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HVDC VSC LINK FOR OFFSHORE WIND:
operation losses and economic evaluation

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Abstract

High voltage direct current (HVDC) is a highly efficient alternative for transmitting bulk electricity over a long distance. Also, with its high controllability and flexibility, HVDC has been considered the key enabler in the future energy system based on renewables. This report presents the cost modelling and power flow simulation of an hybrid Voltage Source Converter-HVDC system.

The first chapter briefly introduces HVDC and the associated technology used for transmitting electric power. Chapter 2 instead is more focused on the HVDC component technology, in particular the purpose of this chapter is to create a system model. Here, considerations are carried out about configuration and the rating value of the system. The following analysis will be based in this default system. Chapter 3 introduces instead an economic evaluation for the investment cost related to cable, transformer and converter. Chapter 4 carry out a technical analysis on the power system losses. The core part consists of the development of an Optimal Power Flow algorithm, elaborated in MATLAB, that allows to determinate the electric value in the system and to minimize power losses. It is necessary to stress out that, in this part of analysis, constriction in the system due to grid code and the coupling with the AC system are considered. Chapter 5 shows results about the work, with respect on power losses, power generated by the offshore wind power plant and length of the connection. An additional consideration can be made by comparing the economic and technical results between HVAC and HVDC. In the last chapter conclusions on this comparison are done and suggestion for future work are drawn.

Contents

List of Abbreviations

BED Break Even Distance

HVAC High Voltage Alternative Current

HVDC High Voltage Direct Current

LCC Line-Commutated Current

LCOE Livelized Cost Of Energy

MMC Multi Modular Converter

OPF Optimal Power Flow

OWPP Offshore Wind Power Plant

PCC Point of Common Coupling

SCC Short Circuit Capacity

SCR Short Circuit Ratio

VSC Voltage Source Converter

WPP Wind Power Plant

WTG Wind Turbine Generator

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Chapter 1

Introduction

Over the last years. high voltage direct current (HVDC) technology has increased its coverage, becoming an advantageous form of transmitting electrical energy over long distances, asynchronous interconnections, underground and submarine cables among others. Currently there are more than 200 HVDC systems around the world, and most of them are located in Europe, Asia and North America. Despite of the numerous projects, there is not a complete DC grid (three or more converters with two or more transmission lines) yet. The growth of this technology is due to the new necessities that the transmission networks are facing nowadays such as longer distances between substations, offshore wind power plants (OWPP), voltage control and reliability. This section deepens into the main characteristics of the HVDC transmission technology, showing strengths,weaknesses, type of technology, viability, applications and reliability.

1.1 Highlights from the high voltage direct current history

The transmission and distribution of electrical energy started with direct current. In 1882, a 50 km long 2 kV DC transmission line was built between Miesbach and Munich in Germany. At the time, conversion between reasonable consumer voltages and higher DC transmission voltages could only be realized by means of rotating DC machines. Nevertheless, in an AC system, voltage conversion is simpler. An AC transformer allows high power levels and high insulation levels within one unit, and presents few losses. It is a relatively simple device, which requires little maintenance. Additionally, a three-phase synchronous generator is superior to a DC generator in every respect. For these reasons, AC technology was introduced at a very early stage in the development of electrical power systems. It was soon accepted as the only feasible technology for the generation, transmission and distribution of electrical energy. However, high voltage AC (HVAC) transmission links present some disadvantages, which may compel a change to DC technology:

- Inductive and capacitive elements of overhead lines and cables set limits to the transmission capacity and the transmission distance of AC transmission links;
- This limitation is of particular significance for cables. Depending on the required transmission capacity, the system frequency and the loss evaluation, the achievable transmission distance for an AC cable will be in the range of 40 to 100 km. It will mainly be limited by the charging current;
- Direct connection between two AC systems with different frequencies is not possible;
- Direct connection between two AC systems with the same frequency or a new connection within a meshed grid may be impossible because of system instability, too high short-circuit levels or undesirable power flow scenarios.

Moreover, the invention of mercury arc rectifiers in the nineteen-thirties made the design of Line-Commutated Current (LCC) sourced converters possible. Since then, several large HVDC systems have been realized with mercury arc valves. The replacement of mercury arc valves by thyristor valves was the following major development. The first thyristor valves were put into operation in the late nineteen-seventies. The outdoor valves for Cahora Bassa were designed with oil-immersed thyristors with parallel/series connection of thyristors and an electromagnetic firing system. Further development went via air-insulated aircooled valves to the air-insulated water-cooled design, which is still state of the art in HVDC valve design. The development of thyristors with higher current and voltage ratings has eliminated the need for parallel connection and reduced the number of series-connected thyristors per valve. The development of light-triggered thyristors has further reduced

the overall number of components and thus contributed to increased reliability. Innovations in almost every other area of HVDC have been constantly adding to the reliability of this technology with economic benefits for users throughout the world.
As a last step, Voltage Sourced Converters (VSC) require semiconductor devices with turn-off capability. The development of Insulated Gate Bipolar Transistors (IGBT) with high voltage ratings have accelerated the development of voltage sourced converters for HVDC applications in the lower power range. The main characteristics of the voltage sourced converters are a compact design, four-quadrant operation capability and high losses. Siemens is offering Voltage Sourced Converters for HVDC applications under the trade name HVDC-plus Power Link Universal Systems, while ABB offered the product HVDC Light.
In the case of long distance transmission, HVDC links, which can be lines or cables, proved to be more efficient and interesting from a commercial point of view than traditional AC connections, with one of the main applications of HVDC been the submarine power transmission. It was already reported 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 cheaper, allowing to transfer efficiently a larger power. 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.

1.2 Types of converters

The use of HVDC connections implies the necessity of specific devices. HVDC is a type 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 already reported, two converters technologies exist : LCC and 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 1.1.

LCC	VSC
Large power ratings	Medium power ratings
Large harmonic filters needed	Smaller harmonic filters needed
Only active power control	Independent power control
Strong AC system required	Can be connected to any system
No black start capability	Black start capability
Cheaper	More expensive
Lower losses	Higher loss

Table 1.1: Comparison of LCC and VSC converter

1.3 Application

The main reason to introduce the HVDC technology into the electrical grids is because in some cases it is cheaper than the HVAC systems. However, there are numerous technical applications to consider the DC transmission lines as a better alternative. This section shows the present and future applications of the HVDC systems that are beneficial for the power networks.

1.3.1 Long distance bulk power transmission

To deliver the power generated of remote generators to the final consumers (for example a rural power plant providing electrical energy to a big city) long distance transmission lines are necessary. An alternate current circuit could be connected to interconnect the remote supplier but the losses would be considerable and the project expensive. Thus, a solution arise to overcome this problem is the implementation of the HVDC technology to connect the consumption center with the production plant. Usually, it is a more convenient alternative for the scenario considered above.
For extra high voltage, HVDC lines gives the system a controllability that

is useful for the parallel transmission because it blocks the loop flow and frees up the transmission capacity in order to provide an outlet for local generation. Since the decisive factor to choose a HVDC system over a HVAC is the cost, there's a concept known as "break-even distance" (BED) that helps the investor to make a decision. This is where the savings in line costs offset the higher converter station costs. Usually, for lines of a length of 500 km, the savings in the line construction are up to 30 % and if the minimization of the losses during its lifetime is considered, the savings are even higher. Furthermore, long distance AC lines require small substations (switching substations) and reactive power compensation (shunt reactors), which increase the cost of the project for an HVAC system.
Another benefit of implementing HVDC in long transmission lines is the reduction of the right-of-way. This is mainly because the towers used for DC lines are narrower than in AC systems, so the transmission system requires less space and is cheaper. Also, this reduction leads to a less visual impact. An interesting example is shown in Fig 1.1, where the top of the picture shows HVDC lines and the bottom displays the HVAC for a system that transmit 3000 MW with a rated voltage of 500 kV. The reduction of space with HVDC line is evident..

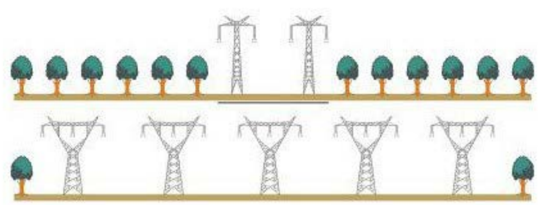


Figure 1.1: Right Of Way for HVDC and HVAC for transmission system

1.3.2 Underground and submarine cables

For the HVDC technology, there's no physical limitations about the distance or the power in underground and submarine cables. Thus, the cost savings are considerable when comparing to AC systems because in this conditions, HVAC technology have certain restrictions. The DC line losses are almost half than the AC cables because it uses less conductors and it avoids physical properties as the skin-effect, reactive current, cable sheath and armor. This is really useful for OWPP since many of them use submarine cables to deliver the power generated.

1.3.3 Asynchronous ties

In order to have a more reliable operation for interconnected asynchronous networks, HVDC systems are used. It provides a buffer for the two networks and avoids the propagation of cascading outages from a system to another. These interconnections are usually at the border of the transmission systems, where networks are weak if they are compared with the power that they need to transfer. HVDC lines provides reliability and it is cheaper than an interconnection using HVAC technology, also it allows fast recoveries from faults and/or outages.

1.3.4 Power delivery to large urban areas

Usually, large cities have high energy demand and no space to place generators. Then, the power supply depends on the capability of importing the power generated in other areas. However, the transmission of energy to large cities is difficult because of land-use and right-of-way limitations. The solution to this problem is the installation of underground HVDC transmission lines that are capable to transmit large amounts of power between the generation and the consumption center. Is an effective way of dealing with this problem because it does not compromise the reliability, provides voltage support and is more economical.

1.4 Transmission system for Offshore Wind Power Plants

The continuous growth in new wind farm installations made wind energy become the second largest form of power generation capacity in Europe in 2018. Out of 189 GW of total installed wind capacity at the end of 2018, 18 GW (9.5 %) correspond to offshore installations [2].
As the technology for converters inprove and driven by EU's 20 % renewable energy target by 2020, the first wave of VSC-HVDC connected offshore wind power plants have been commissioned around the world, but with a notable high concentration to be found in the North Sea. During the last

several years there has been a significant increase in the number of offshore OWPPs. The primary reasons include: lack of suitable onshore locations for additional WPP developments, and OWPP potential to generate significantly higher level of energy, when compared with an onshore WPP project of the same rating. To transfer the offshore WPP energy to the onshore AC grid, the VSC-HVDC link provides technical features and economic advantages when the distance between the offshore WPP and the onshore AC grid extends beyond 100 km according to literature, typically. It must be noted that the choice of HVAC vs HVDC transmission requires further cost-benefit analysis based on individual projects' needs, but it will be investigated in this work as a conclusion.

The ongoing developments in the HVDC technologies, in general, and specifically in the VSC-HVDC technology, indicate a growing trend in further construction and utilization of point-to-point VSC-HVDC connection and multi-terminal VSC-HVDC grids. Although the classical LCC-HVDC systems currently offer advantages for specific applications (e.g., bulk power transfer over very long distances) the VSC-HVDC systems are necessary for integrating long distance OWPPs into the onshore AC grids due to the lack of synchronous generation offshore.

The VSC-HVDC system was first implemented as a test installation in 1997, with growing installed base over the past decade. Currently, there has been an increasing trend in the development of semiconductor technologies, resulting in further consideration of VSC-HVDC technology for transmission projects around the globe. By the end of 2014, advancements in semiconductor devices have seen ratings up to 900 MW at ±320 kV for WPP connection [3]. These early WPP projects have been located 130-200 km from the Point of Common Coupling (PCC), including both offshore and onshore cables to the converter terminal, thereby making HVDC the most appropriate technology to use for power transmission to mainland grids, recognizing the limitations in AC submarine transmission at such distances. In addition, VSC-HVDC technology offers several unique advantages suitable for such environmentally harsh and difficult siting, with yet greater energy yield potentials. A partial list includes:

- Ability to continuously transfer any power level (zero to maximum rating) in both directions, thereby facilitating WPP start up, and operation at low wind speeds;

- Ease of integration with Wind Turbine Generators (WTGs) in islanded grids with very low fault current levels;

- Normally, no need for harmonic filters and additional reactive power resources;
- Black start capability: ability to supply the auxiliary power needs of the offshore WPP when WTGs are not operating (e.g. due to low wind, or excessively high wind, conditions);
- Allow implementation of future multi-terminal expansion.

The first VSC-HVDC connected offshore WPP project (BorWin1, 400 MW, ±150 kV, 125 km off the coast of Germany) was commissioned in 2009. Even though a number of similar projects have been commissioned, or are under various stages of design and construction, it is generally recognized that this method of transferring energy harvested from OWPPs is in its early stages of maturity. Compared to a large population of WPPs connected to AC grids, VSC-HVDC transmission completely changes the electrical environment, presenting new challenges and opportunities for operation during normal and abnormal conditions. Similarly, most HVDC links have been developed as point-to-point connections between AC transmission systems. From the electrical point of view, OWPPs constitute weak isolated grids. At present, the industry is developing standards and commonly accepted grid codes, while gaining deeper understanding of the integrated WPPs and VSC-HVDC systems. Furthermore, there is also growing knowledge of, and experience with, the design and operation of such projects. So, even though current projects have to develop their own design and operational philosophies, with deeper experience, and longer reported operational history, future optimally designed projects are expected.
The topic isn't new in the academic field, though some work are outdated or doesn't analyze in depth the power loss on the transmission system. This elaboration can be consider as a first stage of the planning phase for a HVDC point-to-point link.

Chapter 2

System model

The project planning phase involves all the decision regarding the rating of the systems with respect of voltage and power, the configuration of the cable and the technology related to the converter. A driven factor for this decision is related also to the redundancy of the system in case of a failure.

2.1 Converter

The intrinsic nature of wind power usually collocate the wind farm away from the main AC grid. This can cause voltage collapse in the PCC, forcing the injection of reactive power for sustain the voltage amplitude. Also bus voltage through the transmission system can be controlled for minimize power losses.
For this reason the VSC seems the natural choice for the converter technology. In this category of converter 3 main topology can be found:

- Two Level Converter
- Three Level Converter
- Multi-Modular Converter (MMC)

The latter is being consider the more interesting one for the offshore application. With respect to the others, it results in better power quality and higher converter efficiency, although can results in higher cost due to higher number of components and needs for separating sources. The main advantages can be summarized as follow:

- Low-sized filters (lower harmonic content) and snubbers (lower dv/dt values);
- Higher generator efficiency and grid power quality (lower current harmonics);
- Higher converter efficiency (lower switching losses and filter/snubber losses);
- Suitable for high power applications (high voltages distributed on higher number of components) and with power quality constraints.

Together with some additional consideration on transformer winding, the low harmonic content can lead to not using filters at all. As reported in [4], a VSC converter doesn't generate any harmonics on the connecting system and so does not need filters.

2.2 DC link

The transmission system in DC can vary depending on the configuration, voltage rating and cables.
Configuration can be separated in 2 main topology: mono-polar and bipolar. A mono-polar link consists of a single conductor and a return path through the ground or the sea by the use of electrodes. Many subsea cables are installed as a mono-polar scheme to reduce costs. A bipolar HVDC system configuration consists of two poles, one with positive polarity and one with negative polarity, each with their neutral points grounded. In steady state, the current flows in a loop, causing no current to go through the grounded return, and creating no corrosion concerns. In case of a fault on one of the two poles, the other can function as a mono-polar link with ground return. The amount of transmitted power in a bipolar configuration is double that of a mono-polar system. The great benefit about a bipolar configuration is the redundancy at 50 percent of the total power[5]. As the implementation of bipolar configuration isn't already a used configuration, the choice in the modelling is a symmetrical mono-pole. A single converter with mid-point

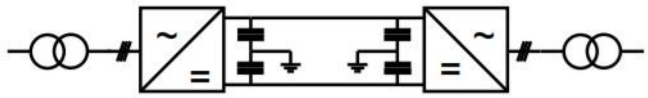


Figure 2.1: Symmetrical monopole configuration for an HVDC link

ground between positive and negative voltage polarities is used. A general scheme is show in Figure 2.1.

The material technology for the cable are mainly two: extrudes or mass impregnated insulated cable. The first one use cross-linked polyethylene (XLPE) for the insulation. The insulation is extruded over a copper or aluminium conductor and covered with a water tight sheath of extruded seamless lead, and a further protective polyethylene plastic coating. Cable intended for submarine use have an additional layer of galvanised steel wire armour to increase the cable's tensile strength so it can better withstand the stresses of submarine installation. On the other hand, HVDC Mass Impregnated (MI) insulated cable permit very high power transfers per cable. The insulation is made from layers of high density of impregnated papers. The insulation is surrounded by a lead sheath witch is covered with a plastic corrosion inhibiting coating. Submarine cables usually utilize copper as the conductor. Conventionally HVDC cable system designs tend to use single concentric conductor designs in a range of configurations depending on the return current arrangements. Presently XLPE extruded cables are only used with VSC-HVDC systems due to the risk represented by voltage polarity reversal and space charge effects [6].
Regarding the rating voltage, the range vary from $\pm 80kV$ up to $\pm 525kV$. For the elaboration different DC voltage rating are chosen, at $\pm 150kV$ and at $\pm 320kV$.

2.3 Phase reactor

The phase reactor is the dominant element on the converter's AC side. It is a large, inductive element with small resistance. Its purpose is to control the complex current. By doing so, it can control active and reactive power. Also, it reduce harmonic current components at the AC side of the converter and reduce any fault currents, separating the AC system (and its short-circuit current) from the converter that it is connected to. Active power is controlled via the voltage phase angle across the phase reactor and reactive power is controlled via the voltage amplitude across the phase reactor.

2.4 Transformer

Transformers may be two winding, three winding or autotransformers (Figure 2.2). Autotransformers are usually smaller in weight and size than an equivalent two winding power transformer, but do not provide electrical isolation between the primary and secondary voltages or lower short circuit levels. Both autotransformers and two winding transformers may have an additional tertiary winding with a delta configuration, which reduces triple harmonics (multiples of 3rd harmonic) passing through the transformer and also helps reduce any voltage unbalance between the phases. Typical transformer designs for offshore application use a star connected primary high voltage winding and double secondary delta windings. The double secondary windings allow the switchgear to be segregated and to not exceed available current ratings and manage fault levels within the wind farm array.

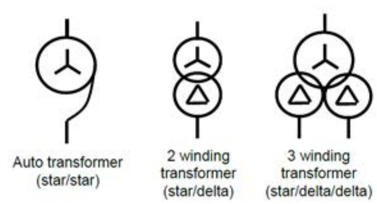


Figure 2.2: Winding of transformer for OWPP application

For this elaboration, it's chosen to use 4 transformers in total, each transformer is a 2 winding with a connection star/delta. By using a VSC and with this assumption, a consequence is that no filters are needed on the transmission system. There are 2 transformers offshore and 2 onshore. The rating voltage has to be consistent with the offshore voltage and the grid one. For a matter of redundancy, each transformer is sized at 60% of the rated power of the wind farm.

2.5 System under study

The previous sections have the aim to explain some consideration about single components. As a result, the next part of the report will be evaluated on a 'default' system as a consequence of this consideration. This is going to serve for having a default model, without considering all the possible variation from it. The scheme is reported in Figure 2.3.

The system can be divided in 3 main subsystem:

- Converter Station offshore: 2 transformer, 1 phase reactance and the VSC;
- DC link: 4 capacitor, 1 bipolar cable and 1 earth return;
- Converter Station onshore: 2 transformer, 1 phase reactance and the VSC.

With regarding voltage rating there are two different Scenario.

Scenario	A [kV]	B [kV]
AC_{off}	33/170	66/333
DC	150	320
AC_{on}	170/400	333/400

Table 2.1: Voltage rating on the HVDC link in 2 different Scenario

The voltage value will be fundamental for defining the power losses on the transmission system.

Figure 2.3: Point to point HVDC link

Chapter 3

Cost model

This chapter investigate the economic impact about a transmission HVDC-VSC system, with respect on the distance from the Point of Common Coupling (PCC) and the power produced by the WPP. The evaluation will be divided in 2 main section: capital cost related to the components cost and the cost associated with the power loss during the lifetime of the power plant. Data collection results difficult to be accurate for each case. What can be done is to formulate a dependence of cost with respect on power and length. The analysis done in this chapter was based on information found in literature. More detail about data collection are shown in Appendix A.
To perform the economic impact of the transmission system to the total cost of WPP the Levelized Cost Of Energy (LCOE) is introduced, which allow to spread through the entire lifetime of the WPP the cost related to loss.

3.1 Capital cost

For the investment cost on each component a set of variable need to be set, which are the base for cost modelling:

- Cable: length, section, voltage rating;
- Transformer, platform, VSC: power generated;

Cable

The HVDC transmission line, as already presented in the previous chapter, can work in a bipolar configuration at the voltage of $\pm 150\,\mathrm{kV}$ and $\pm 320\,\mathrm{kV}$.

For increasing the reliability of the system a earth cable return is used and need to take into account in the following elaboration.
As a first step, section and number of bipolar cable has to be chosen. Catalogue from ABB ([5]) was used and the section are show in Table 3.1. As reported in the catalogue, the value of ampacity and capacity are for a close laying, moderate climate and copper conductor.

Section mm^2	R_{dc} $[\Omega/km]$	Ampacity $[A]$	Capacity($\pm$150 kV) $[MW]$	Capacity($\pm$320 kV) $[MW]$
1200	0.0151	1458	437	933
1400	0.0126	1594	478	1020
1600	0.0113	1720	516	1101
1800	0.0098	1830	549	1171
2000	0.0090	1953	586	1250
2200	0.0080	2062	619	1320
2400	0.0073	2170	651	1389

Table 3.1: Electric parameter for different section

The section is chosen by comparing the power produce by the wind power plant to the capacity of the bipolar cable. If no section is going to fulfill the constraint on capacity, the number of bipolar cable will increase to two, letting the system work with 2 bipolar cable in parallel. The relation between cable section and cost is:

$$\begin{aligned} &C_{material} = (297.72 \cdot Section + 322098) \cdot (k + 0.5) \ \text{ for } \pm 150\,\text{kV} \\ &\text{and} \\ &C_{material} = (474.31 \cdot Section + 225209) \cdot (k + 0.5) \ \text{ for } \pm 320\,\text{kV} \end{aligned} \tag{3.1}$$

In Equation 3.1, k indicate the number of the bipolar cable in parallel and 0.5 is a factor related to the earth cable. Another cost associated with submarine installation is the installation. Cable installation costs vary greatly, depending on the type of cable, configuration and environmental related issue. More detailed information can be found in Appendix A. Nevertheless, a relation can be obtained.

$$C_{inst} = 345000 + k \cdot 575000 \tag{3.2}$$

The dimension in Equation 3.1 and 3.2 are in [€/km].
So the total cost is obtained by simply sum the cost and by multiply the result for the length of the line.

$$C_{cable} = (C_{material} + C_{inst}) \cdot L \;\; [€] \tag{3.3}$$

The section and the associated R_{dc} chosen here will be used next for the solution of the OPF.

Transformer

From data collection (see Appendix A), a linear relation between rated power of transformer and the cost of it can be found, as referred in Equation 3.4.

$$\begin{aligned} & C_{TR} = (0.0092 \cdot P_{TR} + 0.1) \cdot N_{TR} \;\; [M€] \\ & \text{with:} \\ & N_{TR} = \text{number transformers;} \\ & P_{TR} = \text{rated power} \;\; [MVA]. \end{aligned} \tag{3.4}$$

As already discussed, the total number of transformers is 4. The rated power of each is calculated by sizing it as the 60% of the power produced by the WPP. By doing this, the parallel transformers results oversize with respect of the actual power, resulting in better reliability for the transmission system.

Voltage Source Converter

Pricing for the VSC include switchyard costs and excludes platform costs.

$$
\begin{aligned}
&C_{VSC} = (0.0643 \cdot P_{VSC} + 48.76) \cdot N_{VSC} \quad [M€] \\
&\text{with:} \\
&N_{VSC} = \text{number of converter}; \\
&P_{VSC} = \text{rated power} \quad [MVA].
\end{aligned} \tag{3.5}
$$

Platform

Platform cost is one of the cost variable that is more affected by uncertainty. Platform cost can vary depending on the weight, dimension and location on the offshore side. Some article evaluate the cost by considering the price of each piece of the platform. As the focus on the elaboration is more strictly related to the electric component, also the cost relation function of the platform is given with respect of the rated power of the OWPP.

$$
\begin{aligned}
&C_{plat} = (0.1528 \cdot P_{OWPP} + 5.4) \cdot (D_{on} + 1) \quad [M€] \\
&\text{with:} \\
&D_{on} = \text{ratio of the cost of onshore platform by offshore one} .
\end{aligned} \tag{3.6}
$$

The platform onshore could be also consider to be placed on the ground and as a results $D_{on} = 0$. Instead, as the choice is to place the platform near the shore, the resulting ratio is $D_{on} = 0.25$, as referred in [7].

3.2 Annual cost

Annual cost are usually defined as the the the Operation and Maintenance ($O\&M$) cost of a component. The total $O\&M$ cost of the system is the sum of the $O\&M$ costs of each system component. As data on availability isn't readily available, in this section the focus will be on the results on losses from the next chapter, that represent an operational cost during the lifetime of the WPP.
The losses cost is calculated as the cost of non-sold energy. Firstly, for each electrical device, the power losses are estimated. Secondly, the yearly cost of

these losses is calculated with the energy selling price as given in 3.7. The average number of hours in a year is taken as 8765 time the capacitor factor. Thirdly, the total cost of those losses throughout the OWPP lifetime are calculated, show in 3.8.

$$\begin{aligned}
&Cost_{yearly,j} = c_P \cdot P_{l,j} \cdot 8765 \cdot C_E \\
&\text{with :} \\
&c_P = \text{Capacity Factor} \\
&P_{l,j} = \text{power loss on the "j" component } [MW] \\
&C_E = \text{cost of energy [euro/}MW]
\end{aligned} \tag{3.7}$$

The capacity factor is the average power generated, divided by the rated peak power. In 2017, the weighted average offshore capacity factor for newly commissioned plants reached around % 42 [8].

$$Cost_{loss} = \sum_i Cost_{yearly,j} \cdot t_{OWP} \tag{3.8}$$

For the calculation it's been used the following value for c_P, t_{OWP}, C_E:

Parameter	Value
Capacity factor	0.4
Lifetime of OWP	25
Cost of Energy	100

Table 3.2: Value for loss factor cost [1]

For the calculation of the power losses an Optimal Power Flow algorithm is used, and it's explained in the next chapter.

3.3 Levelized Cost Of Energy

The LCOE is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. The LCOE can also be regarded as the average minimum price at which electricity must be sold in order to break-even over the lifetime of the project.
It can be a good indicator for confront the cost about the offshore wind farm with respect to other energy sources. As done in previous section, the generation price can be consider form by two share (Eq.3.9): one related to the initial investment, the second to the cost related to power losses.

$$\begin{aligned} &LCOE = C_{inv} + C_{loss} \quad [€/kWh] \\ &\text{with:} \\ &C_{inv} = \text{cost related to investment} \\ &C_{loss} = \text{cost related to losses} \end{aligned} \tag{3.9}$$

Investment cost can be defined through the capital cost of the system, in relation with the number of hour per year and the actualize discounting rate:

$$\begin{aligned} &C_{inv} = \frac{I_{sp}}{Na \cdot ii} \\ &\text{with:} \\ &I_{sp} = \text{system investment cost}[€/kW] \\ &Na = 8760 \cdot C_f = \text{number of equivalent hour for year } [h] \\ &ii = \text{actualize discount rate} \end{aligned} \tag{3.10}$$

The actualize discount rate can be defined as:

$$\begin{aligned} &ii = \frac{1 - (\frac{1}{1+i})^{t_{OWP}+1}}{1 - \frac{1}{1+i}} \\ &\text{with:} \\ &i = \text{discount rate}[\%] \\ &t_{OWP} = \text{lifetime of the OWPP}[year] \end{aligned}$$

The chosen discount rate i is 6%. As this value can vary also monthly, it wasn't consider for the cost related of the power losses in the previous section.

For the investment cost regarding the turbines, installation and contingency data from [9] was used, and show in Table 3.3. Instead, cost for transmission system is obtained by the ratio between the value of cost from electric equipment (Equations 3.3,3.4,3.5,3.6), and the rated power generated by the WPP.

Element	Cost [€/kW]
Turbines	1724
Foundations	680
Contingency	325

Table 3.3: Breakdown of element cost

The cost related to power losses results during the lifetime is obtained from Equation 3.8, by summing the cost for each components.

$$\begin{aligned} & I_{loss} = \frac{\sum_i Cost_{yearly,i}}{P_{WPP}} \\ & \text{with:} \\ & Cost_{yearly,i} = \text{Cost of loss for each component 'i'} \ \ [€/year] \\ & P_{OWPP} = \text{rated power of the WPP } [kW] \end{aligned} \tag{3.11}$$

As a results, the share of power losses in the LCOE is defined in Equation 3.12.

$$\begin{aligned} & C_{loss} = \frac{I_{loss}}{Na} \\ & \text{with:} \\ & I_{loss} = \text{loss cost for year } \ [€/kW/year] \\ & Na = 8760 \cdot C_f = \text{number of equivalent hour for year } [h] \end{aligned} \tag{3.12}$$

Chapter 4

Power loss in the transmission system

This part of study presents a tool for solving Optimal Power Flows (OPFs) in hybrid high voltage direct current (HVDC) and high voltage alternating current (HVAC) systems for grid integration of large wind power plants located offshore. The OPF departs from the assumption that the power being produced from the wind power plants is known and it's entirely active power. To model the interaction between the DC and AC grids, the active power conservation is expressed between the AC side and DC side of each converter, taking into consideration converter losses (modelled as a second-order polynomial). The tool developed determines the voltages, the active and reactive power in each bus and branch that ensure the selected objective function. Moreover, some additional constraint has to be made in order to ensure grid code. To develop the tool, both HVDC and HVAC grids need to be represented through its impedance and admittance model. The tool has been implemented through MATLAB optimization toolbox.

4.1 Optimal Power Flow

The optimisation problem involves DC and AC power systems and can be thus considered as a non-linear constrained optimisation type. Mainly two strategies can be used to solve DC and AC power flows: sequential and unified. The sequential approach separates the problem in two parts corresponding each one to DC and AC power flow equations, respectively. Unified

approach solves all the equations together. The OPF tool presented here is based on a unified strategy. It is more used than the sequential method because the behavior of the devices has a more accurate representation and the final results are more reliable.
The algorithm for implement the OPF can follow this steps:

1. Data collection: This process consist on identify the electrical topology to be analyzed and to collect all the required data. It includes converter characteristics, transmission lines parameters, base voltage and power. On the reliability of this data depends whether or not the results are accurate. When data is unknown, assumptions are made to have a realistic approach;

2. Determine optimization vector: This step aim to identify the optimization vector x that contains the state and control variables of the HVAC and HVDC system. Where the entries are the vectors of nodal AC voltages, nodal DC voltages, branches current, converter active and reactive power injections to the AC grid;

3. Specify the constraints: The equality and inequality constraints are determined. The modeling of this equations could lead to divergence while solving the optimization problem;

4. Define the objective function: The objective function $f(x)$ is defined depending on the requirements of the problem and depends on the optimization vector mentioned in the step 2;

5. Prepare the optimal power flow: In this final step, the initial point of the optimization problem is selected according to common values.

4.2 Component model

The study of the transmission system need a model for the HVDC point to point link. This is done representing the component of the link by impedance and admittance. The VSC converter results difficult to model, so it will results approximate by a coupling relation between AC and DC side of it.

4.2.1 VSC converter

For the modelling of the converter it's chosen the simplified one. It can be represented as an voltage source in the AC side and as a current source in parallel with a capacitor in the DC side, as show in Figure 4.1. The converter

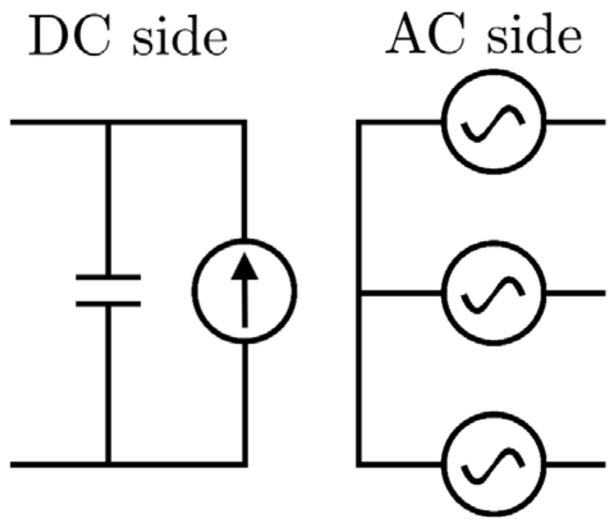


Figure 4.1: VSC modelling

topology chosen for this study is VSC, allowing and independent control of active and reactive power. The active power exchange on the AC and DC side of the converter differ on losses. More detail about losses is show in the section 4.3.1.

4.2.2 Transformers

Each transformer can be modelled as a impedance and an admittance (Figure 4.2).
The transformer impedance has an impact on the following factors [3]:

- Fault current/Protection;
- Reactive power / voltage;
- Harmonics;
- Resonances.

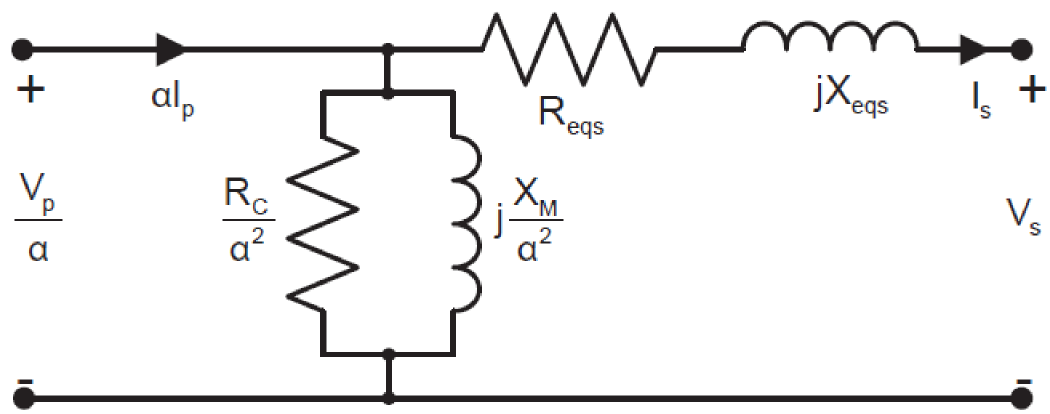


Figure 4.2: Simplified transformer equivalent circuit referred to the secondary voltage

A HVDC scheme provides a relatively small fault current only, i.e. the short-circuit power on the high voltage side of the transformer is low. Therefore the transformer impedance must be low enough to ensure the proper function of the protection system. Low transformer impedance also leads to less reactive power consumption and thus a low voltage drop across the transformer. This can help to meet grid code requirements related to reactive power and voltage. Nameplate rating for obtain the impedance and admittance of one transformer are show in Table 4.1.

4.2.3 Phase reactor

As already stated in the previous chapter, phase reactor is necessary for the separate control of active and reactive power. Ideally, it can assume is purely inductive, but for completeness is chosen to consider also the resistive component. The value reported in Table 4.2 are referred to a base power of $S_{base} = 500MVA$.

4.2.4 DC cable

The DC link can be simply modelled as a resistance R_{dc}. The assumption of using a bipolar configuration means that the power losses due to Joule effect is doubled, one regarding the positive pole, the other respects the negative one. The left side of the DC connection is the connection to the onshore VSC converter, the rectifier, and the right side is the connection to the onshore VSC converter, the inverter. As shown in the scheme in Figure 4.3, the converter on the DC side is modelled as a controllable current source in parallel with capacitors. The voltages of interest are the voltages across the capacitors at each side.

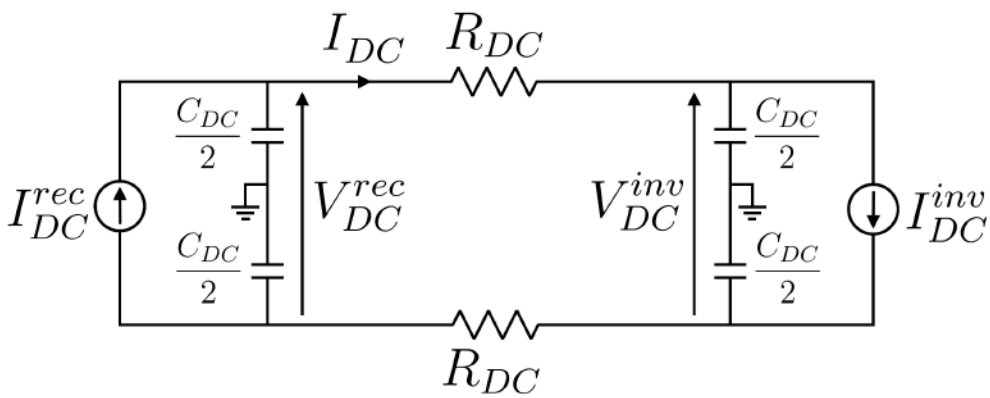


Figure 4.3: Model of the DC connection

4.2.5 Grid connection

A grid can be characterized by different parameters. Beneath its voltage level and its total power capability the Short Circuit Capacity (SCC) can be defined. The SCC is the amount of power flowing at a given point in case of a short circuit. It is mainly dependent on the rated voltage U_G and the absolute value of grid impedance Z_{grid}, which can be measured at this point. The grid impedance is the sum of impedances of many grid components and typically differs from region to region. One part of it consists of the impedance of the transmission line itself which mainly depends on material, diameter and length of the line. Transformers are used to connect lines with different voltage levels. They are typically high inductive. Also loads make a big contribution towards the grid impedance. They can change during the day and can have ohmic, inductive or capacitive character.
If an active load such as a WT with a rated power of $S_{N,WT}$ is connected to the grid, a Short Circuit Ratio SCR can be defined in 4.1:

$$SCR = \frac{SCC}{S_{N,WT}} = \frac{U_G^2}{Z_{grid} \cdot S_{N,WT}} \tag{4.1}$$

Another important factor to characterize the grid impedence is the ratio of reactive and ohmic parts of the grid impedance Z_{grid}, called the X/R-ratio (x_{rr}). With the values of Z and x_{rr} the inductive amount X and the ohmic amount R of the grid impedance can be calculated in 4.2.

$$\begin{cases} R = \frac{Z_{grid}}{\sqrt{1+(x_{rr})^2}} \\ X = \frac{Z_{grid}}{\sqrt{1+(\frac{1}{x_{rr}})^2}} \end{cases} \tag{4.2}$$

As reported in [10], if the SCR is smaller than 10 the grid is considered as weak and an x_{rr} of 0.5 can be considered.
To study the effects of power injection into a weak grid a simplified grid model can be utilized. Therefore the whole grid with all impedances and power sources and sinks can be described by means of Thévenin's theorem as one voltage source and one grid impedance.
For this elaboration, $SCR = 5$ and $x_{rr} = 0.5$ are considered.
By working with the p.u. method, taking $U_G = 1$ and $S_{N,WT} = 1$, results that, from Equations 4.1 and 4.2:

$$z_{grid} = 0.02 + 0.2$$

Nameplate data	Value
P_{cu}	62 kW
$u_c c$	18%
P_{Fe}	40 kW
i_0	1.2%

Table 4.1: Nameplate value for transformer model

AC base voltage	R [pu]	X [pu]
±170 kV	0.0013	0.1298
±333 kV	0.0003	0.0338
±400 kV	0.0002	0.0234

Table 4.2: Value in p.u. of phase reactor's impedance with $S_{base} = 500\,\mathrm{MW}$

4.3 System relation

Now that a model is obtained for every components, it's important to define the relation occurring between them. As stated previously, the transmission system can be divided in 3 distinct subdivision:

- AC offshore circuit (Figure 4.5a): it's the circuit connected to the offshore wind power plant, modelled as a variable voltage source (U_1). In series there is the transformer and the phase reactor. The coupling with the DC link is done by the AC side of the rectifier;
- DC link (Figure 4.5b): in the following representation is indicated only the positive pole of the bipolar configuration. The other pole is symmetric;
- AC onshore circuit (Figure 4.5c): circuit connected to the grid. Is to be pointed out that the power deliver to the grid is the one referred at node 7, that is consider as the PCC, as losses after this point are associated to the grid owner, as long as the grid code requirements are fulfill. For simplify the implementation the 2 series connected impedance of the transformer and the phase reactor can be combined as: $Z_{on} = Z_c + Z_{tr}$.

An important issue related to system model is the VSC. As it represent the coupling between the DC and AC circuit, a relation need to be use in order to approximate the power losses in the converter circuit.

4.3.1 VSC converter

Converter losses can be defined as a function of the AC power, modelled according to a second-order polynomial function. For this implementation two different power loss model are been used.

Converter loss model 1

The converter losses can be taken into account using a generalized loss formula with the converter losses quadratically depending on the converter current I_c:

$$\begin{aligned} &P_{loss} = b_i \cdot I_c + c_i \cdot I_c^2 \\ &\text{with:} \\ &I_c = S_{AC}^2 / V_{AC} = \sqrt{P_{AC}^2 + Q_{AC}^2} / V_{AC} \end{aligned} \tag{4.3}$$

With I_c defined as the current of the generator on the AC side of the corresponding converter. The factors b_i and c_i stand for the individual loss factors of converter i. The content of the individual factors is:

- Linear Current Factor b_i. Switching losses of the valves, more in particular the turn-off losses of the IGBTs and free-wheeling diodes.
- Square Current Factor c_i. Conduction losses of the valves, the value depends on the operating mode.

By simplifying the DC system to its power injections into the AC system, all information on the DC system itself is lost, which makes this simple model approximate. Also, model doesn't consider the different operation point of the converter, that depends also to the reactive power absorbed/injected.

i	b_i	c_i
Rectifier	3.464e-3	4.400e-3
Inverter	3.464e-3	6.667e-3

Table 4.3: Coefficient in p.u. for the power loss model 1

Converter loss model 2

A model for the modular multilevel converter (MMC) efficiency is obtained in [11], by means of a mathematical expression that can describe,over a broad range of active and reactive power flow combinations, the power losses generated by the semiconductors. According to the presented methodology, a polynomial-based model with a reduced number of coefficients is deducted, in such a way that can be directly used for optimal power flow studies.

$$\begin{aligned} P_l(S_f, P_f) = {} & (a_1 \cdot S_f^2 + a_2 \cdot S_f + a_3) \cdot P_f^3 \\ & + (b_1 \cdot S_f^2 + b_2 \cdot S_f + b_3) \cdot P_f^2 \\ & + (c_1 \cdot S_f^2 + c_2 \cdot S_f + c_3) \cdot P_f \\ & + (d_1 \cdot S_f^2 + d_2 \cdot S_f + d_3) \end{aligned} \tag{4.4}$$

with:

$$\begin{cases} S_f = \sqrt{P_{AC}^2 + Q_{AC}^2} / S_{base} \\ P_f = P_{AC} / S_{base} \end{cases}$$

The value of the coefficient used are in per unit.

The model is characterized by estimating the semiconductor's power losses whenever the converter is exchanging active and reactive power with the electrical grid, but with a fixed switching frequency. On the MMC HVDC based applications, typically the average switching frequency varies around 150 Hz due to the semi-conductor limits and practical limitations.

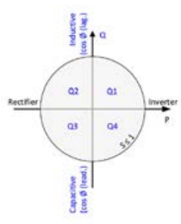


Figure 4.4: VSC power quadrant

For determine the value of the coefficient the Levenberg-Marquardt optimization algorithm was used, which best characterize the MMC efficiency over the four power quadrant. In this elaboration, with the convention show in Figure 4.4, the converter working as inverter is associated with the first quadrant, instead for the converter working as a rectifier the third quadrant is used.

Coefficient	Inverter	Rectifier
a_1	1.536e-3	2.850e-3
a_2	-5.259e-4	-10.530e-3
a_3	-1.333e-3	10.200e-3
b_1	-2.607e-3	3.839e-3
b_2	2.969e-3	-3.053e-3
b_3	1.064e-3	-4.971e-3
c_1	-7.282e-5	-2.658e-3
c_2	-5.397e-5	4.874e-3
c_3	4.923e-4	-9.094e-4
d_1	1.889e-3	1.686e-3
d_2	3.346e-3	3.738e-3
d_3	3.644e-4	5.000e-4

Table 4.4: Coefficient in p.u. for the power loss model 2

4.4 Equation

With respect on the reference in Figure 4.5, a set of equation can be obtained for describe the system in a steady state model. The equations are deriving by using Kirchhoff's Current and Voltage Law at the nodes and power relations.

$$\begin{cases} \boldsymbol{S_1 = U_1 \cdot I_1^*} \\ \boldsymbol{U_1 = Z_{tr} \cdot I_1 + U_2} \\ \boldsymbol{U_2 = Z_c \cdot I_3 + U_3} \\ \boldsymbol{I_1 = Y_{tr} \cdot U_2 + I_3} \\ \boldsymbol{S_3 = U_3 \cdot I_3^*} \end{cases} \tag{4.5}$$

$$\begin{cases} \boldsymbol{U_4 = U_5 + R_{dc} \cdot I_{dc}} \\ \boldsymbol{P_4 = 2 \cdot U_4 \cdot I_{dc}} \\ \boldsymbol{P_5 = 2 \cdot U_5 \cdot I_{dc}} \end{cases} \tag{4.6}$$

$$\begin{cases} \boldsymbol{S_6 = U_6 \cdot I_6^*} \\ \boldsymbol{U_6 = Z_{on} \cdot I_6 + U_7} \\ \boldsymbol{U_7 = Z_{grid} \cdot I_8 + U_8} \\ \boldsymbol{I_6 = Y_{tr} \cdot U_7 + I_8} \\ \boldsymbol{S_{grid} = U_7 \cdot I_8^*} \end{cases} \tag{4.7}$$

$$\begin{cases} \boldsymbol{P_4 = P_3 - P_{L,C1}} \\ \boldsymbol{P_6 = P_5 - P_{L,C2}} \\ \boldsymbol{(4.4) \rightarrow P_{L,C1}, P_{L,C2}} \end{cases} \tag{4.8}$$

For the implementation in MATLAB, the systems of equation 4.5 and 4.7 are separated in real and imaginary part. Also, the value are transformed in *per unit*.

In addiction to this set of equation, additional constraints are added to the problem:

- Voltage bus amplitude:

$$\begin{aligned} &U_{min} \leq |U_i| \leq U_{max} \text{with: } i = 1, ...7 \\ &U_{min} = 0.9 \cdot |U_i| \\ &U_{max} = 1.1 \cdot |U_i| \end{aligned} \tag{4.9}$$

- Ampacity of DC cable:

$$I_{dc} \leq I_{cable} \tag{4.10}$$

- Reactive power injection to the grid:

$$0.95 \leq \cos\phi \leq 1 \quad \text{with:} \quad \cos\phi = \frac{P_{grid}}{S_{grid}} \tag{4.11}$$

- Grid voltage:

$$|U_8| = 400\,\text{kV} \tag{4.12}$$

As a result, inequality equation are added to the problem. The resulting set of equations is reported here.

System of equations referring to the offshore circuit:

$$\begin{cases} P_1 = U_{1,r} \cdot I_{1,i} \\ U_{1,r} = real(Z_{tr}) \cdot I_{1,r} + U_{2,r} \\ U_{2,r} = real(Z_c) \cdot I_{3,r} + U_{3,r} \\ I_{1,r} = real(Y_{tr}) \cdot U_{2,r} + I_{3,r} \\ P_3 = U_{3,r} \cdot I_{3,i} \end{cases} \qquad \begin{cases} Q_1 = U_{1,i} \cdot I_{1,r} \\ U_{1,i} = imag(Z_{tr}) \cdot I_{1,i} + U_{2,i} \\ U_{2,i} = imag(Z_c) \cdot I_{3,i} + U_{3,i} \\ I_{1,i} = imag(Y_{tr}) \cdot U_{2,i} + I_{3,i} \\ Q_3 = U_{3,i} \cdot I_{3,r} \end{cases}$$

System of equations referring to the onshore circuit:

$$\begin{cases} P_6 = U_{6,r} \cdot I_{6,i} \\ U_{6,r} = real(Z_{on}) \cdot I_{6,r} + U_{7,r} \\ U_{7,r} = real(Z_{grid}) \cdot I_{8,r} + U_{8,r} \\ I_{6,r} = real(Y_{tr}) \cdot U_{7,r} + I_{8,r} \\ P_{grid} = U_{7,r} \cdot I_{8,i} \end{cases} \qquad \begin{cases} Q_6 = U_{6,i} \cdot I_{6,r} \\ U_{6,i} = imag(Z_{on}) \cdot I_{6,i} + U_{7,i} \\ U_{7,i} = imag(Z_{grid}) \cdot I_{8,i} + U_{8,i} \\ I_{6,i} = imag(Y_{tr}) \cdot U_{7,i} + I_{8,i} \\ Q_{grid} = U_{7,i} \cdot I_{8,r} \end{cases}$$

System of equations referring to the DC circuit:

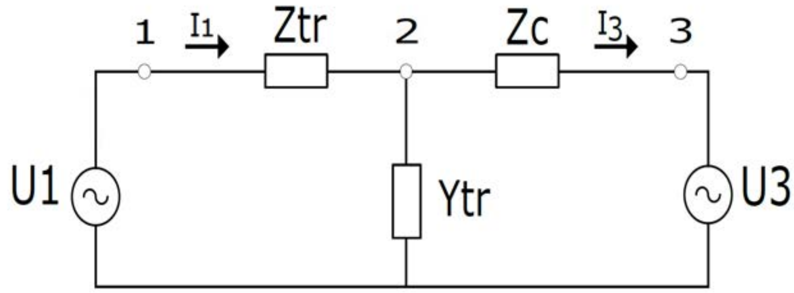
$$\begin{cases} U_4 = U_5 + R_{dc} \cdot I_{dc} \\ P_4 = 2 \cdot U_4 \cdot I_{dc} \\ P_5 = 2 \cdot U_5 \cdot I_{dc} \end{cases}$$

Constrains on grid voltage and power losses on converters:

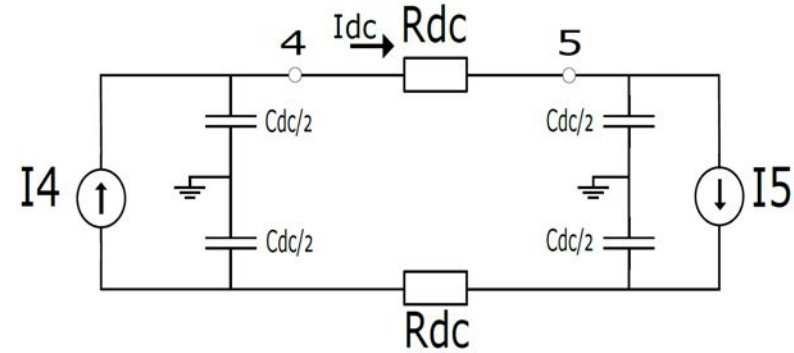
$$\begin{cases} \sqrt{U_{8,r}^2 + U_{8,i}^2} = 1 \\ P_4 = P_3 - P_{L,C1} \\ P_6 = P_5 - P_{L,C2} \end{cases}$$

Inequality constraints on DC ampacity and $cos\phi$:

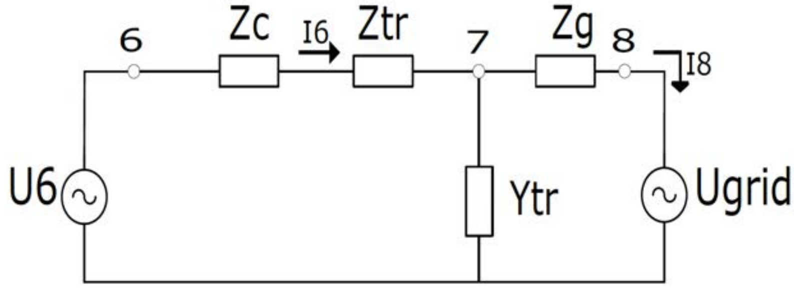
$$\begin{cases} I_{dc} \leq I_{cable} \\ P_{grid}/\sqrt{P_{grid}^2 + Q_{grid}^2} \leq 1 \\ P_{grid}/\sqrt{P_{grid}^2 + Q_{grid}^2} \geq 0.95 \end{cases}$$



(a) Offshore circuit



(b) DC link



(c) Onshore circuit

Figure 4.5: Transmission system modelling

4.5 MATLAB implementation

The optimization problem is based on the function *fmincon* (see Appendix B), which solves a non-linear program based on the interior point method. The optimisation algorithm determines the voltages in all the nodes and the power flowing in the different branches of the system that minimize a user defined objective function and guarantee all the equality and inequality constraints.

The objective function is related to the variables of the system. The objective function can be chosen among several functions which are of interest in terms of operation or planning of the system. For this work, the goal is minimize the active power losses on the transmission system, defined as:

$$\begin{aligned} f(x) = & \, 2 \cdot R_{dc} \cdot I_{dc}^2 \\ & + R_{tr} \cdot I_1^2 + R_c \cdot I_3^2 + R_{on} \cdot I_6^2 \\ & + G_{tr} \cdot U_2^2 + G_{tr} \cdot U_7^2 \\ & + P_{L,C1} + P_{L,C2} \end{aligned} \tag{4.13}$$

The optimization vector that contains the state and control variables is specified here:

$$x = \begin{bmatrix} U_i \\ I_i \\ \vdots \\ U_4 \\ I_5 \\ I_{dc} \\ \vdots \\ P_i \\ Q_i \\ P_{L,C1} \\ P_{L,C2} \end{bmatrix} \tag{4.14}$$

As already presented in the previous section, all the variables are subjected to constraints related to grid code or to physical limitation.

For simplify the computation, all the value are used in *p.u.* Moreover, voltage and current vectors are consider in the cartesian representation, as well active and reactive power component are considered. As a results, all the equation in previous section and in vector 4.14 have to be consider in real and imaginary part . In total the optimization vector contain 33 variables, with 9 referring to power, 24 referring to currents and voltages of the system.

The MATLAB code calculate cost of the system, electric value through the system bus for different value of power, distance from the shore and voltage rating on DC transmission.

Chapter 5

Simulations and results

In this chapter some results are shown and discussion are carried out on it. Two main topic are considered: the technical one, related to the optimization problem with respect on power losses, and the economic one.

5.1 Optimal Power Flow

In this final part of the work results are carried out with different power loss model on converter (see Section 4.3.1), variable power generated and voltage rating on DC link.
The obtained value are confronted in the Scenario A, with DC link voltage at ± 150 kV and base power of 500 MVA. The results elaborated by MATLAB are all fitting the constraints. As it was expected, all the voltage value are chosen as high as possible. By doing this, the magnitude of the currents in the system results to be lowered respect normal operation without implemented the OPF. As a consequence, power losses results lower. Regarding the reactive power elaborated by the converters: the converter working as a rectifier absorb reactive power from the AC offshore grid, instead the converter working as an inverter inject reactive power to the grid. The latter allow the voltage magnitude of the grid to reach the reference value of 400 kV.

5.1.1 Converter model

A comparison can be carried out with regard of the different converter loss model, as was explained in Section 4.3.1. Has to be pointed out that the obtained model result approximate, as the parameters in p.u. was obtained from experimental data. The model is consider affordable for power up to 1 GW.
As the power loss are poorly dependent from the length of the line, the next table present the power losses on converter for different value of power generated.

	Model 1	Model 2
Power generated (MW)	$P_{l,C1}/P_{l,C2}$ (MW)	$P_{l,C1}/P_{l,C2}$ (MW)
200	1.36/1.93	1.12/1.39
400	2.72/3.84	2.25/3.85
600	4.12/5.76	3.37/4.15
800	5.50/7.81	4.50/5.52
1000	6.89/9.76	5.63/6.90

Table 5.1: Power loss on VSC for different model

As it can be seen, model 2, the one that consider the losses with respect to the power flow on the converter, results with lower power losses then model 1. This can be an outcome with respect of the accuracy of the measurement, but also a demonstration about the improvement in the VSC converter efficiency. Model 1 is referred from the work [12] from 2009, instead of the more recent model 2 from [11], dated 2017.
Also, the MMC operation in the rectifier mode is more efficient than the inverter mode. This occurs due to the fact that the average number of conducting diodes over a grid period is larger than the IGBTs, and the non-controllable devices have a lower on-state voltage, which generates less losses. More detailed information can be found in [11].
All the result obtained in the rest of the work are obtained using the model 2.

5.1.2 DC voltage rating

Voltage and current vectors, active and reactive powers in each node of the system are shown in Tables 5.2 and 5.3.
The first one is referred to a DC transmission voltage of ±150 kV, the second one to ±320 kV. The different Scenario were show in Table 2.1. For the converter loss model, the number 2 was choice as it results more accurate as explained previously.

For the Scenario A under study, namely with 500 MW power produced by the WPP and length from the shore of 100 km and DC transmission voltage of ±150 kV, power losses in the transmission system are 12.61 MW, corresponding to the 2.52% of the total transmitted power. Of this, in each components the corresponding losses are:

- Converter Station Offshore:
  - Voltage Source Converter: 2.84 MW (0.569%),
  - Phase reactor and transformers: 0.85 MW (0.169%),
- DC cable: 5.11 MW (1.022%)
- Converter Station Onshore:
  - Voltage Source Converter: 3.45 MW (0.689%)
  - Phase reactor and transformers: 0.37 MW (0.073%)

node number	$\|U\|$ kV	ϕ	$\|I\|$ kA	θ	P MW	Q MVar
1	184.01	43.0	1.5688	43.0	500.000	0
2	184.20	40.4	0.0736	-49.0	499.739	-23.480
3	187	34.1	1.5731	45.7	499.156	-102.203
4	165	0	1.5040	0.0	496.311	0
5	163.30	0	1.5040	0.0	491.199	0
6	402.61	51.4	0.7075	45.0	487.756	56.876
7	400.13	47.1	0.03	-34.5	487.392	0
8	400.00	35.8	0.70	47.1	477.897	-94.961

Table 5.2: Electric values in system bus (±150 kV)

Instead, for the Scenario B, namely with DC transmission voltage of ±320 kV, power losses in the transmission system are 8.55 MW, corresponding to the 1.71% of the total transmitted power. Of this, in each components the corresponding losses are:

- Converter Station Offshore:
  - Voltage Source Converter: 2.80 MW (0.561%),
  - Phase reactor and transformers: 0.43 MW (0.085%),
- DC cable: 1.51 MW (0.301)
- Converter Station Onshore:
  - Voltage Source Converter: 3.47 MW (0.691%)
  - Phase reactor and transformers: 0.37 MW (0.073%)

node number	$\|U\|$ kV	ϕ	$\|I\|$ kA	θ	P MW	Q MVar
1	332.70	60.0	0.868	60.0	500.000	0
2	333.16	56.9	0.035	-32.4	499.778	-20.020
3	334.30	55.0	0.870	62.3	499.576	-64.093
4	352.00	0.0	0.706	0.0	496.770	0
5	350.93	0.0	0.706	0.0	495.266	0
6	388.83	79.1	0.195	45.0	491.809	-0.231
7	389.99	74.5	0.587	-87.3	491.446	-58.886
8	400.00	62.7	0.733	81.3	481.137	-161.978

Table 5.3: Electric values in system bus (±320 kV)

As it can be seen, the different value on power losses are concentrated in the DC link, with a reduction of 3.6 MW (−70%) in power losses between Scenario A and B. in Table 5.4, the different value on power losses in the DC link for different length are show.

Scenario	A	B
Length (km)	$P_{l,DC}$ (%)	$P_{l,DC}$ (%)
50	0.51	0.15
100	1.02	0.30
150	1.53	0.45

Table 5.4: Power losses in the DC connection ($P_{OWPP} = 500\,\mathrm{MW}$)

5.2 Total cost of transmission system

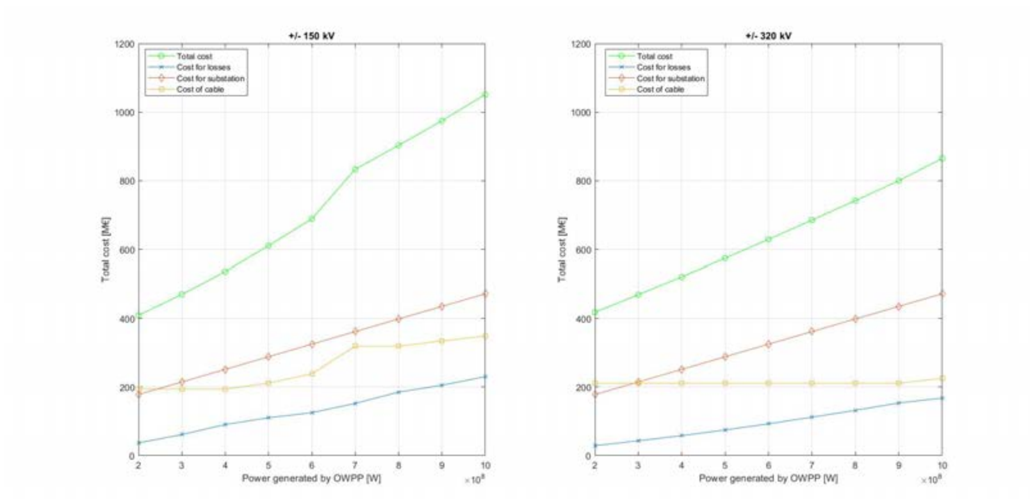
As a consequence of the affordability on the model of converter and data collection, results from the economic evaluation about system cost can be consider reliable up to 1 GW of power produced by the offshore wind power plant.

Figure 5.1 show the dependence of the system cost with respect of power generated and length. It can be seen that the transmission system with the DC voltage of 150 kV can results competitive for power up to 600 MW (Figure 5.1a). This is a consequence about the limit on capability in the DC line due to the lower voltage. Indeed, for higher power, the DC link has to be sized with 2 parallel bipolar cables and so became more convenient use a DC voltage of 320 kV.

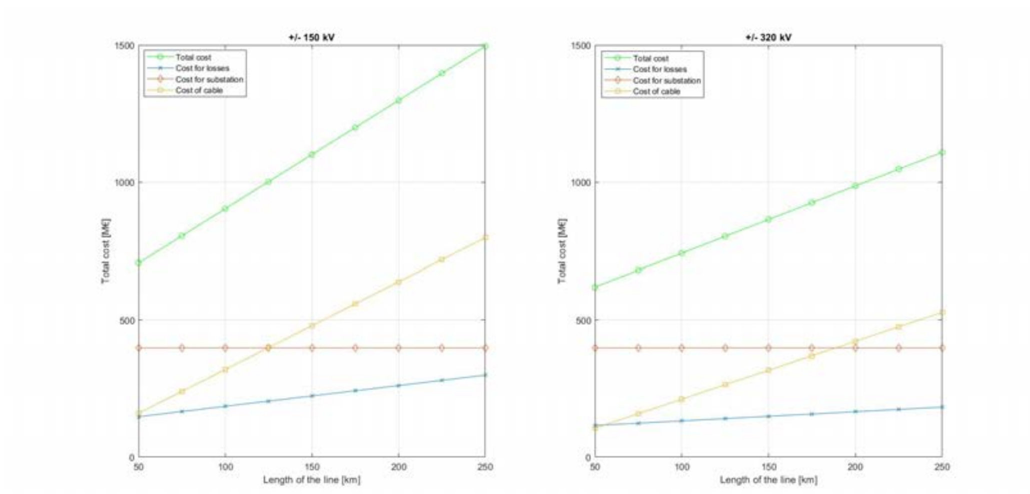
A more detailed cost breakdown for this voltage rating are show in Figure 5.2. As it was expected, the VSC results as the component in the transmission system that is more expensive. By doubling the power generated, an increasing in cost of about the 40% is observe. Also the platform has a huge share in the cost related to the converter station, with a share of 40% with a power generation of 1 GW.

In dependence off the distance from shore, lower section on DC cable means lower material and loss cost.

All the results in this section were benchmark with Ergun elaboration [7], showing only mirror difference. The main deviation is due to the configuration of the DC line, as [7] don't consider the earth return, making the share on cost off the DC cable less important.



(a) Total cost for different value of power generated, L=100 km



(b) Total cost for different length of the line, S=800 MW

Figure 5.1: Total cost in M€for different voltage rating scenario

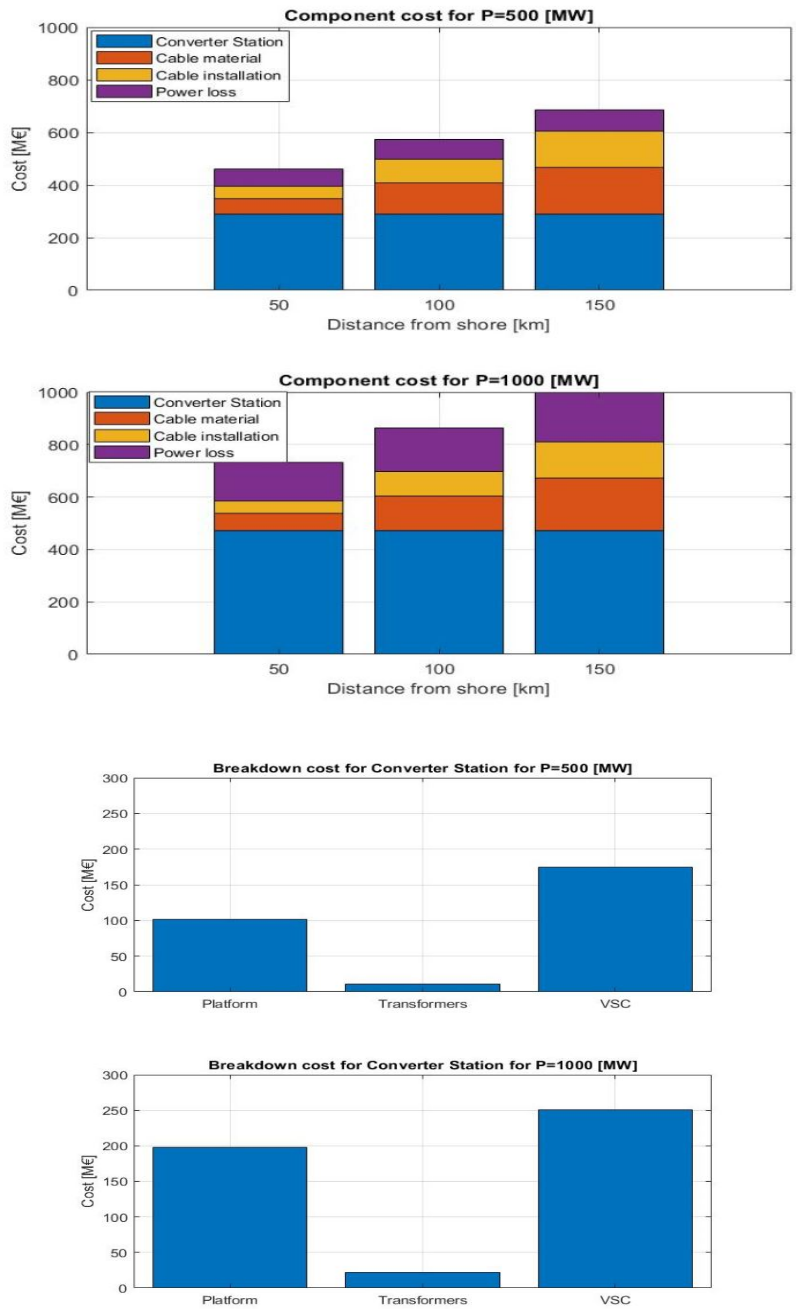


Figure 5.2: Cost in € for a TS at 320 kV and distance from shore of 100 km

5.2.1 Levelized Cost Of Energy

The LCOE can be useful for show the impact of the transmission system in the cost of selling energy. As a matter of fact, the value for losses cost in the previous section was consider in the whole lifetime of the wind farm park. By using the LCOE, the losses cost can be spread through the entire life of the system, given a better context for understanding the impact of its in the system cost.

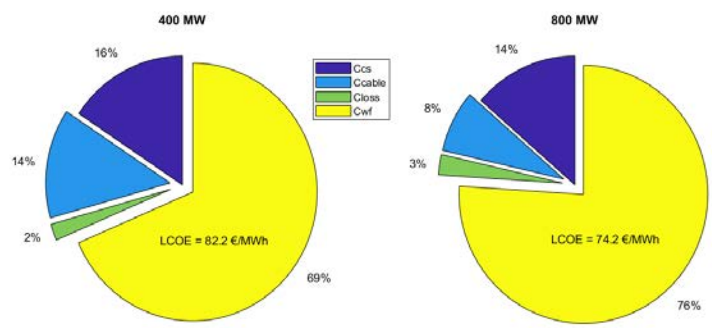


Figure 5.3: LCOE of the OWPP: C_{WF}:cost associated with the wind farm (turbine, installation,contigency); C_{CS}: converter substation cost share; C_{cable}: cable cost share; C_{loss}: loss share

As in can be seen from Figure 5.3, for a fixed distance from the shore($L = 100\,\text{km}$, by increase the power produced, the transmission share on the total cost has less impact in the total cost. The impact on the transmission system is reduced for higher power.

As to be pointed out that the value calculated can't be use as a reference value for the WPP price of energy. Indeed, no evaluation on taxes, assurance, operational and maintenance cost was carried out. The aim was to show how much the electrical transmission system impact on the total system cost, also with respect of the wind park.

Chapter 6

Conclusion

This thesis has exposed the first approach for the planning phase on a HVDC VSC point to point link. The goal of make an economical and technical analysis on the system brought at results that are benchmark with other technical papers. The contributions of this report can be listed as:

- Technological trend for VSC-HVDC system;
- Updated cost model for coomponents;
- Methodology for analysing the optimal operation of hybrid AC/DC grids with large wind power integration for several objective functions;
- Integration of converter loss model in an Optimal Power Flow algorithm;
- Fulfill the grid requirements for the integration of large WPP in a weak AC system.

On the other hand, the accuracy of the results, mainly the economic one, have a great dependence on the data collection. With the implementation of the VSC-HVDC in the future, the chance to have better data regarding the components of the system is expected. For future work, a model of the converter can also lead to approximate better the losses on it.

AC vs DC

The major constraint of transmission lines in HVAC transmission systems is that they tend to generate large amounts of reactive power. HVDC, on the other hand, has relatively lower transmission loss . However, there are several drawbacks of HVDC transmission such as the need of additional conversion equipment, maintenance difficulties and less reliability of the system. The AC-DC conversion process using VSC introduces dominant portion of the overall loss. Therefore, it is essential to understand the pros and cons of both transmission system and carry out detailed research on power losses of both systems over a range of transmission distances and basic components.
The Figures following this section want to be a proof about the so called break even distance (BEA), defined as the distance after which HVDC line cost will be cheaper than HVAC line cost. As it can be seen in Figure 6.1 the BEA is around 100 km, and even less for higher power generated (see Figure 6.2).
Table 6.3 indeed show the different power losses on the transmission system.

Table 6.1: HVAC

L (km)	P=400MW (%)	P=800MW (%)
50	1.75	1.40
100	3.26	2.63
150	4.5	3.79

Table 6.2: HVDC

L (km)	P=400MW (%)	P=800MW (%)
50	2.05	2.10
100	2.59	2.64
150	3.13	3.18

Table 6.3: Relative power loss HVAC/HVDC

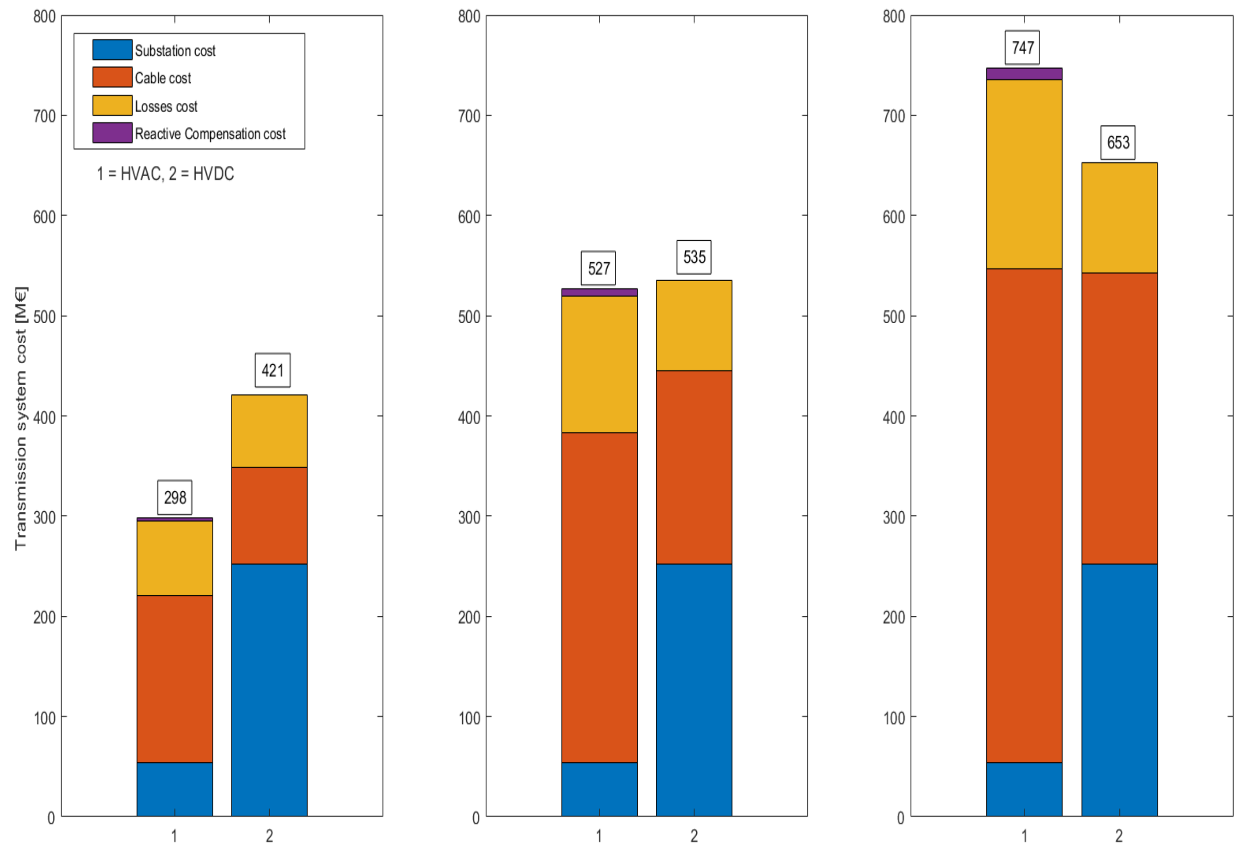


Figure 6.1: HVAC vs HVDC cost brekdown for $P_{WPP} = 400\,\mathrm{MW}$

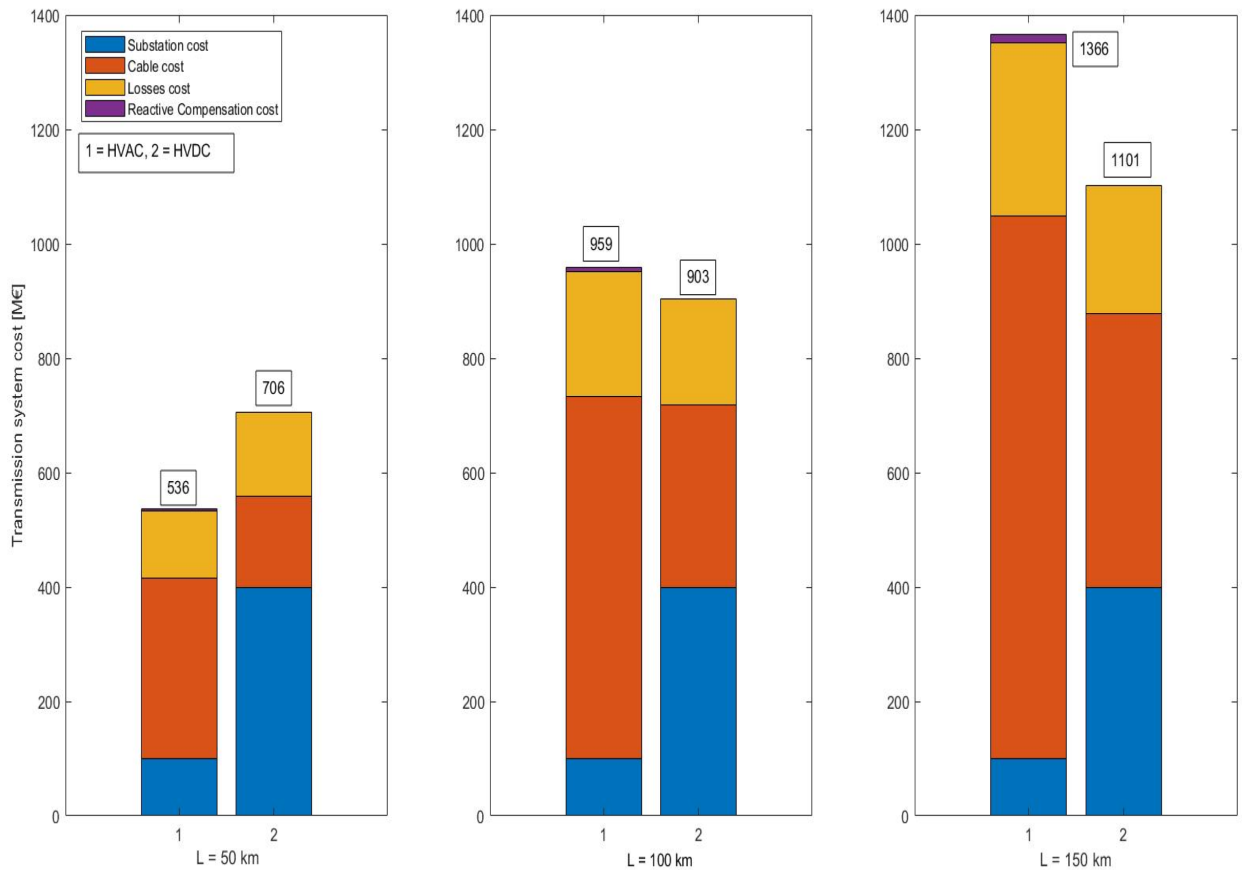


Figure 6.2: HVAC vs HVDC cost brekdown for $P_{WPP} = 800\,\text{MW}$

Appendix A

Component cost model

As the suppliers don't share the cost of each component, a cost breakdown from each component of the transmission system is difficult to achieve with precision. Nevertheless, data can be found in research papers or already collected by association such as ENTSO-E and Europacable.

Cable

The increasing market for HVDC submarine cable is handling the price for cable much cheaper. But, pricing for this category of items is highly volatile depending upon market supply and demand. As a consequence, only data from work after 2010 was used. The relation is given between cost of a XLPE bipolar cable with respect of his section. Price are per *km* of cable supplied.

Section [mm^2]	Cost [€]	Reference
1200	690000	[13]
1500	748000	[13]
1600	800000	[1]
1800	864000	[13]
2000	920000	[13]

Table A.1: Cost for bipolar cable at $\pm150\,\mathrm{kV}$

Section (mm^2)	Cost (€)	Reference
1200	863000	[13]
1500	863000	[13]
1800	920000	[13]
1950	1425000	[14]
2000	1063000	[13]

Table A.2: Cost for bipolar cable at ±320 kV

Transformer

Price for transformers are given with respect of rated power and, when it was provided, with rated voltage.

Rated power [MVA]	Voltage rating kV	Cost [M€]	Reference
180	132/11/11	1.61	[13]
240	150/33	1.2	[13]
240	132/275	2.02	[1]
240	132/400	2.3	[13]
275	150/400	2.64	[13]
300	132/11/11	3.3	[13]
450	132/11/11	4.3	[13]
500	132/11/11	5.43	[13]
800	132/11/11	7.14	[13]

Table A.3: Cost for transformer per unit [M€]

VSC

Rated power $[MVA]$	Voltage rating $[kV]$	Cost $[M€]$	Reference
376	150	43	[13]
500	300	84	[13]
550	300	82	[1]
600	150	120	[13]
850	320	102	[13]
1250	500	136	[13]
2000	500	170	[13]

Table A.4: Cost for converter $[M€]$

Platform

Rated power $[MVA]$	Voltage rating $[M€]$	Reference ?
400	67	[13]
800	115	[13]
800	140	[1]

Table A.5: Cost for offshore platform $[M€]$

Appendix B

MATLAB code

fmincon

The function *fmicon* finds the minimum of the specified problem define as:

$$min_x\ f(x)\ \text{ such that } \begin{cases} c(x) \le 0 \\ c_{eq} = 0 \\ A \cdot x \le b \\ A_{eq} \cdot x = 0 \\ lb \le x \le ub \end{cases} \tag{B.1}$$

b and b_{eq} are vectors, A and A_{eq} are matrices, $c(x)$ and $c_{eq}(x)$ are functions that return vectors, and $f(x)$ is a function that returns a scalar. $f(x)$, $c(x)$, and $c_{eq}(x)$ can be nonlinear functions. x, lb, and ub can be passed as vectors or matrices.

The other equation obtained in the section 4.4 can be implemented as follow:

- c: non linear inequality constraint $\rightarrow$ in Eq. 4.9,4.11;
- c_{eq}: non linear equality equation $\rightarrow$ Eq. 4.5,4.6,4.7,4.4;
- A: linear inequality constraint $\rightarrow$ Eq. 4.10;
- A_{eq}: linear equality equation $\rightarrow$ in Eq. 4.5,4.6,4.7;

The function *fmincon* is recalled in the main code through another function, *costpl.m*.

Main code

The main code for the elaboration is show at the end of this section. In order, it will recall 4 functions:

1. *capCB.m*: this function chose the section and calculate the capital cost for the cables;

2. *capSB.m*: evaluate the capital cost for the converter station. It's only dependent on the base power;

3. *costpl.m*: function related to the topic related to chapter 4. The function implement the optimization problem and calculate the power losses and the associated electric value through the system bus;

4. *pu.m*: convert the p.u. value from the previous section in absolute one.

```
clc
clear

%STARTING DATA: POWER, LENGHT, VOLTAGE
%power produced from WPP
% prompt = 'Power generated by the Wind Power Plant [MW]: ';
% S_base = input(prompt)*10^6;
S_base = 800e6;
%length line
% prompt = 'Lenght of the line [km]: ';
% L = input(prompt);
L = 100;


%% Voltage rating
% % Scenario A
% vAC1_b = 170e3; %BorWin1 voltage rating
% Vdc_b = 150e3;

% Scenario B
vAC1_b = 333e3;
Vdc_b = 320e3;

vAC2_b = 400e3;


%% CAPEX

% CAPITAL COST FOR CABLE
[sec, k, amp, Rkm, inv] = cap_CB(S_base,Vdc_b);

fprintf('\nSection of DC cable: %g mm^2',sec);
fprintf('\nNumber of bipolar cable: %g',k);
Rdc = Rkm*L;

% from [1]
inst=345000+k*575000;
```

```
inv_CB=(inv+inst)*L;
cap_cable = inv_CB/10^6;
fprintf('\nCost of cable (installation+material): %g M \n',cap_cable);

% CAPITAL COST FOR SUBSTATION
[cap_TR, cap_VSC, cap_PL, cap_station_erg] = cap_SB(S_base);
cap_station = (cap_TR+cap_VSC+cap_PL);
fprintf ('\nCost for substation: %g M \n',cap_station);

invCOST = cap_station + cap_cable;
fprintf ('\nTotal cost of investment: %g M \n\n',invCOST);


%% OPEX
%data for factor loss from [2]
t = 25;
%cost of energy [  /MWh]
CE = 100;
Cf = 0.4;

% POWER LOSS ON CABLE
[Pgrid,PLcomp,Qc,elVal] = cost_pl(S_base,amp,Rdc,vAC1_b,Vdc_b);

[T] = pu(S_base,elVal,vAC1_b,Vdc_b);
% input.data = [T];
% latex = latexTable(input);

Ploss = (1-Pgrid)*S_base;
loss_OPF = (Ploss *  Cf * CE * 8765.81 * 25)/10^12;
fprintf ('\nCost of losses after OPF: %g M ',loss_OPF);

Pl_CS1 = PLcomp(1)*100;
```

```matlab
Pl_DC = PLcomp(2)*100;Pl_VSC1 = elVal(32)*100;
Pl_CS2 = PLcomp(3)*100;Pl_VSC2 = elVal(33)*100;
Pl_per = Pl_CS1 + Pl_DC + Pl_CS2 + Pl_VSC1 + Pl_VSC2;
fprintf ('\nPower losses: %.4g %\n\n',Pl_per)
fprintf ('\nConverter Station 1: %.4g\nVSC1: %.4g\n', Pl_CS1,Pl_VSC1);
fprintf('\nDC cable: %.4g\n',Pl_DC)
fprintf ('\nConverter Station 2: %.4g\nVSC2: %.4g\n\n', Pl_CS2,Pl_VSC2)

disp(T);

%% Levelized Cost Of Energy
% %
Na = 8760*Cf; %[h]
i = 0.06;
ii= (1-(1/(1+i))^(t+1))/(1-(1/(1+i)));
fac_loss= 8765.81*CE*(10^-6)*ii;

% from [3]
% CAPEX = cost(TURBINE+FONDATION+CONTIGENCY+TRANSMISSION)
% WT CAPEX
Itr = 1724 + 680 +  325 ;
% converter station CAPEX
Ics = (cap_station*1e6)/(S_base/1e3);
% cable CAPEX
Icb = (cap_cable*1e6)/(S_base/1e3);
% total system cost
Isp = Ics + Icb + Itr; %[   /kW]
Cinv = Isp/(Na*ii); %[   /kWh]

% Cost related to losses
Iom = (loss_OPF*1e6)/(S_base/1e3*t); %[   /kW/year]
Com = Iom/Na; %[   /kWh]

LCOE = Com + Cinv;
fprintf ('\nLevilezed Cost Of Energy: %.3g [   /kWh]\n\n
```

```
',LCOE);

X1 = [ 12.88 11.27 1.7 56.35 ];
ax1 = subplot(1,2,1);
explode = [0 1 1 1 ];
pie(ax1,X1,explode)
title(ax1,'400 MW');

X2 = [10.12 5.78 1.9 56.40 ];
ax2 = subplot(1,2,2);
explode = [0 1 1 1 ];
pie(ax2,X2,explode)
title(ax2,'800 MW');

%%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Ergun elaboration [30] with also power losses cost
% A = -0.1*10^6;
% B = 0.0164;
% Doff = 22*10^4;
% num = 2*k;
% E = 8.98;
%
% Cdc = ((A+B*S_base+Doff)*(9*num+1)/(10*E))*L;
% Cdc = Cdc/10^6;
% fprintf('\nCost DC cable due to Ergun elaboration: %g M \n',Cdc);
% fprintf('\nSubstation cost due to Ergun elaboration: %g M \n',cap_station_erg);
% fprintf('\nCost due to Ergun elaboration: %g M \n',Cdc+cap_station_erg);

%% reference
% [1] ABB Id No: POW-0038 Rev. 7 (2013)
% [2] Rebled Lluch, Joaquin; Power Transmission Systems for Offshore Wind
```

```
%         Farms: Technical-Econmoic Analysis (2015)
% [3] IRENA; Innovation Outlook: Offshore Wind (2016)
```

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