Master Thesis

Stochastic Optimization of Offshore Wind Power Plants Operation For Maximizing Energy Generation

FOCUSING ON THE ELECTRIC POWER SYSTEM OPTIMIZATION AND COST MINIMIZATION

MEMORIA

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ABSTRACT

It is a reality that nowadays the demand for energy is increasing in the world, but at the same time conventional energy resources are becoming expensive, rare, and more pollutant. All these facts are leading the countries to focus on renewable energy sources, as they are cleaner and abundant. In this field Offshore Wind Power Plants (OWPPs) are becoming increasingly relevant in Europe, and worldwide mainly due to space limitations constraints (possibility of using larger wind turbines), the fact wind speeds are potentially higher and smoother at sea (leading to higher power generation), lower visual and noise impact than onshore farms, and finally because of the progressive saturation of propitious onshore sites. Currently, and because of the environmental and social legislation, OWPPs are forced to be constructed further from shore. There are three main factors to be covered when designing AC electric system of OWPPs: investment cost of components, system efficiency, and system reliability. The present project is focus on the first two key factors, and also considers a stochastic optimization of the electric system of an OWPP operation in order to minimize the investment and operational cost, and in this way try to get the best scenario obtaining the most of benefits. GAMS and MATLAB softwares have been used to implement the main program, obtaining a basic engineering tool to design and take decisions for the electric power system applied to real offshore wind farm.

RESUMEN

Es un hecho que hoy en día la demanda energética en el mundo está incrementando, y a la vez las fuentes convencionales de energía se están agotando, son más y costosas, y también contaminantes. Todos estos hechos hacen que los países apuesten cada vez más por las energías renovables, ya que estas son más limpias y abundantes también. En este campo, los parques eólicos marinos van ganando más peso en Europa y a nivel mundial, principalmente debido a las limitaciones de espacio (posibilidad de usar turbinas más grandes), los vientos son potencialmente elevados y uniformes en el mar (mayores potencias de generación), el impacto visual y auditivo es menor comparado con los parques convencionales, y finalmente debido a la progresiva saturación de los lugares aptos para la construcción de parques. Actualmente, y debido a la normativa social y medioambiental, los parques eólicos marinos son forzados a ser construidos cada vez más alejados de la costa. Existen tres factores clave a ser considerados cuando diseñamos sistemas eléctricos de parques eólicos marinos en corriente alterna: coste de inversión de componentes, eficiencia del sistema, y la fiabilidad del sistema. El presente proyecto se centra en los dos primeros puntos, y también lleva a cabo una optimización estocástica del funcionamiento del sistema eléctrico del parque eólico marino, con el fin de minimizar los costes de inversión y de funcionamiento, y de esta manera tratar de alcanzar el mejor escenario, obteniendo los mayores beneficios. Los programas GAMS y MATLAB han sido usados para implementar la programación principal, obteniéndose así una herramienta de ingeniería básica para el diseño y toma de decisiones del sistema de energía eléctrica aplicado a campos eólicos marinos reales.

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1 Introduction

1.1 Motivation

Wind energy is one of the most profitable renewable energy, proven technology to meet current and future electricity demands. Most of turbines are located on land, however the future of wind energy, mainly in Europe, is expected to come from offshore sites. Wind power installed more than any other source in 2015. Offshore wind power accounted for 24% of the total EU wind installations during 2015 [1].

In the beginning of the last decade, with the commission of Horns Rev OWF in Denmark, development of large OWFs has just started. Since this event, some other large projects have been performance in the coast of countries in the North Sea, the Baltic Sea, and the Irish Sea.

The cost per MW of installed capacity of an OWF is much higher in comparison with an onshore wind farm [2]. This difference is mainly due to the foundation cost and the electric power system [2].

The offshore conditions are favourable in comparison with the sites on land: stronger and steadier wind speeds, no obstacles, higher energy yield, etc. However advantages contrast with the increments of installation and maintenance costs, which must be compensated. This is an important motivation to scientist and engineers to optimize offshore wind farm project designs, focusing on the main aspects such as location, installation, layout, availability or operation and maintenance.

Due to the increase of power capacity of the current and future OWFs, the adequacy of the electric power system design becomes critical, because of its extend influence in efficiency, cost, reliability, and performance. For these reasons, the electrical power system needs to be optimized in order to minimize costs, maintaining at the same time a good level of efficiency and reliability. According to literature, several authors [3] have ascertained that system efficiency is strongly affected by the electric power system design and the OWF wind speed distribution.

The system reliability, especially in offshore, plays also an important role in the power system design. It is important because of the size and capacity of the main components of OWFs, and also due to much longer repairs in comparison with onshore wind farms (marine conditions). The inclusion of redundancies in the electric power system of OWFs is a trade-off between investment cost and power security.

The future progress in the optimization of electric power system should lead to deal jointly with the key factors that characterize their design. In addition to this, the electric power system optimization of OWFs requires consideration of the main sources of uncertainty associated with these systems, which are the wind speed and reliability of the system components. Stochastic programming has been widely employed to deal with uncertainties in some areas of power system planning, such as power transmission planning and capacity expansion planning.

In addition to these points, another important factor to take into consideration within the design of an OWPP is the wake effect, which is the interference phenomenon for which, if two turbines are located one close to another, the upwind one creates a shadow on the one behind. This is of great importance in the design of the layout since it results into a loss of power production for the downstream turbines that are also subject to a possibly strong turbulence.

Figure 1-1: Wake effect in Horns Rev 1.

The next sections presents the methodology of the project, an extent explanation of the main components taken into account in this research, AC and DC collection grids, layout topologies, transmission system, optimization of OWPPs and all its details, and finally some conclusions about the study, taking into account the obtained results.

1.2 Purpose and scope

The main goal of the present project is to develop a design tool that optimize the electric power system of the OWPP, but also takes wake effect into account when determining the optimal electrical layout solution, minimizing costs related to component investment and ohmic losses within the system.

The scope of the model is focused on OWPPs with a MVAC collection grid and an HVAC or MVAC transmission system, which are the vast majority of the OWPPs installed so far. Several relevant aspects of the electric power system to take into account in order to increase its profitability such as the wind farm layout, cable routing, substation location (if it is necessary), among others are considered in the present study. Also wake effect within the wind farm will be analysed, with the help of the Jensen Model, in order to be more precise in the results, obtaining an improvement over the previous reference work [4].

Within the main contribution of the model performed in this project is the determination of the optimal inter-array cable routing. The topology of the connections among wind turbines, cable type selection, central collection points (substations), and the point of common coupling are solved in the same optimization which goal is to minimize the total cable costs due to investment and power losses.

This project develops a comprehensive stochastic programming model for optimizing the electrical power system of an OWPP. Stochasticity is considered by taking into account the intermittent behaviour of the wind. For this study, reliability (another source of stochasticity in this kind of problems) is out of scope due to the lack of available data.

1.3 Resources

The problem has been solved using different resources as data collected from different scientific sources and literature, notes from the specific university subjects, computer tools or even manual calculations.

When focus in the specific IT tools with a particular programming language, in this project two main programs have been used. The main program has been developed in GAMS software, whilst MATLAB language has been used to calculate the wake effects within the OWPP. Thus, the results obtained from MATLAB have been introduced as input data in the GAMS code.

The optimization problem is a mixed integer quadratic constraint programing (MIQCP) and the solver used has been Cplex.

2 Offshore Wind Power Plants

2.1 State of the art

EWEA's targets for 2020 are 230 GW installed wind capacity in Europe, 190 GW onshore and 40 GW offshore, respectively. This would imply a production of 14 – 17 % of the EU's electricity, avoid 333 million tonnes of CO2 per year and save to Europe € 28 billion a year in avoided fuel costs and €8.3 billion a year in avoided CO2 costs.

It has been installed 12800 MW of wind power capacity and grid-connected in the EU during the 2015. It represents an increase of 6.3 % on 2014 installations, and 3034 MW were offshore which has doubled its installations compared to 2014 [1].

Germany was the largest market in 2015 (6013 MW of new capacity), 2282 MW of the total was offshore (38 % of total capacity installed in Germany). Poland came 2nd with 1266 MW, more than twice the annual installations in 2014.

Wind power installed more than any other source in 2015. Offshore wind power accounted for 24% of the total EU wind installations during 2015. This confirms the growing relevance of the offshore wind industry in the development of wind energy in the EU.

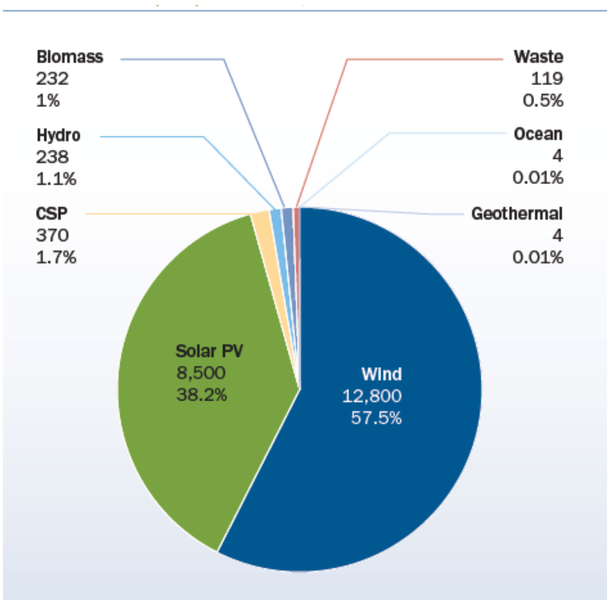


Figure 2-1:2015 share of new renewable power capacity installations (MW). Source:EWEA, 2015 European statistics

There is 142 GW of installed wind power capacity in the EU: 131 GW onshore and 11 GW offshore. Wind energy has overtaken hydro as the third largest source of power generation in the EU with a 15.6% share. Wind power was the first with the highest installation rate in 2015, with a 44% of all new installations. Conventional power sources as fuel oil and coal continue to decommission more capacity than they are installing. Gas, hydro, waste, nuclear and other sources represented with a low installation rate in 2015. Peat and fuel oil did not install any capacity in 2015 [1].

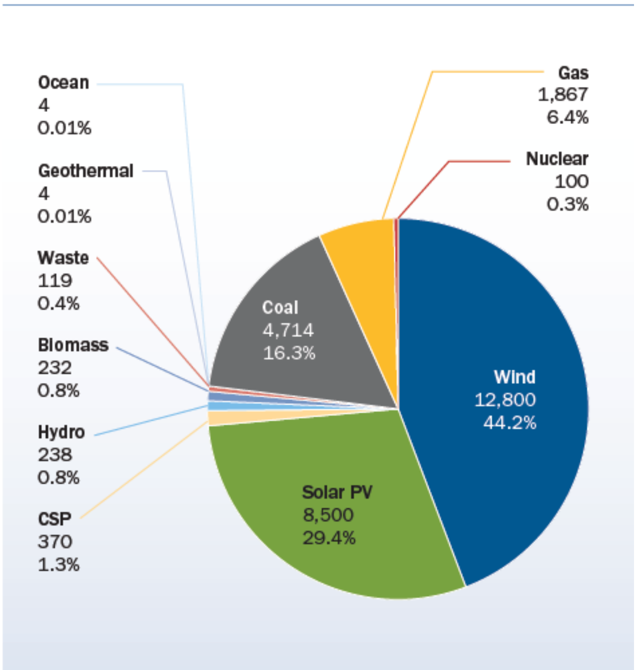


Figure 2-2: Share of new power installations in EU (MW). Source:EWEA, 2015 European statistics

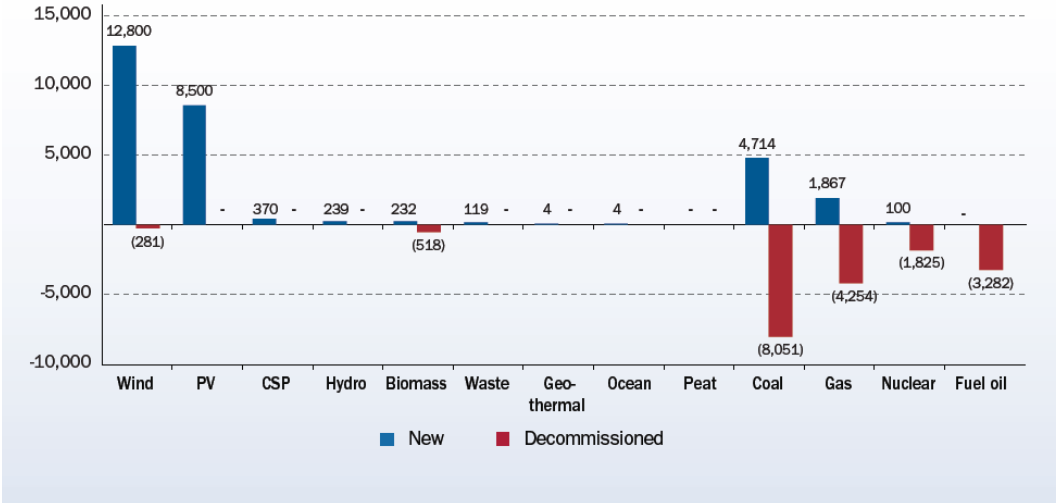


Figure 2-3: New installed and decommissioned power capacity in EU (MW). Source:EWEA, 2015 European statistics

Since 2010, annual renewable capacity additions have been between 21 GW and 35 GW, six to ten times higher than in 2000. In 2000 the share of renewables in total new power capacity additions was 22.4 %, increasing to 77% in 2015, that represents 22.3 GW [1]. There is a big variation between countries that reflect the effectiveness of policy and regulatory frameworks.

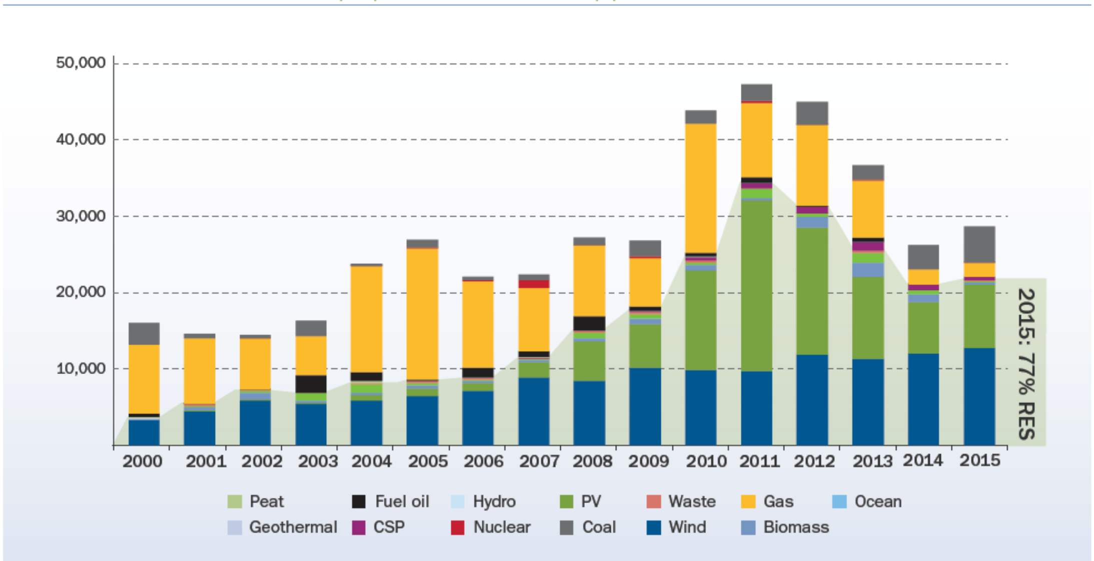
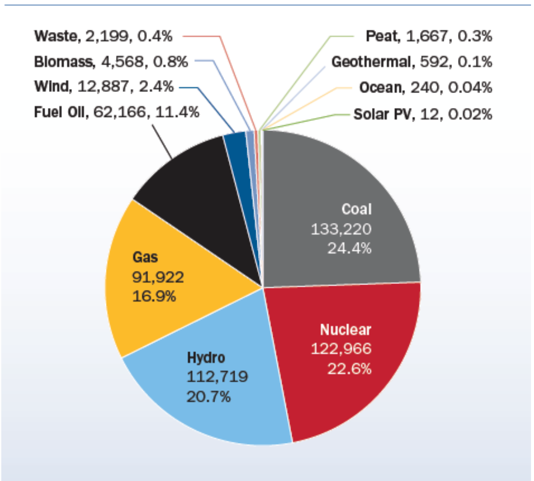


Figure 2-4: Annual installed capacity (MW) and renewable share (%). Source:EWEA, 2015 European statistics

Also, wind power's share of total installed power capacity has increased six-fold since 2000, from 2.4% to 15.6% in 2015, overtaken hydro, as it was said before. It is the first renewable technology in capacity installed.



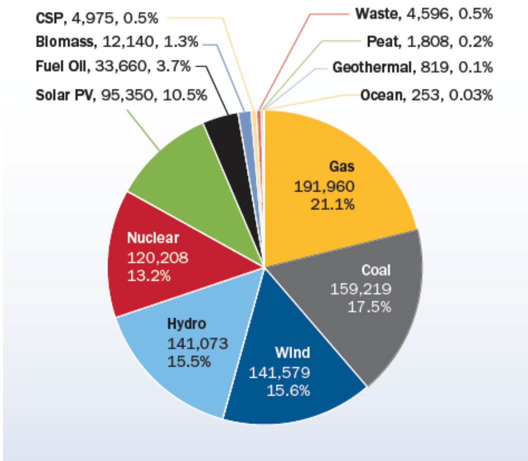


Figure 2-5: EU power mix 200 (MW). Source:EWEA, 2015 European statistics. (Left figure)

Figure 2-6: EU power mix 2015 (MW). Source:EWEA, 2015 European statistics. (Right figure)

The previous year 2015 showed important variation between countries in their capacity additions. Germany remains the country with the largest cumulative installed capacity (45 GW) followed by Spain (23 GW). Almost half of the new capacity installed in 2015 came from Germany and Denmark. In fact, 47% of all new installations in 2015 were performed in just one country: Germany. This is mainly due to the stability of the regulatory frameworks in these countries. In particular, Spain, which has been a strong marked related to wind energy, saw new installations fall to zero as a result of inadequate policies.

Three factor facilitated growth: effective policies, the connection of large amount of offshore capacity installed in 2014, and a desire by the industry to complete installation before Germany moves to marked-based arrangements.

In terms of energy, the total wind power capacity installed at the end of 2015 could produce 315 TWh and cover 11.4% of the EU consumption in one year [1].

Total EU electricity consumption (TWh)	Onshore wind energy production (TWh)	Offshore wind energy production (TWh)	Wind energy production (TWh)	Share of EU consumption met by onshore wind (TWh)	Share of EU consumption met by offshore wind	Share of EU consumption met by wind energy
2,770	274.5	40.6	315	9.9%	1.5%	11.4%

Table 2-1: EU electricity consumption. Source: EWEA, 2015 European statistics.

€26.4 billion was invested in Europe in 2015 to finance wind energy development. This was 40% more than the total amount invested in 2014. The UK had the highest level of investment in this year, attracting €12.6 billion for the construction of new onshore and offshore wind farms [1], accounting for 48% of the total investment in 2015.

The EU's power generation capacity continues to move away from fuel oil, coal, nuclear and gas to a higher share of wind, solar PV and others renewables. In October 2014, EU Heads of States and governments agreed on a 2030 climate and energy framework including a binding 40% greenhouse gas emissions reduction target, a binding target for renewable energy of at least 27% and an energy efficiency target of at least 27% [5]. In the European Commission's reference scenario the renewable energy target translates into at least 46% of electricity consumption being met by renewables.

This modest ambition of 46% of renewables in final power consumption by 2030 will require additional investments in renewables during the post-2030 period if Europe is to decarbonise the European economy by 80-95% by mid-century.

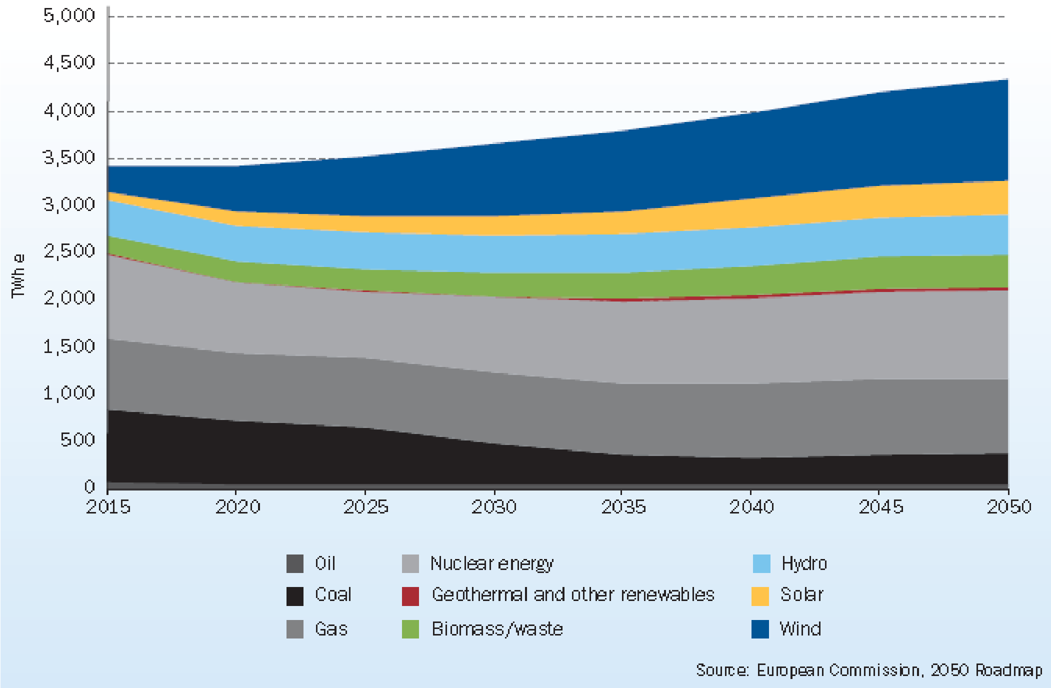


Figure 2-7: The evolution of the power mix going into 2050 from the EU reference scenario. Source:European Comission, 2050 Roadmap

2.2 Wind Power Plants components

In this section is studied the main components of an offshore wind farm, most of them linked with the optimization model implemented in this project. Some of them are the ones explained in the following lines.

2.2.1. Wind turbines

There are many types of wind turbines. There is a classification related to the axis: vertical or horizontal one. The type studied in the wind farm of this project is a Vestas turbine with horizontal axis.

Wind turbines are commonly composed of the following components: blades, tower, nacelle, hub, generator, and depending of the type of turbine also power converter and a gearbox (Fig. 2-8).

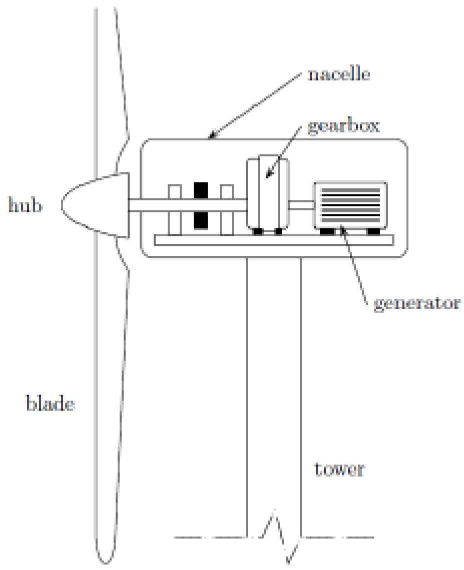


Figure 2-8: Wind turbine control systems. Source: Bianchi 2007.

There is an evolution in the turbines when talking about the size. Along the period 1990 to 2010 the rotor diameter goes from 15 meters to more than 126 meters.

The electrical generator can be: induction generators (squirrel cage and wound rotor doubly fed), synchronous generators (permanent magnet and wound rotor), others (switched reluctance, DC, etc) [6]. The synchronous generators are stable only at synchronous speeds, the torque is proportional to the angle, and the rotor is excited with DC current or using permanent magnets.

2.2.2. Submarine cables

General multilayer structure of a high-voltage insulated power cable (Fig. 2-9):

- ***Conductor***
- ***Inner semiconducting screen***
- ***Insulation***
- ***Outer semiconducting screen***
- ***Sheath***
- ***Armor***

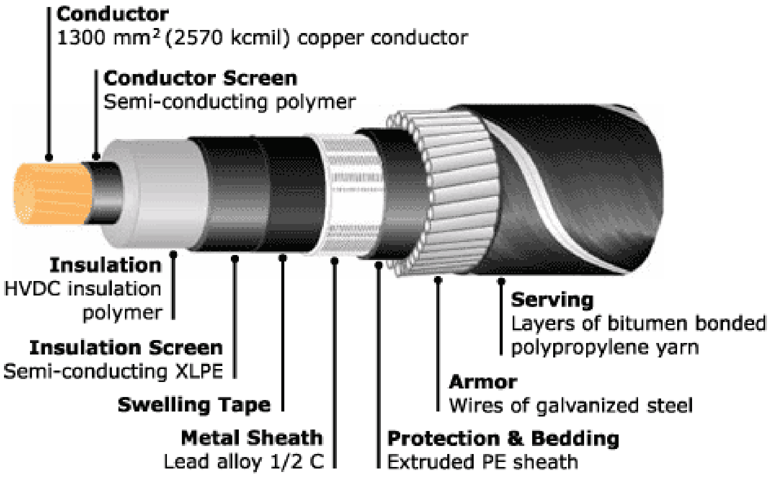


Figure 2-9: General structure of a high-voltage insulated cable.

Some of the layers surrounding the conductor enable the protection against damages of electrical origin (semiconductor screens). Other layers, the most external ones permit the protection against damages of mechanical origin (armor and cover). Cable has at least a conductor cross section adequate to meet the system requirements for power transmission capacity

In addition, due to salty and humid environment, submarine cables should have special protection against corrosion. All submarine cable projects have their own special challenges: voltage, power rating, water depth, route length, protection method, and so on.

The losses in submarine cables appear to depend on the specific cable design and, perhaps, the manufacturer [7]. The cost of energy losses can be reduced by using larger conductor. In this sort of cable, load losses are primarily due to the ohmic losses in the conductor and in the metallic screen [8].

Capacitive charging current of underground cables is 15 – 25 times higher than that of overhead line (OHL). The current rating of submarine cables follows the same rules as for land cables, but there are some differences [8]:

- Three-core submarine cables usually have steel wire armour. Single-core ones have non-magnetic armour.
- Single-core cables can be laid separated or close. Close laying gives lower losses, and the separation eliminates mutual heating, but means higher losses.

In the transmission system, the higher voltage allows a much smaller diameter and lower cost submarine cables to be used for the long run to shore [7]. From the offshore substation, a high-voltage submarine cable carries the power to shore. Once it makes landfall, the run continues, either underground or overhead, to an onshore substation for connection to a transmission line.

Submarine cables require significant capital investments and are relatively inaccessible for maintenance. Buyers are conservative with a strong preference for designs with proven records [7]

- Don't bury the collection system cables in the seabed between wind turbines, since the risk of damage within the wind farm from boat anchors, commercial fishing, etc., is low compared to the more exposed transmission cable to shore. Laying cable on the seabed costs less than buried cable installation.
- For copper conductors, the lead sheath is not strictly necessary. A copper wire sheath can be used instead to provide an effective electrical shield. Lead sheathing is commonly specified as a conservative approach that provides one more seawater barrier for the conductors. Lead sheathing is more expensive because it uses a larger volume of material applied in an extrusion process.
- Alternatively, aluminium conductors can be used in place of copper can reduce both cost and weight.
- Power cables for wind farms should be designed with cable thermal mass in mind. One manufacturer noted that a buried cable/soil system has a thermal time constant of about one week. Typically, wind farms are not at peak power continuously. Intermittency of the wind resource may allow cable thermal design to be based on current level less than that at peak wind farm output. Temperature monitoring of cables is feasible with fiber optics, though the optical fibers are reported to be less robust than the cables.
- One cable manufacturer recommended that performance-based cable specifications be used instead of design-based specifications to give the manufacturers greater flexibility to use their knowledge and experience to explore cost-effective designs.

2.2.3. Offshore substation and Transformers

Another relevant decision that needs to be taken during the design process is to determine the optimum offshore wind power plant location that minimizes both installation and logistics costs, as well as maximizes the energy output.

Offshore substations are built on platforms and have to be shipped offshore. Important issues such as availability of space (limitations in space) and weight due to limits of transport vessels should be taken into consideration when making these decisions.

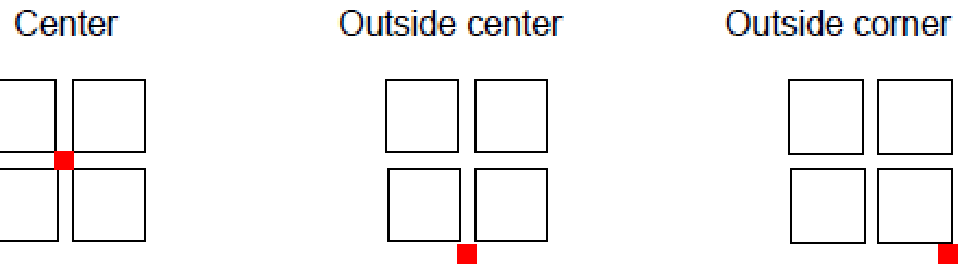


Figure 2-10: Different positions for AC collection grids

The transmission system begins at the offshore substation, which steps up the voltage. Few OWPPs have offshore substations nowadays. However, these stations are expected to be the least-cost option for wind farms that will be larger and further offshore than current practice [7]. From the offshore substation, a high-voltage submarine cable carries the power to shore.

An offshore AC substation, often simply called offshore substations, are offshore platforms containing electrical equipment devote to lead the electrical energy generated in a project (for example, multiple wind turbines) at a point of the network, in which generally converge generators, lines and transformers.

The purpose of an offshore AC substation is to provide the same functions as onshore electrical substations: switching devices to connect or disconnect equipment, protection equipment to respond to faults, and transformation to higher voltages for either transmission to shore or feeding an AC/DC converter station. Basically, the functions of a substation are the following [9]:

- Security: Separate from the system those parts where there has been an electrical fault.

- Operation: Set the electrical system in order to direct energy flows optimally, minimizing losses.
- Networking: connect two different voltage electrical systems, generators connected to the transport system or interconnect several lines of the same voltage level.

In terms of appearance, offshore substations build on the years of experience of the offshore oil and gas industry, and the most common designs use a platform consisting of a ‘topside’ in which the main equipment is housed, and a foundation structure, which is either a steel lattice ‘jacket’ structure, a ‘monopile’ structure, or a gravity base structure [10] (Fig. 2-11).

Depending on the project, there may be more than one offshore substation for one wind farm. They vary in size depending on the capacity of offshore wind farm. The specifications of offshore AC substations are highly project-dependent. Typically, they will be based on considerations such as: [10]

- Required on-board equipment for substation.
- Water depth at substation location.
- Personnel accommodation requirements (if applicable).
- Access requirements (via air/sea) as applicable.
- Structural guidelines imposed by authorities.
- Project-specific platform installation requirements.

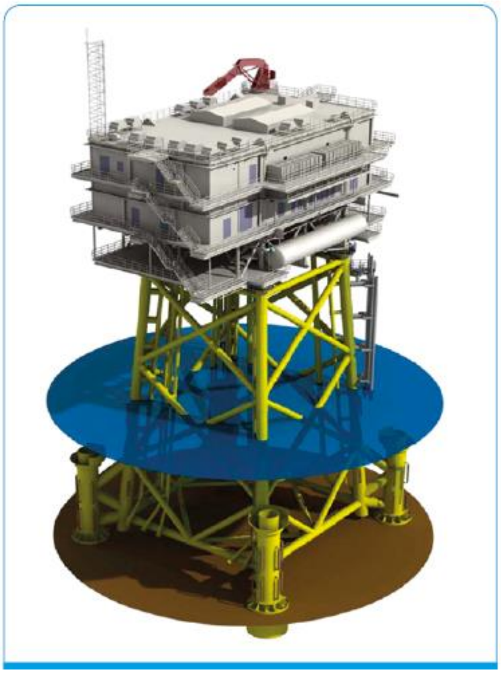


Figure 2-11: Example of an offshore AC substation. Source: DONEnergy.

Operations will all be carried out remotely, most likely from shore. However, there may be scope in the future for permanently manning offshore for O&M purposes.

Maintenance is likely to be carried out by vessel or helicopter but is likely to be less frequently than is required for wind turbines. Most maintenance will be limited to inspection, and minor actions.

Where potential environmental impacts are identified for a specific project, mitigation measures may be implemented to avoid or reduce the impact.

Also it can be in a wind farm, not in the case studied in the present project, offshore AC/DC converter station, which converts power from AC to High Voltage DC (HVDC) for transmission to shore [10]. They are only needed for projects which deploy HVDC assets.

2.3 Topologies overview of OWPPs

2.3.1 Radial

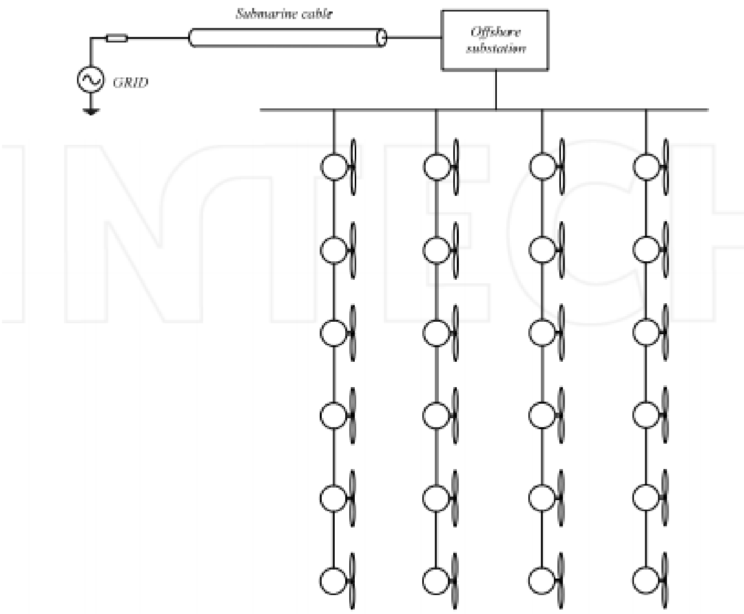


Figure 2-12: Radial inter-array connection.

It is characterized because of its low cost but also low reliability.

2.3.2 Ring

In this type of configuration the cost due to additional cable/s and protections is high and the reliability of the layout is also quite high.

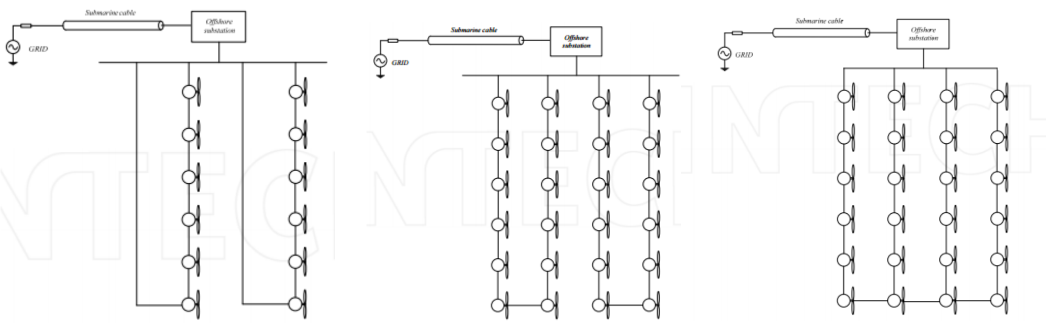


Figure 2-13: Single ring (left), double ring (middle) and multiple ring (right) configurations.

2.3.3 Star

This one has higher cost than radial connection, better reliability than radial connection and easy cable dimensioning.

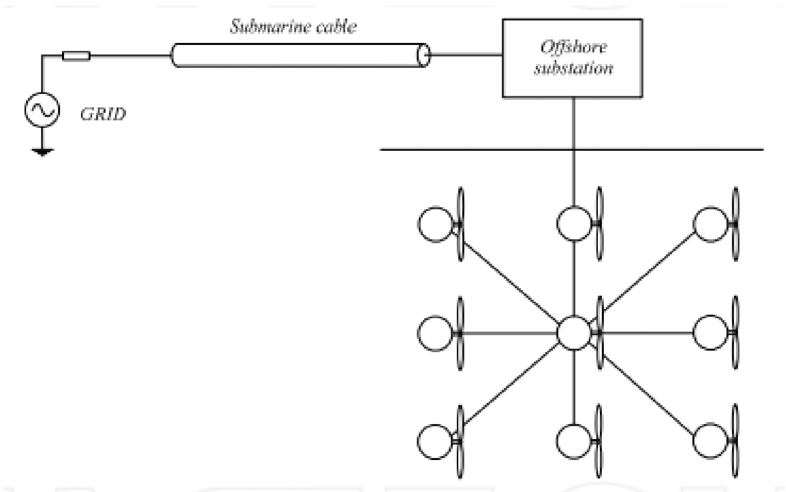


Figure 2-14: Star inter-array connection

2.4 Transmission systems (HVDC, HVAC, MVAC)

A few configurations were identified as suitable for the transmission of energy for offshore wind farms:

- Medium voltage AC (MVAC)
- High voltage AC (HVAC)
- High voltage DC (HVDC)

Today electrical energy is mainly generated, transported and distributed in alternative current (AC) because of the easy generation with synchronous machines, easy voltage step up/down with power transformers and the easy current interruption.

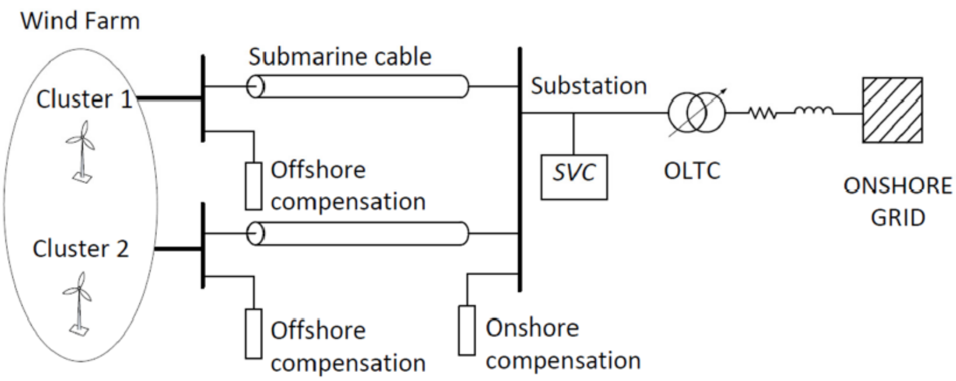


Figure 2-15: Example of MVAC transmission system.

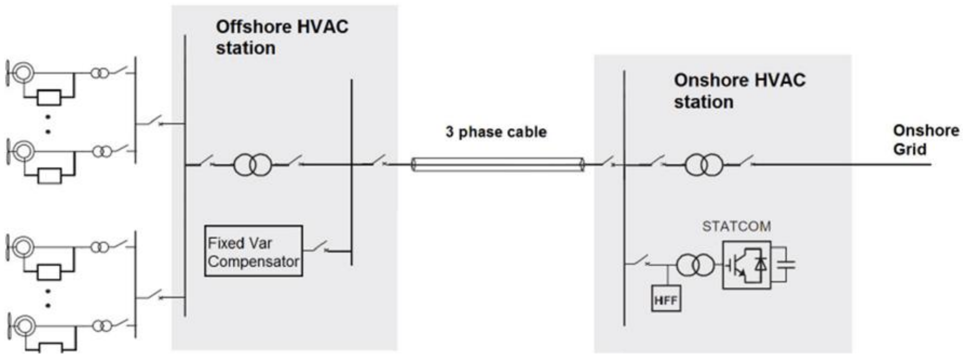


Figure 2-16: Example of HVAC transmission system.

Several studies have demonstrated that if the distance between an OWPP and its grid connection point at the Point of Common Coupling (PCC) exceeds a certain critical distance (approximately 55-70 km), HVDC transmission becomes a more interesting solution than HVAC, since reduce cable energy losses and decrease reactive power requirements. The economic break-even distance is found around 80 km [11], HVDC systems will likely be least cost mainly because the capacity of a given HVAC cable drops off with distance due to the capacitive and inductive characteristics of the cable and their associated losses. DC transmission avoids these losses entirely, so it is the preferred technology for longer distances.

3 Optimization of Wind Power Plant Design

3.1 Problem statement

For the accomplishment of the optimization problem it is necessary to follow a number of steps in order to achieve the final and optimal solution.

The purpose of the present model tool is to optimize the electric power system of the OWPP with the help of some personal skills, but also relying on specific software, mathematical support, and also particular models.

First of all, it is necessary to obtain all the specific data relating to the studied OWPP such as type of turbine, layout, project capacity of the farm, info about wind distribution in the location, cable typology, main distances, economic information, and so on. For this task is necessary to get all the necessary information with the help of internet, and current literature about the thematic.

Hence, wind speed distribution data and the location of the OWF are assumed to be known, as well as, the position of wind turbines in the polygon site and the point of common coupling (PCC) in the transmission grid. The components considered in the optimization problem are medium voltage and high voltage submarine cables and power transformers (different power rates) of the offshore substation.

Different types of cable layout problems can be addressed, and in this thesis it will be studied two main and general layouts for the electric power system, and the difference between them depends mainly on the existence or not of an offshore substation, obtaining an optimal routing to connect offshore turbines and to collect their energy in one central collection point.

The first layout (Fig. 3-1) considers all wind turbines are connected by MV cables. All these MV cables gather in a central collection point (CCP) where an offshore substation is located. If an offshore substation has to be installed and its location, are decisions of the problem. Then the power of the OWF is transmitted from the substation to the PCC through a high voltage line.

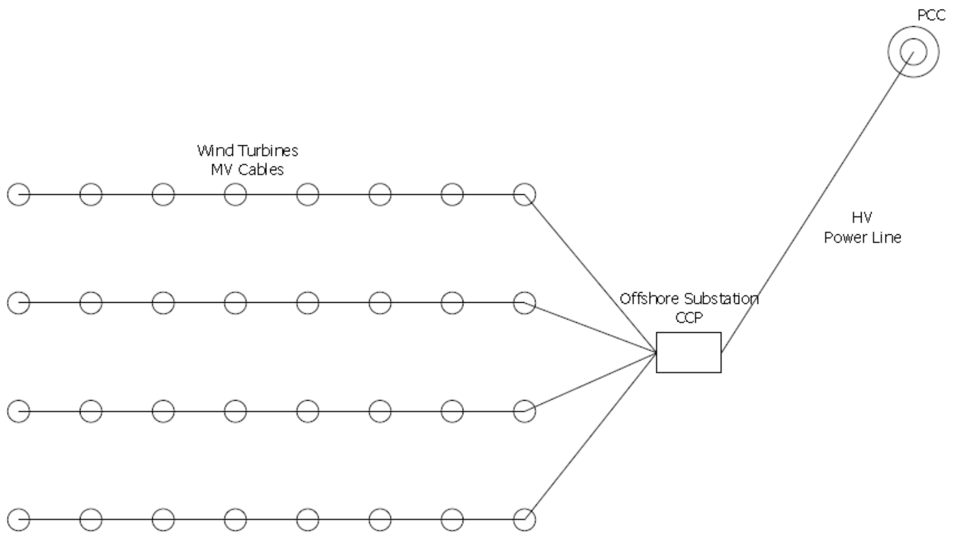


Figure 3-1: First electric power system layout.

The second layout (Fig. 3-2) considers the connection of all wind turbines by MV cables too. These cables gather physically, but not electrically, in a central collection point (CCP) and transmit the power of wind turbines directly to the PCC. Existence and location of the CCP are decisions of the problem, like in the first layout.

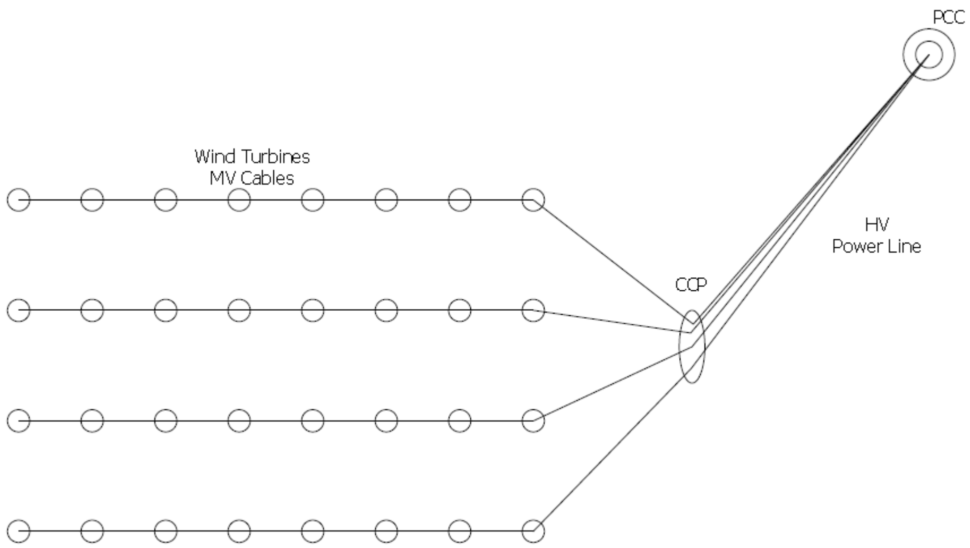


Figure 3-2: Second electric power system layout.

It is assumed that the wind speed, *v*, is common for the upwind turbines, and for the rest of turbines it is taken into account the wake effects in order to work with a more realistic case, including decay of the wind after passing through the upwind turbines. It is assumed that the wind speed, *v*, is distributed according a Rayleigh probability density function of parameter *c* (equation 1), i.e. a Weibull probability density function of parameter *k* equal to two. Consequently, and after an altitude correction (equation 2) (wind shear) due to the fact that the wind speed is not constant with the variation of height, the average wind speed $\bar{v}$ at the site is calculated from this equation (equation 3). Additionally, even though the effect of wake on the wind turbine power output is associated with the incoming wind's direction [12], in this project is assumed only one direction, the main one.

$$f(v) = 2(\frac{v}{c^2})e^{(-\left(\frac{v}{c}\right)^2)} \tag{1}$$

$$\bar{v} = \frac{v_{ref} Ln(\frac{Z}{Z_0})}{Ln(\frac{Z_{ref}}{Z_0})} \tag{2}$$

$$\bar{v} = c\,\Gamma\left(1 + \frac{1}{k}\right) \tag{3}$$

The first program to be executed is the MATLAB programming. This is used for calculating some important inputs which later will be implemented in the GAMS code.

The data extracted from MATLAB programming are the main distances (for example the distance between different turbines, the straight line distance between each wind turbine and the different locations of the substation), but the most important part of the MATLAB model is the consideration of the stochasticity of the wind. The output of this las point will be the power output of each wind turbine for every scenario considered.

Finally, using all this information taken from the MATLAB outputs, input data related to the OWPP, etc. the following step is to implement GAMS advanced language to carry out the main optimization.

In the following sections will be developed every part in order to explain step by step the process followed. Using the two different mains programs, it is carrying out the optimization of the electric power system of the offshore wind farm.

3.2 Wake effect

A wake is the downstream region of disturbed flow, caused by a body moving through a fluid, in our case it is wind. In the turbine case, the wind forces the blades to rotate, thus generating mechanical energy which is subsequently converted to electricity. The energy extraction decreases the wind speed and increase turbulence at the rear of the turbines, which reduces energy production at downwind turbines. The turbulence can cause downwind turbines to be under additional mechanical stress, which may reduce their operating life.

It is shown that not only wind speed but also wind direction of the incoming wind affects the energy amount produced by a wind farm. To reduce the effects, wind turbines should be spaced at least 5 to 9 rotor diameters away from each other in the main wind direction and about 3 to 5 D for winds coming perpendicularly [13].

Several studies which carry out extensive comparison between different wake models [14] allow concluding that there is a high uncertainty in all models performance. However Vanluvanee [14], recommends the N.O. Jensen model for energy predictions, as it offers the best balance between positive and negative predictions errors, so this will be the method used in this project. At the same time this model has a good accuracy and low computational time and complexity (when it applied to programming).

Although Jensen's model is one of the simplest models for computing wake effects, it was selected for this study as it provides adequate accuracy and reduced computational time. It assumes that the wake downstream expands linearly (Fig. 3-3), with a velocity deficit only dependent of the distance behind the rotor section.

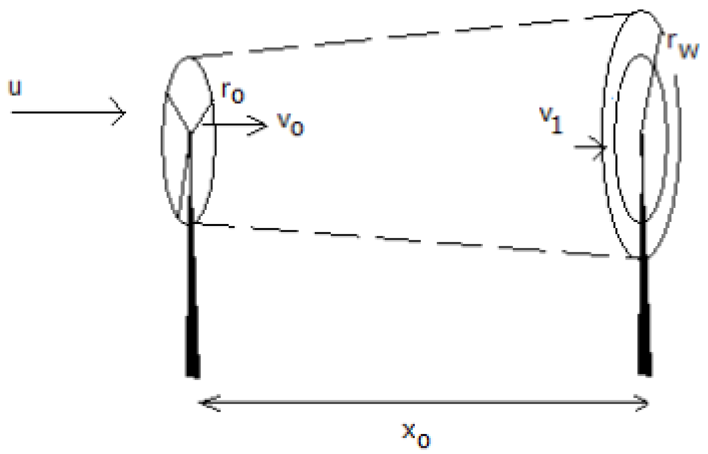


Figure 3-3: Wake of an upwind turbine rotor disc based on Jensen's model

Considering wind direction in analysing wake effects is important, because different wind directions cause different types of wakes. Turbines facing the wind (upwind turbines) are likely to receive more stable and consistent wind. Rear turbines (downwind) receive wind with reduced wind speed and more turbulent.

The wake downstream follows a top-hat distribution, it means that near the edges of the wake the deficit is the lowest.

Despite these last facts, the following assumptions were made when calculating wind speed per turbine:

- Top hat wind speed distribution of the wake is ignored, i.e. the wake wind speed is constant at a given distance.
- The effect of upstream wind speed change, i.e. reduction of wind speed at upwind turbines, takes effect on the downwind ones immediately (in reality there is some delay in this effect taking place due the distance between turbines).
- Turbulence in the wind is neglected.
- It is considered only one predominant direction.

For a location j, downstream wake induced by turbine i, and at a distance d_{ij} projected on the wind direction between i and the point of study j, the wake velocity deficit $v_{def(j)}$ is given by this expression.

$$v_{\mathrm{def}(j)} = 1 - \frac{v_j}{v_i} = \frac{(1 - \sqrt{1 - Ct})}{(1 + \frac{k * d_{ij}}{R})^2} \tag{4}$$

Where v_j is the velocity at location j within the wake, v_i the wind reached by *I* which in the case of only one upwind turbine is the ambient wind speed, Ct the thrust coefficient associated with velocity v_i (but for our study assumed as a constant), *R* the rotor radius, and *k* is the decay factor that is also called the entrainment constant or opening angle which represents the effects of atmospheric stability. Jensen found experimentally the value of k to be 0.075 for onshore applications and 0.04 for offshore applications.

The factor *k* describes how the wake breaks down by specifying the growth of wake in width per meter travelled downstream.

$$k = \frac{A}{\ln(^{z}/_{z_0})} \tag{5}$$

Where *z* is the high of the turbine, *A* is a constant approximately equal to 0.5, and z_0 is the surface roughness.

Also the ratio r_w of the wake disc increase linearly, as it was said before, with distance d_{ij} as:

$$r_w = k\, d_{ij} + R \tag{6}$$

The following equations represent the relative distance s_{ij} and the shadow diameter D_w.

$$s_{ij} = \frac{d_{ij}}{2\,R} \tag{7}$$

$$D_w = D\,(1 + 2k\, s_{ij}) \tag{8}$$

$$r_w = \frac{D_w}{2} \tag{9}$$

The true velocity at the hub high is calculated taking into account the wake effect. Various cases of shadowing are possible: total shadow, partial shadow or a turbine with no shadow of any turbine.

The total or partial shadow is a phenomenon which occurs when one or more upwind turbines cast a single shadow on a downwind turbine (Fig. 3-4). The wind speed at the rotor disc of interest is determined by calculating the ratio (weighing factor, β) of the rotor area in wake to the total rotor area. The equations to calculate the wind speed entering the turbine, extending the above equations to multiple turbine case, are the following:

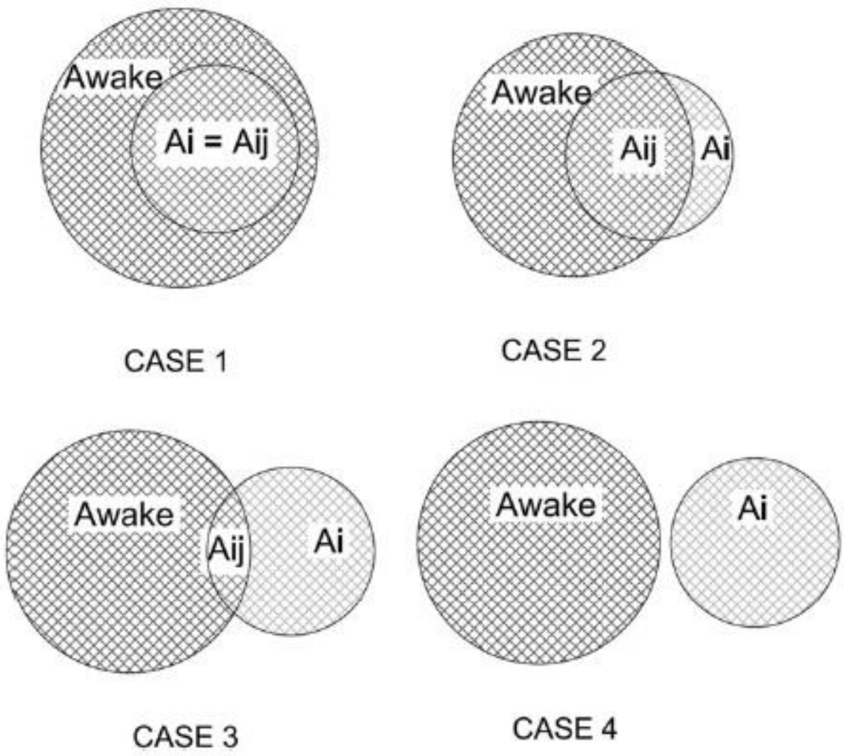


Figure 3-4: Different possibilities for cross sectional intersection area problem

- Case 1: Total shadow case and multiple turbines.

(10)

$$v_{\mathrm{def}(ij)} = 1 - \frac{v_{ij}}{v_i} = \frac{\left(1-\sqrt{1-Ct}\right)}{\left(1+\frac{k * d_{ij}}{R}\right)^2}$$

It is the same equation when only one turbine caste the downwind one, but applied to the case of multiple turbines. $v_{\text{def}(ij)}$ defines the velocity deficit produced by the *i* turbine over the *j* turbine (down wind turbine affected by one or more wakes).

(11)

$$v_{ij} = v_i\left(1 - v_{\text{def}(ij)}\right)$$

The next step is to joint the equation 10 and 11. The resulting equation is the one bellow.

(12)

$$v_{ij} = v_i(1 - \left(\frac{\left(1 - \sqrt{1 - Ct}\right)}{\left(1 + \frac{k * d_{ij}}{R}\right)^2}\right)$$

Now the last step is to refer the last calculations to only one speed, and this speed will be the free wind speed u_0. It is very important to take into account that this is done due to the possible upwind turbines *i* affecting the *j* turbine are not always receiving the free steam wind speed u_0.

(13)

$$v_{\text{def}(ij_{uo})} = 1 - \frac{v_{ij}}{u_0}$$

(14)

$$v_{\text{def}(j)} = \sqrt{\sum_{i \in wake\_j} \left(v_{\text{def}(ij_{uo})}\right)^2}$$

(15)

$$v_j = u_0\left(1 - v_{\text{def}(j)}\right)$$

Where $v_{\text{def}(ij_{uo})}$ represent, as it was said before, the velocity deficit of *i* over *j*, but referring to the mean wind speed of the offshore wind farm. In the next equation $v_{\text{def}(j)}$ is the total velocity deficit of turbine *j* referred to the mean wind speed (u_0). Finally, the real wind speed facing the downwind turbine *j*, after take into account multiple turbines affecting it, is v_j as it is shown in equation number 15.

- Case 2 and 3: Partial shadow case and multiple turbines

It occurs when the upwind turbine cast a shadow, but this one affects only partially the rotor are *A* of the downwind turbine.

$$A = \pi R^2 \tag{16}$$

$$A_{shad} = cos^{-1}\left(\frac{r_w^2 + d^2 - R^2}{2\, r_w\, d}\right) r_w^2 + cos^{-1}\left(\frac{R^2 + d^2 - r_w^2}{2\, R\, d}\right) R^2 - sin\left(acos\left(\frac{r_w^2 + d^2 - R^2}{2\, r_w\, d}\right)\right) r_w\, d \tag{17}$$

$$\beta_{ij} = A_{shad}/A \tag{18}$$

Where A_{shad} is the rotor affected area by the shadow, d is the distance between the two centres (wake area centre and rotor area centre) and β_{ij} represents the fraction of affected rotor area by the wake.

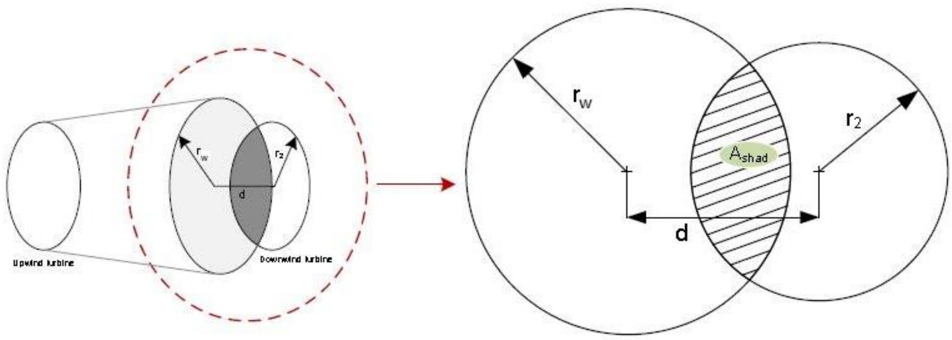


Figure 3-5: The shade area of a downstream wind turbine in partial wakes.

The equations to calculate the wind speed facing by the downwind turbine j are the same used before, but some of them have some modifications. These adapted equations are explained here bellow.

$$v_{\text{def}(j)} = \sqrt{\sum_{i \in wake\_j} \beta_{ij}\left(1 - \frac{v_{ij}}{u_0}\right)^2} \tag{19}$$

And finally and using the last two equations used for the Case 1, the speed of the wind receiving the downwind turbine j is v_j, taking into account the total velocity deficit referred to u_0 (15).

In this study, the wind speed per turbine is evaluated taking into account rotor radius, thrust coefficient value (*Ct*) as a constant, wake of wind turbine, partial shading and multiple wakes according to distance between turbines.

As we have data about the wind farm, and also about the turbines, the power curve of them is assumed to be known. Using this information, the generated power P_i^e is obtained (Eq. 20).

$$P_i^e = \frac{1}{2} c_p \rho \pi \frac{D^2}{4} (v_i^e)^3 \tag{20}$$

3.3 Stochasticity

In the present project the source of stochasticity could come from two different sources, the wind speed at the OWF site and the reliability of the electric power system components. As it was stablish at the beginning the reliability is not considered for this project.

For using this speed that is a random variable in an optimization problem, the option taken has been the discretization of the probability density function in a finite number of values. Each value will represent a wind speed scenario *e*, and after obtain the corresponding speeds of every upwind turbine, the wake effects will be taken into account thought out the application of the Jensen model. The probability of each scenario is obtained by means of the integration of the Weibull probability density function along the scenario. The period duration of every speed scenario,T^e, is obtained multiplying the probability of each scenario with the life span, *L*, of the OWF.

3.4 Mathematical model

Hypothesis

Given an OWF of *N* wind turbines, the location of a generic wind turbine *i* is defined by its coordinates *(x,y)* in a rectangular coordinate system.

It is assumed that the possible locations of the CCP inside the OWF polygon site are known. These locations are defined by its position in the farm, *sub*, in the case of an offshore substation location, or by *p* in the case of locating a collection point of MV cables. The location of the PCC is also known and fixed.

Sets

- i, j generic turbines.
- sub offshore substation (CCP).
- p collection point of MV cables (CCP).
- m, h type of MV or HV cables.
- t type of power transformer of the offshore substation.
- e wind speed scenario.

Parameters

- N number of wind turbines.
- L life span of the OWF [years].
- C cost of non-served energy [EUR/MWh].
- U_{mv} rated medium voltage level [KV].
- U_{hv} rated high voltage level [KV].
- Int interest rate [p.u.].
- P^e wind turbines power generation in scenario e [MW].
- P_r maximum power generation of wind turbines [MW].
- T^e period duration of scenario *e* [h].
- F_m rated active power of cable type *m*, for medium voltage [MW].
- F_h rated active power of cable type *h*, for high voltage [MW].
- C_m investment cost of cable type *m*, for a medium voltage cable [EUR/m].
- C_h investment cost of cable type *h*, for a high voltage cable [EUR/m].
- R_m conductor resistance of cable type *m*, medium voltage at 90º Celsius degrees [ohm / m].
- R_h conductor resistance of cable type *h*, high voltage at 90 Celsius degrees [ohm/m].
- P_t rated power of transformer type *t* [MVA].
- C_t investment cost of transformer type *t* [EUR/unit].
- M_1 Large scalar
- d_{ij} straight-line distance between wind turbines *i* and *j* [m].

- d_2 straight-line distance between the wind turbine *i* and the CCP with substation [m].
- d_3 straight-line distance between CCP with substation and the PCC [m].
- d_{2_3} straight-line distance between the wind turbine *i* and the CCP plus straight-line distance between the CCP and the PCC [m].
- P_E^s probability of the system state *s*.
- E_{i_ccpm} availability (1) or unavailability (0) of the connection of cable type *m* between the wind turbine *i* and the CPP in the sate *s*.
- E_{s_pcc} availability (1) or unavailability (0) of the connection of cable type *h* between CCP and PCC in the system state *s*
- $E_{i\_ccp\_pcc}$ availability (1) or unavailability (0) of the connection of cable type *m* between the wind turbine *i* and the PCC passing through the CPP in the sate *s*.
- E_t availability or unavailability of the transformer type *t* in the system state *s*
- G_h percentage of transmission capacity when one cable type *h* of the connection between the CCP and PCC in unavailable in the state *s*; otherwise it takes value zero.
- N_h minimum number of cable type *h* to withstand the maximum power generation of the OWF in the connection between the CCP and the PCC
- G_t percentage of transmission capacity when one transformer type *t* in unavailable in the system state *s*; otherwise it takes value zero.

<u>Variables</u>

Binary Variables [0, 1]:

- x_1 installation or not of cable type *m* between wind turbine *i* and *j*.
- x_2 installation or not of one cable *m* between wind turbine *i* and CCP in the offshore substation
- x_3 installation or not of one cable *m* between wind turbine *i* and PCC passing through the CPP.
- x_4 installation of connection of cable type *h* between the CPP (substation) and the PCC. Then it has to be multiplied by two values: no connections [0] or installing the minimum number of connections to withstand the maximum generation of the OWF [$(N\,P_r)/F_h$].
- r_2 installation or not of a redundant cable type *m* between the wind turbine *i* and the CPP in the offshore substation.
- r_4 installation or not of a redundant cable type *h* between the CPP and the PCC.

- r_3 installation or not of a redundant cable type *m* between wind turbine *i* and PCC passing through the CPP.
- R_t installation or not of a redundant transformer type *t* in the offshore substation.
- y_1 installation or not of an offshore substation in *sub*.
- y_2 installation or not of a CCP of MV cables in *p*.
- z_h installation or not of connection cable type *h* between the CCP and the PCC.
- z_t installation or not of power transformers type *t* in the offshore substation.
- x_t installation of power transformer type *t* in the offshore substation. Then it has to be multiplied by two values: no power transformers [0] or installing the minimum number of power transformers to withstand the maximum generation of the OWF [$(N\,P_r)/P_t$]

Positive variables:

- f_1 active power flow from wind turbine *i* to wind turbine *j* through cable type m in scenario *e* and system state *s* [MW].
- f_2 active power flow from wind turbine *i* to the CPP through cable type *m* in scenario *e* and system state *s* [MW].
- f_3 active power flow from the CPP to the PCC through cable type *h* in scenario *e* and system state *s* [MW].
- f_4 active power flow from wind turbine *i* to the PCC passing through the CPP through cable type m in scenario *e* and system state *s* [MW].
- *pns* power not served by wind turbine *i* in scenario *e* and system state *s* [MW].

Objective Function

The objective function to optimize is composed of three different parts. These parts are the investment costs of system components and redundant elements, the costs associated with energy not served due to unavailability and the costs associated with power losses in MV and HV cables.

- Investment costs of system components and redundant elements

Investment costs are expressed considering the French system of amortization:

$$\mathrm{C}_{inv} = \left(\frac{\mathrm{Int}(1+\mathrm{Int})^{L}\mathrm{L}}{(1+\mathrm{Int})^{L}-1}\right)\Bigg(\sum_{i,j,m}\mathrm{C}_{m}\mathrm{d}_{\mathrm{ij}}\mathrm{x}_{1} + \sum_{i,sub,m}\mathrm{C}_{m}\mathrm{d}_{2}(\mathrm{x}_{2}+\mathrm{r}_{2}) + \sum_{sub,h}\mathrm{C}_{h}\mathrm{d}_{3}\left(\mathrm{x}_{4}\left(\frac{\mathrm{NP}_{r}}{F_{h}}\right)+\mathrm{r}_{4}\right) + \sum_{i,p,m}\mathrm{C}_{m}\mathrm{d}_{2_{3}}(\mathrm{x}_{3}+\mathrm{r}_{3}) + \sum_{t}\mathrm{C}_{t}\left(\mathrm{x}_{t}\left(\frac{\mathrm{NP}_{r}}{P_{t}}\right)+\mathrm{r}_{t}\right)\Bigg) \tag{21}$$

- Costs associated with energy not served due to unavailability in the system components:

$$C_{unav} = \sum_{i,e} C * T^{e} P\_E^{s} pns \tag{22}$$

- Costs associated with power losses in MV and HV cables of the system:

$$\mathrm{C}_{\mathrm{loss}} = \sum_{i,j,m,e}\mathrm{C\,T^{e}P\_E^{s}}\,3\left(\frac{\mathrm{f}_{1}}{\sqrt{3}\mathrm{U}_{\mathrm{mv}}}\right)\mathrm{R}_{\mathrm{m}}\mathrm{d}_{\mathrm{ij}} + \sum_{i,sub,m,e}\mathrm{C\,T^{e}P_{E}}^{\mathrm{s}}\,3\left(\frac{\mathrm{f}_{2}}{\sqrt{3}\mathrm{U}_{\mathrm{mv}}}\right)\mathrm{R}_{\mathrm{m}}\mathrm{d}_{2} + \sum_{sub,h,e} C\,T^{e}P_{E}{}^{s}\,3N_{h}\left(\frac{f_{3}}{\sqrt{3}U_{hv}N_{h}}\right)R_{h}d_{3} + \sum_{i,p,m,e} C\,T^{e}P_{E}{}^{s}\,3\left(\frac{f_{4}}{\sqrt{3}U_{mv}}\right)R_{m}d_{2\_3} \tag{23}$$

The objective function consists of minimizing the cost of the electric power system:

$$Total\_Cost = \mathrm{C}_{inv} + C_{loss} + C_{unav} \tag{24}$$

<u>Constraints</u>

- Balance of active power flow in turbines:

$$P^{e} - \sum_{j,m}\overrightarrow{f_{1}} + \sum_{j,m}\overleftarrow{f_{1}} - \sum_{sub,m} f_{2} - \sum_{p,m} f_{4} - pns = 0 \quad \forall e, i \tag{25}$$

- Balance of active power flow in the CCP (offshore substation):

$$\sum_{h} f_3 = \sum_{i,m} f_2 \qquad \forall e, sub \tag{26}$$

- Installation of cable connection among turbines if there is active power flow:

$$f_1 \leq F_m x_1 \qquad \forall e, m, i, j \tag{27}$$

- Installation of cable connection between turbines and the CPP (substation) if there is active power flow:

$$f_2 \leq F_m \left(x_2 E_{i\_ccpm} + r_2 \left(1 - E_{i\_ccpm}\right)\right) \quad \forall e, m, i, sub \tag{28}$$

- Installation of connection between the CPP (substation) and the PCC if there is active power flow:

$$f_3 \leq F_h \left(\mathrm{x}_4 \left(\frac{\mathrm{NP}_r}{F_h}\right) \left(E_{s\_pcc} + G_h\right) + r_4 \left(1 - E_{s\_pcc}\right)\right) \quad \forall e, h, sub \tag{29}$$

- Installation of cable connection between turbines and PCC passing through CPP (MV cables) if there is active power flow:

$$f_4 \leq F_m \left(x_3 E_{i\_ccp\_pcc} + r_3 \left(1 - E_{i\_ccp\_pcc}\right)\right) \quad \forall e, m, i, p \tag{30}$$

- Installation of power transformer in the offshore substation if there is active power flow:

$$\sum_{sub,h} f_3 \leq \sum_{t} P_t \left(\mathrm{x}_t \left(\frac{\mathrm{NP}_r}{P_t}\right) (E_t + G_t) + r_t (1 - E_t)\right) \quad \forall e \tag{31}$$

- Large scalar for ensuring minimum number of power transformers to withstand the maximum generation of the OWF (if it exists):

$$\mathrm{x}_t \left(\frac{\mathrm{NP}_r}{P_t}\right) \leq z_t M_1 \qquad \forall t \tag{32}$$

- Joint installation of power transformers of different type t is not allowed:

$$\sum_{t} \mathrm{z}_t \leq 1 \tag{33}$$

- Large scalar for ensuring minimum number of connections using cable h between CCP and PCC to withstand the maximum generation of the OWF (if exists):

$$\frac{x_4 N P_r}{F_h} \leq \mathrm{z}_h M_1 \qquad \forall sub, h \tag{34}$$

- Joint installation of cable connection of different type h between the CCP (substation) and the PCC is not allowed:

$$\sum_{sub,h} z_h \leq 1; \tag{35}$$

- Only one cable type can be selected from each cable connection:

$$\sum_{m} x_1 \leq 1 \quad \forall i, j \tag{36}$$

$$\sum_{m} x_2 \leq y_1 \quad \forall i, sub \tag{37}$$

$$\sum_{m} x_3 \leq y_2 \quad \forall i, p \tag{38}$$

- One cable connection can leave at most from each wind turbine:

$$\sum_{j,m} x_1 + \sum_{sub,m} x_2 + \sum_{p,m} x_3 \leq 1 \qquad \forall i \tag{39}$$

- Installation of a redundant cable connection if there is a cable connection:

$$r_4 \leq x_4 \left(\frac{NP_r}{F_h} \right) \quad \forall sub, h \tag{40}$$

$$r_2 \le x_2 \quad \forall i, sub, m \tag{41}$$

$$r_3 \le x_3 \quad \forall i, p, m \tag{42}$$

- Installation of a redundant power transformer type t if there is a power transformer type t:

$$r_t \le \mathrm{x}_t \left(\frac{\mathrm{NP}_r}{P_t}\right) \quad \forall t \tag{43}$$

- Unique location of CCP:

$$\sum_{sub} y_1 + \sum_{p} y_2 = 1 \tag{44}$$

- Bounds of variables:

$$\mathrm{pns} \le \mathrm{P^e} \quad \forall \mathrm{e}, \mathrm{i} \tag{45}$$

3.5 Case Study

A particular case was used to validate the model as well as to analyze the computation-time performance. This was compared with the results obtained in the literature [4] where the same OWPP is tested and in this way to check if the results are close to the reality or to the literature ones.

The wind farm used in the present project is the Barrow Offshore Wind Farm (BOWF). This is a real offshore wind farm located in the west of England at the East Irish Sea, and was selected to validate the optimization GAMS model.

The main data related to the BOWF are available in some officials web-sites [internet][internet]. The area where is located BOWF is a rectangular site covering approximately 10 Km^2.

This park consists of a total of 30 Vestas-V9 wind turbines [15][16][17] (Fig. 3-6) distributed in four rows, two with seven and two with eight wind turbines (Fig. 3-7). The distance between wind turbines is around 500 m in the normal direction to the wind and between rows is about 750 m in the main wind direction [15][16].

Figure 3-6: Vestas – V9 3MW in the BOWF. Source: 4C Offshore resear organization

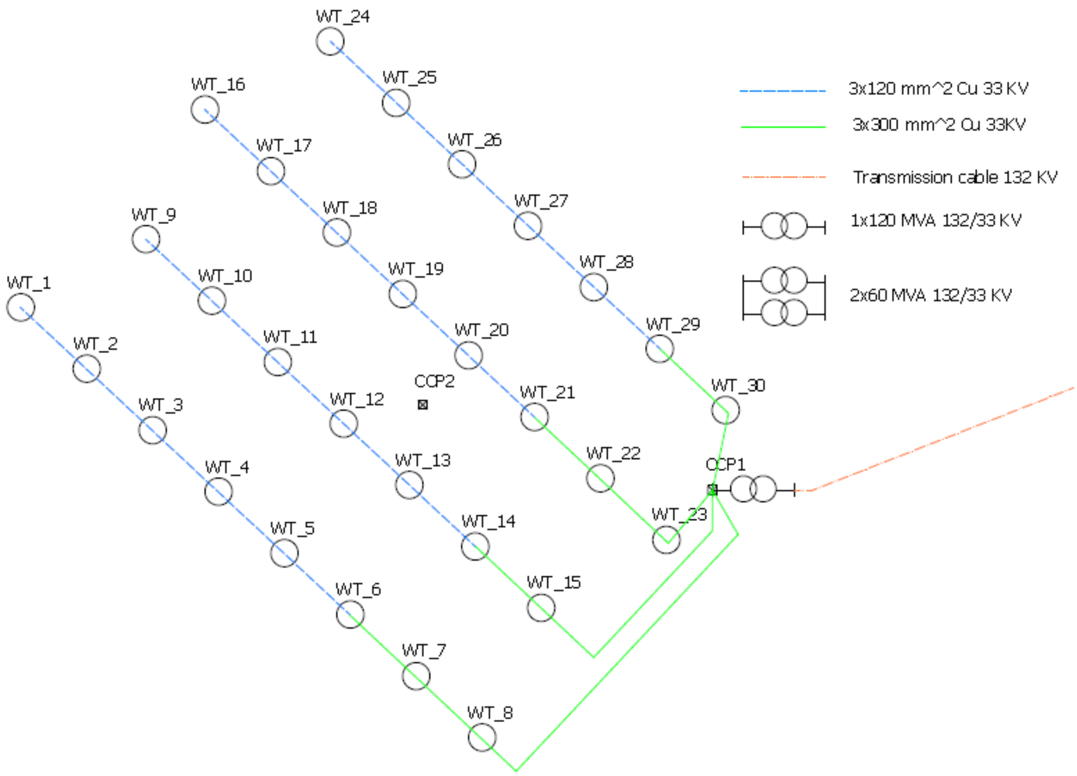


Figure 3-7: Actual layout of the electric power system of BOWF.

The rated power of every wind turbine is 3 MW (total installed power is 90 MW). BOWF has a 132/33 kV offshore substation with a 120 MVA power transformer. The power generated by BOWF is exported to the grid connection point (PCC) through a 27.5 km subsea transmission cable.

It has to be taken into account that some simplifications were done due to the complexity of the programming and to minimize the size of the problem without losing weight in the solver:

- Two possible locations of the CCP were considered (plus to these two possible locations there is one more variable, and this is the existence of an offshore substation or a collection point of MV cables with no offshore platform).
- The cable connections between wind turbines were limited to those pairs which are at a straight-line distance of less than 700. That means connexions with the adjacent turbine, but no between turbines of different rows.
- Two types of MV (medium voltage) and HV (high voltage) cables were taken into account, it means two different conductor cross-sections.
- Also two power transformers with different rated power were considered for the offshore substation.
- Twenty-six wind speed scenarios were taken into account, covering the whole spectrum since zero to the cut-out wind speed, passing through the cut-in and nominal wind speed.

As the Table 3-1 shows, and resulting of these simplifications, the number of variables (single and discrete), number of equations, and so on is as follow:

MODEL STATISTICS			
Block of equations	25	**Single equations**	56091
Block of variables	22	**Singles variables**	56230
Non zero elements	267265	**Non linear N-Z**	51584
Derivative Pool	6	**Constant Pool**	164
Code Length	361094	**Discrete Variables**	606

Table 3-1: GAMS model statistics.

The input data used in the main optimization program is described in the following lines.

Input data of the BOWF problem are as follows:

- A life span of 20 years was supposed.
- An interest rate of 4% was considered.
- A cost of 80 EUR/MWh for energy not served was taken.

- 10 years mean wind speed at 100 meters of height in BOWF is 9.78 m/s [15][16]. Therefore, wind speed was distributed through a Rayleigh density function of parameter c=10.834 according to (3) and the mean wind speed at hub high (75 m) was calculated though out altitude correction (wind shear) according to (2). The correction of speed at different levels is done because it is not constant with the variation of high. The twenty six wind speed scenarios are shown in Table 3-2as well as the Table 3-3 where the results of parameter c and the mean wind speed are obtained.

		Speed interval Low (m/s)	Speed interval High (m/s)
WIND SPEED SCENARIOS	e1	0	1
	e2	1	2
	e3	2	3
	e4	3	4
	e5	4	5
	e6	5	6
	e7	6	7
	e8	7	8
	e9	8	9
	e10	9	10
	e11	10	11
	e12	11	12
	e13	12	13
	e14	13	14
	e15	14	15
	e16	15	16
	e17	16	17
	e18	17	18
	e19	18	19
	e20	19	20
	e21	20	21
	e22	21	22
	e23	22	23
	e24	23	24
	e25	24	25
	e26	25	26

Table 3-2: Wind speed scenarios.

Determining the average wind speed and the wind shear correction	
C weibull(75m) scale parameter	10.8335
K weibull shape parameter	2.0000
C ref (m/s)	9.7800
Z ref (m)	100.0000
roughness	0.00002
wind shear V at 75 m (m/s)	**9.6009**

Table 3-3: Determination of mean wind speed at hub high and weibull parameter c.

- Rated voltages at MV and HV were set to 33 and 132 kV, respectively.
- Wind turbines and PCC coordinates were taken from [16][17].
- One CCP was considered in the current location of the offshore substation (cp1), while the other was located in the middle of the wind farm (cp2). Location of wind turbines and CCPs are shown in Fig. 3-7.
- MV cables are the same used in the wind farm (three-core cables of copper with 120 and 300 cross-sections) [15][16]. For the HV cables selection, three-core cables of copper with 400 and 630 cross-sections were chosen. Current ratings of cables were taken from [8], resistance values were taken from [18], and cost of cables from [7]. Table 3-4 shows these relevant data mentioned before.

		MV Cables		HV Cables	
		120 mm^2	300 mm^2	400 mm^2	630 mm^2
Rated Active Power	F_m F_h (MW)	19.43	30.29	134.89	163.47
Conductor resistance at 90ºC	R_m R_h (ohm/m)	0.000196	0.000079	0.0000631	0.0000416
Investment Cost	C_m C_h (€/m)	258	354	450	578

Table 3-4: Input data of cables.

- The transformers rated power was set to 60 and 120 MVA, which is the real rated power of the current transformer used in BOWF, Fig. 3-7. The data cost of the transformers was extrapolated from [19]. The costs were 0.73 and 1.20 million EUR/unit, respectively.

Some other input data necessary to be analysed by the main optimization model (made it in GAMS) were obtained by means of the programing in MATLAB software, as it was explained before.

Relevant information was extracted from this tool such as the straight line distance matrix between turbines (d_{ij}), the straight line distance between wind turbine i and the CCP with substation (d_2), the straight line distance between the wind turbine i and the CCP plus the straight-line distance between the CCP and the PCC (d_{2_3}).

3.6 Test and results

First of all, it is necessary to talk about the results obtained from the MATLAB programming with the wake effect study applied to the offshore wind farm.

Using this software and all the mathematical formulation in the section 3.2, some important and relevant data are obtained. The main one is the speed matrix, which contains the speed facing each turbine for every wind scenario. Therefore, using this information and applying the equation (20), is obtained the wind power generation matrix, which accounts for the power in every scenario and for each turbine in MW. In the Table 3-5 is showed some info about the first fifteen turbines and for the scenarios from one to six (due to the size of the real matrix, all this info is attached in the annexes).

P^e						
	sc1	sc2	sc3	sc4	sc5	sc6
t1	0	0	0	0.07517919	0.15978318	0.29173032
t2	0	0	0	0.07517919	0.15978318	0.29173032
t3	0	0	0	0.07517919	0.15978318	0.29173032
t4	0	0	0	0.07517919	0.15978318	0.29173032
t5	0	0	0	0.07517919	0.15978318	0.29173032
t6	0	0	0	0.07517919	0.15978318	0.29173032
t7	0	0	0	0.07517919	0.15978318	0.29173032
t8	0	0	0	0.07517919	0.15978318	0.29173032
t9	0	0	0	0.07517919	0.15978318	0.29173032
t10	0	0	0	0.07517919	0.15978318	0.29173032
t11	0	0	0	0.07517919	0.15978318	0.29173032
t12	0	0	0	0.07517919	0.15978318	0.29173032
t13	0	0	0	0.07517919	0.15978318	0.29173032
t14	0	0	0	0.07517919	0.15978318	0.29173032
t15	0	0	0	0.07517919	0.15978318	0.29173032

Table 3-5: Power generation matrix accounting every scenario and wind turbine in MW

Other important data extracted from this MATLAB programming is the period duration of scenario e , T^e (Table 3-6). As it was explained before, this data is obtaining multiplying the probability of each scenario with the life span of the OWPP (L).

		Speed interval Low (m/s)	Speed interval High (m/s)	Probability of scenario e (%)	Period duration of scenario T^e (h)
WIND SPEED SCENARIOS	**e1**	0	1	0.850%	1489.4689
	e2	1	2	2.507%	4392.9130
	e3	2	3	4.039%	7076.2176
	e4	3	4	5.373%	9413.0197
	e5	4	5	6.453%	11305.0659
	e6	5	6	7.243%	12688.8673
	e7	6	7	7.727%	13538.5770
	e8	7	8	7.914%	13865.0148
	e9	8	9	7.826%	13711.2588
	e10	9	10	7.503%	13145.6254
	e11	10	11	6.994%	12253.1037
	e12	11	12	6.351%	11126.3759
	e13	12	13	5.626%	9857.4570
	e14	13	14	4.869%	8530.7567
	e15	14	15	4.120%	7218.0621
	e16	15	16	3.411%	5975.6211
	e17	16	17	2.764%	4843.2173
	e18	17	18	2.195%	3844.9140
	e19	18	19	1.707%	2991.0165
	e20	19	20	1.302%	2280.7626
	e21	20	21	0.973%	1705.2877
	e22	21	22	0.714%	1250.4908
	e23	22	23	0.513%	899.5446
	e24	23	24	0.362%	634.9012
	e25	24	25	0.251%	439.7464
	e26	25	26	0.171%	298.9333

Table 3-6: Period duration of each wind speed scenario e, in hours.

Furthermore, and after commenting this part of the project where is obtained important data to be used in the optimization model of the electric power system, it is showed the main results of the optimization made in the GAMS software.

The current electric power system layout of BOWF is shown in Fig. 3-7. It is consists of four MV circuits. Each circuit connects all the wind turbines in a row. Cables of 120 mm^2 cross-section connect the furthest six wind turbines from the offshore substation in each MV circuit, whilst cables of 300 cross-sections are connecting the closest wind turbines of each MV circuit to substation. The cable of the 132 kV power line is a three-core cable with 400 mm^2 cross-section. The offshore substation is located in the eastern part of BOWF (*CCP1*). Redundancies of cables or transformers are not installed in the actual wind farm.

The cost of the electric power system layout of BOWF, calculated from the model, is shown in Table 3-7.

	Actual layout	optimal solution of reference literature	optimal solution
Investment Cost in components C_{inv} (million €)	25.15	25.23	21.55
Cost associated with energy not served C_{unav} (million €)	5.87	5.29	--
Cost asscociated with Power Losses C_{loss} (million €)	3.94	4.09	4.01
TOTAL COST (million €)	**34.96**	**34.62**	**25.56**

Table 3-7: Comparison of costs.

In this table is also shown the solution of the optimization of the reference literature [4] where is taken into account the stochasticity of the reliability. The optimal solution from the model is shown in Fig. 3-8 and Table 3-7. The computation time is 14533 s in a Personal computer of 2.1 GHz, with 8 GB RAM memory, running Microsoft Windows 8.1. In Fig. 3-9 is showed also a summary of the GAMS optimization program after getting the optimal solution.

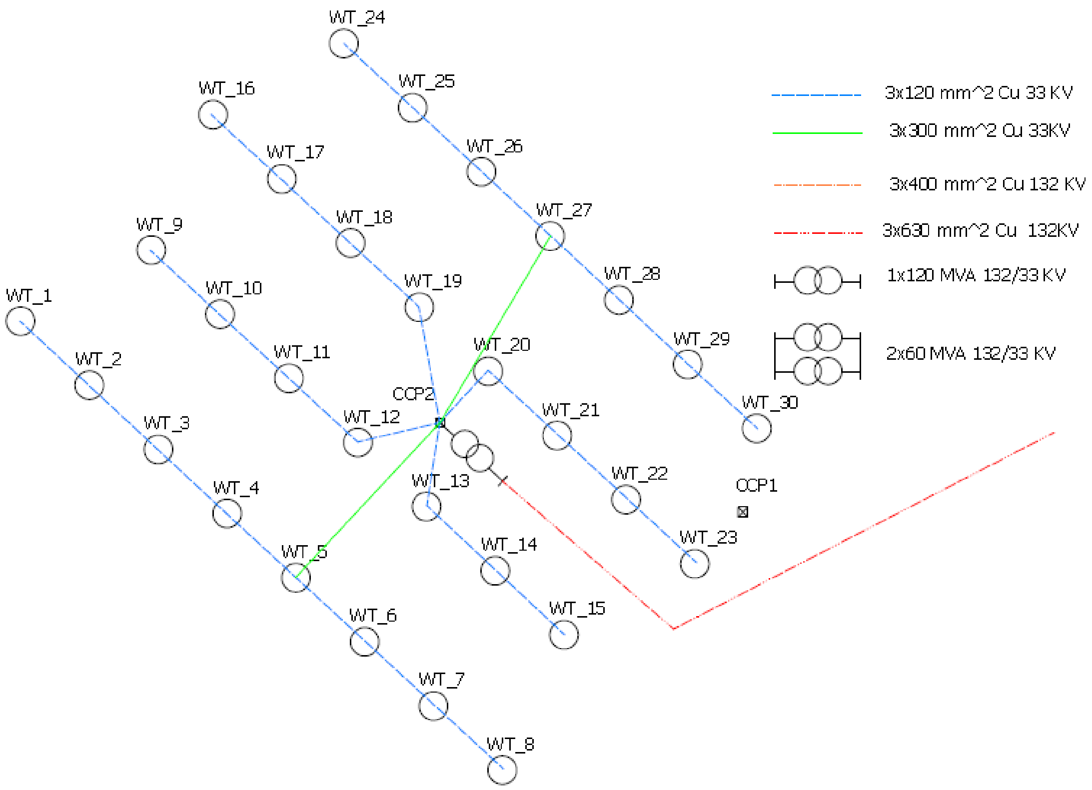


Figure 3-8: Optimal solution for the electric power system of BOWF.

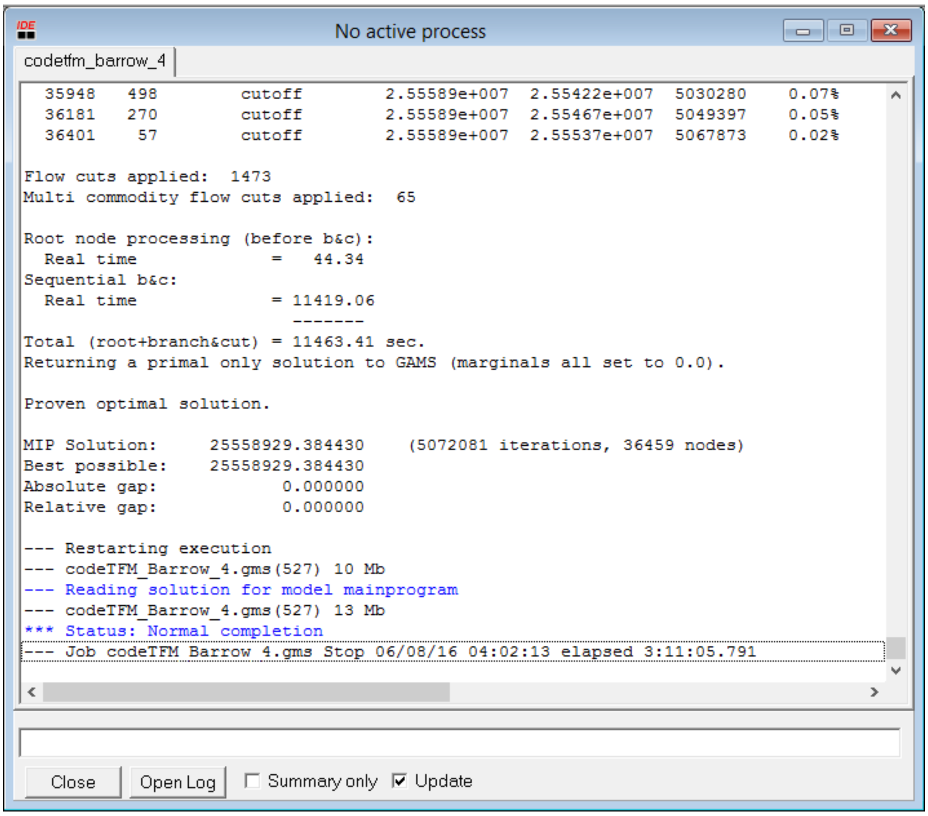


Figure 3-9: GAMS summary of the optimal solution obtained.

According to the results extracted from the GAMS software which solved the mixed integer quadratic constraint programming (MIQCP), it is obtained that redundancies in MV cables, HV cables or power transformers are not required. Moreover, as in the present project the reliability is not taken into account, the cost associated with energy not served (C_{unav}) is zero.

As you can see in the Fig. 3-8 the optimal solution of the present project is quite different in comparison to the actual layout of the electric power system of BOWF. The offshore substation is located in the middle of the farm (*CCP2*) and the inter-array connections, between turbines of the same raw, is made by means of MV cables of 120 mm^2 cross-section. Then the groups of three, four, seven and up to eight turbines are joint to the offshore substation using MV cables of 300 mm^2 cross-section, they are the closest wind turbines of each group to the offshore platform. The selected power transformer is one 120 MVA and from here to the shore the electricity is shipped to shore by means of only one 630 mm^2 cross-section HV cable.

If it is checked the Table 3-7 also is shown that by assuming the input data and hypotheses of the model, the optimal solution extracted from the model is more economical (by 1%)

than the actual layout by 26.9 %. Also, and only making an assumption, if it is added the cost associated with energy not served energy (C_{unav}) of the actual layout (5.87 million €), then the saving is 10 %.

4 Conclusions

This model covers the main aspects that determine the layout of the electric power system of OWFs: investment costs and system efficiency. An interesting and dynamic decision support model for optimizing ac electric power systems of OWPPs has been presented in the present project. Also, an important aspect to model OWFs as the stochasticity in wind speed has been taken into account

The location of the OWF is also considered in this model. Likewise, the model can handle a range of CCP locations. A large variety of OWPPs may be studied with this model because it can deal with electric power systems with or without offshore substation.

As you can see in the Fig. 3-8 the optimal solution of the present project is different in comparison to the actual layout. This permit to get savings mainly in component investment costs. Moreover, checking the results on Table 3-7 is seen the model works properly as they are close to the reality, at least when measuring the same studied parameters.

The reason why an 630 mm^2 cross-section HV cable has been selected for the model instead of a 400 mm^2 cross-section cable, is due to: equations 23, accounting for energy losses, and 24 whose objective is minimize the total costs, give this output as solution because it is searched not only a cheaper cable, but also one which has less energy losses (also less cost associated to this factor). According to literature [8] by means of using larger conductor, the load losses primarily due to the ohmic losses can be reduced.

Moreover the chosen optimum cable routing is quite suitable since it is very important try to avoid cable crossing when it is possible. Cable crossing is highly not recommended in practice, because building one cable on top of another is expensive and increases the risk of damages [20].

Finally, it is listed a series of possible implementations to be considered into the model presented in this project, both in the MATLAB programming and the main optimization GAMS program.

Considering ring layouts for the MV collection system or locating more than one offshore substation are some of the possible extensions to be performed in the model. Other important improvement could be the addition of several (instead of only the main one) wind directions in order to take a more realistic simulation, taking into account the wind rose and the Weibull parameters (probability) of the location of the OWPP.

System reliability assessment is maybe the most interesting improvement to be taken into account for future versions of this optimization model. This assesses the possibility of having redundancy for system components subject to failure.

For the implementations of these improvements a more complex programming is necessary. It means the removal of some of the current constrains, additions of new formulation and variables, sets, number of scenarios, etc. to the detriment of the execution time which has to be checked along with the main programming after all this changes in order to analyzed if the optimization model is feasible or not. This point is very important because the optimization time in the solver increases exponentially and in the present project, when it was tried to consider ring layout, it was no possible to obtain any result because the running time was huge.

To sum up, this model is useful for basic engineering design and it works as a decision tool for the planning of the electric power system of an OWPP.

5 References

[1] The European Wind Energy Association, European Statistics February 2016.

[2] The European Wind Energy Association, Wind Energy – The Facts, 2009.

[3] G. Quinones – Urela, G.W.Ault, O.Anaya-Lara, and J.R. McDonalds, " Electrical Collector System Options for Large Offshore Wind Farms", IET Renew. Power Gener., Vol. 1, no. 2, pp. 107-114, June 2007.

[4] Marcos Banzo, Member, IEEE, and Andres Ramos, "Stochastic Optimization Model for Electric Power System Planning of Offshore Wind Farms", IEEE TRANSACTIONS ON POWER SYSTEM, Vol.26, no. 3, August 2011.

[5] The European Wind Energy Association, Rewarding Ambition in Wind Energy, November 2015.

[6] Oriol Gomis-Bellmut, "Wind Energy", UPC – Master's Degree in Energy Engineering, 2014.

[7] J. Green, A. Bowen, L.J.Fingersh, and Y. Wan, "Electrical Collection and Transmission System for Offshore Wind Power", in Prac. Offshore Technology Conf., 2007.

[8] "XLPE Submarine Cable Systems, Attachment to XLPE Land Cable System – User's Guide", ABB.

[9] I. Perez Carretero, "Modelo y comparativa técnico-economica de subestaciones" , Universidad Pontificia de Comillas. 2007. Available: http://www.iit.upcomillas.es/pfc/resumenes/46e9219f4524b.pdf]

[10] "Transmission Infrastructure Components – Offshore", Transmission Infrastructure for Offshore Generation, Available: http://www.transmissioninfrastructure-offshoregen.co.uk/media/9360/Offshore_AC_substation_and_ACDC_converter_station.pdf

[11] Van Eeckhout, B., Van Hertem, D., Reza, M., Srivastava, K., & Belmans, R. (2010), " Economic comparison of VSC HVDC and HVAC as transmission system for a 300 MW offshore wind farm", European Transactions on Electrical Power, 20(5), 661-671.

[12] F. Koch, M. Gresch, F. Shewarega, I. Erlich, U. Bachmann, "Consideration of Wind Farm Wake Effect in Power System Dynamic Simulation," in Power Tech IEEE, Russia, 2005.

[13] Merete Bruun Christiansen, Charlotte B. Hasager, "Wake effects of large offshore wind farms identified from satellite SAR", Remote Sensing of Environment 98, pp. 251-268, March 2005.

[14] Vanluvanee DR. Investigation of observed and modelled wake effects at Horns Rev using windpro, Report, Technical University of Denmark, MEK Department, Fluid Mechanics Section, Denmark 2006.

[15] "Offshore Wind Capital Grant Scheme, Barrow Offshore Wind Farm 2nd Annual Report", WIND POWER PROGRAM – Department of Energy 8 –Climate Change. Available: www.wind-power-program.com

[16] 4COffshore website. Available: www.4coffshore.com

[17] Vestas website. Available: www.vestas.com

[18] General Cable, Tables on Conductors. Available:
http://www.generalcable.es/Productos/AyudasTécnicas/tabid/378/Default.aspx.

[19] L. P. Lazaridis, "Economic comparison of HVAC and HVDC solutions for large offshore wind farms under special consideration of reliability," M.S. thesis, Dept. Elect. Eng., Royal Inst. Technol., Stockholm, Sweden, 2005.

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