Connecting offshore wind farms to the electric power system: A brief overview

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Paulo Fernando Santos Dias de Carvalho
Rio de Janeiro Federal University (UFRJ), Rio de Janeiro, Brazil;
E-mail: paulofsdc@poli.ufrj.br

André Fernando Schiochet
Brazilian Petroleum Company (Petrobras), Rio de Janeiro, Brazil;
E-mail: eel.afs@gmail.com

Leonardo de Carvalho Rocha
Brazilian Petroleum Company (Petrobras), Rio de Janeiro, Brazil;
E-mail: leocr82@yahoo.com.br

Thiago Trezza Borges
Fluminense Federal University (UFF), Niteroi, RJ, Brazil
E-mail: thiagotrezza@id.uff.br

Paulo Roberto Duailibe Monteiro
Fluminense Federal University (UFF), Niteroi, RJ, Brazil
E-mail: pauloduailibe@id.uff.br

ABSTRACT

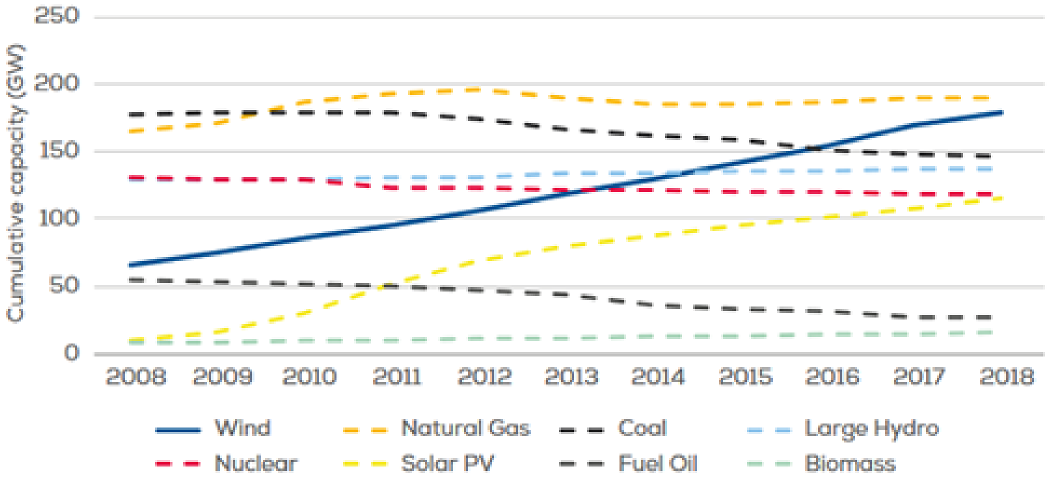
This paper presents an overview of the implementation of the main wind farms Offshore carried out so far, most of which is in Europe. A summary of the solutions applied and consolidated in the industry, related to the transmission technologies used in the connection of wind farms Offshore to existing power grids is shown. Some of the topics covered are: the type of transmission used (direct or alternating current), the technology adopted in the converter bridges in the enterprises that chose to use direct current transmission (VSC) and its advantages, the magnitude of the distances and transmission capacities achieved and the technologies for compensation of reactives. In addition, regulatory and economic aspects related to the connection of these wind farms to the transmission grid are also addressed. Finally, a case study is presented in which several alternatives for the connection of two parks are compared Offshore to the transmission system from an economic point of view.

Keywords: Offshore wind farms, Electric power system, Transmission technologies, Electric powerlines, Connection of windfarms.

1 INTRODUCTION

The growth of the participation of renewable energies in the national and global energy matrix is a trend over the last decades. The growing concerns about climate change and the greenhouse effect, the concentration of fossil resources, the geopolitical developments resulting from international competition for oil and the cheapening of the technologies used to generate energy in a sustainable way are some of the factors that contribute to this movement. This trend can be observed in the Figure 1, which presents the evolution of the installed capacity of each energy source in Europe. On the one hand, there is a slow decline in sources such as fuel oil and coal. On the other hand, there is a rapid growth in the installed capacity of renewable sources, especially solar and wind.

Figure 1 Evolution of the energy matrix in Europe[1]



Source: WindEurope

Although the predictions of the expiration date of the exploitation of fossil resources differ greatly, it is known that these are a finite resource and their exploitation can not occur eternally. Given this scenario, it is observed that many companies in the oil and gas sector go through a metamorphic phase. Increasingly, these include in their portfolios projects of renewable energy generating plants, so that these are no longer mere energy companies focused on oil and gas and seeking to expand their energy matrix with renewable energies.

One of the new technologies that have been studied and applied by oil companies is wind generation Offshore (i.e. the installation of wind turbines in the open sea). Given that these companies already have the know-how of oil exploration at sea, they can take advantage of the accumulated experience in the areas of geological prospecting at sea, marine civil engineering structures, ships, etc., and can have the competitive advantage in this new branch that is starting in Brazil. Given Petrobras' pioneering spirit in the exploration of oil and gas in deep and ultra-deep waters, the emergence of this new segment represents an opportunity for the growth of the company's portfolio of activities.

In this context, the implementation of such projects goes through a new challenge: the integration of these generating units into the existing power grid. Some of the peculiarities for these transmission projects are: the fact that they involve large blocks of power and the use of submarine cables. For these reasons, the costs of transmission in a wind farm project Offshore They represent more than a fifth of the total cost of the project, a much larger share than in a conventional wind project Onshore, which is about a tenth, second [2].

The objective of the present work is to take stock of the current state of the technologies adopted in the transmission of electric energy generated in wind farms Offshore in the world. The most recent projects of this segment are presented, whether they are already in operation, or in the construction phase or even in the design phase. The main projects, both from the point of view of the magnitude of energy transmitted and the maturity of the technology used, are concentrated in a restricted set of countries in Europe, each of which has a characteristic portfolio of projects.

In addition to technical aspects, regulatory and economic aspects that concern the installation of such enterprises are also being addressed. Because it is a technology still in the initial phase of implementation in our country, a legal and regulatory framework necessary for an attractive environment for entrepreneurs interested in investing is being created. The analysis of the economic aspects is essential as in any engineering project. Because it is an area little known to most energy companies operating in the country, there is still no great knowledge on the part of the technical staff of the energy area of the magnitude of the costs of such types of projects. As one enters an area in which one does not have a consolidated experience, more care is needed in the economic analysis of a project, as the profitability of the investment project has a higher risk.

2 DIRECT CURRENT TRANSMISSION TECHNOLOGIES

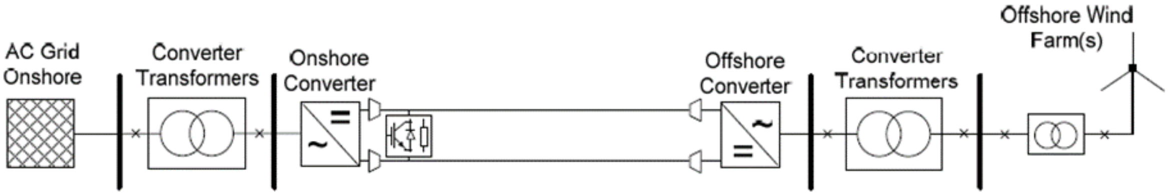
The Figure 2 presents the basic topology of an offshore park connected to the grid through a direct current transmission line (LT). The so-called collector network, which interconnects the turbines to each other and connects them to the substation Offshore, is usually sized in alternating current at the voltage level of 33 kV. At the substation Offshore, there is an elevator transformer and the rectifier bridge, from which the power is transmitted to the earth. At the substation Onshore, there is the inverter bridge and the transformer so that the voltage coincides with the voltage of the receiving network. You can use a converter of the type Chopper (DC-DC), which is responsible for reducing the voltage at the terminal Onshore in the occurrence of a fault on the AC side in order to avoid losing the transmission line in the occurrence of faults.

In direct current transmission, there are two main converters for the rectification and inversion of the voltage: Line Commutated Converter (LCC), also called current source converters, and Voltage Source Converter (VSC), also called voltage source converters.

The current source converters (LCC) are formed, in general, by three-phase thyristor bridges, which are bidirectional switches in voltage and unidirectional in current. The control of the firing angle of these thyristors determines the mode of operation of the bridge (inverter or rectifier), and this control depends on the voltage of the network on the AC side. This converter is indicated for applications involving large distances (of the order of several hundred kilometers) and large powers (of the order of several GW), being the solution applied in the direct current lines present in the country, which connect the Southeast to large hydroelectric plants in other regions. Some of the disadvantages of this converter are: the high consumption of reactive power, the high rate of harmonics produced and the high rate of switching failures, which occur due to disturbances in the AC network.α

The voltage source converter (VSC) is formed by bridges of IGBTs (or another similar switch, such as IGCT or GTO) in anti-parallel with diodes. The differential of this type of converter in relation to the one presented above is that it uses keys with driving capacity and blocking, while it is not possible to send a signal to block a thyristor. These switches are bidirectional in current and unidirectional in voltage. In this type of converter, the output voltage on the AC side is emulated by controlling the trigger signals of the switches, which generally use PWM (Pulse Width Modulation) logic. As the voltage on the AC side is "imposed" by the control of the switches, the AC side sees the converter as a voltage source, hence the name of the converter.

Figure 2 Scheme of underwater transmission in HVDC. [3]



The main applications of VSC converters are in subsea transmission and in STATCOMs (Static Synchronous Compensator). STATCOM is a FACTS equipment (Flexible AC Transmission System), which is composed of a DC source and a VSC converter, being able to provide voltage regulation, increased transmission capacity, damping of oscillations and performance improvement in transient stability. In Brazil, there is only one STATCOM in operation, in Rio Branco, Acre.

According to [4], VSC converter manufacturing companies have specific trade names to designate them. For example, Siemens calls this technology HVDC Plus, ABB, from HVDC Light, and Alstom, from HVDC MaxSine.

Some causes are crucial to prevent the use of converters of the current source type for connection of wind farms Offshore and cause this technology not to be currently used in this application:

- LCC converters do not have black start capability. This means that in case they lose the connection to the electrical grid, they are not able to leave on their own, that is, it is necessary that the AC bar on the generator side is already energized with a voltage. This is since the switches in this type of bridge occur thanks to the reference voltage present in the bar. The voltage dependence on the AC side also leads to the occurrence of switching failures, which affects the performance and reliability of the connection;
- LCC-type converter bridges are significantly larger than VSC-type converter bridges. This is because, in addition to transformers, current source converters require more robust filters, because the harmonic rate is significantly higher than in voltage source converters.

Since the size of the offshore substation has a very strong relationship with its cost, the LCC solution becomes economically unviable;

- The LCC's reactive power consumption is on the order of half of the transmitted power, which demands equipment with high reactive compensation, which in addition to being expensive, takes up more space in the offshore substation. VSC, on the other hand, can consume or produce reactives.

In general, current source converters are larger, simpler converters that are suitable for applications in large power systems to design Links DC that transmit high power values, on the order of several GW over very long distances, from about 800 to 1000 km. Already voltage source converters constitute a newer technology and, therefore, more expensive. They are suitable for applications Offshore, do not present the same problems as the current source converters with reactive and harmonic, but their power is still limited, up to the order of 1 GW. There are no voltage source converters in the Brazilian electrical system.

3 ALTERNATING CURRENT TRANSMISSION TECHNOLOGIES

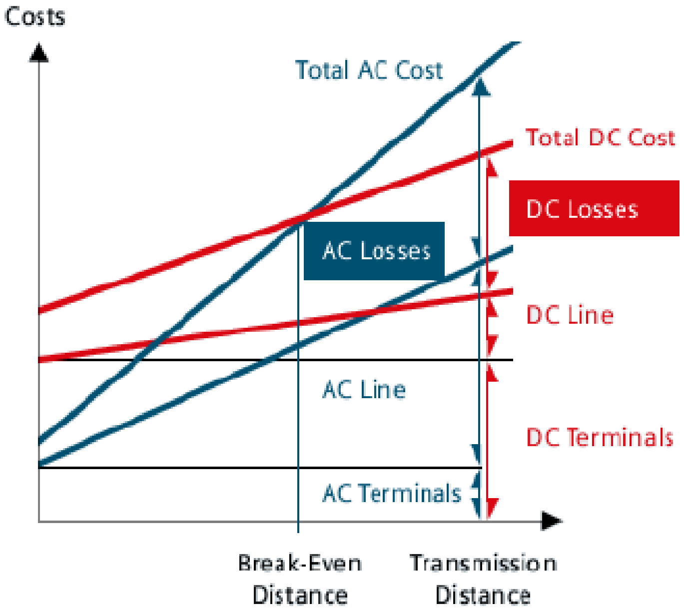
3.1 COMPARISON BETWEEN DIRECT CURRENT AND ALTERNATING CURRENT TECHNOLOGIES

Alternating current is widely used in overhead line applications, so that HVDC technology is used only in exceptional cases, such as: transmission of large powers, transmission lines with length from the order of 1000km and connection of uncoupled electrical systems, such as networks of different countries that use different frequencies. When it comes to underground and submarine cables, however, this outlook becomes more favorable to direct current. The comparison of AC and DC transmission solutions basically constitutes a balance of costs that are:

- Length-independent costs: costs of substations and their equipment. These costs are higher for the DC solution, because the converters are expensive equipment and, depending on what their type, they may require filters and reactive compensation equipment;
- Length-dependent costs: cables and insulators. Since the DC solution requires fewer cables (2 cables in bipole mode) than the AC solution (3 cables per circuit, one cable per phase), the cost sensitivity of the latter in relation to length is greater than for the AC solution.

This relationship between fixed costs and length-dependent costs of the cables can be observed in the Figure 3.

Figure 3 Costs of AC and DC solutions as a function of length. Source: [5]



As noted, there is such a distance that the costs of an alternating or direct current transmission line are comparable. This distance is called break even distance, and for lengths greater than this value, direct current transmission is more advantageous and vice versa.

Some aspects that differentiate overhead transmission lines from submarine insulated cables are:

- Insulated cables are much more expensive than bare cables used in overhead lines, due to the robust insulation and mechanical supportability;
- The capacitance of insulated cables is much higher than that of overhead lines. This leads to the need for greater reactive compensation, greater losses and more voltage regulation problems;
- The laying of submarine cables is a more costly and complex activity than the installation of overhead lines.

These aspects make that the derivative of the subsea transmission design cost in relation to the length of the connection is much higher than in the case of overhead lines. In this way, the break even distance for applications Offshore it is much inferior to that of conventional transmission. While in context Onshore, this distance is usually on the order of 1000km, in the context Offshore, this distance is in the range of 50 to 100km, depending on the solutions adopted in alternating current for control of reactive and the power generated.

As will be noted in this paper, there are both park connection solutions Offshore in the length range up to 100km, which corroborates the conclusion of the previous paragraph. Despite this, this rule is only indicative, and there may be projects that escape this logic. For example, according to [6], the Gemini project, which connects two wind farms Offshore to the Dutch power grid, it has an alternating current subsea transmission line of 110km in length to transmit 600 MW.

3.2 DISADVANTAGES OF ALTERNATING CURRENT TRANSMISSION

The main disadvantages of using alternating current for subsea transmission stem from the high capacitance of the insulated cables. They are: the high generation of reactive power by the line and the decrease in the power transmitted as the length of the line increases. With regard to reactive compensation, some of the adoptable solutions are: the use of reactors Shunt on the bars or ends of the line, or power electronics devices such as STATCOMs and SVCs (Static Var Compensator). The SVC is composed of a capacitor Shunt in parallel with a thyristor-controllable reactor (TCR Thyristor Controlled Reactor), whose control determines whether the equipment injects or absorbs reactive from the network. The STATCOM has a greater flexibility than the SVC, because it can inject or absorb higher values of reactive power, being more complex and expensive than the latter.

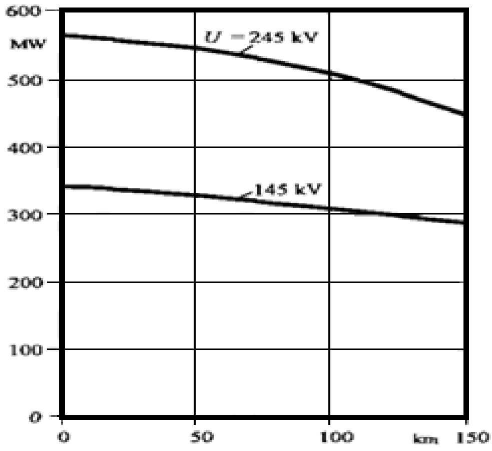
According to Equation (1), taken from [7], the larger the transmission line, the lower the active power transmitted due to the capacitance of the line. The higher the capacitance of the line, the greater the decrease in the transmission capacity with the length of the line, so that the sensitivity of the capacity of an alternating submarine current line in relation to its length is very strong, as can be seen from the Figure 4.

$$P = \sqrt{S^2 - Q^2} = \sqrt{\left(\sqrt{3}.V.I\right)^2 - \left(\frac{1}{2}V^2.2\pi f.C.l\right)^2} \qquad (1)$$

3.3 ALTERNATIVE SOLUTIONS IN ALTERNATING CURRENT: LFAC AND GIL

Two technologies that are studied in order to mitigate the disadvantages of alternating current transmission are: transmission at low frequencies – LFAC (Low Frequency Alternate Current) and gas insulated lines – GIL (Gas Insulated Line). Despite their advantages, no records of applications of these technologies for the connection of wind farms have been found offshore.

Figure 4 Capacity of subsea lines in alternating current as a function of length. Source: [8]



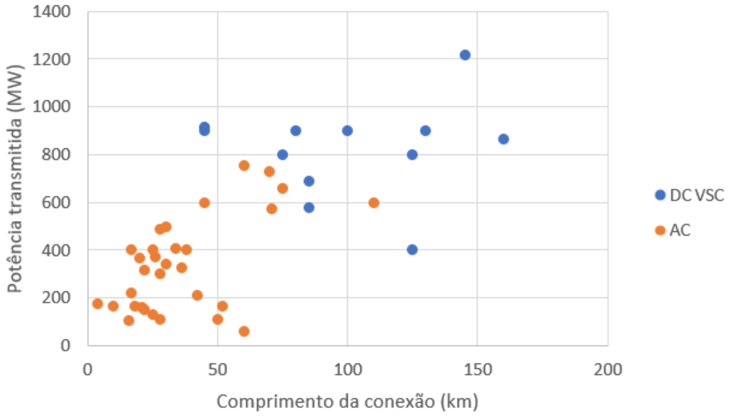
In low-frequency transmission (typically 20 or 16 2/3 Hz), power is generated at this lower frequency and the line is connected to the grid onshore through a connection back-to-back which changes the frequency of the voltage. The main advantage of LFAC is the decrease in the effects of the high capacitance of the cable. It is possible to transmit powers over longer distances without the need for reactive compensation, and without the capacity of the line being greatly reduced. In addition, it allows the use of smaller wind turbines, with fewer poles, and gearboxes with a lower speed ratio, so that the wind turbine assembly is less costly [8].

A GIL technology considers the use of gas-insulated lines and substations (usually sulfur or nitrogen hexafluoride), which allows the reduction of the dimensions of the substations Offshore which usually have a high cost due to the space occupied. In the scenario Offshore, gas-insulated lines are encased in an aluminum casing that passes through tunnels below the seabed. According to [9], other advantages of this solution are the high transmission capacity (of the order of 4 GW to 800 kV), low losses due to the large straight section of the conductor and low capacitance, which makes it not necessary reactive compensation for lengths up to 200 kilometers.

4 OVERVIEW OF OFFSHORE WIND FARM CONNECTION

The Figure 5 presents a survey done in 2019 considering the distribution of the main wind farm connections Offshore according to the length, power and transmission used (alternating or direct current). As discussed earlier, the distance range of 50 to 100km is the transition between the application of direct and alternating current. In this range, the transmitted powers are of the order of 600 to 800 MW.

Figure 5 Characteristics of the main offshore wind farm connections found. Source: Own Author



A Table 1 presents the installed capacity in the main wind producing countries Offshore in recent years. Most of the main producing countries are bathed by the North Sea, a region with very high wind potential. China, the third largest producer today, has been growing strongly and is expected to become the world's largest producer in a few years. In the annexes chapter, the Table 2, which presents the main projects of wind farm connections offshore.

Table 1 Installed capacity in the main offshore wind energy producing countries. Source: irena.org/wind

Country	Installed capacity ()GW			
	2015	2016	2017	2018
UK	5,29	5,29	6,99	8,3
Germany	3,28	4,13	5,43	6,41
China	0,56	1,48	2,79	4,59
Denmark	1,27	1,27	1,30	1,36
Belgium	0,71	0,71	0,88	1,18
Netherlands	0,36	0,96	0,96	0,96

4.1 MAIN PROJECTS AND PRODUCING COUNTRIES

The UK is now the largest producer of wind energy offshore in the world and predicts that this energy source will supply 10% of its energy demand by 2020 and 30% by the year 2030. Three wind farms are under construction and design that will become the largest wind farms offshore of the world: Hornsea One, Two and Three with a capacity of 1.2, 1.4 and 2.4 GW, respectively, and distances between 100 and 150km to the coast. Or Hornsea One is set to be the UK's first HVDC wind farm connection.

The second largest producer of wind energy in the world today, Germany has 8% of its energy demand supplied by wind farms Offshore. This technology is part of a strong policy of energy transition to low carbon, called Energy transition. All park connections Offshore in direct current in operation in the world are located in this country and he was a pioneer in the use of this technology, having implemented the first connection of this type in 2010, the project BorWin 1 Ads, which transmits a power of 400 MW through 125km of submarine cables and 75km of underground cables. Currently, the country has the longest and highest capacity connections in the world, all in direct current: SylWin 1 Ads (845 MW 160km) and DolWin 2 (916 MW 45km).

China is now the world's third largest producer of this type of energy and, due to its rapid development, is expected to become the world's largest producer in a few years. Most of its wind farms are located at short distances from the coast and have reduced capacities, up to 300MW.

Denmark pioneered wind energy Offshore, having installed the first wind turbine of this type in 1991, of 5MW (Vindeby). The park is currently under construction Kriegers Flak, of 600MW, which will feature an unprecedented solution: it will have two connections, one with Denmark and the other with Germany, through another wind farm in the German sea. The latter must have a connection back-to-back in the onshore substation, as the networks of Denmark and Germany are decoupled.

4.2 REGULATORY ASPECTS

In recent years, European energy legislation has evolved to try to boost this area of the economy. In 2009, legislation called Third Energy Package of the European gas and electricity market. This device has the concept of unbundling (decoupling), which means the separation between generating and transmitting agents [10]. This legislation, with the aim of unifying the European energy market and opening it up to new competitors, provides that generators cannot own transmission assets and cannot control the operation of these assets. Despite this, generators can still build the transmission assets that will be useful to them, having to pass them on to the transmitters after construction.

Under the British regulatory regime, generators can choose between building the grid connection themselves ("Generator build") or commission the design and conception of the connection to a transmitting company Offshore, chamada of Offshore Transmission Owner (“OFTO build") [11]. After construction, regardless of who was responsible for it, the ownership and operation of the line passes to a transmitter. A bidding process is conducted, in which broadcasters compete with each other to decide which one has the lowest cost to build ("OFTO build") or buy ("Generator build") the transmission line, and operate it over a period of 20 years. This regime is very positive because it gives the generator the freedom to build its own connection, making the process less time-consuming and costly, as well as enabling greater competitiveness and innovation. The body responsible for this process is the OFGEM (Office of Gas and Electricity Markets).

Second [12], the German transmission system operator, TenneT, has a monopoly on the construction and ownership of the transmission assets offshore in the North Sea. Normally connections are made to several wind farms, and when there is an idle connection capacity, the government holds auctions to meet the energy demand. These auctions are held every nine months, at first, and among the wind farm projects that apply, the criterion is the best price offered. The body responsible for regulation in the country is the Federal Network Agency (Federal Network Agency). The Netherlands, which has the same company operating the transmission system, has a regulatory model like Germany's.

4.3 ECONOMIC ASPECTS

As previously commented, the cost of the electrical connection in relation to the total cost represents a much larger share in the case of wind farms Offshore that in parks onshore. Two peculiarities entail this: the fact that the transmission is submarine and the need to use substations Offshore. The latter have a cost very sensitive to their weight and size occupied. Therefore, it is essential to seek to minimize the dimensions of these, minimizing the amount and size of the equipment used. This is also true to determine the number of transformers to be used, which constitutes a compromise relationship between reliability and cost. The more transformers that are used, the more reliable the connection and the more expensive the substation Offshore.

One way to measure the cost of energy produced by different energy sources is via the LCOE indicator (Levelized Cost of Energy), which represents the average cost per unit of electricity generated that is required to cover the costs of building and operating a generating plant over a financial life cycle [13]. According to [14], the LCOE of wind energy Offshore It reduced from to between 2010 and 2018. Despite the cheapness of this energy, it is still more expensive than all other renewable sources analyzed, with the exception of solar thermal energy (heliothermic).0,159US$/kWh0,127US$/kWh

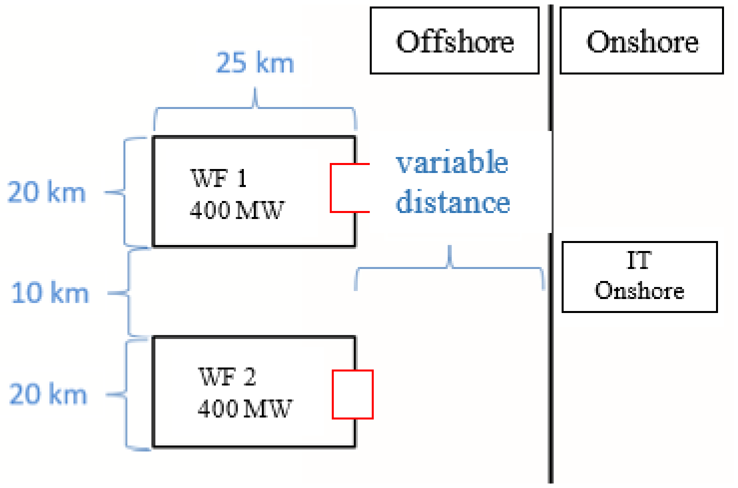
5 CASE STUDY

This chapter presents a case study of the connection of two wind farms Offshore hypothetical located on the Brazilian coast. Several alternatives will be proposed for the flow of production, involving direct and alternating current technologies, and the costs of each alternative will be estimated for distances from the parks to the coast ranging from 0 to 150km, to identify which alternative is the most economically advantageous for each distance range. In addition, the economic analysis will be detailed for 30km between the park and the coast, which is a typical distance, according to the analysis carried out of the existing parks in item 4.

5.1 PREMISES

Two parks with an installed capacity of 400MW each and dimensions of 20 by 25km were considered, totaling an area of 500km2, as shown in the Figure 6. These parks are at 10km from each other and at a certain distance from the coast, where a substation is located onshore that will receive the energy generated by the parks. It was considered that the collecting substations of both parks are located at the midpoint of the side of the park that is closest to the coast.

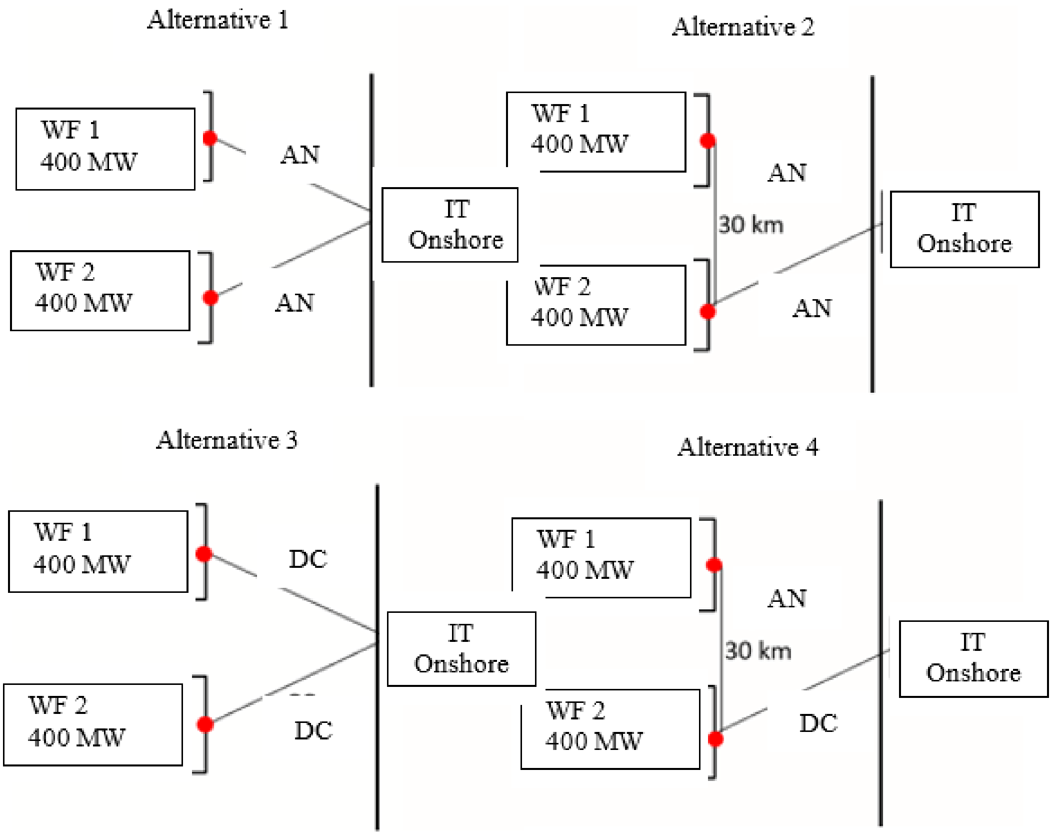
Figure 6 Schematic of offshore wind farms to be studied



5.2 PROPOSED ALTERNATIVES

The case study will involve the comparison of four alternatives for connecting wind farms to the onshore power grid, as can be seen in the Figure 7.

Figure 7 Alternatives proposed for the flow of wind farm generation


Alternative 1

Alternative 2

Alternative 3

Alternative 4

Alternative 1 consists of the direct connection of both parks to the substation onshore through subsea transmission lines in alternating current. These transmission lines will have the same parameters and length and each will have a transmission capacity of 400 MW.

Alternative 2 consists of the interconnection of the two substations Offshore, through an alternating current subsea line, with a transmission capacity of 400 MW. Regardless of the distance from the parks Offshore On land, this connection will have the length of 30 kilometers. The interconnection of the parks to the land will take place through a single subsea line with a capacity of 800 MW in alternating current leaving one of the substations Offshore.

Alternative 3 consists of connecting both parks via two direct current subsea transmission lines to the same substation Onshore. Each substation Offshore will therefore have a rectifier, while the substation Onshore It should have two inverter bridges. These DC transmission lines will have the same parameters and length and each will have a transmission capacity of 400 MW.

Alternative 4 consists of the alternating current interconnection between the two wind farms, with a length of 30 kilometers and a transmission capacity of 400 MW. One of the substations Offshore It must have a rectifying bridge and from it will come a single subsea line in direct current connecting this substation to the substation Onshore. This direct current line will have a capacity of 800 MW.

5.3 METHODOLOGY

The methodology adopted for the calculation of the costs of implementation and losses of the alternatives was the same methodology adopted in [7]. In this work, formulas are established for the calculation of each component of costs, whether installation or losses, for subsea lines interconnecting wind farms Offshore to the ground, both in alternating current and in direct current. The total cost of each subsea line can be divided into installation costs and loss costs:

$$CustoTotal = CustosInstalação + CustosPerdas \qquad (2)$$

The installation cost can be divided between substation cost Offshore, from the substation Onshore, the required reactive compensation and cables. The costs of the losses are divided between the losses that occur in the offshore substation, in the substation onshore and on the cables. The costs related to the internal collector network of the park are not considered, since these are the same regardless of the alternative adopted.

$$\begin{aligned} CustoInstalação = CustoSE_{off} + CustoSE_{on} + CustoCompensação \\ + CustoCabos \end{aligned} \qquad (3)$$

$$CustoPerdas = PerdasSE_{off} + PerdasSE_{on} + PerdasCabos \qquad (4)$$

Substation costs offshore, from the substation onshore, reactive compensation and cables for AC lines are given by the following formulas:

$$CustoSE_{off_{AC}} = 5 + 0{,}045.P \qquad (5)$$

$$CustoSE_{on_{AC}} = 0{,}02621.P^{0{,}5713} \qquad (6)$$

$$CustoCompensação_{AC} = 0{,}02.V^2.2\pi f.C.l \qquad (7)$$

$$CustoCabos_{AC} = t_c.l.n_c \qquad (8)$$

where is the power transmitted in MW, is the line voltage in kV, is the frequency in Hz, is the capacitance in nF/km, is the length of the line in km, is the cost of the cables in million pounds (£) per kilometer and is the number of circuits.PVfClt_c n_c

The cost of the substation offshore, of the substation onshore and cables for direct current lines are given by the following formulas:

$$CustoSE_{off_{CC}} = 25 + 0{,}11.P \qquad (9)$$

$$CustoSE_{on_{CC}} = 0{,}08148.P \qquad (10)$$

$$CustoCabos_{CC} = t_c.l.n_c \qquad (11)$$

The cost of losses at the substation offshore, at the substation onshore and cables for AC lines are given by the following formulas:

$$PerdasSE_{off_{CA}} = 0{,}00911.P \qquad (12)$$

$$PerdasSE_{on_{CA}} = 0{,}00911\left[0{,}994.P - \left(\frac{0{,}994.P}{n_c.V}\right)^2 r_c.l.n_c\right] \qquad (13)$$

$$PerdasCabos_{CA} = 1{,}51767\left(\frac{0{,}994.P}{n_c.V}\right)^2 r_c.l.n_c \qquad (14)$$

where is the resistance of the cable by length in Ω/km.r_c

The cost of losses at the substation offshore, at the substation onshore and cables for DC lines are given by the following formulas:

$$PerdasSE_{off_{CC}} = 0{,}0261.P \qquad (15)$$

$$PerdasSE_{on_{CC}} = 0{,}02747\left[0{,}9828.P - \left(\frac{0{,}9828.P}{n_c.V}\right)^2 r_c.l.n_c\right] \quad (16)$$

$$PerdasCabos_{CC} = 3{,}03534\left(\frac{0{,}9828.P}{n_c.V}\right)^2 r_c.l.n_c \quad (17)$$

These formulas and their premises are set out in [7].

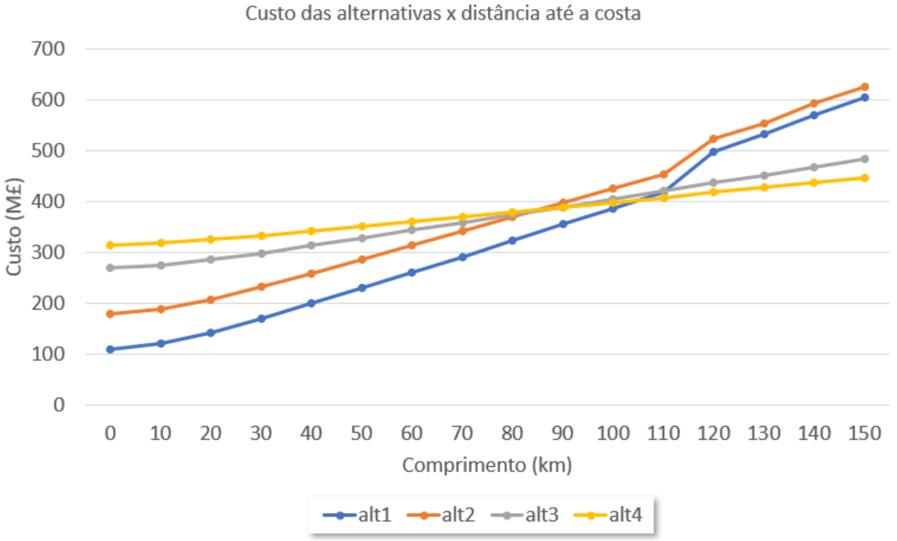
To size the cables of the transmission lines for each alternative and, consequently, to select the respective parameters of resistance, capacitance and price to be used, the same cable tables and parameters that the reference [7] used were used.

The criteria used for the design of the cables were the transmission capacity and the economic criterion. Of course, the chosen cable must have a capacity greater than the power it must transmit, which, in alternating current, decreases as a function of the length of the line. In addition, the economic criterion was also used to judge the best solution considering the different possibilities of voltage levels and number of circuits. In some cases, it was chosen to reduce the voltage and increase the number of circuits as the distance between the parks and the coast or the power transmitted increased. Although lowering the voltage to longer line lengths seems at first glance counterintuitive, this was done because it was found that, in some cases, it is more economical to use more circuits of a lower voltage level than to increase the cable gauge and use a higher voltage, given the cable options of the tables used and the cost equations presented in this item.

5.4 RESULTS

The Figure 8 shows the cost results obtained in millions of pounds for each of the proposed alternatives for distances from the park to the coast from 0km to 150km.

Figure 8 Result of costs of each alternative for different distances between the parks and the coast



Analyzing the results, it is concluded that the most economically advantageous alternative is:

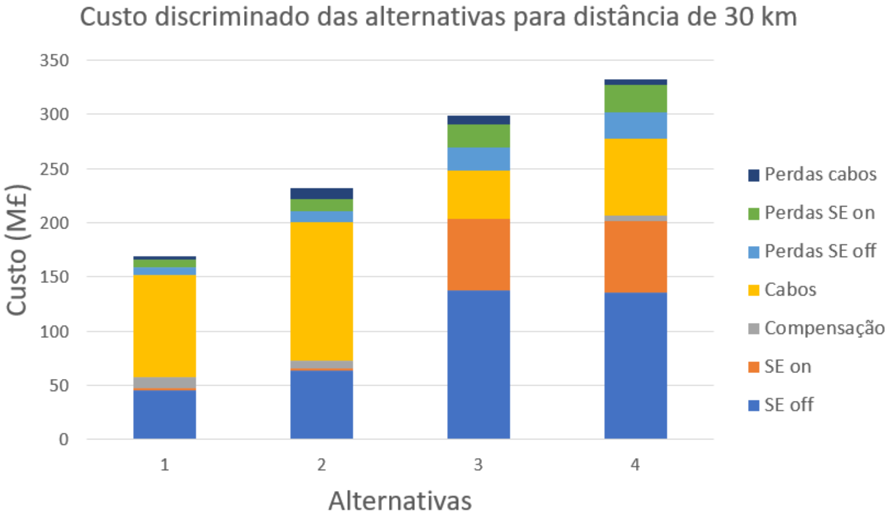
- For distances up to 100km: Alternative 1;
- For distances from 110 to 150km: Alternative 4.

As expected, it was observed that alternating current proved to be more advantageous for transmission up to a certain distance and, for distances greater than this, the direct current solution becomes more economical.

It is surprising that Alternative 2 does not beat Alternative 1 for any distance value. This comes from the fact that most of the cost of AC lines comes from the cost of cables. In Alternative 2, the line connecting the parks and the coast must be sized to a capacity of 800 MW, so that its cost ends up being close to the cost of two lines of 400 MW, as in Alternative 1. Therefore, for this case studied, it is more advantageous to connect the parks separately to the coast through 2 lines in alternating current than to make a single line in alternating current for both parks. In addition, it is observed that from the distance of break even, comparing solutions involving direct current transmission, Alternative 4 is more advantageous than Alternative 3.

In addition to the comparison between the costs of all alternatives within a range of distances, an in-depth analysis of the results obtained for a distance from the park to the coast of 30 kilometers was also carried out. A Figure 9 presents the cost of each alternative for this circumstance. In addition, costs are separated between losses on cables, substations, cable costs, substations, and reactive compensation.

Figure 9 Detailed costs of each alternative for a distance between the parks and the coast of 30 kilometers



Analyzing the detailed costs, one can make some observations about results obtained that were expected:

- Because it is a short distance, the most economical alternatives were those involving alternating current transmission;
- Most of the costs of AC solutions are due to cable costs;
- Within each alternative, offshore substations proved to be much more costly than onshore substations. This is due to the high cost of the footprint in the offshore scenario;
- In direct current solutions, most of the total cost comes from the costs of substations, which is caused by the high cost of converters;
- Losses in DC substations are significantly higher than losses in alternating current substations. This is due to losses in the converter bridges, which use switching at high frequencies.

6 CONCLUSIONS

The particularities related to the development of wind farm connections were presented throughout the work Offshore. Since it is a very recent technology, and still unpublished in the country, the purpose of this work was to give an overview of the current scenario of offshore wind farm connections to the transmission system. It focused, especially, on reporting on the latest advances and projects in the world of parks Offshore as well as describing the most appropriate and applied technologies to date. Throughout this work, not only technical aspects of the electrical engineering area were addressed, but also relevant issues such as economic, regulatory, marketing aspects, etc.

The evaluation of the international scenario is of paramount importance so that one can reflect on what may be the possible barriers to the development of this technology in Brazil.

Some of the barriers identified are listed below:

- Structural problems such as deficient infrastructure and the absence of a strongly consolidated base industry, unlike the countries that lead the application of this technology;
- The distancing of the large specialized manufacturers, which are concentrated in Europe and North America;
- Legal aspects such as the impossibility of obtaining the prior environmental license for the installation of these projects still in the planning phase and the absence of a body responsible for delegating eligible area to receive such projects [15].

On the other hand, some factors that can constitute assets that help the development of this technology in the country are:

- The robustness of the National Interconnected System (SIN), which is one of the largest integrated power grids in the world, with good experiences in the development of direct current transmission for example. In addition, the Brazilian electrical system has unique independent bodies of operation and planning, the ONS and EPE, respectively, which have a well-consolidated performance;

- The national experience, especially of Petrobras, in the exploration of oil and gas in deep and ultra-deep waters. It is known that the know-how acquired by the big oil companies can be used in other offshore applications and many of these are already pioneering this new market. Since Petrobras is one of the largest oil and gas companies in the world and is responsible for important technological advances in this area, the operation in this new type of generation is an opportunity that opens for the expansion of its portfolio.
- The high wind potential present in the country, both onshore and offshore, especially on the coast of the Northeast region. Brazil is the world's eighth largest producer of onshore wind energy [16].

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