CHALMERS
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Feasibility study of sea based wind park

A life cycle cost analysis of sea based wind parks with different electrical layouts

Master's thesis in Industrial Engineering

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Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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Cover: Wind visualization constructed in Matlab showing a surface of constant wind speed along with streamlines of the flow.

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Abstract

The offshore wind energy power installed over the world is growing nearly 30 % per year as well as the size of the offshore wind parks. Due to that, new types of collection and transmission systems such as DC collection and HVDC transmission are being developed. In this thesis, three different offshore wind park layouts are investigated which are AC/AC, AC/DC and DC/DC. The aim is to compare these three different options in order to establish the feasibility of the new DC/DC technology. Precisely the DC Series layout. The main characteristics of this system is the 250 kV DC cable used in the collection system where the wind turbines feed them with voltage instead of current. To do that, the AC transformer of the wind turbine is replaced by a DC-DC converter with medium frequency transformer inside it. Moreover, this same cable is used for the transmission system too. Then, the number of offshore platforms is reduced resulting with economical savings in the investment cost. The results show as the DC Series the most economical and productive as 107 M€ and 466 M€ in wind parks of 500 MW and 1000 MW are saved. Also, the efficiency is higher than for the other two systems, AC/AC and AC/DC. Furthermore, the case, where the largest offshore wind park in Sweden (Lillgrund) is evaluated, shows the benefits of DC Series from medium distances (20 km). As a result of that, the feasibility of DC series system is insured for future offshore wind parks projects in Sweden.

Keywords: DC Series, offshore wind park, VSC HVDC, levelized cost of energy, model costs, net present value, DC-DC converter, medium frequency transformer.

Acknowledgements

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Finally, I would like to express my at most gratitude for my family for their patience and for the love and support you gave me during this time. I love you!

Oriol Guillén Sentís, Göteborg, June 2020

List of Abbreviations

AC	Altern Current.
DC	Direct current.
HVAC	High Voltage Altern Current.
HVDC	High Voltage Direct Current.
kV	Kilo Volt.
LCOE	Levelized cost of energy.
LF	Low frequency.
MFT	Medium Frequency Transformer.
MF	Medium Frequency.
MML	Modular Multi-Level converter.
MVAC	Medium Voltage Altern current.
MVA	Mega Volt-ampere.
MW	Mega Watt.
M€	Million Euro.
NPV	Net present value.
OWP	Offshore Wind Park.
OWWPs	Offshore Wind Parks.
SST	Solid State Transformer.
VSC	Voltage Source Converter.
WACC	Weight Average Cost of Capital.
WT	Wind Turbine.

Contents

1

Introduction

1.1 Problem background

Climate change is forcing countries to take measures to reduce greenhouse over the next decade to prevent the planet temperature increasing. In 2015, the Paris Agreement was adopted in order to keep the increase in global average temperature to well below 2 °C. Also, to pursue efforts to limit the increase to 1,5 °C due to this would be substantially reduce the risks and impacts of it [1].

Since the second industrial revolution, in the final third of 19th century and beginning of the 20th, new energy sources have been need to feed the industrialization of the factories [2]. The vast of them have been fossil fuels as coal and petrol but soon the greenhouse gases became a planetary issue. Then, in the mid-20th century nuclear power became the baseload power generation but serious accidents as Chernobyl (1896) and Fukushima (2011) among others and the radioactivity waste problems changed the vision of a free-greenhouse power generation. In 21th century, renewable energy projects have been developing in order to substitute the fossil fuels. The main renewable technologies are the photovoltaic and wind energy. The main issue of these technologies are their discontinuity as the sun and the wind depends on meteorology. As a result, an hybrid system based on hydrogen and the two technologies mentioned before can achieve the regularity needed in the electrical system. Even though, this technology is not mature at this time. So that, further investigations are been developing [3].

Back then, the wind energy as the offshore wind power which has been grew nearly 30 % per year between 2010 to 2018 and it presents a great potential in the incoming years as the quality of the wind and the shallow waters of the North and Baltic Sea. Even more, offshore wind power is a category of its own as the only variable baseload power generation technology [4]. As new projects presents a capacity factor of 40 % to 50 % which approaches the values of efficient gas-fired or coal-fired power plants. To reach to these capacity factors a good quality of wind is needed, therefore the spots of the offshore wind parks are located deeper in the sea.

Moreover, the size of wind parks is increasing as well as the wind turbines capacities. Thus, the offshore wind parks have to be located further to the sea. With all this, new offshore transmission technologies have to be developed in order to guarantee the transfer and the quality of the power. In 2010, the first DC connection (BorWin 1) between a wind farm and the shore was built in the German North Sea. The capacity of the connection was 400 MW and the total distance was 200 km, 125 km offshore cable and 75 km onshore cable [5]. Besides in 2016, the most powerful offshore converter platform, DolWin beta, was built. With a power capacity of 916 MW and 135 km of cable, 45 km offshore and 90 km onshore. This new HVDC connections have been made possible by the VSC-HVDC technology which is getting importance as new renewable projects such as photovoltaic parks have been made currently and near term. Furthermore, solid-state transformers (SST) can completely change the scene of wind turbines as new converters such DC/DC where several research projects are been developed at present. Basically, SST are AC-AC or DC-DC high power converters whereby the voltage adaptation and the high frequency, to reduce the volume and weight, are achieved [6].

Due to all of this, different electrical layouts for offshore wind parks can be made. Depending on the power capacity and the distance to the grid connection one type can be preferable than other. Mainly, there are three different electrical layouts of OWPPs: AC/AC, AC/DC and DC/DC (DC Series). All of them can admit several modifications related with the specifications of the project such location, installed power or type of grid connection. The AC/AC system is the most mature technology for offshore wind projects. Then, AC/DC system is starting being commissioned in some European project in the North Sea. In contrast, DC/DC (DC Series) system is still developed in research project as some electrical equipment such MFTs are not commercially implemented.

1.1.1 VSC-HVDC technology

Voltage source converter (VSC) technology use IGBT's for the switching. As a result, the controlling of the switching provides VSC the ability to not rely on synchronous machines in the AC for this operation instead of line commuted converters (LCC) technology which means they can provide energy to passive grids. In addition, for applications where the space is at a premium as offshore platforms are preferred. Then, a complete VSC system consists of AC transformers, AC filters, phase reactors at the AC side and DC capacitors, DC cables, DC chopper, and DC switchgear in the DC side. The electrical diagram can be seen in Fig. 1.1 [7].

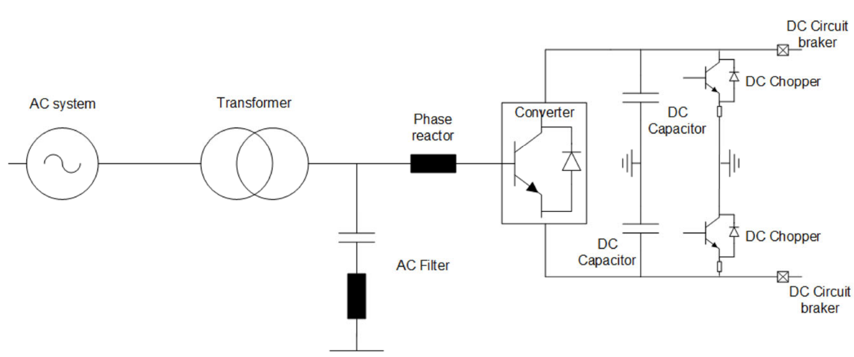


Figure 1.1: Electrical scheme for the VSC-HVDC converter.

1.1.2 Medium frequency transformer

The medium frequency power transformers are the key elements of the SSTs as they can potentially replace the LF transformers. The main characteristic is to use medium frequency, kHz ranges, in order to convert the power therefore a weight and volume reduction is achieved Consequently, the weight and the volume is reduced considerably. Although, As an example where in [8] a reduction of three times for a 3 MW, 500 Hz transformer is built.

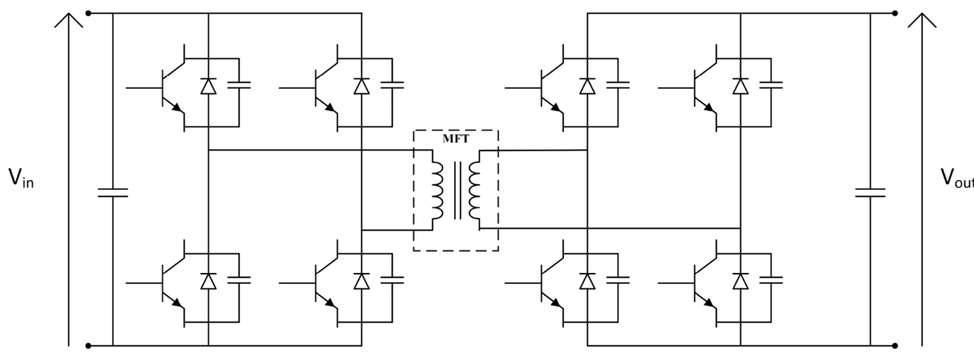


Figure 1.2: Electrical diagram of DC-DC converter based on a solid state transformer with a medium frequency transformer.

1.1.3 Offshore wind parks sustainability

Despite the carbon free of the wind energy production, several aspects have to be counted in order to evaluate the sustainability and the environmental impact of the construction of these parks. It is estimated around 80 % and 90 % of the weight can be recycled. Which mainly corresponds to the construction materials and metals. However, the rotor blades cannot be currently recycled according to the EU standards [9]. Moreover, some technical studies as [10] conclude the environmental impact in marine life is limited. Even so, some considerations as the bird migration routes, the seasonal prohibition of construction for the marine cycle or the new habitat changes as the creation of it due to the wind turbine structure into the water.

1.2 Purpose of the Thesis

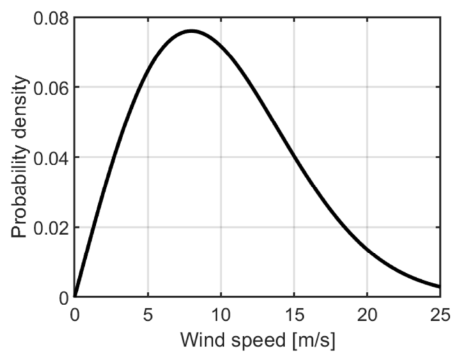
The purpose of the thesis is to determine and compare the life cycle cost and the energy efficiency of different offshore wind parks which are AC/AC, AC/DC and DC/DC. Specifically, the objective is to evaluate the characteristics of them in different locations and power capacities in order to determine the number of offshore infrastructures such as transformer or converter platforms are used. In addition, the purpose is to evaluate the energy losses and costs of the transmissions systems used to know the suitability for each case. The last, but not the least, objective is to develop a procedure that can be used to determine different costs in the OWPPs such as the investment costs and the cost of power loss.

2

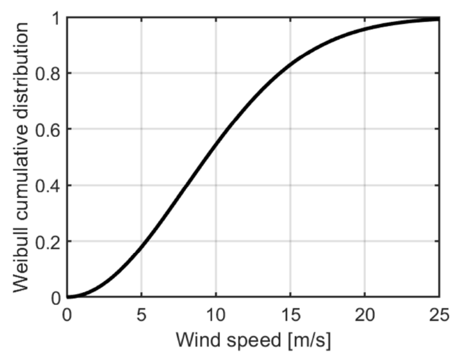
Short about energy conversion of wind turbines

2.1 Wind distribution

The wind energy production depends on the strength of the wind and the fluctuations over the time. To know how it would be, the wind speed is important as it can be decisive for the manufacturers and investors when they decide to develop a wind park project. There are several statistical distributions where the wind distribution can be explained but the most suitable is the Weibull distribution, and an example can be seen in Fig. 2.1.



(a)



(b)

Figure 2.1: (a) Probability density of Weibull distribution and (b) Weibull cumulative distribution.

The mathematical formula of Weibull distribution is

$$f(w) = \frac{k}{c}\left(\frac{w}{c}\right)^{k-1} \exp^{-\left(\frac{w}{c}\right)^k} \tag{2.1}$$

where w is the wind speed, w_{av} is the average wind speed, k the shape parameter and c is the scale parameter. Then, when k is equal to 2 the distribution is known as Rayleigh and the mean wind speed w_{av} is easily to calculate as

$$w_{av} = \frac{\sqrt{2}c}{2}. \tag{2.2}$$

When the wind distribution is known, it becomes possible to know the total energy that an offshore wind park (OWP) can produce based on the wind speed. The formula of the aerodynamic power of the wind and the energy able to be captured are respectively

$$P^G(w) = \frac{1}{2}\rho A C_p(\lambda, \beta) w^3 \tag{2.3}$$

$$E^G = NT \int_{w_{min}}^{w_{max}} P^G(w) f(w) dw \tag{2.4}$$

where $P^G(w)$ is the power generated by a wind turbine, ρ is the air density, A is the swept area an $C_p(\lambda, \beta)$ is the power coefficient. In Equation (2.4) shows the total energy that can be generated from the wind. However, the electrical losses are not counted so the correct expression to evaluate the power generated for an OWP is

$$E^G = NT \int_{w_{min}}^{w_{max}} \left[P^G(w) - P^L(w)\right] f(w) dw \tag{2.5}$$

where $P^L(w)$ is the electrical losses of the OWP. To be more precise in (2.4), the capacity factor has to be added to obtain the real net annual power from the wind farm. But this parameter depends mainly on the operation, maintenance and grid availability rather than on an aerodynamically aspect. Furthermore, the wind speed values are limited by design as the standard operational wind speed for a wind turbine is rated from 4 m/s to 25 m/s. These values are called cut-in and cut-off wind speed respectively. That means that the wind turbine cannot harvest all the availability wind energy as it is not possible to run the generator below 4 m/s and above 25 m/s. In addition, above 12,5 m/s the turbine only harvest a part of the available energy as it shows Fig. 2.2 where the maximum power of the generator comes when it has reached the rated wind speed, 12,5 m/s. Consequently, some positional controls are needed in order to take advantage as much as possible from the wind. These controls are the stall control and the pitch control which are explained shortly in Section 6.1.

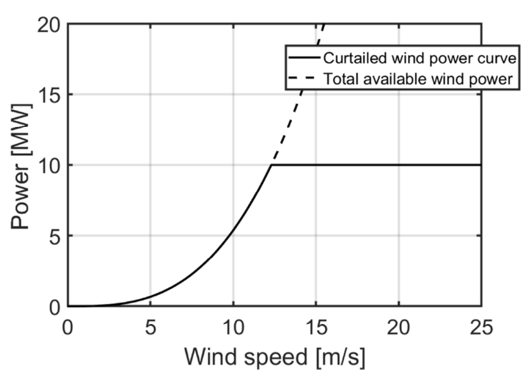


Figure 2.2: Power generation curve of a wind turbine and total available wind power curve based on the wind speed.

3

Model costs and economical parameters

Several papers, reports and other information have been analyzed in order to obtain the cost model for the different components of a wind park. Then, to compare the data from guide of offshore wind parks exposed in [11] has been used. Even though, it has not been possible to split all the parts and get a price of each individual one. In some cases, the cost given include all the parts of the system. For example, in the VSC-HVDC case, the cost of the protection equipment is included. Furthermore, some components have been inaccessible so some assumptions had to be made.

3.1 Wind turbine

The cost of the wind turbine include the nacelle, the rotor and the tower. The foundations are not included. The cost comes from [12] and it has been compared with the data given in [11]. The formula follows a logarithmic curve

$$C_{wt}(p_{wt}) = 2,95 \cdot 10^3 ln(p_{wt}) - 375,2 \tag{3.1}$$

where C_{wt} is the component cost in k€ and $_{wt}$ is the power rating of the wind turbine in MW.

3.2 Wind turbine foundation

The foundation cost does not include the installation cost. The installation cost is estimated to be 1,15 M€ [11]. The cost formula is a linear curve

$$F_{wt}(p_{wt}, D) = 5,382(D - 5) + 306,77 \tag{3.2}$$

where $F_{wt}(p_{wt}, D)$ is the foundation cost in k€/MW and D is the deep in m.

3.2.1 Cable cost

Due to that, the LCC analysis is with different typologies of cable such as AC and DC, real prices have been collected in order to make a reliable comparison. Table 3.1 shows the prices for the AC and DC collection system used in this project.

Table 3.1: Collection cable costs.

Cable parameters	Cost [M€/km]	Reference
66 kV AC 240 mm^2	0,200	[13]
66 kV AC 630 mm^2	0,425	[13]
230 kV AC 1200 mm^2	0,719	[14]
150 kV AC 150 mm^2	0,166	[14]
250 kV DC 1200 mm^2	0,388	[14]
250 kV DC 2000 mm^2	0,495	[14]
320 kV DC 1200 mm^2	0,431	[14]
320 kV DC 2000 mm^2	0,565	[14]
Sub-sea cable installation	0,575	[14]

3.3 Offshore AC platform

This wind farm components is the most difficult one to calibrate by means of a formula as there are several different parts. Such as the structure, the electrical equipment and the services for the operation and maintenance. To evaluate it in a reliable way various references have been used. The amount of electrical components and assumptions to be made in order to calibrate the total cost are explained in sections 6.3.1 and (EL CASE SETUP). In table 3.2 the cost for the different components of an offshore AC platform are shown.

Table 3.2: Offshore AC platform costs.

Position	Cost	Reference
Platform 500 MW 40x30x18m 3000t	85 M€	[13]
Auxiliary services	23 M€	[11]
Main transformer	$42,688 \cdot A_{TR}^{0,7513}$ k€	[12]
HVAC Reactors	0,029M€/MW	[15]
MW Switchgear 72,5 kV	0,4 M€	[16]
HV Switchgear 220 kV	3,09 M€	[15]

Auxiliary services includes the crew quarters, the crane, the heliport and the diesel back-up.

3.4 VSC-HVDC platform

The VSC-HVDC platform is characteristic for the AC/DC systems. This technology is relatively new for offshore wind park projects. Due to this, the splits cost of the platform is uncountable, and the data found corresponds to the entire converter with the safety control equipment and the platform cost. Most of these projects are installed outside the German shore and the commissioning numbers are volatile due to the few experiences in the installation process. Even though, a cost model can be designed in [17] according to real data from VSC-HVDC connections between the offshore wind farms to the shore.

Table 3.3: VSC-HVDC platform costs.

Position	Cost	Reference
Platform	$k_c\left[217,5P_R+\left(\frac{P_R}{1000}146,5\right)\right]$ M€	[17]
VSC converter	$k_c\left[59,6P_R+\left(\frac{P_R}{1000}63,4\right)\right]$ M€	[17]

The crew quarters, the crane, the heliport and the diesel back-up are included in the platform cost.

3.5 Onshore substation

To determine the onshore substation the data cost of Tab. 3.2 for the transformers and the switch bays and Tab. 3.3 for the converter have been used. In addition, the building, access and security cost are described in [11].

Table 3.4: Oshore susbtation cost.

Position	Cost	Reference
Building, acces and security	8 M€	[11]
Main Transformer	$42,688 \cdot A_{TR}^{0,7513}$ k€	[12]
HV switchgear bay 400 kV	4,545 M€	[12]
VSC converter	$k_c\left[59,6P_R+\left(\frac{P_R}{1000}63,4\right)\right]$ M€	[17]

3.6 Net present value

The Net present value (NPV) is is a procedure that allows the calculation of the present value of a certain number of future cash flows, originated by an investment. The methodology is to discount the future and present cash-flows into a present current value. It becomes very useful when it comes to evaluate and compare different projects as those brought forward in this project. So, when the NPV result is positive it means that the investment will be profitable. If it is negative, the investment will never give back the initial investment cost. The mathematical formula is

$$NPV = \sum_{t=1}^{n} \frac{V_t}{(1+i)^t} - I_0 \tag{3.3}$$

where I_o is the initial investment, V_t represents the cash-flows for each period t. This cash-flows is the result of the profits of the power plants which means operating and maintenance costs are included in the V_t. Then, i is the interest rate and n the number of periods considered for the investment.

3.7 Levelized cost of energy

The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost for electricity generation for a generating plant over its lifetime. Basically, LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by the discounted sum of the actual energy amount delivered. It is a useful tool to compare the different cost of energy production that would be required to recovered the total costs of building and operating over the years of lifetime. As a consequence, it can be known for which case or power plant is more competitive than another. The LCOE mathematical formula is

$$LCOE = \frac{I_o + \sum_{t=1}^{n} \frac{O_c}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{3.4}$$

where n is the expected lifetime of the power plant, I_o is the initial investment, O_c is the operational and maintenance cost, i is the interest rate and E_t is the electrical energy generated in period n. Even though, some cautions must be taken, since in this formula, hypothetical failures of the plant and the taxes related are not counted.

3.8 Capacity factor

The capacity factor of a power plant is the ratio between the net generated energy in a time period divided by the total energy if the plant would be operating full time over the time period. The calculation of this parameter is

$$Capacity \quad Factor(f_c) = \frac{Actual \quad ENERGY \quad Generated \quad [MWh]}{CAPACITY[MW] \quad x \quad TIME \quad Period[h]} \tag{3.5}$$

4

Electrical losses

In this chapter the electrical losses models used in this project are presented. The special focus is on the transmission systems which represents a large part of the energy losses. Then, for the electrical equipment such as transformers and converters a fix rated losses are determined. For the main transformers, located in the offshore platforms and the onshore substation is 0,25 %. Then, the converters located in the offshore platforms and the onshore substation present 0,7 % of electrical losses.

4.1 AC transmission losses

The AC submarine cables have a resistance, inductance and capacitance component per length unit. To carry out an efficiency analysis a good option is to convert the AC cable into his equivalent circuit, as Fig 4.1. shows, to be analysed using the load-flow method.

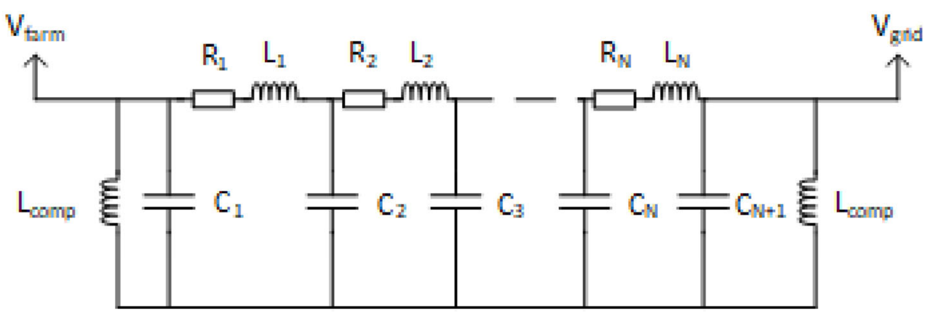


Figure 4.1: Submarine cable model with n π circuits.

The load-flow method consists in defining n nodes where the current and the voltage are known or unknown. Once they are defined, the next step is to built the admittance matrix as in this method the resistance are not used. The matrix size would be as big as the number of nodes. To calculate the matrix elements, Kirchhoff's circuit laws are used. Its relations are

$$\sum_{k=1}^{n} \underline{I_k} = 0 \tag{4.1}$$

$$\sum_{k=1}^{n} \underline{V_k} = 0 \tag{4.2}$$

where (4.1) is the Kirchhoff's current law and I_k is the current of each n branches of the node. Equation (4.2) is the Kirchhoff´s voltage law and V_k is the voltage of each n branches of the node. Then, looking at Ohm's law equation

$$\underline{I} = \frac{\underline{V}}{\underline{R}} = \underline{V} \cdot \underline{Y} \tag{4.3}$$

where I is the current, V is the voltage, R is the resistance and Y is the admittance. When the matrix elements are known, then it is possible to solve the system which looks like

$$[I_1 I_2 I_3 I_4]^T = [Y][V_1 V_2 V_3 V_4]^T \tag{4.4}$$

To simulate the wind farm side a current source to settle the power to transmit to the shore and a voltage source to fix the grid voltage are used.

4.2 DC losses

The main characteristic of the HVDC transmissions are the lower losses presented compared to HVAC transmissions. The frequency of the transmission is 0 Hz, therefore the skin effect does not occur. Then, due to the steady state scenario analysed in this project the losses model for DC cables are reduced to the conductor resistance R_c as shown in Fig. 4.2 and the mathematical formula is

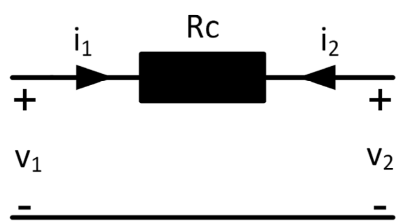


Figure 4.2: Equivalent circuit of the cable for DC voltages.

$$P_{loss} = R_c I^2 \tag{4.5}$$

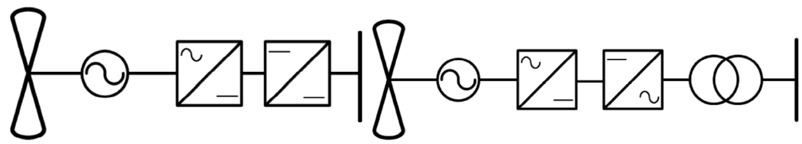
where P_{loss} is the power losses [W], I is the intensity [A] and R_c is composed by

$$R_c = \frac{\rho L}{S} \tag{4.6}$$

where ρ is the material resistivity [Ω·m], in this case copper, L is the cable length [m] and S is the cross section of the cable [m^2].

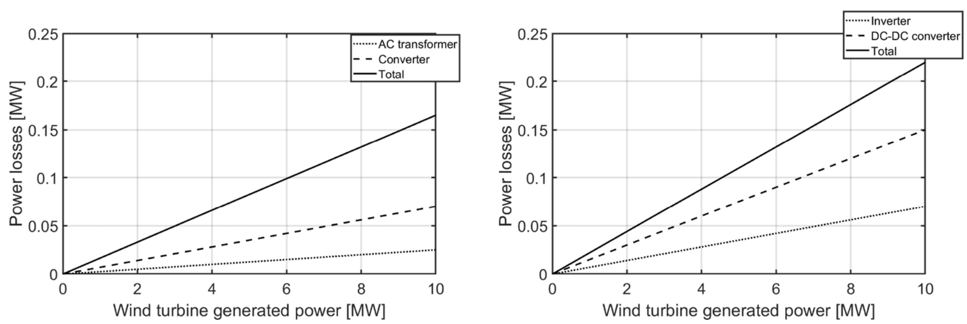
4.3 Wind turbine losses

In this project two different collection systems, based on AC and DC current, are used. AC collection corresponds to AC/AC and AC/DC system and the DC collection to the DC Series system. Fig. 4.3a represents the AC wind turbine layout, where is observed three different elements after the generator in order to transform the power to be feed in the collection system. These are the two converters to control the speed of the wind turbine and the AC transformer to boost the voltage to feed the collection system. The efficiencies of these equipment are 0,993 %, 0,993 % and 0,997 %. Then, in Fig. 4.3b two electrical components after the generator are observed. These are the rectifier and the DC-DC converter based on solid state transformers. It must be clarified that the DC-DC converter contains a medium frequency transformer as Subsection 1.1.2 shows. The efficiencies are 0,993 % and 0,985 % respectively. Furthermore, in Fig. 4.4, the different electrical components power losses are shown.



(a) (b)

Figure 4.3: Electrical diagram of the wind turbines used in this project. (a) represents the wind turbine used in the DC series system and (b) represents the wind turbine used in the AC/AC and AC/DC systems.



(a) (b)

Figure 4.4: Electrical losses of the different electrical components of the wind turbine (10 MW of rated power). Where (a) is the AC wind turbine and (b) is the DC wind turbine. The losses are expressed in MW.

5

Wind park configurations

In this chapter, the main characteristics of the OWPPs analysed in this project are presented. These three are AC/AC, AC/DC and DC series. Actually, a large quantity of configurations for each type of wind park depending on the power rating and the distance from the shore exist. Also, depending on the electrical equipment used as the inter array cables or the power capacity of the offshore platform the final layout can change considerably. It would be only explained as the big picture and the main characteristics of each one. Even though, the tendency shows that the upcoming OWP would be larger with power capacities around 500 MW to 1000 MW as it can be seen at the North Sea Hub [18]. All of them share similarities in the structure which are the following:

- Wind Turbines
- Collection system
- Offshore platform
- Transmission system
- Onshore substation

The technical data and the convenience of one configuration or other would be discussed further in Chapter 8 .

5.1 AC/AC

AC/AC offshore wind park was the first electrical system used for offshore wind energy. The first OWP was built at 1997 in Denmark and called Vindeby [19]. The power capacity was 4.95 MW. Then, the parks erected since then are usually AC/AC systems as this is the most developed technology. This system is used from distances to land lower than 90 km. Moreover, the maximum power capacity installed on this type is close to 500 MW. Even though, new improvements are allowing capacities around 700 MW [20]. Therefore, with these installed powers an offshore platform to transmit the energy properly is needed. The number of offshore AC platforms needed are not strictly defined, but typically one station can hold 400 to 500 MW [11]. The collection system as it can be seen in Fig 5.1 is based on several feeders where the energy is carried to the offshore platform.

Then, the voltage is boosted through two or three transformers to reach HV which of course is preferable for long distances. The standard voltage of a transmission is rated between 132 kV to 230 kV HVAC and a single HVAC cable, normally XLPE technology, can hold between 300 and 400 MW. So when the installed power of the wind park is higher than these values, more cables are needed. Once onshore, another transformation step is needed to modify the voltage to the mainland grid as the main overhead lines operate at 400 kV AC.

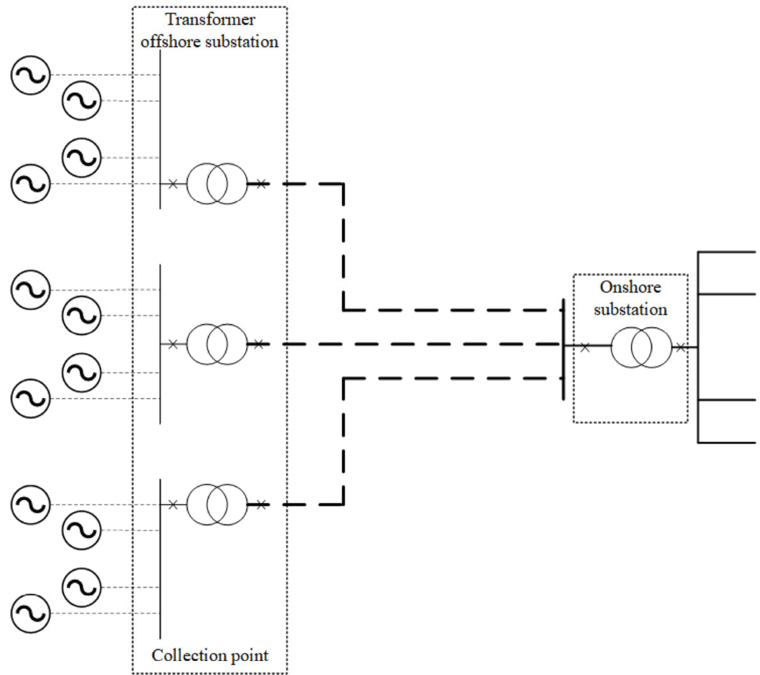


Figure 5.1: The electrical system for a 1 GW OWP. 3 offshore AC platforms rated on 400 MW and 3 HVAC cables to transmit all the power to the land.

5.2 AC/DC

The AC/DC system is a combination between an AC/AC OWP and a HVDC transmission. This system is deployed when the wind farm is located over 80 to 90 km from the shore. These distances are not feasible to transport energy via HVAC cables as will be shown in Section 6.2.2, mainly since an HVAC cable forms a big capacitance involving a significance reduction of the efficiency. The HVDC connections are not new in the electrical market but they are new for offshore wind parks applications. The first offshore HVDC connection to the shore was realized in 2010 in the German side of the North Sea. The power capacity of the line was 400 MW with a total length of 125 km. Other advantages of an HVDC connection is the facilities to control the output power of the park.

The layout of the system as it can be observed in Fig. 5.2 is various AC/AC OWP with offshore AC platforms where the AC collection voltage is boosted to 155 kV or 230 kV to be transmitted to the offshore converter station. Depending on the size of the park, this step can be omitted and the collection system can have the converter station directly. This single station is responsible for the collection of all the power and transform it to HVDC. The technology used is the VSC-HVDC which is explained in Subsection 1.1.1. This converter is much bigger than the transformers used in the AC platforms so as a result, the offshore converter stations are considerably bigger than the AC ones. The cables used are HVDC bi-pole with a voltage of ± 320 kV, a single one can hold up to 1000 MW or more. Once onshore, the HVDC voltage is converted again to HVAC and the final step is to match the voltage with the mainland grid, where an AC transformer is required but moderns MML - converter can skip this step. With the HVDC transmission, the wind park is isolated from the main grid improving the control and the operation of it.

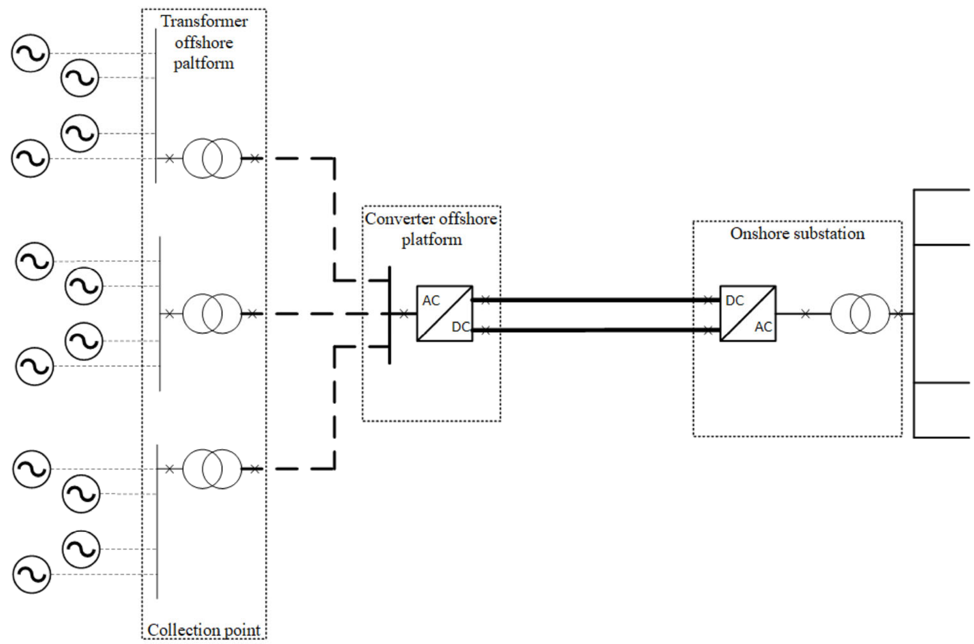


Figure 5.2: The electrical system for a large AC/DC wind park.

5.3 DC Series

This system is a new technology so no wind park is commissioned up until today. The main difference between the other two systems is that the power output of the wind turbine is based on medium frequency transformers (MFT) which is explained in Subsection 1.1.2. The wind turbines are connected in series as batteries with an output DC voltage of 10 kV where they are added to the collection system allowing to handle around 15 to 25 turbines per feeder. The collection voltage is rated to ± 250 kV meaning that the offshore transformer step can be saved. Anyway, due to the size of the parks and the distance from the shore, an offshore platform is needed in order to provide location for the switch bays and control systems for an optimal operation of the park. In addition, crew quarters would be needed for the operation and maintenance. The transmission system is based on a bi-pole cable as in the AC/DC system. Then, due to the high voltage used in the collection system, the converter step can be skipped as the transmission voltage would be equal to the collection system and where Fig. 5.3 shows. In addition, it can be observed how the feeders are drastically reduced with this collection system. Once onshore, the substation is pretty similar to the AC/DC system with the converter to transform to AC again and the transformer to match the voltage to the mainland electrical grid but as said in Section 5.2 it cannot be needed with a MML - converter.

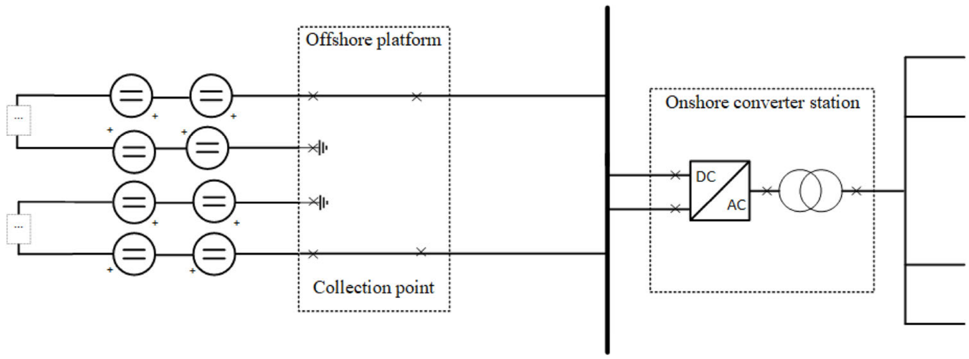


Figure 5.3: The electrical system for 500 MW OWP. 1 offshore DC platform is used.

6

Wind park components

In this chapter the different wind park components will be explained emphasizing the differences of each system explained in Chapter 5.

6.1 Wind turbine

6.1.1 Parts of the wind turbine

The wind turbine is the device of the wind park which converts the wind kinetic energy into electrical. It can be divided by three main parts [11]:

i. Nacelle
ii. Rotor
iii. Tower

The most remarkable items of each part would be described below:

Nacelle The nacelle supports the rotor and converts the rotational energy from the rotor into three-phase AC electrical energy.

(i) **Yaw system** Mechanism that rotate the nacelle to face the changing wind direction.
(ii) **Brake system** Disc brakes bring the turbine to a halt when required.
(iii) **Generator** Converts mechanical energy into electrical energy. The general output voltage is rated in 690 V.
(iv) **Main bearing** The main bearing supports the rotor and transfers some of the rotor loading to the nacelle bed place.
(v) **Gearbox** Converts rotor torque at a speed of 5-15 rpm to a speed of up to 600 rpm for a medium speed gearbox and 1500 rpm for a high-speed gearbox for conversion to electrical energy by the generator.
(vi) **Control system** Provides supervisory control (including health monitoring) and active power and load control in order to optimise wind turbine life and revenue generation.
(vii) **Power take-off** Receives electrical energy from the generator and adjusts voltage and frequency for onward transfer to the wind farm distribution system.

Rotor The rotor extracts kinetic energy from the air and converts this into rotational energy in the drive chain.

(i) **Spinner** contains the anemometer which utilizes the flow over the spinner of the wind turbine to measure the wind speed, yaw error and flow inclination angle.

(ii) **Blades** capture the energy in the wind and transfer torque and other unwanted loads to the drive train and rest of turbine.
(iii) **Pitch system** The pitch system adjusts the pitch angle of the blades to control power output from the turbine, minimise loads and start/stop turbine is required.
(iv) **Hub casting** The hub connects the blades to the main shaft.
(v) **Blade bearings** enable adjustment of blade pitch angle to control power output from the turbine, minimise loads and start/stop turbine as required.

Tower is typically a tubular steel structure supports the nacelle. It also provides access to the nacelle and houses electrical and control equipment. Also provides shelter and storage for safety equipment.

6.1.2 AC Power take-off

This part of the WT is responsible for the power transfer between the generator and the collection system. There are some key differences between the AC and DC power output. In the AC system the converter sequence is a rectifier and inverter where the power is transformed to AC-DC-AC in order to control the generator speed and to adjust the quality of the output power. These devices are a 4-quadrant frequency converter. Then, the last step before the collection grid is to boost the AC voltage to the rated 66 kV with a LF transformer [6].

6.1.3 Wind turbine foundation

The foundation provides the support for the wind turbine, transferring the loads from the turbine and transition piece to the sea bed where the loads are reacted. Also, it provides the access to where the cables are disposed, in so called J-tubes and the access to the nacelle for the crew. The first foundation systems were the gravity base due to the shallow waters, less than 10 m water depth, where the first OWPPs were located. For deeper waters as today's locations, the monopile and jacket system are used. The monopiles are used for water depths of 30 m and the jackets for 40 m. The jackets do not require as much steel as monopiles. Also, jackets can be used in a wider range of ground conditions, where the ground is either too hard or too soft to suit monopiles. Then, when the water depths are greater than 60 m the floating solutions are expected as the technology and feasibility would improve allowing to go commercial in the mid-2020s [11].

6.2 Cables

This section would expose the cables used in the different cases of offshore wind parks. Pointing out if they are used for AC systems or DC systems. The cables set up is an important part of the OWP as it represents the majority of the losses and the choice of AC or DC transmission involves the type of onshore and offshore substations. At the end of this section, the technical data of the cables explained would be shown in Tab. 6.1.

6.2.1 66 kV AC

The 66 kV AC cable is used in the collection system of the AC/AC and AC/DC OWPPs. Up until now the 33 kV cable is the most installed in the collection system, though new projects have been designed with the 66 kV cable [20] due to increase of power capacities of the wind turbines the 33 kV inter array cables cannot be used as the number of feeders needed for a large OWP would be not feasible for the lacking of space in the sea bed. In addition, the same cross section for a 66 kV cable can handle 80 MVA rather than 40 MVA in the 33 kV size, giving as a result a reduction of the number of feeder used. What is more, the size of the busbar and the switchgear bays would be less for a 66 kV feeder system of the same size, causing a decreasing used of space and weight in the offshore platform.

Furthermore, the way of collecting the energy in the OWPPs allows to use more than a cross section for the same feeder, that is, for the first wind turbines of the feeder cable a smaller cross section is enough to carry the energy instead of using the 80 MVA rating 66 kV cable everywhere. Fig. 6.1 shows the border of the change of cable section in a feeder for wind turbines with a capacity of 10 MW [13].

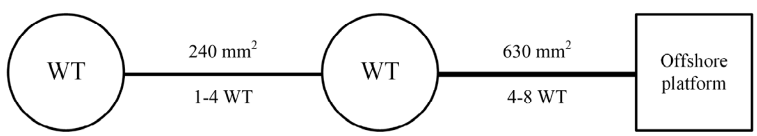
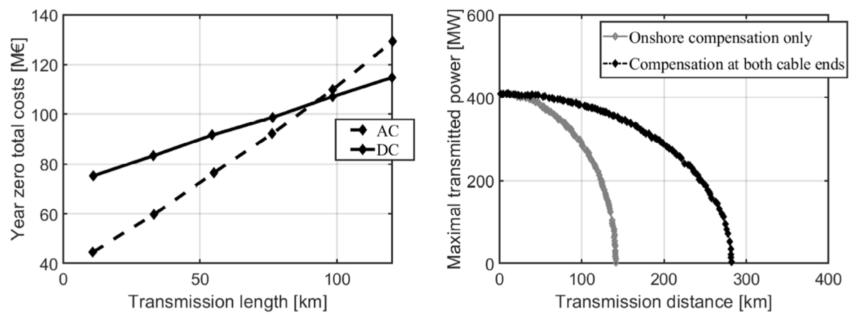


Figure 6.1: Different cross-sections in a 66 kV feeder for 1 GW offshore wind park with 10 MW wind turbines.

6.2.2 230 kV AC

The 230 kV AC cable is used in the transmission system for the AC/AC systems and also it is used in the AC/DC systems to connect the offshore AC platforms to the HVDC offshore stations. Then, as this voltage is not reached in the collection system a transformer step is needed to boost the voltage from 66 kV to 230 kV. On the other hand, the long HVAC cables present a big issue related with the formation of capacitance along its longitude, blocking the transmission of the active power as is shown in Fig. 6.2b. Due to that, when the cable length overpass a certain longitude, the HVDC transmission becomes a better solution. Then, the power capacity has a maximum in 400 MW. So for an OWP of 1 GW at least three 230 kV AC cables have been used to transmit all the power [11].



(a) (b)

Figure 6.2: (a) AC vs. DC transmission [14], (b) Power limits based on reactive compensation [21].

6.2.3 250 kV DC and 320 kV DC

The first projects of HVDC transmission were to interconnect islands to mainland or between countries. Currently as an improvement of the technology this kind of connection can be used to transmit large amount of power using submarine cables. As the size of OWPPs is increasing continuously and the shore distance too, it has become a competitive solution. In Fig. 6.2 it is seen that above 90 to 100 km of transmission distance, the HVDC technology is a better solution. The ± 250 kV is used for the collection system of DC series OWP. With this layout, up to 25 wind turbines with an output of 10 kV DC can be connected on a single feed reaching a power capacity of 250 MW. Then, the ± 320 kV is used for the power transmission in the AC/DC OWP. A single bipole cable allows to transfer up to 1200 MW [7].

Table 6.1: Technical parameters of the cables used in this project.

Cable	Cross section (mm^2)	Current rate (A)	Resistance (ohm/km)	Capacitance (μF/km)	Inductance (mH/km)	Reference
66 kV AC	240	480	0,089	0,220	0,380	[22]
66 kV AC	630	715	0,034	0,320	0,330	[22]
230 kV AC	1200	1000	0,017	0,200	0,380	[22]
150 kV DC	150	436	0.143	-	-	[7],[22]
250 kV DC	1200	1474	0.015	-	-	[7],[22]
250 kV DC	2000	1987	0.009	-	-	[7],[22]
320 kV DC	1200	1474	0.015	-	-	[7],[22]
320 kV DC	2000	1987	0.009	-	-	[7]

6.3 Offshore platforms

To control and transform the energy produced in the wind turbines, an offshore platform is needed due to the long distances to the land. As the collection system of an OWP is based on AC, except the DC Series system, the power cannot be transmitted directly but it has to be transformed in to high voltage that could be HVAC or HVDC. The main purpose of the platform is to reduce the electrical losses during the transmission. Then, depending on the system used, three different platforms have been explained in this project, the offshore platform would present different characteristics. In addition, having an offshore infrastructure gives support to the operation and maintenance as well as a location for the human personal. Furthermore, one of the keys when a wind park is designed is the usage of a single platform or more as they represent an important percentage of the total expenditure cost of the wind farm. Then, as it is said in 1.2, the main purpose of this project is to determine the saving produced when the offshore platform is omitted.

The offshore platform is constituted by two main parts:

- **Topside:** It contains all the electrical equipment and the facilities for the O & M.
- **Jacket** It is the structure of the platform and put together all the feeders of the collection system and the export cables to the shore.

6.3.1 AC Offshore platform

This type of offshore platform is used in the AC/AC and AC/DC (depending on the size of the park) OWPPs. The main function is to increase the voltage in order to be transmitted properly as the collection system is based on MVAC voltage. So the voltage boost is from 66 kV to 230 kV. Then, these 230 kV cables will go to the land if the system is AC/AC or to the VSC-HVDC offshore platform to be converted into HVDc. Moreover, the total full operational weight for an offshore platform rated around 400 to 500 MW is 2.293 tonnes. Although this power capacity of the platforms is not the maximum reachable as there are new projects where the power capacity reaches the 700 MW [20]. Even so, the equipment used in the topside of the platform is [23]:

- Main AC transformers
- Auxiliary transformers
- Shunt reactors
- Reactive compensation
- Busbar
- HV&MV GIS Switchgear
- Emergency diesel generator
- Park diesel generators (for Turbines)
- Control system
- Heliport
- Crane
- Crew quarters

6.3.2 VSC-HVDC Offshore platform

This offshore platform is used in the AC/DC systems. The main function is to convert AC to DC in order to be transmitted . These platforms are built when the distance from the shore is up to 80 to 90 kilometers and also when the power to transmit is big as Section 5.2 explains. The first offshore converter platform was built on 2010 and it is called Borwin1. The power capacity is rated on 400 MW and the distance from the land is 125 km. Also, it is located in the German North Sea and it is operated by TenneT [24]. Due to the conversion of the energy into DC an AC/DC converter is needed. The technology used is the VSC-HVDC converter and the space requirement is much bigger than the AC transformers. As a consequence, the size of this type of platforms are greater than an offshore AC platform. For example, the topside for a 1 GW OWP the platform weight rises to 11.500 tonnes. Then, the electrical layout of this platforms consists of an input voltage of 155 kV to 230 kV for AC and an output of ± 320 kV DC. Even though, depending on the size of the OWP the collection system can be attached directly to the offshore converter platform and skipping the AC platforms. The main equipment for the converter offshore platform is:

- HVDC converters
- Busbar
- HV & MV GIS Switchgear
- Emergency diesel generator
- Park diesel generators (for Turbines)
- Control system
- Heliport
- Crane
- Crew quarters

6.3.3 DC Series Offshore platform

A DC series OWP has a particular electrical layout which does not need an energy transformation for the transmission. Due to DC series collecting and the adding of voltage instead of current in the feeders, an HVDC range of 250 kV can be reached. Consequently, the offshore platform can save one of the heaviest parts of the topside equipment, the transformers. Which means the structure would be drastically reduced as is explained in Section 7.1. Despite of this advantage, it is critical as much as possible to secure the working time of the park. Due to the large feeders some redundancies have to be applied. For example, if there is a problem with one wind turbine and it has to be disconnected that cannot end to an interruption of the power flow in the feeder cable. Consequently, each WT has to be by-passed as is explained in [25] to ensure a higher reliability. Moreover, multiple feeders need a busbar system to be connected. For all of that, an offshore infrastructure is necessary to give support in the O & M. The list of equipment at the topside part is:

- Busbar
- HVDC GIS Switchgear
- Emergency diesel generator

  - Park diesel generators (for Turbines)
  - Control system
  - Heliport
  - Crane
  - Crew quarters

7

Case set-up

In this chapter, the different cases of offshore wind parks to be investigated are presented. The main objective is to determine the feasibility of different OWPPs layouts in specific cases. The two parameters that would be modified through the set-up cases would be:

i. Distance from the shore.
ii. Power capacity of the wind park.

The modification of one parameter or both would determine the suitability of the layout. In addition, the number of offshore platforms can be a decisive parameter too, as many modifications can be made in the same parameters case described above. Even so, some parameters of the OWP would be fixed in order to focus on the feasibility of DC series system instead of AC/AC and AC/DC. The fixed parameters and the assumptions in the set-up cases are described in the following section.

7.1 Components and cost assumptions

The assumptions adopted in the case studies is described in the following list

- The wind turbine foundation system would be the jacket and the sea depth is rated on 30m.
- The distance between wind turbines would be six times the rotor diameter.
- The collection cable for the AC/AC and AC/DC system would be the 66 kV AC cable with a cross section of 240 and 630 mm^2.
- The collection cable for the DC Series system would be the 250 kV DC with a cross section of 1200 mm^2.
- 50 % of the offshore platform cost is assumed to be the steel cost [15]. Then for 1 ton saved in the topside means 2 tons in the structure of the platform.
- The MFT used in the wind turbine for the DC Series system is 75 % lighter than the AC transformer used in the other two systems [26].
- 4 switchgear bays for the busbar ties, 4 switchgear bays for the auxiliary transformer, 4 switchgear bays for the HV transformer, 4 switchgear bays for the shunt reactors. In the case of the AC platform.
- The VSC-HVDC converter price would include the control and safety equipment such as switchgear bays and circuit breakers.
- HVDC switchgear is assumed to cost the same as HVAC switchgear.

– The cable installation is the same for all cables due to the most expensive item is the renting of vessels.

7.2 Electrical equipment of the Offshore platform

To properly evaluate the component costs for the different types of offshore platforms is necessary to set up some parameters. It is about how many switch bays have to be installed, the power of the the shunt reactors for reactive power, the number of transformers for reliability and the power capacity of the HVAC cables. In Figure 7.1 shows a basic electrical scheme of MV/HV substation on the offshore AC platform is shown. It is used one switch bay for each feeder coming from the wind turbines. Then, two switch bays for each HV transformer are installed and one switch bay for each HVAC circuit leaving the platform. Furthermore, for each busbar used to collect the energy from the feeders it would be necessary one switch bay for the grounding and one switch bay for the auxiliary transformer.

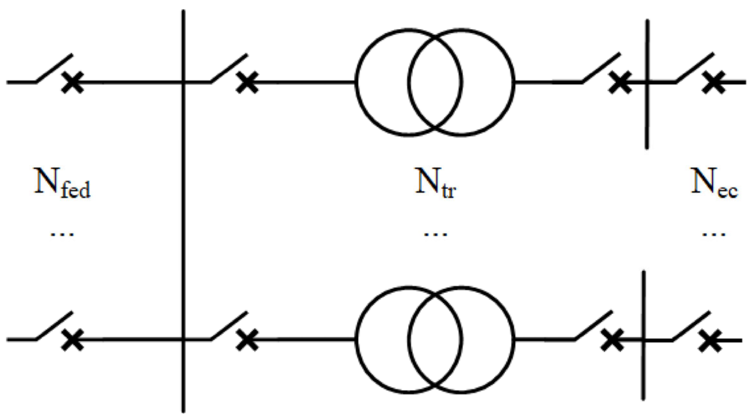


Figure 7.1: General scheme for MV/HV offshore AC substation.

In VSC-HVDC offshore platforms the methodology is almost the same. One switch bay would be used for each feeder and two switch bays for the converter. Then, as it is one bi-pole transmission in HVDC two switch bays would be needed.

In the case of the DC series platform, despite being a new technology the electrical scheme becomes really important as it ensures the reliability of the wind park. Basically, each feeder would have two switch bay as there is on for the ground and other for the export cable. Then the equal voltage cables would be connect with a busbar tie in order to prevent disconnections if one feeder falls and to be connected to the transmission cables. Also, the other side of the platform would be one switch bay per export cable.

7.3 Case 1

The offshore wind park would have 1000 MW of power capacity and four different distances form the land: 60, 80, 100 and 120 kilometers. The following list shows the components for each electrical system.

- AC/AC system
  - 100 Wind turbines (10 MW of rated power)
  - 66 kV AC cable (240 mm^2 and 640 mm^2)
  - 3 Offshore AC platforms 400 MW
  - 230 kV AC cable (1200 mm^2)
  - Onshore substation
- AC/DC system
  - 100 Wind turbines (10 MW of rated power)
  - 66 kV AC cable (240 mm^2 and 640 mm^2)
  - 3 Offshore AC platforms 400 MW
  - 230 kV AC (1200 mm^2) between AC platforms to HVDC platform
  - 1 HVDC offshore platform
  - 320 kV DC cable (2000 mm^2)
  - Onshore substation (Converter + Transformer)
- DC Series
  - 100 Wind turbines with DC output of 10 kV (10 MW of rated power)
  - 250 kV DC cable (1200 mm^2)
  - 1 DC series offshore platform
  - 250 kV DC cable (2000 mm^2)
  - Onshore substation (Converter + Transformer)

7.4 Case 2

The offshore wind park would have 500 MW of power capacity and four different distances form the land: 60, 80, 100 and 120 kilometers. The following list contains the components for this case.

- AC/AC system
  - 50 Wind turbines (10 MW of rated power)
  - 66 kV AC cable (240 mm^2 and 640 mm^2)
  - 1 Offshore AC platforms 400 MW
  - 230 kV AC cable (1200 mm^2)
  - Onshore substation
- AC/DC system
  - 50 Wind turbines (10 MW of rated power)
  - 66 kV AC cable (240 mm^2 and 640 mm^2)
  - 1 HVDC offshore platform
  - 320 kV DC cable (1200 mm^2)
  - Onshore substation (Converter + Transformer)
- DC Series
  - 50 Wind turbines with DC output of 10 kV (10 MW of rated power)
  - 250 kV DC cable (1200 mm^2)

  - 1 DC series offshore platform
  - Onshore substation (Converter + Transformer)

7.5 Case 3

This case would be focus in the commissioned offshore wind park located between Malmö and Copenhagen called Lillgrund. It has 48 wind turbines of 2,3 MW reaching an output power of 110 MW, the distance to the shore is 9 kilometers and it disposes a single offshore AC platform to boost the voltage from 33 kV to 132 kV in order to be transmitted to the land. It had an expenditure cost of 190 M€ and was finished in 2008. In addition, it would be analysed too the case of Lillgrund power capacity but with a different distance to the shore (100 kilometers).

The current developments in the 66 kV AC and 250 kV DC cables for the collection system make possible to omit the construction of an offshore platform when the power capacity and the distance from the shore are small as in the Lillgrund park. Furthermore, the AC/DC system in this layout is unreasonable because the AC losses in the 66 kV cable are not as high as can be with greater capacity and distance. Then, only the AC/AC and DC Series systems would be evaluated.

- AC/AC system
  - 11 Wind turbines (10 MW of rated power)
  - 66 kV AC cable (240 mm^2 and 640 mm^2) with two feeders.
  - Onshore substation
- DC Series
  - 11 Wind turbines with DC output of 10 kV (10 MW of rated power)
  - 150 kV DC cable (400 mm^2)
  - Onshore substation (Converter + Transformer)
- Lillgrund offshore wind farm
  - 48 Wind turbines (2,3 MW pf rated power)
  - 33 kV AC (95 to 240 mm^2)
  - 1 Offshore AC platform
  - 132 kV AC cable 630 mm^2.
  - Onshore substation.

Then, the Lillgrund case 60 km away from the sea the components will be the following.

- AC/AC system
  - 11 Wind turbines (10 MW of rated power)
  - 66 kV AC cable (240 mm^2 and 640 mm^2)
  - 1 offshore AC platform
  - 230 kV AC cable (500 mm^2)
  - Onshore substation
- DC Series
  - 11 Wind turbines with DC output of 10 kV (10 MW of rated power)
  - 150 kV DC cable (400 mm^2)
  - Onshore substation (Converter + Transformer)

8

Life cycle cost analysis

In this chapter, it will be the Life Cycle Cost Analysis where the different case studies have been evaluated. For each case a bar-plots with the total expenditure cost, the energy losses based on the operational wind speed and the financial analysis with the NPV and LCOE tools to evaluate the incomes of the wind parks and the energy production cost will be presented.

The operational and maintaiance, O&M cost has been set to 81.85 M€ for the 1000 MW case, 40,92 M€ for the 500 case and 6,52 M€ in the Lillgrund OWP as it is explained in [27]. Also, an increase of 3 % each year to represent the amortization over the years has been used. Then, the interest rate or WACC has been rated in 6 % and the lifetime of the project has been settled in 27 years. Moreover, to establish an income in the NPV evaluation an electricity price of 50€/MWh have been taken.

The project development and decommissioning costs are not shown in Tabs. 8.4, 8.5 and 8.6. However, in the LCOE and NPV calculations it have been addressed. The project development takes plane five years before the first operational year. Then, the decommissioning is counted one year after of the last one. The cost of these items are 0,138 M€/MW and 0,380 M€/MW. Finally, the investment has been done in year 0.

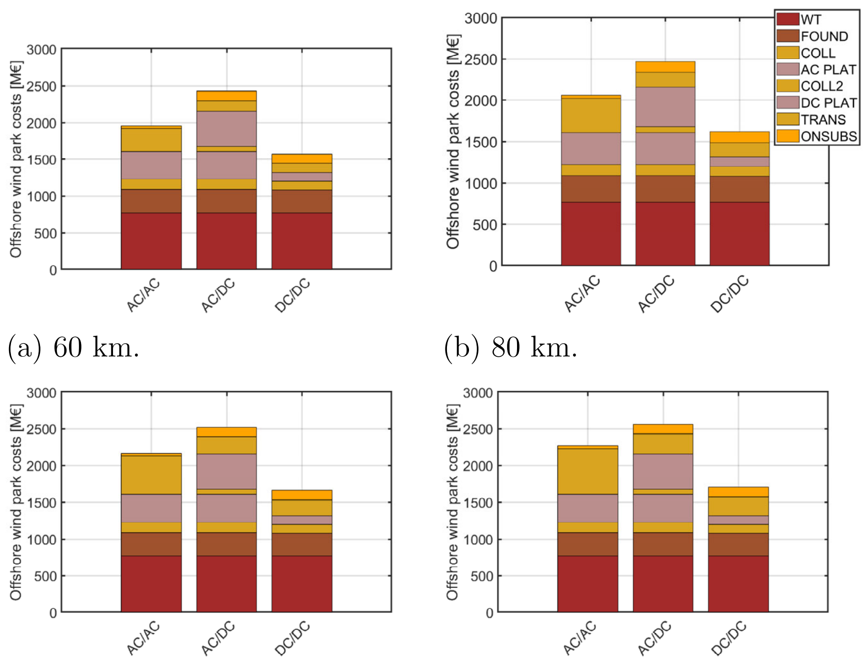
Furthermore, there is an important parameter to have in mind. It is the capacity factor of the OWPPs. The values for new OWPPs are around 50 - 55 % according to [28]. In this analysis the Case 1 and Case 2 a capacity factor has been rated to 51 % as the large distances give a good wind condition. Then, in case 3, the Lillgrund OWP, it is known that f_c equal to 34 % [29]. In addition, the average wind speed explained in Section 2.1 modifies the scale parameter c. So in Case 1, 2 and 3 the average wind speed is equal to 10 m/s but not in Lillgrund at 9 km which is equal to 8,5 m/s as it is explained in the technical report of the wind park [30] due to the proximity to the shore.

8.1 Case 1 results

In this case an OWP of 1 GW of power capacity is analysed with the parameters explained in Section 7.3. Fig 8.1 shows that an AC/AC system has an investment cost lower than AC/DC for the different distances values. Checking the components list in Section 7.3 the half of the components are the same in both cases. Also, AC/DC adds an extra costs of the HVDC converter station in both sides of the transmission line. Even though, as the distance increases the cost variation gets smaller. It is caused by the high cost of the HVAC cables and also it is necessary to use three cables rated to 400 MW to transmit the total power. Furthermore, the offshore infrastructure costs represents in the AC/AC and AC/DC around 20% and 35 % of the total cost respectively. Observe that with this numbers in the DC Series layout 266 M€ can be saved compared to the AC/AC case, where the costs ascend to 744 M€. Hence, the offshore infrastructure costs mean a huge influence on the final expenditure cost. In this case, the AC/AC system needs three offshore platforms and four for the AC/DC system. However, the DC Series system has only one offshore platform. Then, in Fig 8.4 observe how the differences between systems decreased significantly when the number of offshore platforms is reduced.

In terms of energy loss, as observed in Fig. 8.2, at 60 km the losses at rated wind speed are similar between AC/AC, AC/DC and DC Series systems. In addition, the main loss item for the AC/AC layout is the transmission system as Fig. 8.3 shows. Then, there is a significance difference too in the efficiency of the onshore substation. Considering that, AC/DC and DC Series present bigger losses such a converter is needed as well as the AC transformer too. Furthermore, DC Series wind turbine is less efficient since the high power density DC-DC converter is used. More, the other distances to the land (80, 100 and 120 km) point how the AC transmission becomes useless for such long distances owing to the large difference of power losses as Fig. 8.2 shows. Besides that, DC Series system has larger losses than the AC/DC system due to the transmission voltage value used whose are 250 and 320 kV respectively. In spite of DC Series not present any energy losses in the offshore platform items. That are not enough to hold the higher losses in the wind turbines, collection system as well as the transmission system.

Despite the fact that DC Series system presents a slight energy losses compared with the AC/DC, a better economical results are seen in Tab. 8.1 as a result of the lower investment values which Tab. 8.4 shows. Globally, DC Series system result the better system in the energy cost and economical profits point of view. Moreover, when the distance to shore reaches about 80 km the switch, where the AC/DC system becomes a better option than AC/AC system, is produced. This matches with the conclusions of [31] where for longer distances a DC connection is needed.



(a) 60 km.

(b) 80 km.

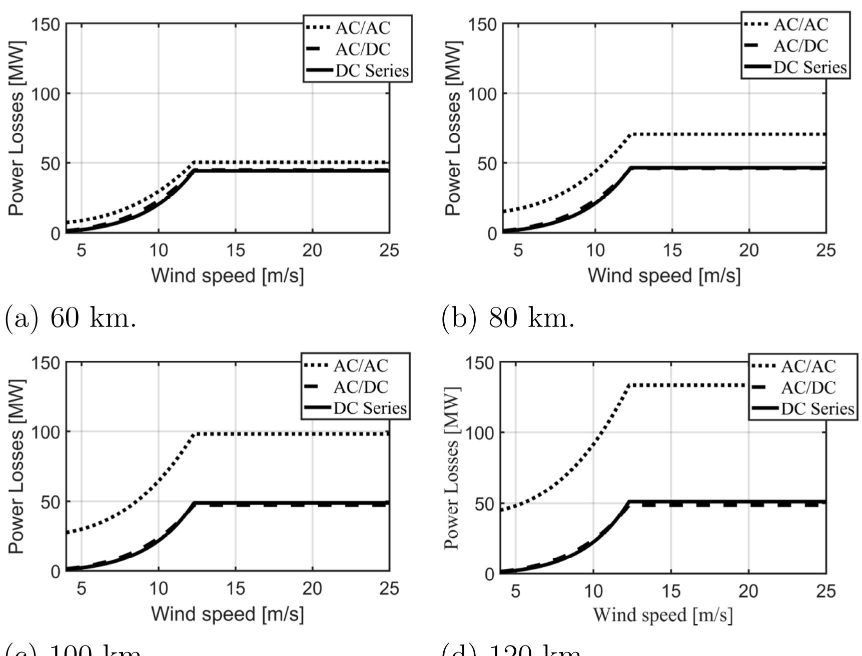
(c) 100 km.

(d) 120 km.

Figure 8.1: Expenditure costs for a 1 GW OWP based on the distance and the electrical system used. In the AC/AC case, the order of components cost from bottom-up are; wind turbines (WT), WT foundations (FOUND), collection system (COLL), offshore AC platforms (AC PLAT), transmission system (TRANS) and onshore substation (ONSUBS). In the AC/DC case are: wind turbines (WT), WT foundations (FOUND), collection system (COLL), offshore AC platforms (AC PLAT), connection between AC to DC platforms (COLL2), offshore HVDC platform (DC PLAT), transmission system (TRANS) and onshore substation (ONSUBS). In the DC Series (DC/DC) case are: wind turbines (WT), WT foundations (FOUND), collection system (COLL), offshore DC platform (DC PLAT), transmission system (TRANS) and onshore substation (ONSUBS). The costs are represented in M€.

Table 8.1: Investment cost [M€] for an OWP of 1 GW at different shore distances [km].

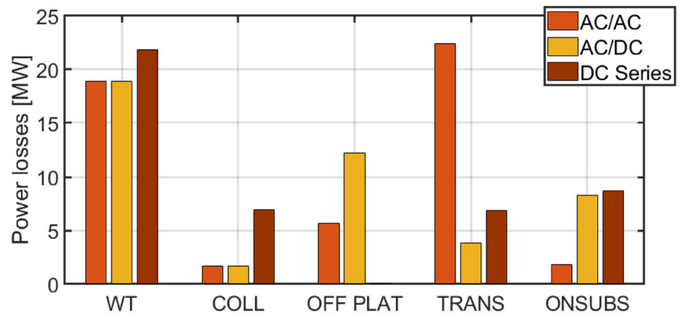
Dist	System	LCOE [€/MWh]	NPV [M€]
	AC/AC	23	3291
60	AC/DC	26	2965
	DC Series	19	3824
	AC/AC	24	3090
80	AC/DC	24	2919
	DC Series	19	3778
	AC/AC	26	2794
100	AC/DC	27	2872
	DC Series	20	3732
	AC/AC	28	2445
120	AC/DC	27	2882
	DC Series	21	3637



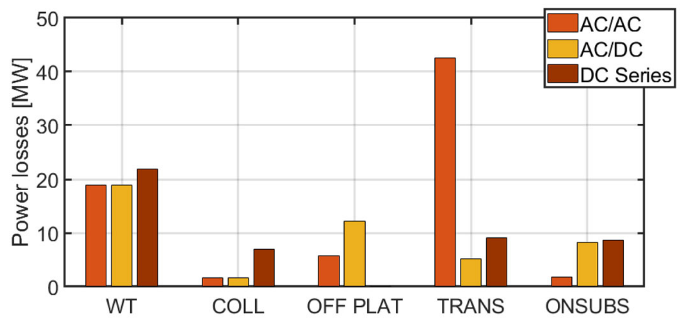
(a) 60 km. (b) 80 km.

(c) 100 km. (d) 120 km.

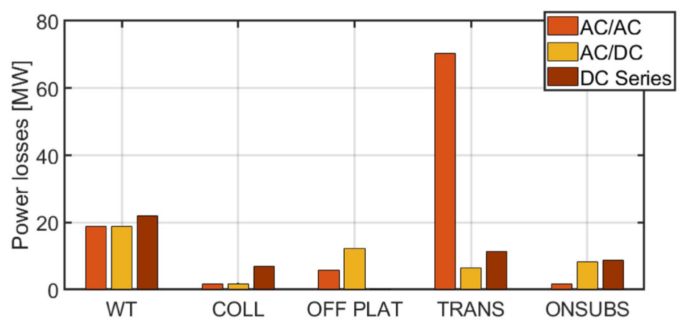
Figure 8.2: Electrical power losses based on the wind speed and evaluated in four different distances to the shore. The wind speed is rated between 4 m/s to 25 m/s wich are the cut-in wind speed and the cut-off speed respectively. The distances are in kilometers where (a) is 60 km, (b) 80 km, (c) 100 km and (d) 120 km. The power losses are represented in MW.



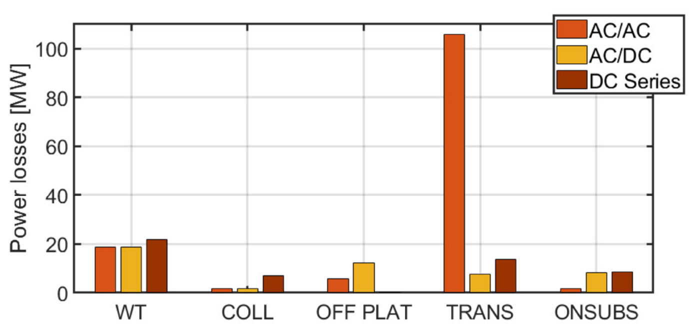
(a) 60 km.



(b) 80 km.



(c) 100 km.



(d) 120 km.

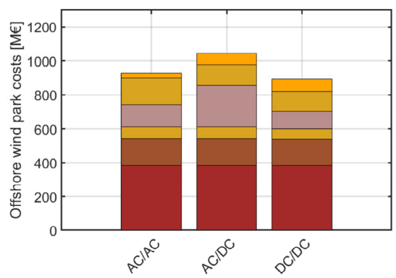
Figure 8.3: Electrical power losses split based on different distance to the shore [km]. WT means wind turbine losses, COLL means collection system losses, OFF PLAT means offshore platform losses (transformers, converters and interconnections), TRANS means transmission power losses and ONSUBS means onshore substation losses. All the electrical losses are measured in MW.

8.2 Case 2 results

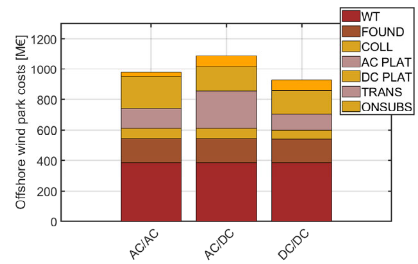
Case 2 represents an offshore wind park with a power capacity of 500 MW. In Section 7.3, the amount of offshore equipment needed is explained. Then, a single offshore platform for each electrical system (AC/AC, AC/DC and DC/DC) would be needed for this case. Due to this reduction, the expenditure costs are closer to each other compared with the Case 1 where, for example, the AC/AC system has three more platforms than the DC Series layout. Fig 8.4 shows how much close are. In average, Case 1 has around 850 M€ of variation between the AC/DC and DC Series system. Meanwhile, only a difference of 160 M€ in average is observed in this case. Even though, the offshore infrastructure costs still represent the 14 %, 23 % and 11% of the total cost for the AC/AC, AC/DC and DC Series systems respectively. Furthermore, 26 M€ is the variation cost of the offshore platforms between AC/AC and DC Series system. Due to that, the expenditure costs are differed by 60 M€ in average. Then, for all the distances to the shore analysed, the DC Series layout is once again the most economical OWP. In addition, the economical parameters present the same results as Case 1, where the most profitable wind park is the DC Series.

Looking at Tab. 8.2 it is observed how AC/DC produces more incomes at 60 km than the AC/AC. In the LCOE values, the break point is produced around 80 km. Moreover, the LCOE values in the AC/AC system are lower for 60 and 80 km for Case 1 but higher for 100 and 120 km for the Case 1. In addition, the energy losses of AC/AC and AC/DC are closer on account of the use of two HVAC cables instead of three used as in Case 1. Then, in the AC/DC system the costs reduction is larger as the offshore platforms have been reduced to one. Furthermore, DC Series LCOE's values are higher compared to Case 1 as the decreasing of power rating has not been followed by the reduction in an equal percentage of expenditure costs of the wind park.

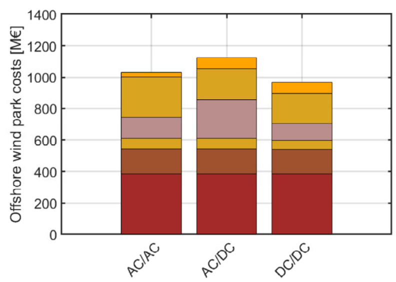
In terms of energy losses, the notorious contrast compared with Case 1 is the sightly higher losses for the AC/DC system. Due to the wind turbine electrical configuration, the series collection system and the lower voltage value used in the transmission system higher losses are presented for DC Series layout. Even though, these electrical losses for a 500 MW OWP have been reduced in a larger way compared to the offshore platforms losses produced in AC/DC system. In addition, as is said in 8.1, the AC transmission system represents the vast energy losses. But the distance to the DC connection is closer in this case because to transmit 500 MW two HVAC sub-sea cables are needed instead of three.



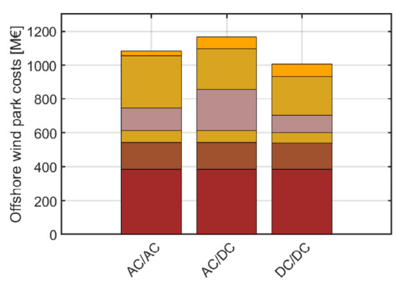
(a) 60 km.



(b) 80 km.



(c) 100 km.

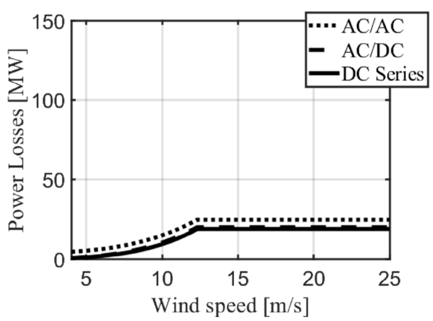


(d) 120 km.

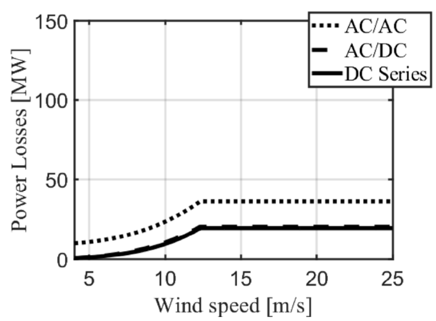
Figure 8.4: Expenditure costs for a 500 MW OWP based on the distance and the electrical system used. In the AC/AC case, the order of components cost from bottom-up are; wind turbines (WT), WT foundations (FOUND), collection system (COLL), offshore AC platforms (AC PLAT), transmission system (TRANS) and onshore substation (ONSUBS). In the AC/DC case are: wind turbines (WT), WT foundations (FOUND), collection system (COLL), offshore AC platforms (AC PLAT), connection between AC to DC platforms (COLL2), offshore HVDC platform (DC PLAT), transmission system (TRANS) and onshore substation (ONSUBS). In the DC Series (DC/DC) case are: wind turbines (WT), WT foundations (FOUND), collection system (COLL), offshore DC platform (DC PLAT), transmission system (TRANS) and onshore substation (ONSUBS). The costs are represented in M€.

Table 8.2: Investment cost [M€] for an OWP of 500 MW at different shore distances [km].

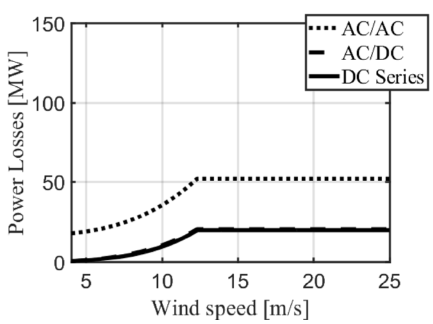
Dist	System	LCOE [€/MWh]	NPV [M€]
	AC/AC	23	1602
60	AC/DC	24	1591
	DC Series	21	1751
	AC	25	1412
80	AC/DC	24	1514
	DC Series	22	1710
	AC/AC	28	1168
100	AC/DC	25	1502
	DC Series	23	1669
	AC/AC	32	873
120	AC/DC	26	1460
	DC Series	23	1626



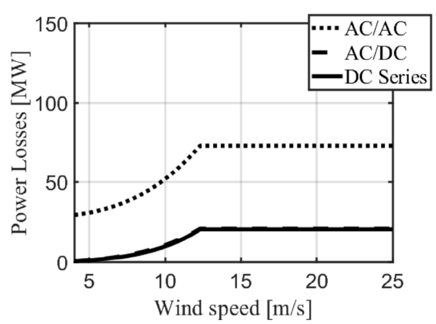
(a) 60 km.



(b) 80 km.

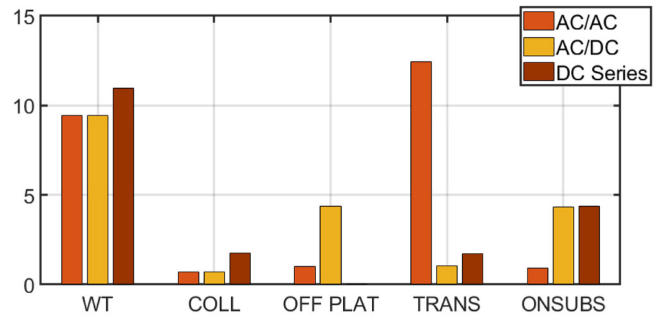


(c) 100 km.

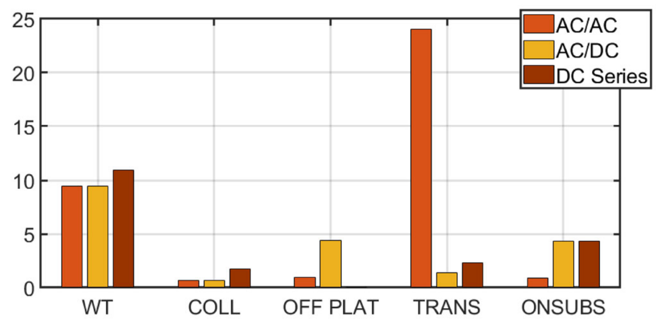


(d) 120 km.

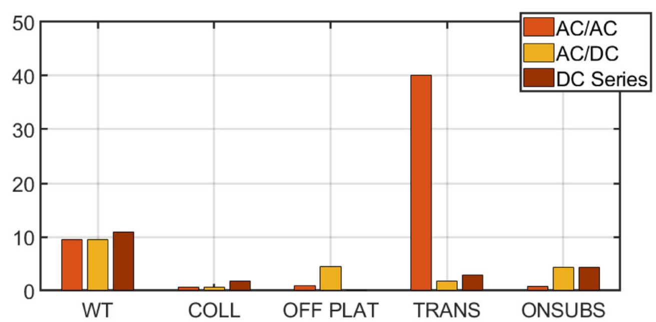
Figure 8.5: Electrical power losses based on the wind speed and evaluated in four different distances to the shore. The wind speed is rated between 4 m/s to 25 m/s which are the cut-in wind speed and the cut-off speed respectively. The distances are in kilometers where (a) is 60 km, (b) 80 km, (c) 100 km and (d) 120 km. The power losses are represented in MW.



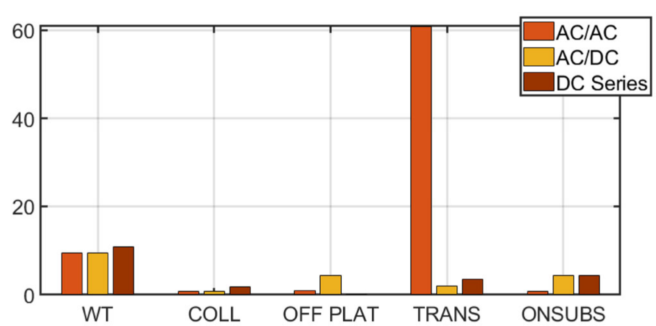
(a) 60 km.



(b) 80 km.



(c) 100 km.



(d) 120 km.

Figure 8.6: Electrical power losses split based on different distance to the shore [km]. WT means wind turbine losses, COLL means collection system losses, OFF PLAT means offshore platform losses (transformers and converters), TRANS means transmission power losses and ONSUBS means onshore substation losses. All the electrical losses are measured in MW.

8.3 Case 3 results

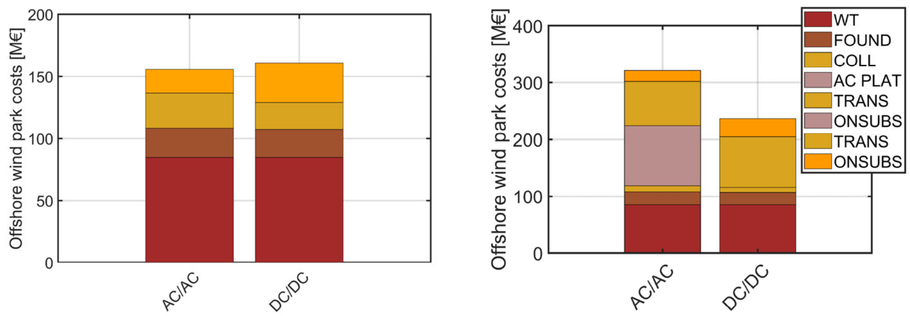
In this case, the Lillgrund wind farm is evaluated. The power capacity of this OWP is 110 MW as Section 7.5 explains. The actual location is 9 km away from the shore. Besides, a location of 60 km away from the land is analysed too. Due to the small size of the park, the analysis of 9 km case the offshore platform can be omitted. Moreover, the 66 kV AC cable used for the collection system can hold the power without too much stress. Even though, the real Lillgrund park has 33kV AC cables as the collection system and an offshore AC platform to boost the voltage to 132 kV AC to transmit the 110 MW to the shore [30]. However, not an offshore platform for 9 km case would be used in the AC/AC system and neither to the DC Series system. Then, the analysis of 60 km away from the shore an offshore AC platform for the AC/AC system is needed. Then, the DC Series system it can be omitted.

In Fig. 8.7 the AC/AC layout is cheaper than the DC Series system. Observe the difference between them is not large, but the onshore substation cost due to the converter increase substantially the price of this part of the wind park. Furthermore, Fig. 8.8 shows how the AC/AC energy losses are lower compared to DC Series. Even so, the difference is small. The reason, as Fig. 8.9 shows, is the efficiencies of the wind turbine DC-DC converter and the converter, located in the onshore substation, are lower compared to the AC transformer used in the AC/AC scheme. As a result, the profitability parameters proof the AC/AC system as the most profitable for the actual Lillgrund park.

In the case of 60 km, the results are completely opposite. Being as for the DC Series system, as stated above, the offshore platform is not needed. Resulting a saving of 85 M€, where the wind turbine foundation cost, the collection cost and the platform are cheaper. Not the transmission system as the HVDC connection a bi-pole technology is used. In addition that, the HVAC connection needs only a single cable. due to the small power to transfer. In the energy losses aspect, Fig. 8.9 shows how the AC transmission losses have skyrocket. That matches with the results of Case 1 and Case 2 obtained where the main electrical losses item is the HVAC connection.

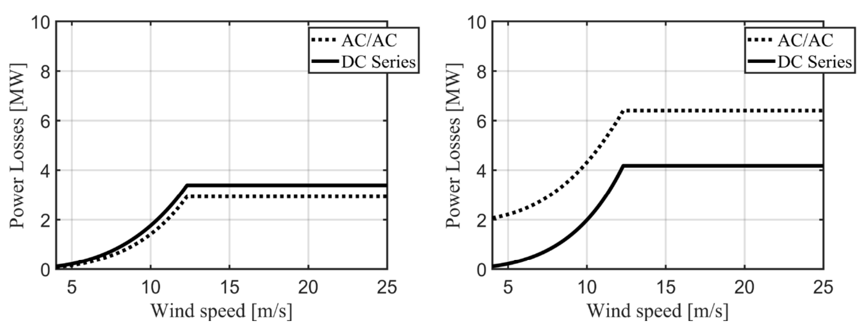
Table 8.3: Investment cost [M€] for an OWP of 110 MW at different shore distances [km].

Dist	System	LCOE [€/MWh]	NPV [M€]
9	AC/AC	30	145
	DC Series	33	123
60	AC/AC	42	64
	DC Series	32	161



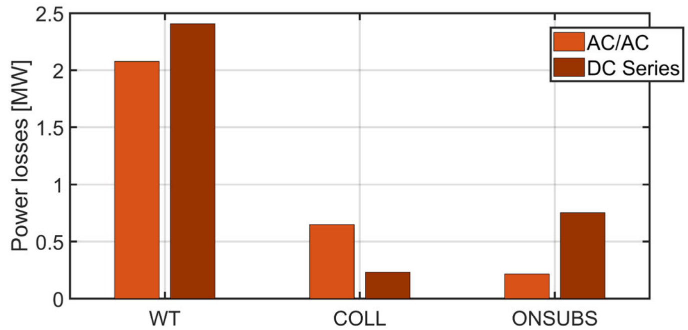
(a) 9 km. (b) 60 km.

Figure 8.7: Expenditure costs for a 110 MW OWP based on the distance and the electrical system used. In the AC/AC case, the order of components cost from bottom-up are; wind turbines (WT), WT foundations (FOUND), collection system (COLL), offshore AC platforms (AC PLAT), transmission system (TRANS) and onshore substation (ONSUBS) In the DC Series (DC/DC) case are: wind turbines (WT), WT foundations (FOUND), collection system (COLL), transmission system (TRANS) and onshore substation (ONSUBS). The costs are represented in M€.

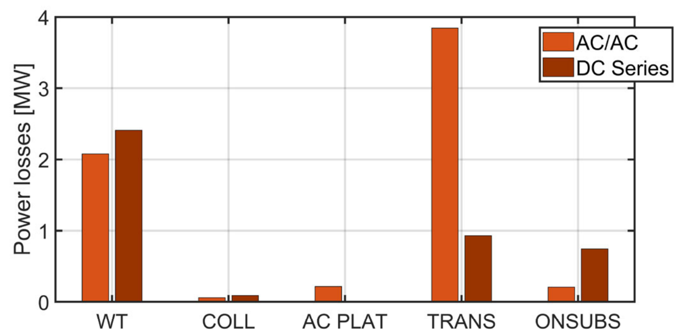


(a) 9 km. (b) 60 km.

Figure 8.8: Electrical power losses based on the wind speed and evaluated in four different distances to the shore. (a) is the actual Lillgrund distance to shore and (b) is the Lillgrund park located 60 km further to the sea. The wind speed is rated between 4 m/s to 25 m/s which are the cut-in wind speed and the cut-off speed respectively. The power losses are represented in MW.



(a) 9 km.



(b) 60 km.

Figure 8.9: Electrical power losses split based on different distance to the shore [km]. WT means wind turbine losses, COLL means collection system losses, TRANS means transmission power losses and ONSUBS means onshore substation losses. All the electrical losses are measured in MW.

8.4 OWP costs table

Table 8.4: Investment cost [M€] for an OWP of 1 GW at different shore distances [km].C_{wt} is the wind turbine cost, C_{found} is the WT foundation, C_{coll} is the collection system cost, C_{ACP} is the offshore AC platform cost , C_{coll2} is the transmission cost between the AC offshore platform to HVDC converter station cost, C_{DCP} is the HVDC converter platform, C_{trans} is the transmission system cost, C_{OS} is the onshore substation cost and T_{COST} is the total expenditure cost of the OWP.

Dist	System	C_{wt}	C_{found}	C_{coll}	C_{ACP}	C_{coll2}	C_{DCP}	C_{Trans}	C_{OS}	T_{COST}
60	AC/AC	770	318	135	384	–	–	311	37	1.995
	AC/DC	770	318	135	384	71	478	137	132	2.425
	DC Series	770	311	116	–	–	118	128	132	1.575
80	AC/AC	770	318	135	384	–	–	414	37	2.058
	AC/DC	770	318	135	383	71	478	182	132	2.469
	DC Series	770	311	116	–	–	118	171	132	1.618
100	AC/AC	770	318	135	385	–	–	518	37	2.163
	AC/DC	770	317	135	383	71	478	228	132	2.514
	DC Series	770	311	116	–	–	118	214	132	1.661
120	AC/AC	770	318	135	386	–	–	621	37	2.267
	AC/DC	770	318	135	384	71	478	274	132	2.562
	DC Series	770	311	166	–	–	118	256	132	1.753

Table 8.5: Investment cost [M€] for an OWP of 500 MW at different shore distance [km].C_{wt} is the wind turbine cost, C_{found} is the WT foundation, C_{coll} is the collection system cost, C_{ACP} is the offshore AC platform cost , C_{coll2} is the transmission cost between the AC offshore platform to HVDC converter station cost, C_{DCP} is the HVDC converter platform, C_{trans} is the transmission system cost, C_{OS} is the onshore substation cost and T_{COST} is the total expenditure cost of the OWP.

Dist	System	C_{wt}	C_{found}	C_{coll}	C_{ACP}	C_{coll2}	C_{DCP}	C_{Trans}	C_{OS}	T_{COST}
60	AC/AC	385	159	68	131	–	–	155	29	927
	AC/DC	385	159	68	–	–	243	121	71	1.042
	DC Series	385	156	58	–	–	105	116	71	891
80	AC/AC	385	159	68	131	–	–	207	29	979
	AC/DC	385	159	68	–	–	243	161	71	1.087
	DC Series	385	156	58	–	–	105	154	71	929
100	AC/AC	385	159	68	132	–	–	259	29	1.032
	AC/DC	385	159	68	–	–	243	201	71	1.127
	DC Series	385	156	58	–	–	105	192	71	967
120	AC/AC	385	159	68	133	–	–	310	29	1.082
	AC/DC	385	159	68	–	–	243	241	71	1.167
	DC Series	385	156	58	–	–	106	231	71	1.007

Table 8.6: Investment cost [M€] for an OWP of 110 MW based on Lillgrund park located 9 km away from the land..C_{wt} is the wind turbine cost, C_{found} is the WT foundation, C_{coll} is the collection system cost and the transmission system as the distance is 9 km and no offshore platforms are installed, C_{ACP} is the offshore AC platform cost , C_{DCP} is the HVDC converter platform, C_{OS} is the onshore substation cost and T_{COST} is the total expenditure cost of the OWP.

Dist	System	C_{wt}	C_{found}	C_{coll}	C_{ACP}	C_{coll2}	C_{DCP}	C_{OS}	T_{COST}
9	AC/AC	84,8	23,34	28,42	-	-	-	19,20	156
	DC Series	84,8	22,31	21,91	-	-	-	31,75	161
60	AC/AC	84,8	23,34	10,44	105	-	77,40	19,20	321
	DC Series	84,8	22,31	8,58	-	-	88,92	31,75	236

9

Conclusions and Future Work

In this thesis, some of the components and economical aspects of offshore wind farms are addressed. Also, since the wind energy can be a renewable replacement as a baseload technology in the electrical grid system, new locations to reach optimal wind qualities have to be found. As a result, new type of collection and transmission system such as DC collection and HVDC transmission are developed.

Three different electrical configurations of wind parks have been investigated for the energy production cost. The investigation was done for various parks sizes and different transmission lengths. The results show DC Series as the most economical configuration in power capacities of 500 MW and 1000 MW since as the reduction of offshore platforms and the electrical equipment used. As a result, in average 107 M€ and 655 M€ are saved in the DC Series case respectively. Moreover, DC Series also presents the best electrical efficiency compared with the AC/AC and AC/DC systems. Then, the AC/AC system gets more expensive as the AC/DC solution when the distance to the shore reaches about 80 km to 100 km, due to the huge cost and energy losses of the HVAC transmission system. Consequently, when large power capacities and moderate distances are installed the solution is to move to the HVDC technology either the AC/DC or DC/DC systems. Furthermore, reducing the energy losses of the converter in the onshore substation would decrease the distance needed to determine DC connection as the best option.

On the other hand, the Lillgrund OWP size for the actual location, 9 km, and 60 km further in the sea have been analysed. It results for 9 km of distance, the AC/AC system is more profitable than the DC Series system. Although the small difference, the higher losses related with the converters located in the wind turbines and the onshore substation are detrimental. Even so, improving the efficiency and the costs for the substation, for example, with the Modular Multi-Level (MML) converter the difference of 12,5 M€ between them can be vanished. Moreover, when the distance to the land increase, as in the 60 km case, the feasibility potential of the DC Series stands above. Due to the small power capacity, the offshore platform needed to control the park can be omitted as only eleven wind turbines of 10 MW at Lillgrund are counted. As a result, 85 M€ are saved compared to the AC/AC system. In addition, the efficiency of the DC layout is higher reaching a difference of 2 MW of energy losses at rated power.

9.1 Future Work

Several assumptions in cost models and energy losses to compare the feasibility of the three different wind parks analysed have been made. Due to that, the expenditures cost of the offshore wind parks are an estimation. Even so, the cost and the losses results have been compared with actual data provided for various technical reports and papers. In addition, the cables variety used in this project is short as the available prices were not many. Then, for further investigations and interesting branch of analysis would be an evaluation between the AC/AC and DC/DC for different DC cable cross sections.

Furthermore, the converter energy losses used in this project have been constant. To improve, different types of VSC converters should be evaluated in order to determine the energy losses and the chance to omit the AC transformer in the onshore substation to reduce the price and increase the efficiency of it. Such transformation can be done by MML converter.

Moreover, the solid state transformer based on MFT installed in the DC wind turbines is still on researching process so his commercial application would take some years. Anyway, the potential of it can solve several issues related with the renewable energy production.

Then, in this project, the failures and maintenance of the OWPPs have been evaluated as a constant without considering the different operational characteristics. In future projects, DC Series should be analysed in detail to ensure an optimal reliability as the series collection system is a new electrical layout inside the offshore wind production.

Finally, due to the increasing of wind parks, the surrounding electrical grid infrastructure, that can be a restraining factor for the development, has to be analysed.

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A

Appendix A

A.1 Matlab code

Listing A.1: Wind turbine formula cost

```
function [Total_cost,Turbine_cost] = Wind_turbine_cost(nt,pr)
% Wind turbine cost Equations related with the Wind turbine costs
% nt —> number of turbines
% pr —> power rating (MW)
Turbine_cost  = (2.95*1000*log(pr)−372.2)/1000; % in Meu
Total_cost    = Turbine_cost*nt; % in Meu
end
```

Listing A.2: Wind turbine foundation formula cost

```
function [Total_cost,Found_cost] = Foundation_cost(pr,nt,deep)
% Foundation cost Equations related with the foundations cost
% pr     —> power rating (MW)
% deep   —> meters of depth (m)
% nt     —> number of turbines
Found_cost = (5.382*(deep−5)+306.77)*pr*0.001; % Meu
Total_cost = Found_cost*nt; % Meu
end
```

Listing A.3: AC transmission losses formula

```
function [Ploss, eff] = AC_transmission_losses(R,L,C,d_shore,V,Pin)
Length_total = d_shore; %distance in kilometers (km)
number_of_sections = 4; % number of 'pi' equivalents circuits
f = 50; % frequency in Hz
w =2*pi*f; % omega in rad/s
R_per_km = R; % resistance ohm/km
L_per_km = L*10^−3; % inductance H/km
C_per_km = C*10^−6; %  capacitance C/km
Rsection = R_per_km*(Length_total/number_of_sections);
XLsection = w*L_per_km*(Length_total/number_of_sections);
XCsection = −1/((C_per_km*w)*(Length_total/number_of_sections));
XL_comp = −0.5*XCsection; % compensation for the capacitance of the cable

% Parameter definition voltage and frequency

U=V*1e3;     % Voltage

y11=1/(Rsection+1i*XLsection)+1/(−1i*XCsection)+1/(1i*XL_comp);
y12=−1/(Rsection+1i*XLsection); y21 = −1/(Rsection+1i*XLsection);
y22= 2/(Rsection+1i*XLsection)+1/(−1i*XCsection);
y23 = −1/(Rsection+1i*XLsection); y32 = −1/(Rsection+1i*XLsection);
y33 = 2/(Rsection+1i*XLsection)+1/(−1i*XCsection);
y34 = −1/(Rsection+1i*XLsection); y43 = −1/(Rsection+1i*XLsection);
y44 = 1/(Rsection+1i*XLsection)+1/(−1i*XCsection)+1/(1i*XL_comp);
y13 =0; y14=0;y41=0;y31=0;y42=0;y24=0;
YMAT=[y11,y12,y13,y14; % matrix of admittances
    y21,y22,y23,y24;
```

```
    y31,y32,y33,y34;
    y41,y42,y43,y44];

%Initial guesses

Ubus1=V*1e3; % votlage of the cable
Ubus2=230e3;
Ubus3=230e3;
Ubus4=230e3;

Upresent=[Ubus1;Ubus2;Ubus3;Ubus4];

% Definition of powers

P_wind_farm = Pin*1e6;
I_wind_farm = P_wind_farm/(3*Ubus1);

IMAT=[0;0;0;I_wind_farm];  % Current of the wind farm

Uanswer=inv(YMAT(2:4,2:4))*(IMAT(2:4)-YMAT(2:4,1)*Ubus1);
Uanswer2=YMAT(2:4,2:4)\(IMAT(2:4)-YMAT(2:4,1)*Ubus1);

UMAT=[Ubus1;Uanswer];

IMAT(1)=YMAT(1,1:4)*UMAT;

S=3*U(1)*conj(IMAT(1));

Ploss = (P_wind_farm + real(S))*1e-6; % Power losses of the cable
eff = 1-(P_wind_farm + real(S))/P_wind_farm; % efficiency of the cable
end
```

Listing A.4: DC transmission losses formula

```
function [Ploss,eff] = DC_transmission_loss(R,d_shore,VC,prating)
% R -> Resistance of the cable (ohm/km)
% d_shore -> Distance to the shore (km)
%  prating -> Power to transmit (MW)
I = (prating*1000)/(2*VC); % Current of the cable. bipole*
Ploss = (R*I^2*d_shore)/(10^6); % Power losses
eff = (prating-Ploss)/prating; % efficiency of the transmission
end
```

Listing A.5: Main transformer cost

```
function [Transformer_cost] = Transformer_cost(ptrans)
% Main transformer cost
% ptrans -> Power of the transformer (MVA)
Transformer_cost = (42.688*ptrans^0.7513)/1000;% in Meu
end
```

Listing A.6: Transformer electrical losses.

```
function [Ploss, eff] = Transformer_loss(Pin)
Ploss   = Pin*(1-0.998); % Power Losses set it 0,25% of the input power
eff     = (Pin-Ploss)/Pin; % efficiency of the transformer
end
```

Listing A.7: AC collection sytem losses.

```
 function [Ploss, eff] = AC_collection_loss(R1,R2,l,VE,prating)
% It is considered only resistance losses for the collection system as the
% small length of the circuit
% feeders of 80 MVA as maximum
IM = [80000/(sqrt(3)*VE),70000/(sqrt(3)*VE);60000/(sqrt(3)*VE),...
    50000/(sqrt(3)*VE),40000/(sqrt(3)*VE),30000/(sqrt(3)*VE),...
    20000/(sqrt(3)*VE),10000/(sqrt(3)*VE)];
    % Average current in the collection system AC/AC and AC/DC.
```

```
RM = mean([R1, R2]);
Ploss   = (3*RM*mean(IM)^2*l)/(10^6);
eff     = (prating-Ploss)/(prating);
end
```

Listing A.8: DC Series cable losses

```
function [Ploss,eff] = DCSeries_cable_loss(R,d_shore,VC,prating,nf,type1)
% type1 = 0 % DC Series collection system
% type1 = 1 % DC Series transmission system
% nf        % Number of feeders
if type1 == 0
    I = (prating*1000/nf)/VC; % Current of the feeder
    Ploss = nf*(R*I^2*d_shore)/(10^6);
else
    I = (prating*1000)/(2*VC); % Current in the bipole cable
    Ploss = (R*I^2*d_shore)/(10^6);
end
eff = (prating-Ploss)/prating;  % Efficiency of the transmission
end
```

Listing A.9: Offshore AC platform cost.

```
function [Offshore_platform_cost] = Offshore_AC_platform(prating,d_shore)
% 230 kV --> 0.502MVar/km
Platform_cost   = 85; % Platform cost for 400 - 500 MW of power capacity
Trafo_cost = Transformer_cost(prating*0.5); % Main transformer cost
Services_cost   = 23; % Crew quarters, control system, cranes...
HV_SW_cost = 3.09; %230 kV switch bay cost (Meu)
MV_SW_cost = 0.406; % 66 kV switch bay cost (Meu)
% Number of switchgear of 66 kV
n_sw = floor((prating)/70); % number of switch bays for the feeders
SW_cost = 4*HV_SW_cost+(n_sw+4)*MV_SW_cost; % Total switchgear cost (Meu)
React_p         = 0.502*d_shore; % Reactor compensation needed
Rea_comp_cost = (React_p*0.5/50)*1.437; %Reaction compensation cost

Offshore_platform_cost = Platform_cost + 2*Trafo_cost+...
    Services_cost+SW_cost+ Rea_comp_cost;
end
```

Listing A.10: Offshore DC platform cost.

```
function [HVDC_platform_cost,Converter_cost,Platform_cost] = Offshore_DC_platform(pr)
% pr --> power rating in MW
Np  = 59.6; % Meu/GW
No  = 63.4; % Meu
Sp  = 217.5; % Meu/GW
So  = 146.5; % Meu
PT  = 2; % GW
k   = 5/4; % correction
pr1 = pr/1000; % change of units to GW
MV_SW_cost = 0.406; % Meu for 66 kV
n_sw = floor(pr/70); % number of feeders
SW_cost = (n_sw+4)*MV_SW_cost; %Switchgear cost
Platform_cost   = k*(Sp*pr1+(pr1/PT)*So); % Platform cost
Converter_cost  = k*(Np*pr1+(pr1/PT)*No); % Converter cost
HVDC_platform_cost = Platform_cost + Converter_cost + SW_cost;
end
```

Listing A.11: Offshore DC Series platform cost.

```
function [Offshore_platform_cost] = Offshore_DCSeries_platform(prating,d_shore)
% Crown state (22.6, 68,52) facilities structure electrical material
% 230 kV --> 0.502MVar/km
% (400-500MW)
% 1t saved --> 2t of structure
% 50 % of the cost of the platform (total cost) comes from the structure
% -400t --> -800t ----> -32%
```

```
Platform_cost   = 85*(1-0.32); % reduction of the weight applied on the price
Services_cost   = 23; % Meu Crew quarters, control system, cranes...
HV_SW_cost = 3.09; % 230 kV HV switchgear cost
nf  =  8; % feeders, eac one 250 MW
ntr =  4; % more bays for the busbar and the transmission.
SW_cost = (8+4)*HV_SW_cost;

Offshore_platform_cost = Platform_cost+...
    Services_cost+SW_cost;
end
```

Listing A.12: Offshore DC Series platform cost.

```
function [Total_cost] = Onshore_substation(type,pr)
% type ->  0 AC system
% type ->  1 AC/DC or DC Series system
BAS = 8;
tr_cost   = Transformer_cost(pr*0.5);
HV_switch_220 = 3.09;
HV_switch_400 = 4.545;
if type == 0
    HV_switch_220 = 3.09;
    HV_switch_400 = 4.545;
    React     = 0.028;
    Total_cost = 2*tr_cost + 2*HV_switch_220 + 2*HV_switch_400 + BAS + React*pr*0.5;
elseif type == 1
    [HVDC_platform_cost,Converter_cost,Platform_cost] = Offshore_DC_platform(pr);
    Total_cost = Converter_cost+BAS+2*tr_cost+2*HV_switch_400+2*HV_switch_220;
end
end
```