instead separated voltage and power regulators. In the following graphics it is observed how voltage and power are balanced because of the droop control.

As in the previous section, HVDC1 and HVDC2 are the onshore plants and HVDC3 is the offshore station.

HVDC3 has the same DC line resistance than in the previous section, HVDC1 has the double, but HVDC2 now has four times this impedance. In this model, the power reference of the offshore station, HVDC3, is $0.8\ pu$, HVDC2 has in its power reference $0.5\ pu$ and HVDC1 $0.8\ pu$. $640\ KV$ is the voltage reference in both onshore stations.

When offshore power varies, consequently voltage and power in HVDC1 and HVDC2 change too and, therefore, currents. Both power and voltage changes are sharing equally into the different stations. It is observed in the Figure 4.4 that power decreases $80\ MW$ in HVDC3, this power droop is sharing between HVDC1 and HVDC2, diminishing their power in $40\ MW$ each.

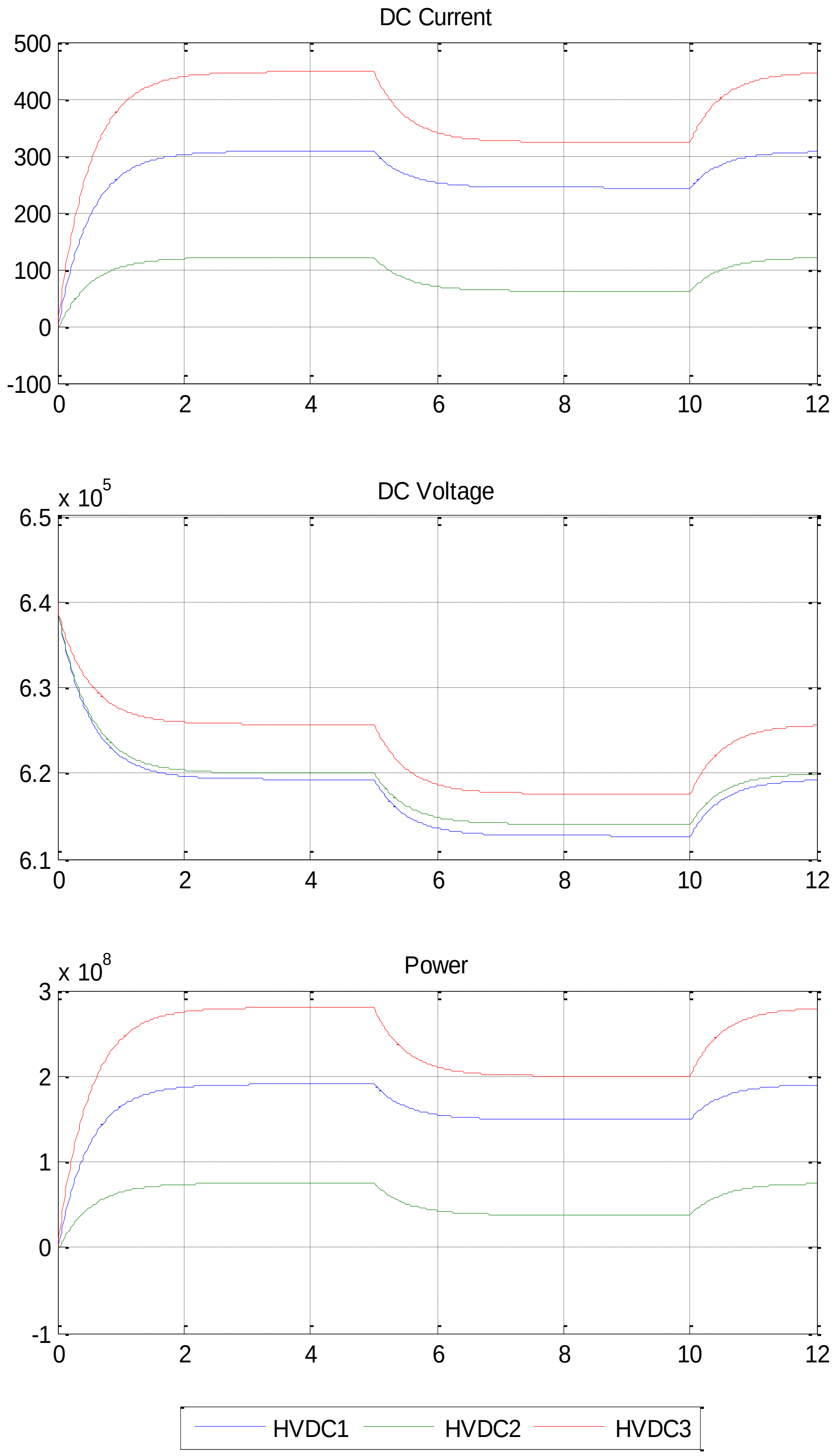

Figure 4.4 Three MTDC with Droop Control.

Keeping the same DC lines values, the gain of the HVDC2 droop control is four times the gain of the HVDC1. The results are showed in Figure 4.5.

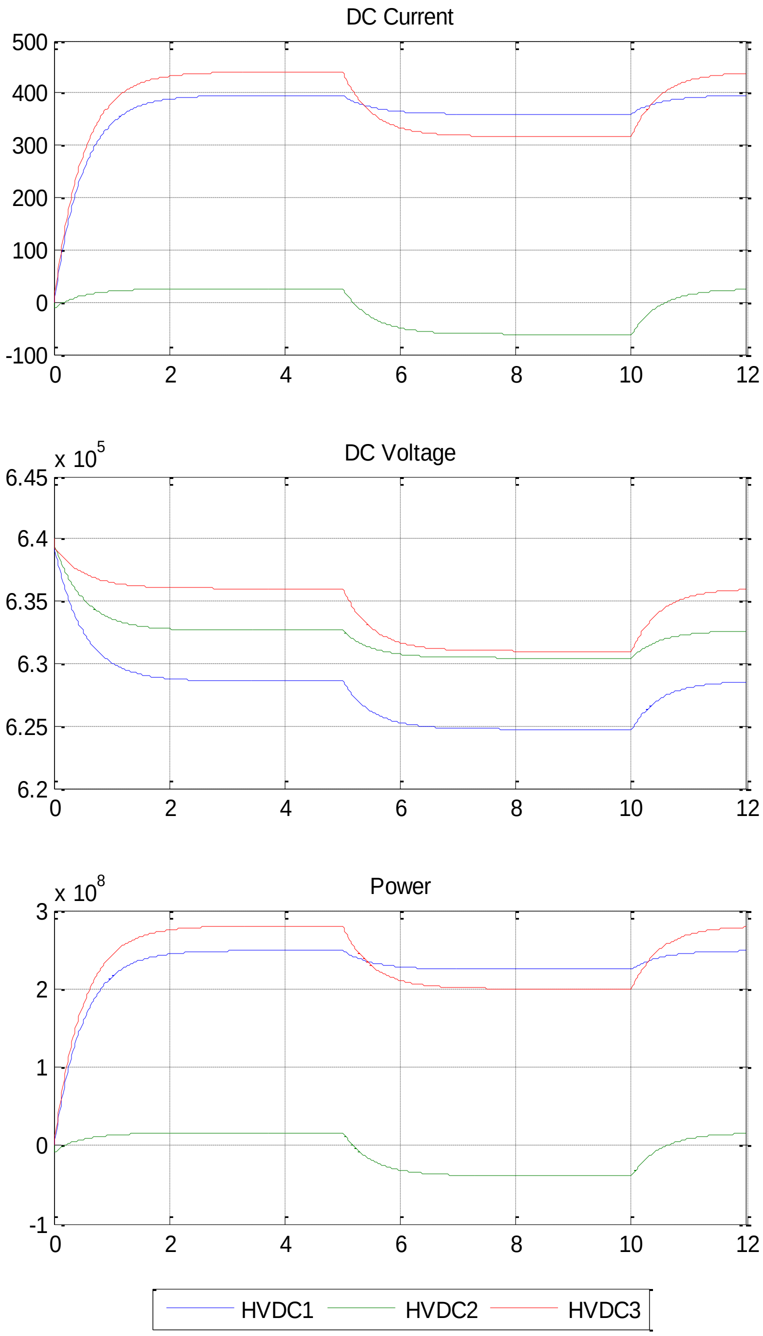

Figure 4.5 Three MTDC with Droop Control, changed gain.

It can be observed in Figure 4.5 how the droop voltage and power is different shared in this case. The fact that the gain of the HVDC2 droop control is four times the gain of HVDC1 affects to the droops. The droop of the offshore station is shared between the onshore terminals, but this time HVDC2 will have more droop power. The HVDC2 power droop will be four times larger than the one in HVDC1.

The conclusion was the same, testing with different droop gains, as much as the gain of the droop control increases, as much as the droop power decreases.

In Figure 4.5 it also can be seen that the variation of the power is compensated by the voltage, where HVDC1 has more voltage droop than HVDC2, around four times.

The next case is represented in Figure 4.6. HVDC1 and HVDC2 return to have the same gain in the droop control. However, the HVDC1 DC Line is decreased to 1.1 times the HVDC3, while HVDC2 is decreased to three times this impedance.

The decrease in the DC Line of HVDC2 is higher than in HVDC1. It can be seen that the current of HVDC2 diminishes its value, hence power also get low and the droop control causes the reduction of the voltage. To compensate this decrease, HVDC1 has to increases its values.

In this last case, the difference is not greater, but if the change in the DC Line is more different, the decreases or increaser will be higher.

Another change implemented in the model was increasing the power reference of the stations. If the reference rises, the higher steady value of the stations also grows and vice versa.

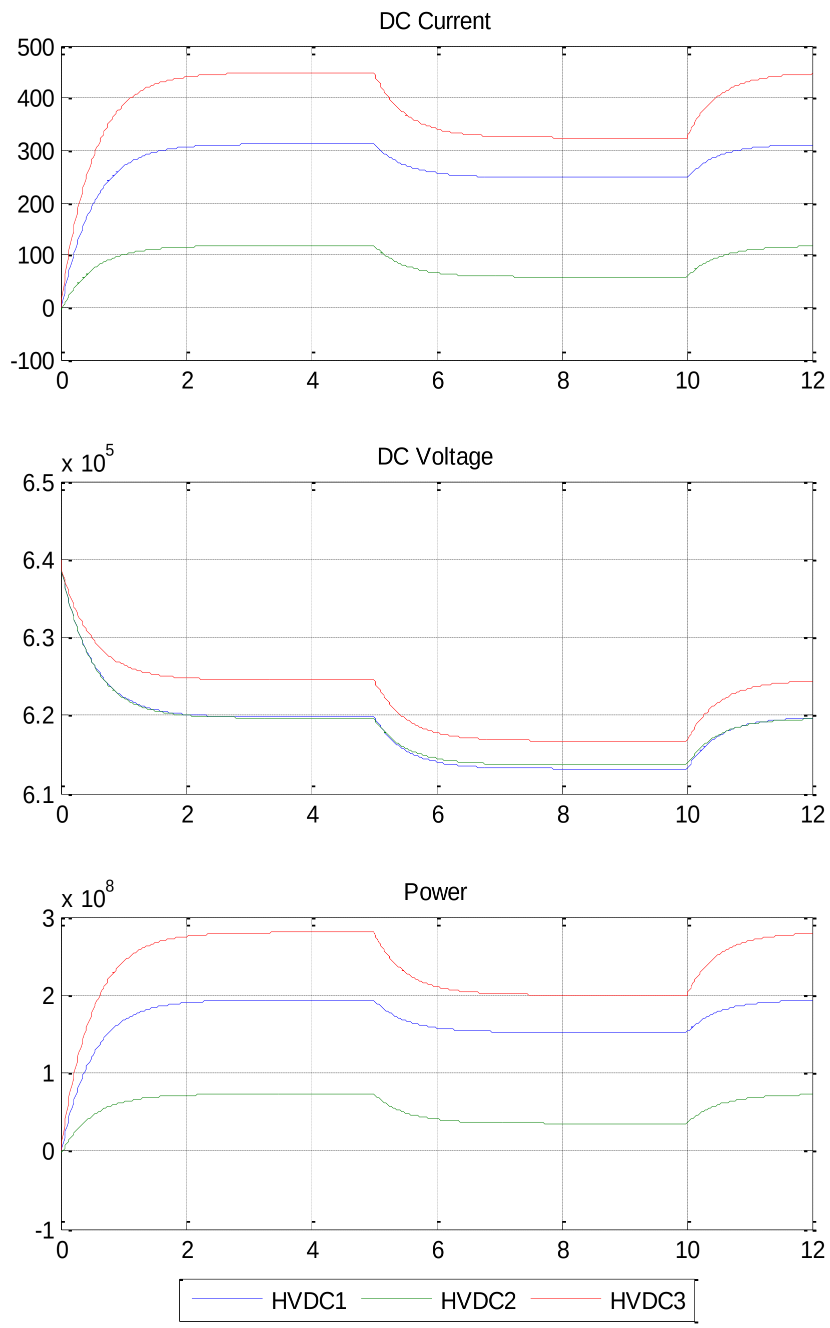

Figure 4.6 Three MTDC with Droop Control, different DC line impedances.

In conclusion, droop control is a better choice when there are more than two terminals. It makes equal the voltage droop and the power change of each station. This control operates sharing the power between the different onshore plants, getting a balance between voltage and power.

If an unexpected change in power flow happens in some terminal, the droop control will compensate for the power unbalance through the rest terminals.

4.2 Four terminal MTDC

In this model a forth terminal is included as an offshore station, HVDC4. It has another pulse generator with amplitude of 0.3 and it changes every 5 seconds, but this station has a delay of 2.5 seconds. In this manner, HVDC4 changes first at 2.5 seconds and then at 7.5, while HVDC3 do it at 5 and 10 seconds.

Figure 4.7 represents the scheme of this model.

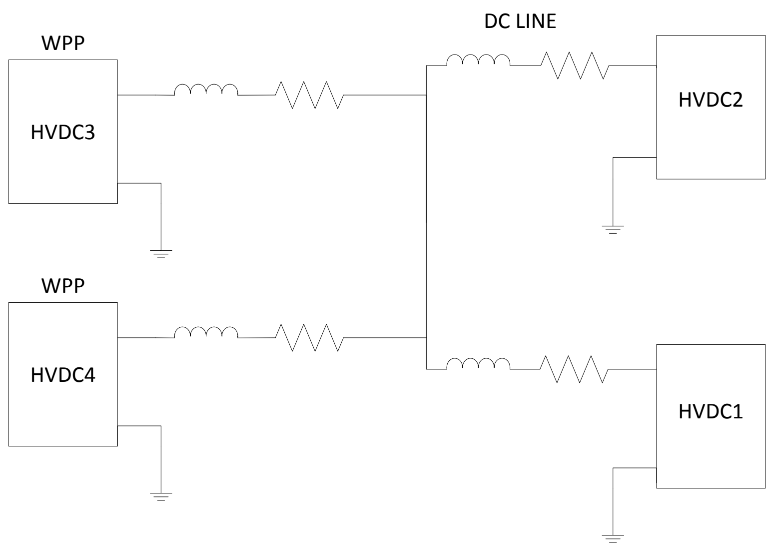

Figure 4.7 Four MTDC.

It can be seen in Figure 4.8 the obtained results. Observing the power graphic, the first change is produced in HVDC4 at 2.5 seconds, it causes that HVDC1 and HVDC2 also change, in this case, increasing their value. In this study the gain of the droop controllers are the same, thus the growth is equally distributed in both terminals, that is, half of the HVDC4 increase. At 5 seconds, HVDC3 decreases its value, hence HVDC1 and HVDC2 diminish theirs too. Once again, HVDC4 at 7.5 seconds decrease, then HVDC1 and HVDC2 reduce more. Droop controller is working properly, due to the correct power sharing between terminals.

The voltages of HVDC1 and HVDC2 decrease when the power reduces its value, because of the droop controller action. The voltages of the offshore stations are forced to do the same than the onshore terminals, due to the shared DC line.

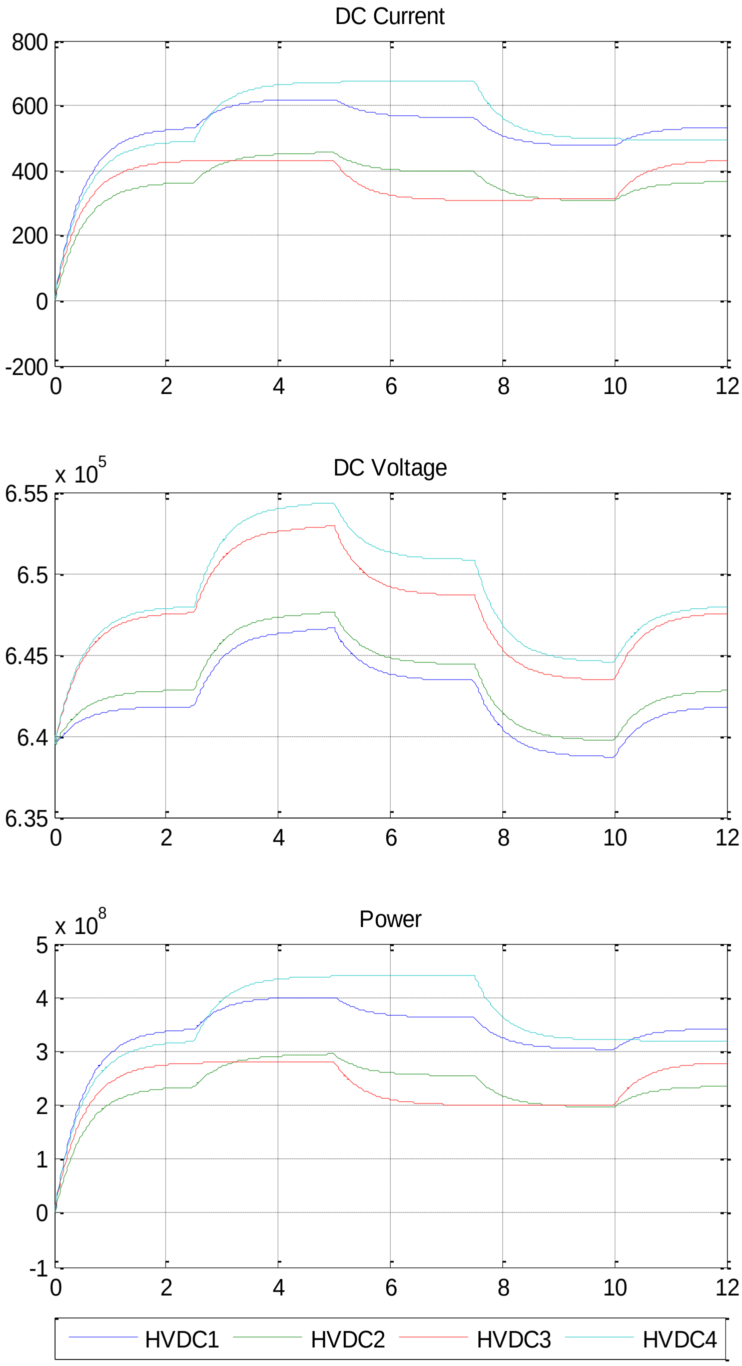

Figure 4.8 Four MTDC with Droop Control.

If the DC line of HVDC1 and HVDC2 are increased, maintaining the offshore in the same value, growing four times and twice, respectively, in relation to the offshore, final results change, as it can be observed in Figure 4.9.

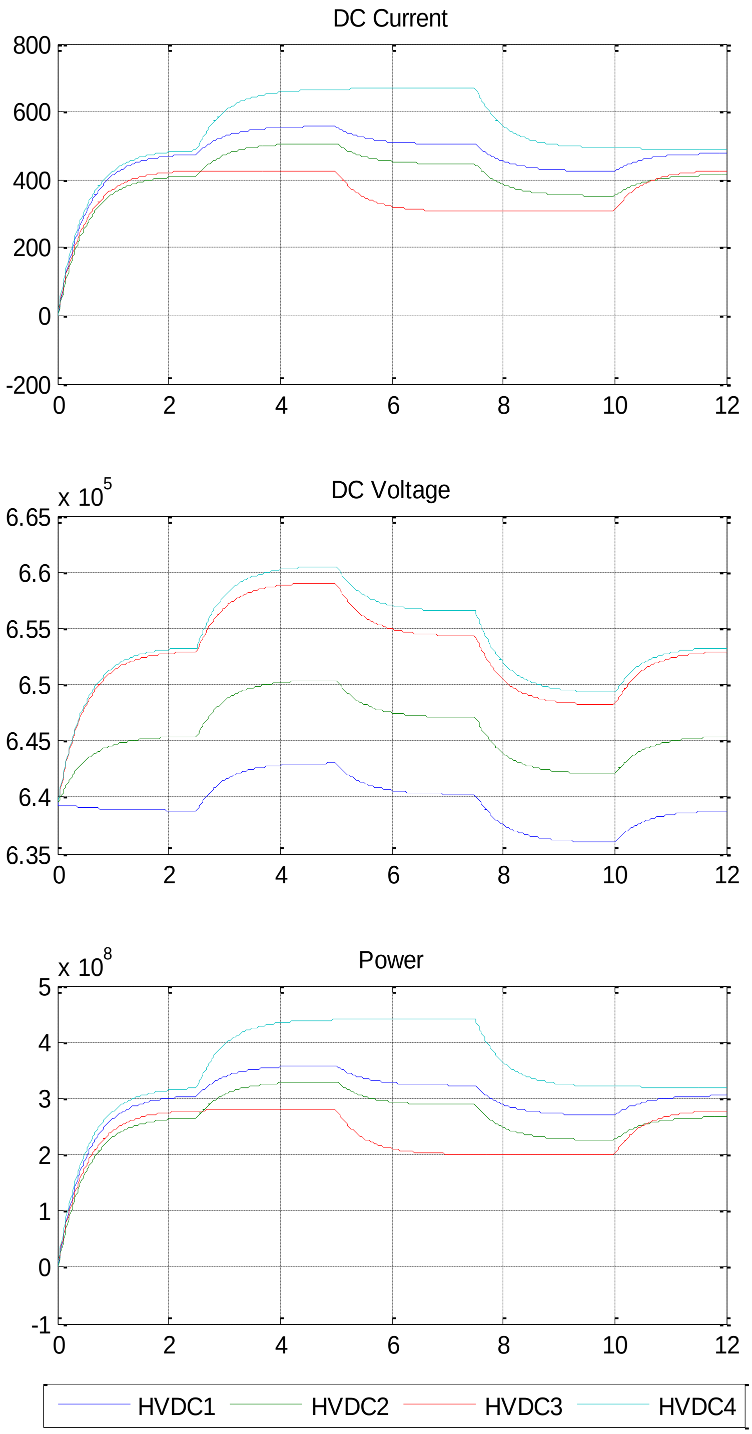

Figure 4.9 Four MTDC with Droop Control, changed DC line impedances.

In this case, HVDC1 reduce its power, due to the growth of the line and its power reference value, hence the voltage diminish, caused by the droop control, and therefore the current. To compensate de unbalanced power, HVDC2 power increases and the voltage of all the stations is higher.

If the gain of the droop controllers is changed, it would happen the same than in the previous section. The station which has the higher droop gain value will have a larger droop in the power, as high as the equivalence of times in relation with the other droop controller. As a consequence, voltage would compensate this, having a larger voltage droop the station with lower droop gain.

4.3 Five terminal MTDC

This model has a new fifth onshore terminal, the rest is the same as in the previous section.

The model is showed in Figure 4.10.

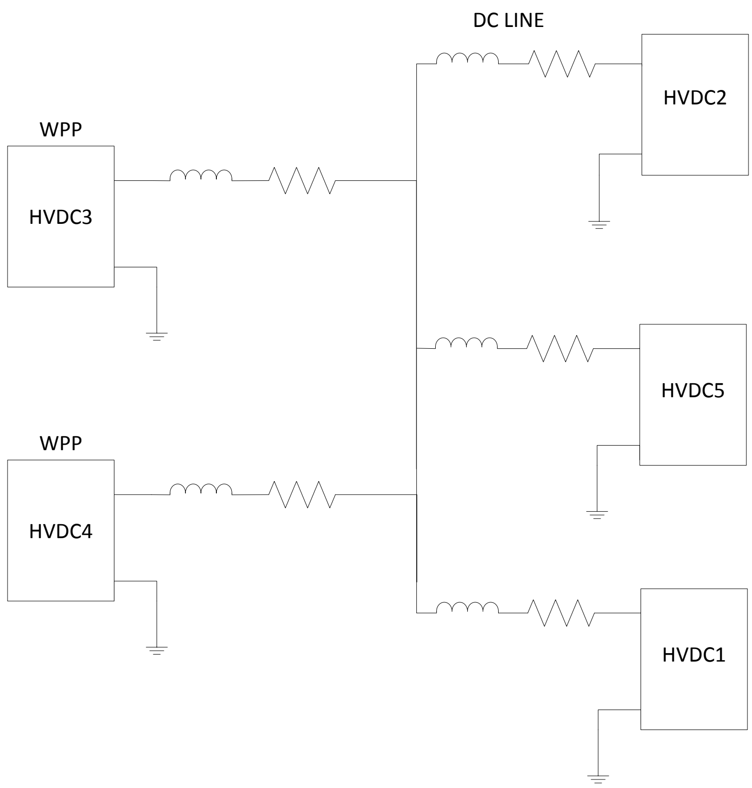

Figure 4.10 Five MTDC.

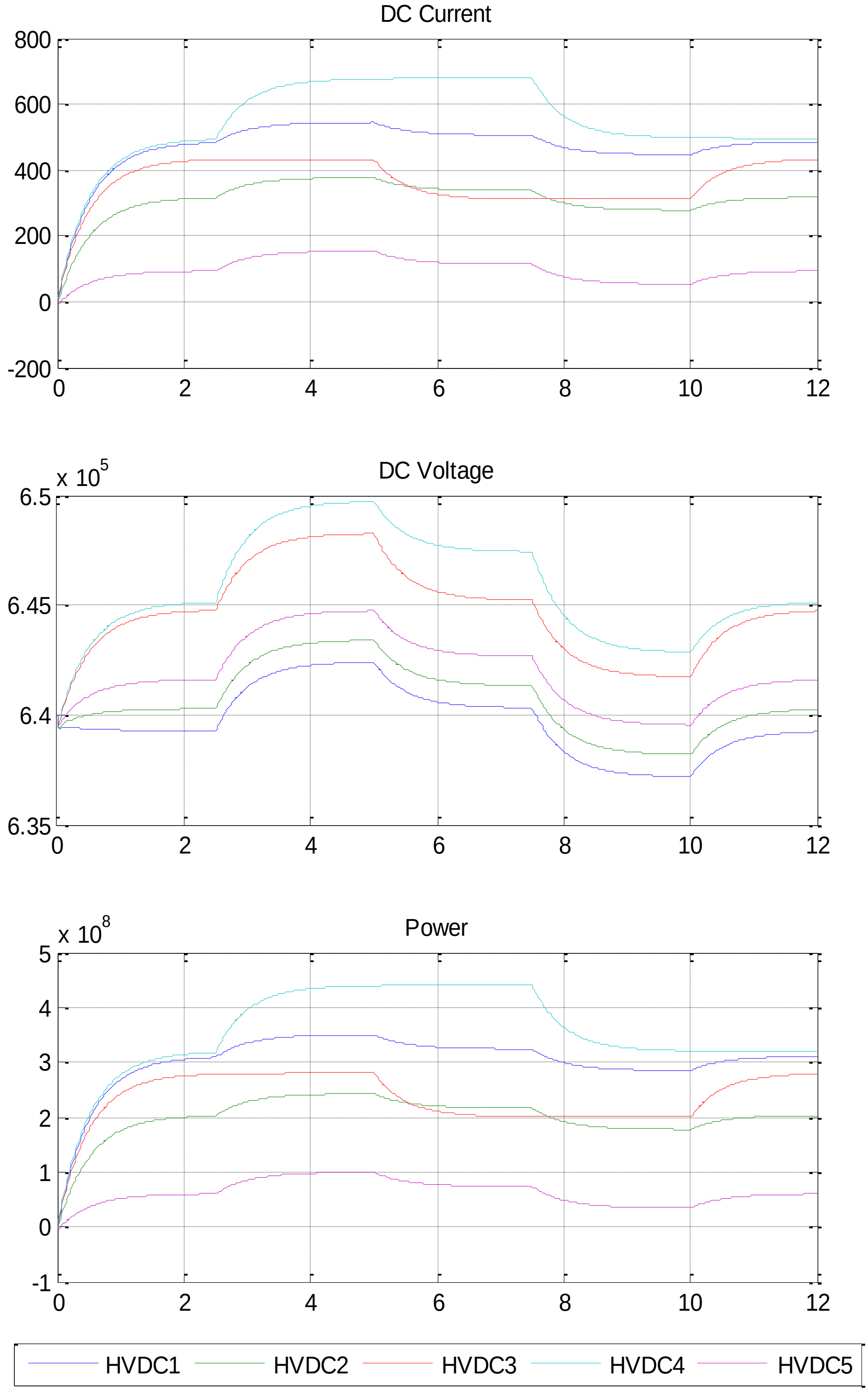

Figure 4.11 Five MTDC with Droop Control.

These results are similar to the obtained in the previous section. The difference is that an onshore terminal is added. The droop control works correctly, sharing the power equitably between the different onshore terminals and forcing the voltage to decrease when the power diminish its value.

The outcome of changing the droop controller gain is the same than in the other studies, if some station has more gain value than others, it will have more power droop and less voltage droop.

DC lines values were increased and in HVDC1 station, which has the higher power reference and DC line impedance, the power diminishes, thus the current and therefore the voltage by the droop controller. The rest stations compensate this decrease with their voltage and power growth.

5 Conclusions

Nowadays, MTDC is considered in many future projects, based on VSC-HVDC technology. A Multi-terminal DC was developed in this project, it consists of three terminals, two of them are onshore stations, while the third is an offshore wind farm. Different controllers were implemented to this model and, afterwards, simulated. Furthermore, two more terminals were added to confirm the correct operation of the system. Based on the results, some conclusions can be stated.

Voltage and power controllers maintain the given reference value, regardless dynamic problems in other stations or abnormal conditions.

The droop control works properly, even when the DC lines impedances, the power and voltage references of the converter or the gain of the droop control are changed. Conforming with the slope of the regulator, achieving the decrease of the voltage when the power is reducing and vice versa.

The addition of more terminals does not affect to the control of other stations, being unnecessary add more controllers or modifying the model.

5.1 Future work

- More realistic models

In this project, to focus in the scope many components have been simplified, considering them ideal or building the average model. The scope was observing the working of the entire MTDC, hence some systems, like the converter or the transformer were simplified. To get an improved and more real model, these simplified systems have to be replaced for the entire model, keeping in mind their losses, their disturbances and their problems. In this manner, a more real operation of MTDC would be observed.

- Real simulation

Once the realistic model is implemented it could be simulated to get more real results. It could be simulated in different environments than MATLAB/Simulink, where disturbances and extremely changes of the wind could be introduced.

- Dspace

Dspace is a tool where the controllers can be changed in real time, they can be tuned until getting the expected outcomes and it is possible improving the final results using this tool.

- Adaptive droop control

To improve the droop control implemented in the project an adaptive control could be designed. This adaptive controller is built to ensure that all the converters participate in power sharing, depending on their ratings and the difference between the rated capacity and the present loading available, under every operating condition. Unlike fixed droop control, which can work incorrectly, if the converters are not equally loaded, because of some unusual environment.

It is extensively explained in literature [21].

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