



Design procedure for inter-array electric design (D2.2)

Atsede G Endegnanew, Harald G Svendsen, Raymundo E. Torres-Olguin
SINTEF Energy Research, Trondheim

Luis Mariano Faiella
Fraunhofer IWES, Kassel

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1 INTRODUCTION

This report describes the procedure for wind farm inter-array electrical design, i.e. the design of the wind farm collection grid. This includes the electrical design from the wind turbine terminal to the wind farm or cluster hub. It is assumed that the technology, capacity and location of the wind turbines have been determined beforehand.

The aim of this report is to describe the overall design process, the main drivers or factors that determine the choices, the design variables and the analyses that are performed to support the design process. There are many inter-dependent design variables and it is infeasible to devise a generic algorithm for making an optimal choice. Instead, the design procedure described in this report focusses on describing the technical content and implications of each design variable.

This report, and the procedure it describes, provides a high-level overview intended for a broad group of people without necessarily a background in electrical engineering. As such it is likely to be useful for those wanting to understand the electrical design process without going into great detail. It is explicitly not the aim of this procedure to be a recipe for an optimal electrical design, as the optimal design is very case specific and dependent on a large number of input parameters that change continuously due to technology improvements and maturing.

The collection grid in this context refers to the electrical grid between the wind turbine terminals to the wind farm substation. The electrical design of the turbine itself, including generator and converter concepts, is therefore not included. It has been assumed in this discussion that the location of the turbines is given. In reality, however, the location of the turbines is influenced by the electrical design, whereby electrical power losses and investment costs counterweight the reduced wake losses with increased distance between turbines.

The report is divided in three main sections. Section 2 gives an overview of the design-process with a flow-diagram illustrating a step-by-step approach. Section 3 discusses the most important design variables with an indication on how different choices affect other variables. Section 4 summarises very briefly different analyses that needs to be performed as part of the electrical design process. Some concluding remarks are given in the final section.

1.1 Design objective

Electrical design of a wind farm concerns all electrical components and how these are put together in a suitable grid structure. The overarching goal is to design an electrical system that ensures that as much as possible of the available wind power is transferred to the transmission system with as small as possible costs.

At a more detailed level, different views are possible regarding what the above statement should mean: From the point of view of the society as a whole, the most relevant variable to minimise might be the cost of energy. However, this is rarely the most relevant variable for a wind farm developer, who might be most interested in maximising the return on investment.

Regardless of such details, it is clear that the "best" design will not have prohibitive costs, will have low electrical losses and be reliable and operate at high availability during the wind farm lifetime. It is, however, not the purpose of this report to undertake detailed comparisons based on costs and reliability, as these are very dependent on the specific situation.

1.2 Design drivers

This section outlines the main drivers which determine the wind farm electrical design. These reflect the design objectives mentioned above and also include constraints such as commercial availability of sufficiently mature technology.

1.2.1 Cost

It goes without saying that investment cost is very important for the electrical design. However, investment cost is only a part of the entire cost/income picture, and equally important is the expected income. A higher investment cost may be compensated by increased income, e.g. through reduced power losses or higher reliability (fewer days out-of-operation).

The term "cost" does not have a unique definition and can have different meaning in different contexts. In the present context, it is important to be clear whether it refers only to investment costs or whether it also includes operational and maintenance costs and "costs" associated with power losses and lost production.

1.2.2 Constraints

Physical dimensions

In offshore circumstances, the lack of space around the wind turbines forces the developers to implement technical solutions suitable to be mounted into the wind turbines' tower or over a side auxiliary platform.

Directly related with the size, the weight of the installed components determine the characteristics of the foundations and those characteristics -again- their acquisition and installation costs.

Commercial availability

An important design decision for developers is the choice between research-level designs and well-proven commercial designs. Designs of actual wind farms are usually based on technology that is commercially available and well proven: known capital expenditure (CAPEX), installation and operation and maintenance (O&M) costs, known reliability and already available know-how. Often, new technological solutions can be custom-made, but this represents a risk for the wind farm developer and as such a cost that is weighed against the benefits.

1.2.3 Reliability

Reliability of components and systems are key factors due to the fact that maintenance, repairs and replacement of defect components on offshore locations are extremely complex and expensive. Well-proven technology is usually preferred over too innovative solutions due to the experience achieved on previous operation. Nevertheless, the same expensiveness and complexity of offshore operations are the reason of technological innovations and new practices that should be tested finally to improve reliability and the O&M procedures, and consequently, decreasing the operational costs.

The level of reliability within the wind farm is generally a trade-off between the extra investment cost and the cost savings from reduced repairs and loss of production. Finding the optimal balance in this regard is associated with significant uncertainty because of the underlying uncertainties in failure rates and repair times (which may be weather dependent). However, formal reliability analyses can be done, such as described e.g. in ref. [1], to assist the decision making.

It is important to keep in mind that the consequences of failure in the wind farm grid are purely economical, as no people are directly affected. This is different from e.g. onshore distribution systems where grid failure often has social costs as well. The required level of reliability may therefore not be as high as in onshore distribution grids. The desired level of reliability influences the choice of grid topology and protection scheme in the wind farm. It may also affect the choice of equipment if there is a difference in presumed failure rate.

1.2.4 Innovative or conservative design

As basic principles, implementing well-proven technology and following a conservative design are important precepts at development time in order to minimise the design associated risks.

Nevertheless, the implementation of new techniques and concepts could lead to improved procedures to minimise cost and losses and to maximize the return of investment.

This document focusses on known, state-of-the-art technology and procedures, but includes some discussion of innovative concepts as well, such as cabling layout and cable type for floating wind farms, and the use of higher grid voltages.

1.2.5 Bottom-fixed or floating turbines

A fundamental distinction for offshore wind farms which also affect the electrical design to some degree is whether turbines are bottom-fixed or floating. At present, two full-scale floating wind turbines are in operation (Hywind and WindFloat), but floating concepts are seen to be the only viable options for deep waters (of more than about 50 m). There is currently no "standard" floating design, with many widely different concepts under development. A generic discussion of floating wind farms is therefore difficult. However, it is clear that floating vs. bottom-fixed is a driver also for the electrical design – to some degree. Particular issues related to floating designs are discussed in Section 3.7.

1.3 Existing design tools

By wind farm layout optimisation we mean the task of finding a wind farm layout where initial investment cost and losses are minimised while energy production, reliability and life time profit are maximised. This optimisation is today typically solved by hand or brute-force techniques by the developer, whose main interest is an economic optimisation such as maximum return on investment. However, there exist commercially available software tools capable of performing at least parts of the tasks involved, such as *WindPro*, *EeFarm*, and *TopFarm*. These programs take into account factors that are significant for a wind farm in general like turbine cost, wake effect, operation and maintenance, distance from shore, spacing between turbines, etc. [2].

These software tools are used to evaluate the electrical and economical aspects of different electrical layouts by calculating cost of energy from investment cost, wind speed distribution and wind farm power output. *WindPro*¹ is a software tool developed by the Danish energy consultant EMD. It can optimize a wind farm layout using data such as the space between turbines, and restriction such as setback distances, and noise level. The tool is able to perform the electrical design such as load flow, losses from cables, voltage fluctuations, and short circuit current analysis. Moreover, it is also able to perform economy calculation and environmental analysis. *EeFarm* is a software tool developed by the Energy Research Centre of Netherlands (ECN) [3]. *EeFarm* is performed using a steady state model to calculate the currents, voltages and losses of the wind farm layout including wind speed data. Economical restrictions can be included to calculate the overall production cost. *TopFarm* [4] is a tool developed in a research project led by DTU, which optimises turbine locations using a coupled model including aerodynamics, electrical grid and a cost model.

There are also other types of optimization functions that are more focused of finding an optimal electrical collection grid layout in order to fully benefit from potential cost savings. One example of such optimisation algorithms is the Offshore Wind farm Layout optimizer model (OWL) [5]; which performs full optimization of collection and transmission systems for an offshore wind farm. The model is not restricted to any standard configurations and considers wind scenarios, losses, reliability and HVDC as one option of connection to shore. Inputs to the model include characteristics and positions of the individual wind turbines, the point of common coupling (PCC) and possible locations of offshore substations, as well as cable, transformer and converter types available and their features. The model returns as an output an optimal electrical layout with selected types of cables, transformers and location of converter stations.

¹ <http://www.emd.dk/WindPRO/>

2 DESIGN PROCEDURE

This chapter outlines a step-wise procedure for designing the electrical system for the internal collection grid of an offshore wind farm. Since design choices are very dependent on the specific circumstances, including cost data that is difficult to obtain on a generic level, this outline does not intend to provide a recipe for making "best" choices. Instead, it aims to describe which electrical engineering considerations need to be addressed, in which order to proceed, and what the options are. This procedure is intended for present and near future wind farms, such that the solutions which are considered are either presently available or expected to be available in the near future.

Figure 2-1 shows the flowchart of the proposed design procedure for the electrical designing of the internal collection grid of an offshore wind farm. The flowchart is composed by *selection*, *calculation*, and *decision* processes. These are represented in the chart by blocks with blue line, green line, and red line respectively. In the following, each block is described briefly. More detailed discussions are given in Section 3 and Section 4.

Input

As mentioned above, it is assumed that the capacity and physical layout of the wind farm have been defined previously. This means that wind patterns, wake effects, structural constraints, and all relevant studies concerning with the location are assumed to be available data.

Select AC or DC

The internal electrical grid of an offshore wind farm can have either AC or DC collector system. The selection between AC and DC affects the choice of wind turbine technology. It is dependent on whether the transmission system to the onshore grid is AC or DC.

Select voltage level

Voltage level is selected according to standard voltages. At higher voltage levels the cables will have higher power carrying capacity and lower ohmic losses. However, availability, cost and the size of the transformers in the offshore turbines are the main drawback to employ higher voltage level.

Number of substation and locations

Selection of substations is related with the capacity of the wind farm and voltage level. However, the number of substations needed may change with a power flow analysis. A power flow analysis will estimate the power losses in the collection grid. If power losses are too high, then it may be necessary to select more substations and locate them appropriately. The idea is to reduce the length of each cable to the substations.

This design procedure proposes, as the first approach, to use the minimum number of substation according to the voltage level, capacity of the wind farm and commercial availability of equipment. Once a reference layout is decided, an iteration with increasing number of substations can be conducted until power losses are acceptable.

Cabling optimization

The radial cable feeder configuration is the most common grid topology. However, the selection of topology and cable layout may be optimised to give e.g. the shortest total length. The typical approach is to do this by hand or using brute-force such as generic algorithms.

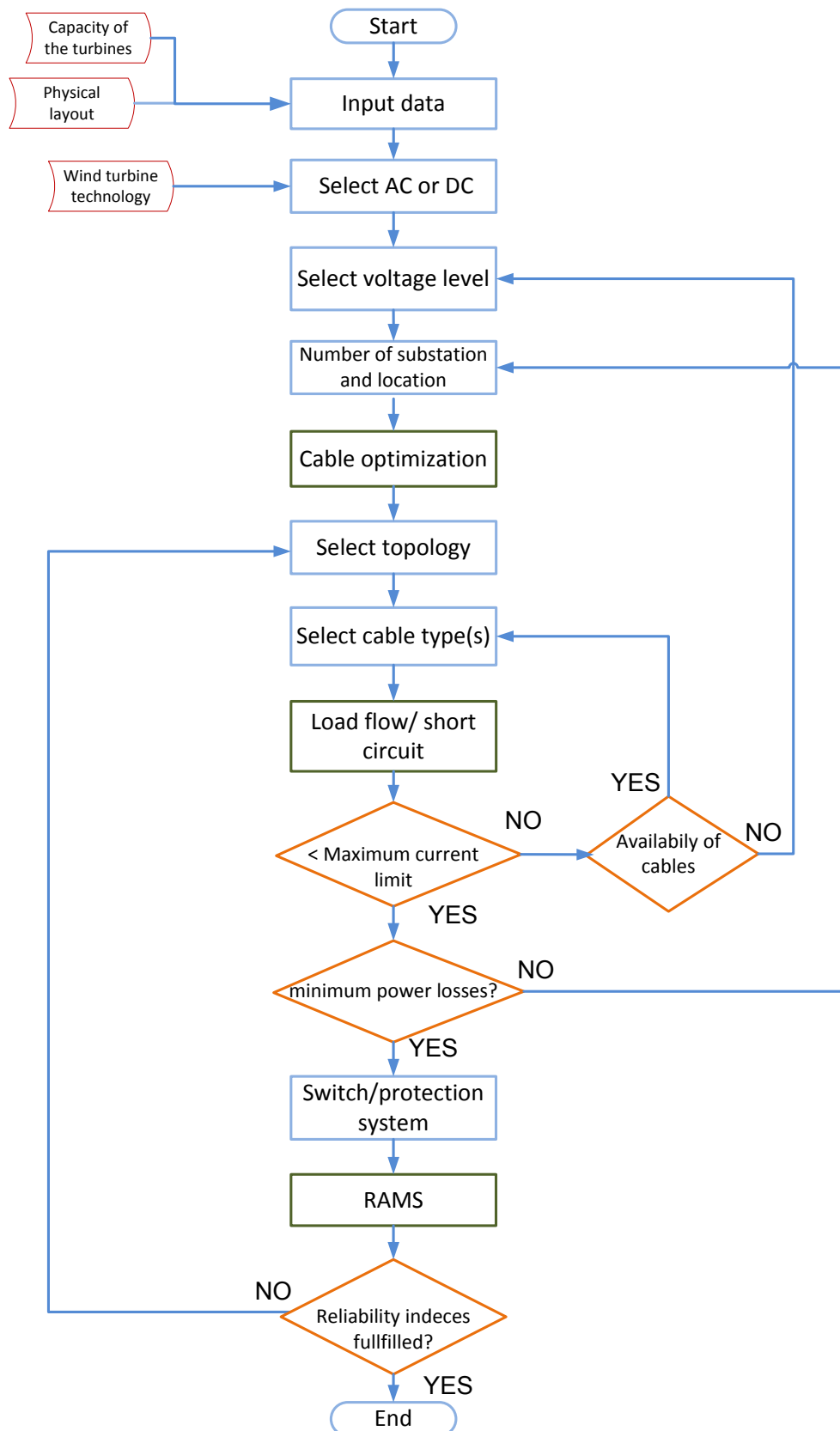


Figure 2-1: Overview of design process

Select topology

There are several options for the wind farm grid topology. The selection should be based on an assessment taking into account the total investment cost, power losses, maintenance, and amount of non-harvested energy due to unavailability. Redundancy may increase the energy production since it can reduce losses during failure of some inter-turbine cables, but is an extra cost that should be evaluated.

This procedure proposes to select an initial topology using a simple optimization procedure, and use this as a basis for further modification according to additional criteria such as e.g. reliability.

Select cable type(s)

Submarine cables are available in wide ranges of cross-sections. There are several factors that determine the appropriate cable sizes, such as the maximum amount of current, heating and power losses.

Cable cross-sections are determined iteratively using the power flow, and short circuit analyses (see below). In the beginning, it is assumed the lowest available cross-section cable for the voltage level. Then, the current rating is determined using the power flow analysis. It verifies that the thermal limits and short circuit currents are not exceeded in each cable. If not, it goes to next step. If yes, a new number of cables or a new cable cross-section is calculated. The iteration ends when the minimum cross-section for the minimum number of cables is determined for all cables in the layout. Another possibility is that certain cross-sections are not commercially available. In this case, a new voltage level should be selected.

Load flow /short-circuit analyses

Short-circuit analysis is performed to determine the maximum short circuit current support for cables and other equipment. Power flow analysis allows verifying that the magnitude of the voltages at each node is between the set voltage limits, and that the maximum amount of power injected in the points of common coupling is never exceeded. Moreover, power flow analysis allows checking if some equipment is overloaded.

Besides the analyses mentioned above, the cable manufactures specify the maximum permissible temperature limits. It is important to identify the short circuit requirements but also to verify that cable temperatures are within the maximum permissible limits.

Switch/protection system

The design of the protection system affects availability and amount of lost production, and of course, the investment cost.

Short-circuit analyses can provide information to determine appropriate equipment rating and settings of the protection system, e.g. the protective relay settings. Thus, mal-operation of the protection system can be avoided. AC protection systems consist of transducers, relays, circuit breakers, disconnectors, auxiliary power and all wirings in between.

Reliability, Availability, Maintainability, and Serviceability (RAMS)

In general, high reliability is required from offshore wind farm components due to difficult and expensive access to perform repairs. Overall reliability is usually calculated based on a number of reliability indices specified at component level. These indices include for example failure rate and time-to-repair. For the internal wind farm grid where there are no critical loads to supply, availability rather than reliability in itself is the primary concern. Availability refers to the ability of the wind farm to produce the maximum possible amount of power. It is dependent on the reliability, but can be increased by including redundancy, e.g. redundant cables.

The level of reliability/availability within the wind farm is a trade-off between the extra investment cost and the cost savings from reduced loss of production. The choice affects the grid topology and switchgear and protection system in the wind farm. It may also affect the choice of equipment if there is a difference in presumed failure rate.

As noted, access for maintenance is difficult and expensive. So, maintainability, and serviceability are also important for the overall design.

Once the reliability indices have been defined, the RAMS assessment is done. Based on this information, the topology can be modified to improve wind farm availability or to make the system less costly. If the topology is modified all the power flow and short-circuit analyses must be done again to ensure the cables and protection systems are correctly calculated.

Output

The results include: electrical layout of the wind farm, voltage levels, number and location of substations, cable cross section, choice and setting of the protection system, and redundancies in the system.

3 DESIGN VARIABLES

This chapter describes different design parameters and choices that determine the wind farm collection grid design.

3.1 AC or DC

The internal electrical grid of an offshore wind farm can have either AC or DC collection system. AC collection systems are the only type of collection systems that exist today. The technology is well known and has been used for a long time both in onshore and offshore wind farms. On the other hand, DC collection systems are relatively new and have, so far, never been applied in a real wind farm. But, DC collection systems are active topics in current research, and might emerge as a viable option in the future.

With a power converter interface to the grid, both AC and DC collection systems can be used with the same types of wind turbine generator (WTG), such as induction generator (IG), permanent magnet synchronous generator (PMSG), or doubly-fed induction generator (DFIG). Schematic drawings of wind turbines in AC and DC collection grids are shown in Figure 3-1. The main difference between the two is that the DC to AC converter and step up transformer in the wind turbines in AC collection systems are replaced by DC/DC converter in wind turbines in DC collection systems.

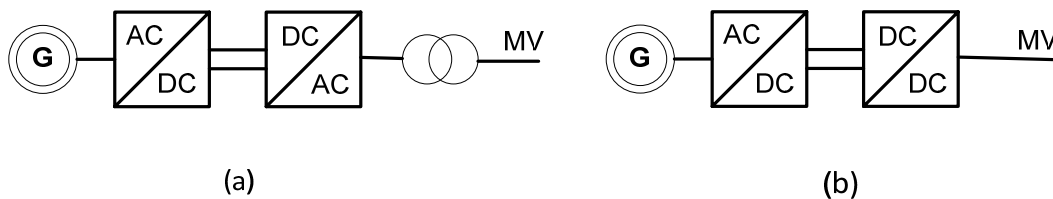


Figure 3-1: (a) WTG in AC collection systems, (b) WTG in DC collection systems

In AC collection systems, wind turbine generators are connected to a step up transformer either directly or via a back to back converter. The step up transformer increases AC voltage from low voltage generation level to MV level that is suitable for internal collection systems. AC collection system, made up of AC cables and electrical components, is used to collect and transfer produced power to wind farm offshore collection point. Normally AC collection systems have a frequency of 50Hz or 60Hz, and most of standard network components are designed and optimized to operate around these frequencies. But there have been some studies that consider having a variable frequency in AC collection systems where medium frequency transformers (400Hz - 500Hz) are used in the WTGs. It is claimed that for DFIG WTGs with variable AC frequency, power capture can be maximized and converter ratings can be reduced, and thereby reducing the overall cost of the wind farm [6]. It should be noted here that this kind of arrangement is feasible for wind farms connected to shore via HVDC links where the wind farm and grid frequency are decoupled.

If the size of the wind farm is small and is located close to shore, then an offshore substation is not needed. The collection grid can be connected directly to an onshore transformer substation where voltage is stepped up to HV transmission grid level. For large wind farms located far from shore, voltage level is increased from collection to transmission level by transformer(s) located on offshore substation platforms. AC power is then transferred to shore by HVAC transmission cables. If the distance to shore is long (>90km), then HVDC, which requires a converter station to convert AC power to DC power after the HV transformer, is the preferable power transmission solution.

In DC collection systems, a wind turbine generator is connected to a rectifier that converts the generator's terminal voltage from AC to DC. Then, the DC voltage is stepped up to MV level by a DC/DC converter inside the turbines. The DC/DC converters can have a topology such that an inverter and a rectifier are connected through a high frequency (greater than 500 Hz) transformer;

which has much lower weight than transformers with 50 Hz. The advantage of this kind of inverter-transformer-rectifier topology is the possibility of achieving higher DC voltage on the MV side. DC cables are used to collect the power from each turbine to the wind farm substation. Depending on the voltage level in the collection grid and distance from shore, the wind farm might have an offshore converter station with another DC/DC converter to step up the voltage to HVDC transmission level. It is highly unlikely for a wind farm to have a DC collection system and an AC transmission to shore as this would require inverters with large capacities to convert power back to AC. DC collection systems have an advantage of lower weight, which is very important for offshore application, because the transformers in the WTGs and at the wind farm substation are replaced by DC/DC converters. However, it should be noted that DC/DC converters required for this kind of application are not standard elements and are still under development [7, 8].

3.2 Voltage level

Currently, the typical medium voltage (MV) voltage level in collection grids is around 33 kV. At this voltage level, transformers, cables and switchgears suitable for offshore applications are commercially available. Most of existing offshore wind farms and offshore wind farms that are under construction (e.g. London array, BARD) have collection grid voltage level at this level (33 kV). Internal collection grids with higher voltage levels (48 kV to 72 kV) are discussed in the literature but so far have not been realized. However, this will most likely change in the future as the size of offshore wind turbines and farms are getting bigger and as developers consider the lifetime cost saving potentials of higher collection grid voltages. Some wind turbine manufacturers are already supplying 66 kV output generators as standard voltage level, e.g. the V164 8MW turbine from Vestas [9], and some vendors are supplying the required power electronics. The Carbon Trust in the UK is currently supporting development of 66 kV solutions for offshore wind farms as it sees this as a key element of life cycle cost reduction [10, 11].

Ohmic power losses are lower in collection cables at higher MV level and the collection cables will have higher power carrying capacity. In addition, for *small* offshore wind farms near to shore, it increases the possibility of connection directly to shore (without an offshore substation) since the higher voltage allows a longer transmission distance. In such cases, costs associated with the offshore substation are avoided, giving significant cost savings. However, at greater distance from shore, an offshore substation with a medium to high voltage step-up transformer to higher transmission voltages will remain the standard solution. The balance is determined by investment costs (increasing with voltage) versus total power losses (decreasing with voltage) [12].

It is common practice to select LV/MV transformers inside the WTGs with kVA rating at least as large as the kVA rating of the WTG [13].

Even though submarine cables and switchgears with higher voltage capacities exist, the collection grid has until now been limited to 33 kV mainly because of issues related to LV/MV step-up transformer inside the wind turbines. A transformer with higher voltage level on the secondary side will have larger weight and physical dimensions, thus requiring more space inside the wind turbines. The available space inside the turbine tower is not enough to accommodate bigger transformers (with today's tower dimensions and transformer technologies) [14, 15]. Another important issue is dry type transformers, which are the preferred type of transformers in offshore wind turbines. This is because oil cooled transformers have fire and spillage risks; which poses danger to safety and pollutes the environment. Dry type transformers that can step up voltage from LV (0.66 to 1 kV) to MV voltage higher than 33 kV have not been commercially available [12]. But now, at least ABB manufactures dry type transformers that have compact designs and with voltage ratings up to 72 kV [16]. This shows that the transformer issues are being addressed by manufacturers and makes higher collection grid voltages more feasible.

Some examples of offshore wind farm collection grids voltage levels are presented in Table 3-1.

Table 3-1: Examples of offshore wind farm collection grid voltage level

Offshore wind farm	Collection grid voltage level [kV]	Capacity [MW]	Status
Horns Rev	34	209	Operational
Alpha Ventus	30	60	Operational
BARD 1	33	400	Under construction
Gwynt y Mor	33	576	Under construction
Anholt	34	400	Under construction
Dogger Bank Teesside	33 – 72	4 x 1200	Planned

3.3 Number and location of substations

The number of substations is determined by

- Size of wind farm, hence the total length of cables
- Voltage level, which affects maximum length of a feeder
- Capacity of wind farm, and capacity of transformer and high voltage (HV) cable

At short distance from shore, small wind farms can be connected directly to shore. In such cases, MV level is used to connect to shore. The feeders can be divided into different groups with each group having separate connection to an onshore substation. Switchgear is used at the shore end of transmission cables. Therefore, there will be no need for an offshore substation. As the capacity of the wind farm increases, the need for having an offshore substation increases. This is because the lifetime cost of power losses due to transmission of large power at MV level becomes comparable to the capital cost of having an offshore substation. At large distance from shore, offshore substations are required to transform voltage to HV level suitable for long distance transmission. Besides larger installed power, large wind farms will also cover larger area. This means that long cables are required within the wind farm area to connect each feeder to the offshore substation. But with MV level, there is a limited length a feeder cable can have before the power losses become too large and compensators for voltage regulation are needed. The solution is therefore to divide the total turbine area in two or more parts, depending on the total areal coverage of the wind farm, and have an offshore substation within each area. Each offshore substation will have separate transmission cable link to shore. Other constraints that affect the decision regarding number of offshore substations include existing offshore industries, shipping, subsea cables, pipelines, etc. in the wind farm area.

As discussed in section 3.2, higher voltage level increases transmission capacity and reduced ohmic losses. In some cases, near-shore wind farms that have higher collection grid voltage can be directly connected to shore, which would not be possible with a standard 33 kV grid. In general, higher collection grid voltage level increases the possibility of connecting small wind farms at longer distances and large wind farms at shorter distances to shore without an offshore substation. For wind farms covering a large area, with higher collection grid voltage, longer feeder cables can be realized which would lower the need for having more than one offshore substation.

The size of the offshore transformer can be a limiting factor for the total amount of power that can be transmitted. For wind farms with capacity of several hundreds of MW, it could be possible to have more than one substation transformers connected in parallel in order to support higher wind farm production capacity. This will also increase the availability of the wind power because in case of transformer disconnection due to fault, at least some of the power can be transported. Cost of transformers and their corresponding physical sizes and weight increase with their ratings. This also implies that the cost of offshore platforms needed to support the transformers and switchgears also increases. For future offshore wind farms with very large installed capacity in the ranges of GW, several substation transformers located on one large or more than one offshore platform will be required.

The ideal location of the wind farm substation, seen from a collection grid loss minimisation point of view, is within the central areas of the wind farm [13] so that the total length of the collection cables will be shorter. However, this arrangement might always not be physically possible. In the common rectangular, radial layout of offshore wind farms, the substation is usually located on the side on the wind farm which is closest to shore.

3.4 Grid topology

The topology of the electrical grid refers to the overall structure of the cable layout (in this context), i.e. whether the wind farms are connected along a radial string, in a ring, or any other configuration. Different topologies offer different possibilities regarding redundancy and availability. To date, the simple string feeder topology with wind turbines connected in parallel has been the most common, largely because of minimised total cable distance and relative simplicity of installation. However, other types of collection grid layouts are of course possible and may be beneficial. In determining the grid topology, the most relevant factors to consider are total cost, cable length, power losses, and reliability. Redundancy, which usually comes with added cost, is also important; especially for offshore wind farms that are far from shore and have limited accessibility due to weather conditions.

The following sections discuss some different alternatives for AC and DC wind farm grid topologies.

3.4.1 AC wind farms

Radial – Radial collection systems have several parallel feeders that are connected to a common offshore MV bus. Wind turbine generators (WTGs) are connected along each feeder, sometimes via a branch string. The maximum number of turbines on each feeder is determined by subsea cable rating. The required size of the cables decreases as the distance from the substation increases. This means that cables that are closest to the substation transformer have the biggest cross section while cables farthest from the offshore substation have the smallest cross sections. This is because cables at the farthest end carry power produced by a single turbine and cables closest to the substation carry power produced by the total number of wind turbines on the feeder. Radial collection grids are simple to control and inexpensive because of tapering and shorter total length of cables [17]. However, radial collection grids have relatively poor reliability as a fault somewhere on the feeder would lead to disconnection of the whole feeder or at least disconnection of the WTGs located behind the fault, depending on the location of the protection equipment. Figure 3-2 shows schematic of a wind farm with radial collection grid.

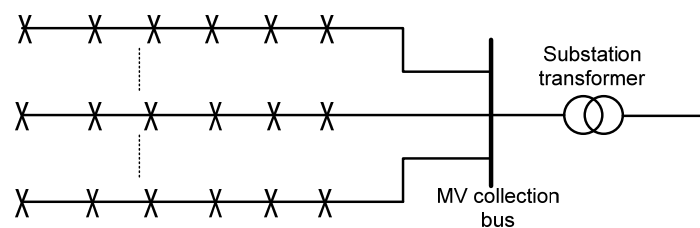


Figure 3-2: Schematic for radial wind farm topology

Single-sided ring – Single-sided ring layouts have WTGs that are connected along a single feeder in a similar way as in radial layouts. The only difference between radial and single sided ring layout is the additional redundant cable in single-sided ring layouts that connects the last turbine on a feeder to the offshore MV collection bus. In case of fault on the inter-turbine cables, this redundant path will be used to transfer power to the offshore substation, thereby increasing reliability. However, this arrangement is costly as there is a long additional cable in parallel with the main feeder. In addition, there is higher cable rating requirement throughout the circuit compared with the radial layout as the direction of power flow reverses during faulty conditions. Figure 3-3 shows schematic of a wind farm with single-sided ring layout.

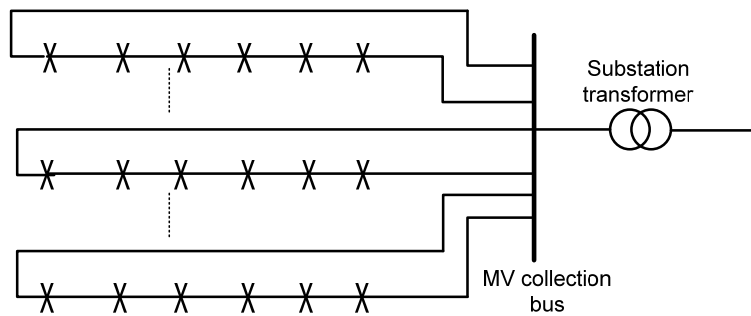


Figure 3-3: Schematic for single-sided ring wind farm layout

Double-sided ring – In double-sided ring layout, two radial feeders are connected at their farthest end from the wind farm substation. Figure 3-4 shows schematic for a wind farm with double-sided ring layout. Double-sided ring layout has high reliability, but at the same time high cable capacity requirement. The cables closest to MV collection bus need to be sized twice the full power of WTGs on single string if they are expected to carry the total power from the two connected feeders. The cost of higher cable capacity and equipment requirement should carefully be examined against the need for redundancy. For wind farms <100MW the probability of fault and associated costs are lower than the costs associated with additional equipment [17]. The case might be different for offshore wind farms >100MW.

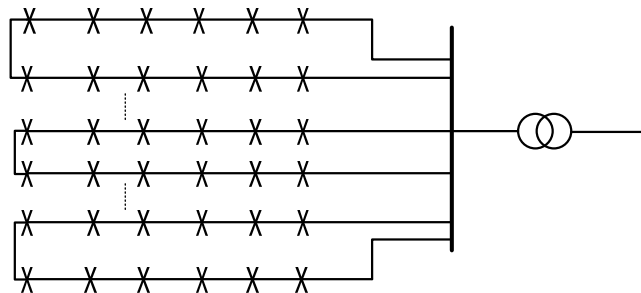


Figure 3-4: Schematic for double-sided ring wind farm layout

Star – In star topology each turbine is connected to one other turbine except the ones which are in the middle and are acting as a hub; and those WTGs connected to the MV collection bus at the substation. Figure 3-5 shows schematic for a wind farm with star topology. Cables that are connected to the MV collection bus have high capacity requirement but they are few and probably short in length. Most of the cables in star topology have low capacity requirements because of the single connection between WTGs and turbines in the middle. Furthermore, this type of layout has high reliability as a fault on interconnection cable will only disconnect a single WTG. Star layout is better for voltage regulation as the converter in each turbine will regulate the turbine's output voltage. The major cost implication of this arrangement is the complex switch gear requirement at the wind turbine at the centre of the star [17]. It also involves a more time-consuming cable laying process, requiring more turns and back-and-forth trips with the expensive installation vessel.

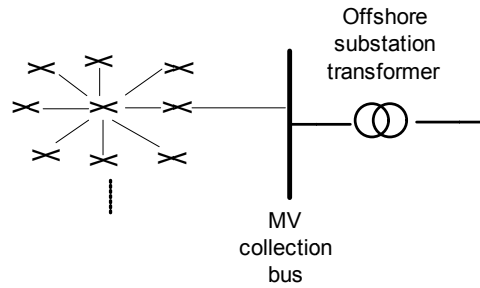
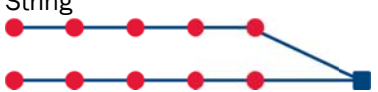
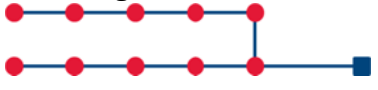




Figure 3-5: Schematic for star wind farm layout

The different topologies have different characteristics regarding reliability. This can be illustrated by computing what we may call the overall *availability-adjusted capacity fraction*, defined as the *expectation value* (presumed average) of the fraction of the total power which is able to reach the substation as a result of faults on branches (cables including switchgear). This computation relies on probability analysis. The availability, a , of a single branch is determined by the probability of failure and the average repair time, and is a number between 0 and 1, where 1 means that the branch is always available. Table 3-2 shows the availability-adjusted capacity fraction, A , for different topologies and different values of the single branch availability, a , and number of turbines, N , per feeder (a ring is considered a joining of two string feeders). Note that the values of a used in this example are purely for illustration, and do not represent realistic values. It was assumed that each single fault can be immediately isolated to a single branch.

Table 3-2: Overall availability-adjusted capacity fraction for different grid topologies (for illustration only)

Grid topology	Availability-adjusted capacity fraction	$N=5$ $a=0.99$	$N=5$ $a=0.98$	$N=10$ $a=0.99$	$N=10$ $a=0.98$
String 	$A = \frac{a(1-a^N)}{N(1-a)}$	0.9704	0.9416	0.9466	0.8963
Dual string 	$A = \frac{a(1+a)(1-a^N)}{2N(1-a)}$	0.9655	0.9322	0.9419	0.8874
Double ring 	$A = A_{\text{ring}}(N, a)$	0.9979	0.9920	0.9930	0.9745
Star 	$A = a^2$	0.9801	0.9604	0.9801	0.9604

The overall availability-adjusted capacity fraction for the double ring structure is given by the expression

$$A_{\text{ring}}(N, a) = a^{2N+1} + (2N + 1)(1 - a)a^{2N} + \frac{a(1 - a^{2N})}{N(1 - a)} - 2N(1 - a)a^{2N} - a^{2N}(1 + a).$$

Ref. [18] discusses different wind farm topologies and protection schemes from a technical point of view.

3.4.2 DC wind farms

One type of DC collection grid layout involves connecting WTGs along a single feeder (in parallel), and then connecting all the feeders in parallel to a common MV DC bus at the offshore converter station. This kind of topology is exactly the same the radial layout for AC wind farms except that the WTGs output voltage is DC and DC electrical components are used. At the converter station, DC-DC converter is used to step up voltage to HVDC transmission voltage level. Figure 3-6 shows schematic for a wind farm with radial DC collection grid. Note that the wind turbines in DC wind farms are the same as shown in Figure 3-1 (b). DC radial collection systems have an advantage of reduced weight compared with AC radial collection systems as the LV/MV transformers in the WTGs and MV/HV transformer at the substation is replaced by DC-DC converters. This weight reduction is important in offshore wind farms. However, the steady state losses in this DC radial collection systems are higher than losses in similar AC systems [19]; with DC-DC converters contributing most to the losses.

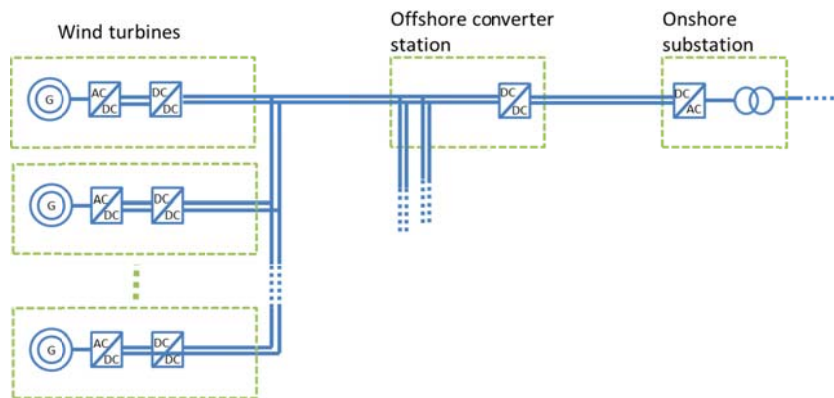


Figure 3-6: Schematic for radial DC collection layout

Another alternative for DC wind farm layout is to connect WTGs in series as shown in Figure 3-7. The major advantage of such topology is that the voltage level needed for transmission can be reached by connecting WTGs in series without the need for an offshore converter station. Since turbines are connected in series, the voltage builds up along the row, and there will be a high voltage to earth value in the turbines, something which raises issues related to insulation and maintenance. The number of turbines in series required to reach required transmission voltage depends on the output voltage of the wind turbine. DC collection grid for offshore wind farms is currently a hot topic for research.

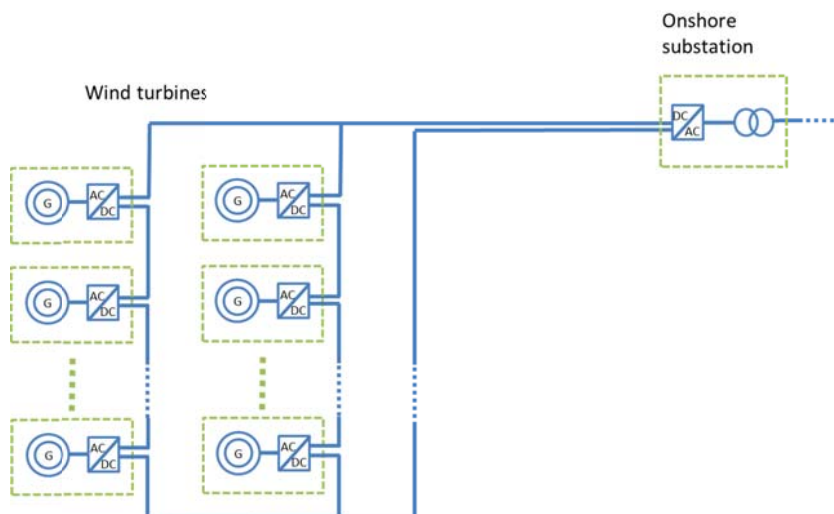


Figure 3-7: Schematic for DC wind farm with turbines connected in series

3.5 Cables

3.5.1 Cable layout

Thorough environmental and geological studies are carried out before wind farm cables are laid. The environmental study covers the impact wind farm cables will have on local waves, currents, sediments, seabed features and marine environment. Subsea cables are generally buried 1–2 m below the seabed level to protect them against wave, abrasion, anchoring and trawling. However, there is a low likelihood of internal array cables being damaged by ships because it is obvious for ships that there are cables between the turbines. There might also be a restriction preventing ships from entering the wind farm area. So in this sense, it may not necessary to bury array cables.

Before excavation work for the cable trench is started, surveying is carried out to make sure that there are no obstacles such as boulders and existing pipelines, cables, etc. on the seabed. If there are any pipelines or cables that need to be crossed, then careful design is needed for the crossing methods so as to ensure proper operation and safety of all elements. In case of failure on turbine interconnecting cables, then the damaged cables are abandoned and a new section is laid in parallel to the old one.

The detailed determination of cable layout takes into account all relevant constraints, such as the ones indicated above, and is generally a result of an economic optimisation, either by hand or using suitable computer software. This optimisation has different objectives that can be combined using a cost function based on the developer's cost models. Some of these are:

- Minimise cable length (thereby procurement and installation cost, and power losses)
- Minimise installation complexity (thereby installation cost)
- Limit number of cable types (thereby simplifying installation and procurement process)
- Ensure required level of redundancy
- Avoid forbidden areas

Cable layout optimisation is discussed further in Section 4.1 and in Section 6 Appendix: Algorithmic optimisation of cable routing.

3.5.2 Cable type

Cross-linked polyethylene (XLPE) insulated submarine cables are the most common types of internal collection cables used in offshore wind farms. They have low electrical losses. In addition, they have high reliability and are environmentally friendly. The conducting material can be either aluminium or copper. Aluminium conductors, which are less commonly used, have a lower current-carrying capacity, and thus require larger diameter [8, 20].

Submarine cables can be three separate cables, one cable for each phase, also known as 3x1-core or they can be three cables bundled up together in common shield and armouring (1x3-core). Single-core (3x1-core) cables have a higher current carrying capacity than 3-core (1x3-core) cables. But, at the same time, single-core cables have higher losses than 3-core cables. This is because in single-core cables there is current flowing through the armour that creates additional losses. There exists a magnetic coupling between the phases in single-core cables for separation distance lower than 50m [21]. Since the cables are not transposed, the magnetic coupling results in different impedance in the cables and unbalance in the three phase system. In 3-core systems, there is little or no coupling between the phases and therefore, the system remains symmetrical. All three cables are laid separately for single-core cables while for 3-core cables the cable is laid in one instance which makes the installation cost cheaper. In general, single-core cables are more expensive than 3-core cables. Both single and 3-core cables' shield has to be grounded to avoid over-voltages. To increase reliability an additional fourth cable can be laid in parallel to the other cables in single-core systems while for 3-core a system a second cable in parallel can be installed. There is a possibility of integrating a fibre optic cable to be used communication purposes with 3-core cables.

Internal collection cables closest to the substation carry the total sum of power produced by all the WTGs linked to them. This requires higher current carrying capacity of these cables. The total number of wind turbine generators that can be connected in series is therefore limited by the maximum current carrying capacity of the submarine cables. As already mentioned, higher current carrying capacity for wind farm cables can be achieved if three single-core-cables are used instead of one three-core-cable. But the additional costs have to be justified.

Another factor that affects cables' current carrying capacity is soil thermal resistivity, i.e. the ability of the soil to dissipate heat generated by energized and loaded power cables. Underground feeders are generally limited to roughly 25 to 30 MW per string due to soil thermal conditions [13]. There are several methods that can be used to improve soil's thermal resistivity. Two examples are providing Corrective Thermal Backfills (CTB) and Fluidized Thermal Backfills (FTB) within the trench and surrounding the circuit cables [13]. In offshore wind farms where there is no sea traffic or where there is low risk of cables being damaged by anchors or fishing vessels, it might not be necessary to bury the interconnection cables. This avoids issues related to soil thermal resistivity and also reduces costs related to cable wash downs.

Submarine cables are available in wide ranges of cross sections ranging from 95 mm² to 1000 mm². One factor that determines collection system cable sizes is the maximum amount of current that the cable segment is expected to carry. Depending on the wind farm layout, many different types of cable sizes can be used within a wind farm. Using many different cable types within a wind farm leads to more costly installation, so in practice, only a small number of different cables are used. If redundancy is designed into the grid (e.g. a ring topology) the same power capacity may be required throughout the grid, and a single cable type may be the best option.

As an example, consider the Lillgrund offshore wind farm in southern Sweden, which has a radial grid layout. The cable sizes in one of the feeders are shown in Figure 3-8. The cable sizes at the end of a feeder are smaller than cable sizes found at the beginning of the feeder closest to the substation transformer. Heating and losses are also factors that are considered when selecting the appropriate cable sizes.

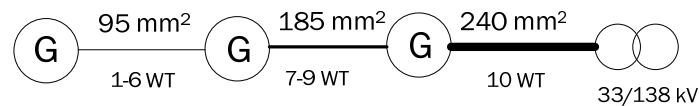


Figure 3-8: Different cable cross-sections in Lillgrund offshore wind farm [22]

Some of the major submarine cable manufactures in the world include ABB, JDR Cable Systems, Nexans, Prysmian, NSW, and Parker Scanrope. Some key parameters for example cables are shown in Table 3-3.

Table 3-3: Example values for a 33 kV, 3-core copper conductor XLPE cable from Nexans [23]

Cross section (mm ²)	Current rating, buried (A)	Transmission capacity, buried (MVA)
95	352	20
120	399	23
150	446	25
185	502	28
240	581	33

3.6 Protection scheme

In the event of fault in the internal collection grid, it is necessary that the protection system identify and isolate the faulty part. AC protection systems consist of transducers, relays, circuit breakers, switches, auxiliary power and all wirings in between. DC breakers are still immature technology. For instance in high voltage DC systems, there exists currently no installation with DC circuit breakers, all relying instead on circuit breakers on the AC side of the converters. Recently, DC circuit breakers have been announced and for high voltage, but uncertainty remains regarding costs and performance. This section therefore focuses on AC protection.

MV switchgears are used in offshore wind farms for protection and they are located inside each wind turbine and on the offshore substation. The number and type of protection used is different depending up on the design, grid topology and required level of availability.

In each turbine, there are breakers for LV and MV circuit protection. The LV protection clears internal wind turbine faults while the MV protection is used to clear faults in the LV/MV transformer and faults in the cable connected to the next turbine. The MV circuit breakers may have the functionality to be operated remotely from shore. Gas insulated switchgears (GIS) are also used to manually disconnect and ground transformers and cables.

Protection elements on the offshore substation are used to protect against faults in the MV/HV transformer and disconnect feeders in event of faults on the feeders. The offshore substation transformer will have additional protection for oil temperature, pressure, and so on.

Depending upon the internal grid topology, the types of protection differs. For example, in radial layout wind farms, it could be sufficient to place switchgear only at the beginning of feeders. So that in case of a fault somewhere on the feeder, the whole feeder will be disconnected. For instance, in Horns rev, the first turbines in each row are equipped with motor operated disconnectors which can be operated from land.

Figure 3-9 shows examples of different protection schemes for different types of wind farm layouts and different levels of reliability. Two classes of switches are used to isolate faults:

- Circuit breaker – automatically operated switch that detects over-currents and breaks the circuit if necessary.
- Switch – manually operated electrical switch; requires that the current is zero.

In case of a fault, it is the (nearest) circuit breakers that isolate a fault and reduce the currents to zero in the fault area. Once this has been done, manual, possibly remotely operated, switches can be used to isolate the fault even further, allowing other parts of the grid to be re-energised. For a wind farm, where the consequences of short disruptions in the power output are small, there is little gain in adding more circuit breakers than necessary for the protection of critical equipment, and instead use manual switches for fault isolation.

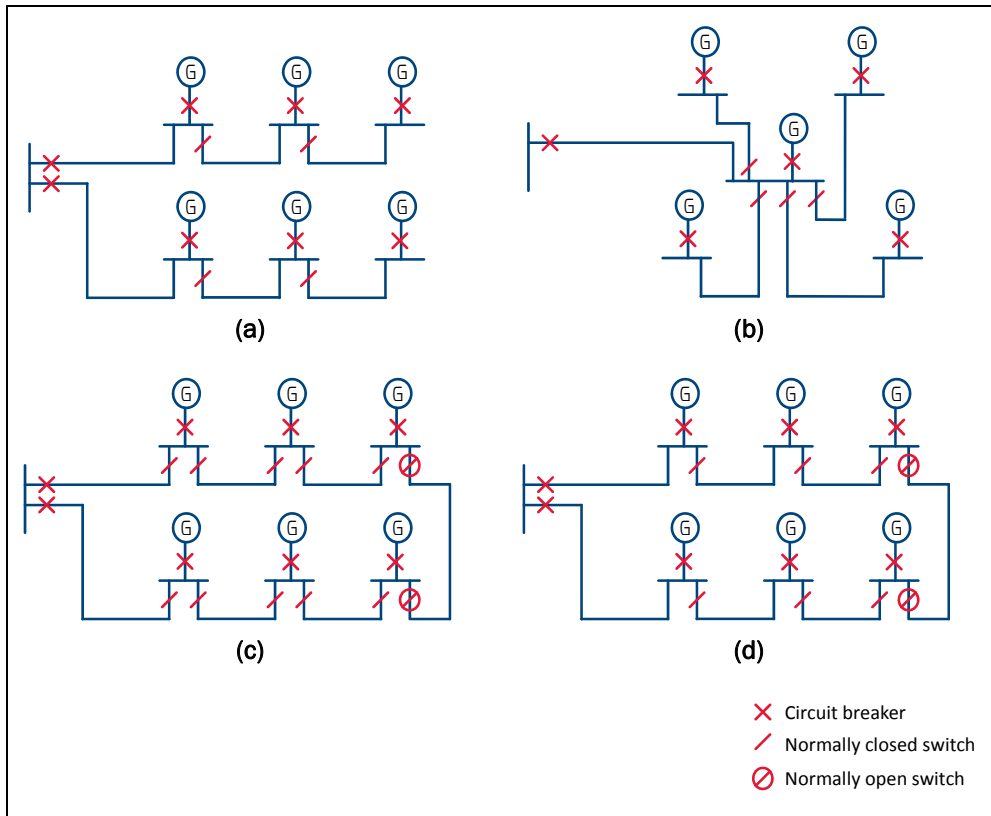


Figure 3-9: Examples of configurations with circuit breakers and manual switches with different grid topologies. (a) String topology. (b) Star topology. (c) Ring feeder topology; a fault on any cable can be isolated and power from all six turbines can be transmitted to the substation (provided cable capacity is sufficient everywhere). (d) Ring topology where cable capacity is sufficient to carry max generation from 4 turbines only; with a fault in the one of the first two cable segments, power output from two turbines will be lost.

3.7 Floating wind farm

From an electrical point of view, the difference between a floating turbine and a bottom-fixed turbine is not fundamental, and in many regards, the electrical design of the wind farm is similar. However, at least two factors are relevant.

Firstly, floating turbines move in the sea, and power cables need to handle this movement, i.e. there is a need for *dynamic cables*. Such cables are already extensively used in the offshore oil and gas business, as well as for the two demos mentioned above.

Secondly, floating turbines are anchored to the seabed, and it may be beneficial for multiple turbines to share anchor points in order to minimise costs. This influences the layout of the farm; with three anchor points per turbine, a hexagonal pattern emerges.

Some concepts consider not just floating turbines, but floating platforms with multiple turbines on the same structure. For example, the Hexicon concept² considers 24×3 MW turbines on one platform. With such a set-up it makes more sense to talk about floating wind farms rather than floating turbines. Each platform is akin to an individual wind farm, or more likely a wind farm feeder. One can imagine several different floating structures connected together at a central wind farm transformer and converter platform(s).

² www.hexicon.eu

4 ANALYSES

This chapter outlines electrical analyses that are normally performed as part of the electrical design process.

4.1 Cable layout optimisation

Most current wind farms connect the turbines to the wind farm substation in a radial configuration. This configuration is the conventional choice because of its simplicity and low cost. In general, however, the optimal cable layout is not self-evident, and is a matter of optimisation with multiple objectives and constraints. One objective is generally to minimise the total cable length. The problem is to determine the cable layout such that all turbines are connected to the substations, all capacity constraints are satisfied, and the total cost is minimized. The typical approach is by hand or using brute-force. However, this becomes increasingly complex for larger wind farms and in cases with less regular placing of the individual wind turbines.

One approach to the layout problem is to formulate it mathematically with graph theory. The problem is to find a tree to meet required design characteristics in a graph (V, B) where V is the nodes and B are the cables. There can be many trees satisfying the design constraints. However, if the objective is to minimize the total length of cables the problem can be simplified using the Steiner tree problem [24, 25].

This approach is not always the most reliable and efficient. A few studies have been conducted to investigate the collection grid electric layout of a wind farm. The general conclusion is that the system efficiency is strongly influenced by the layout and the wind speed distribution. A general methodology to design the electric layout of a wind farm has been presented in ref. [26]. In ref. [27] a genetic algorithm is applied to the optimization of the electrical layout in terms of not only the energy production costs but also the efficiency. However, genetic algorithms have some limitations, e.g. premature convergence to local minima. In [28] a genetic algorithm is improved in the local convergence using an immune algorithm. In [29] a geometrical optimization is used. In general, the drawback with geometrical optimization is that certain types of constraints may be difficult to be formulated as polynomials. However in [29], the problem is formulated in terms of costs and reliability. In [24] a clustering-based algorithm is proposed for the cable layout of a wind farm. This algorithm is compared with the radial configuration. The main conclusion of this work is that the reliability of the system can be improved significantly without significant cost. An optimization of the investment cost, system efficiency and system reliability considering the stochastic nature of the wind speed and reliability of the main components is presented in [30]. Finally, in the appendix (Section 6) of this document, a cable distance minimisation procedure is presented using a mixed integer linear programming approach similar to the approach used by the Net-Op tool for offshore clustering and grid optimisation.

4.2 Power flow analysis

Power flow analysis allows verifying that the system constraints are respected. First, the magnitude of the voltages in each node must be between the set voltage limits. Second, the maximum amount of power injected in the points of common coupling, which is set by the TSO, must never be exceeded. Finally, power flow analysis can determine if equipment, such as transformers or cables, is overloaded [31].

In general, the power flow analysis aims to find the power flows and voltages of a transmission system for specified nodes. The system is assumed in steady state and balanced to perform the power flow analysis. To solve the power flow equations, the system can be formulated using the admittance matrix as follows:

$$\begin{bmatrix} \tilde{i}_1 \\ \vdots \\ \tilde{i}_n \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1n} \\ \vdots & \ddots & \vdots \\ Y_{1n} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} \tilde{v}_1 \\ \vdots \\ \tilde{v}_n \end{bmatrix}$$

where Y_{ii} is the self-admittance of node i , \tilde{i}_i and \tilde{v}_i represent phasors of the current and voltages at node i , respectively, and n is the total number of nodes. The admittance matrix depends of the topology of the transmission system i.e. all line transmissions, transformers and loads should be used to formulate the above-mentioned matrix. The voltages at each node could be easily found if the current at each node were available. However, in the general case, there is insufficient number of known variables in the above equation. Moreover, the power is non-linear function of the current and voltage. In fact, special attention should be given to the effect of the reactive power since the submarine cables have much higher capacitance compared with overhead lines. The current at the node k can be found as follows:

$$\tilde{i}_k = \frac{P_k - Q_k}{\tilde{v}_k}$$

where P_k and Q_k represent the active and reactive power, respectively. Due to the non-linear relation between the power flow and voltages and current equation, there is no analytical solution for the power flow equations, so iterative methods are often used to find the solution [32]. There are several methods to solve the above equations. The classical methods such as: Gauss-Seidel method, Newton-Raphson method, and Fast Decoupled method [32]. Other methods include Fuzzy logic [33], genetic algorithm [34], and particle swarm method [35].

4.3 Short-circuit analysis

Short-circuit analysis is performed to determine the maximum short circuit current support for cables and other equipment. The transmission system can be correctly dimensioned and protected using the short-circuit studies. Several methods can be used in short-circuit analysis [36]. The level of accuracy is chosen depending on the application. A brief review of the most common methods is presented below.

Short circuit calculation based on nodal method

In this method assumes only balanced three phase short-circuit faults. Fault levels can be expressed as per-unit impedances, so Thevenin equivalent can be used to determine the magnitude of the fault current in per unit [37]. Fault level may be written as:

$$Fault\ level = \frac{S_{fault}}{S_{base}} = \frac{\sqrt{3}V_n I_{sc}}{\sqrt{3}V_n I_{base}} = I_{sc,pu}$$

where S_{fault} and S_{base} are fault level expressed in MVA and nominal power, respectively. V_n is the nominal voltage. I_{sc} and I_{base} are the short circuit line current and base line current, respectively.

Since the per unit voltage for nominal value is unity

$$Fault\ level = I_{sc,pu} = \frac{V_{n,pu}}{Z_{pu}} = \frac{1}{Z_{pu}}$$

where Z_{pu} is an equivalent impedance of the fault level.

This method uses a non-detailed system model and is recommended to be applied to extreme-case estimation, e.g. verification of the current limits of cables, and dimensioning earth grounding systems.

Symmetrical components method

According to the symmetrical components decomposition, the current in a transmission line is composed by three symmetrical components, i.e. positive sequence, negative sequence and zero sequence currents. Symmetrical components can be calculated from phase currents as follows:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

where $[I_a \ I_b \ I_c]^T$ are the phase currents; $[I_0 \ I_1 \ I_2]^T$ are the zero, positive and negative sequence currents, respectively; and $a \triangleq -\frac{1}{2} + i\frac{\sqrt{3}}{2}$ and $a^2 \triangleq -\frac{1}{2} - i\frac{\sqrt{3}}{2}$.

Thevenin equivalents in the sequence components can be obtained. Symmetrical current components can be calculated. The symmetrical component method is similar to the nodal but the symmetrical short-circuit current for different types of fault can be obtained [38].

Other methods

There are additional methods for short-circuit analyses, such as the superposition method or methods based on time-step simulations, but these are not commonly used in the wind farm planning process. It is important, for example, that the analysis methods applied are compliant with relevant standards.

4.4 Reliability, Availability, Maintainability, and Serviceability (RAMS)

4.4.1 Reliability analysis

Reliability is the probability of that the wind farm will produce the power that corresponds to the wind conditions. Reliability analysis may be performed considering deterministic or probabilistic methods [39]. On the one hand although deterministic methods are still used for worst-case studies, Deterministic methods are unable to take into account the variability of some variables which are relevant for some systems i.e. wind power generation. So, probabilistic methods use stochastic data to provide more meaningful information.

Two main approaches can be considered for the probabilistic methods: Analytical and Monte Carlo [39]. Analytical approach is a-priori method where the wind speed records are grouped by a set of wind speed states forming the called wind speed capacity table. Once the table is built, it is possible to associate the system component availability data with the wind speed capacity table. For each state, a vector including a wind speed state and the availability of each component can be defined as follows:

$$[wSi \ S1 \ S2 \ \dots \ Sj]$$

Where wSi is the i -th wind state, Sj is the status of the component j which takes values between 0 and 1, which is defined as unavailable and available, respectively. Once all the vectors are known, it is possible to calculate the probability for each state, state frequency, average state duration and state energy. All these data are fundamental for the calculation of the reliability indices such as expected available wind energy with and without failures. This method is an efficient tool to provide information only of the power delivery ability of the entire wind farm.

A Monte Carlo approach is an a-posteriori method which uses the current random behaviour of the system. First, the layout and component data must be specified. Second, a wind speed probability table is calculated using for instance a Markov chain with finite number of states. Then, since the wind can be described by an exponential distribution, a synthetic wind speed time series can be easily calculated for each sampled period, e.g. a year. Then, since failure and repair residence times of each component can be assumed as exponentially distributed, it is possible to define the random availability of each component. Then, the availability of each turbine is determined using

methods such as pseudo breadth first search (PBFS). Finally, with the above data, it is possible to evaluate the wind farm output power and reliability indices. It is important to select proper stop criteria for the method. The main advantage of this method is that it accounts the random variation of the wind [40].

4.4.2 Availability, Maintainability, and Serviceability analysis

Availability is the probability that the wind farm will operate satisfactorily. Availability is a similar concept as reliability but availability is related with maintenance or repair actions. A wind farm can be very reliable, i.e. a high probability to supply the power that corresponds to the wind conditions. But if no maintenance or repair actions can be performed after a failure the wind farm availability is poor. Maintainability refers to the ability to ease of repairing the wind farm, and serviceability refers to the ease of regular maintenance [41].

5 CONCLUSION

A step-wise procedure for designing the internal collection grid of an offshore wind farm has been presented, covering the electrical system from wind turbine terminals to wind farm substation. The main focus has been the overall design process, the main drivers or factors that determine the choices, the design variables, and the analyses that are performed to support the design process. The emphasis has been on describing the technical content and implications of each design variable, highlighting electrical engineering considerations that need to be addressed, in which order to proceed, and what the currently available options are. This procedure is *not* a recipe for an optimal electrical design, as the design optimisation is very case specific and dependent on a large number of input parameters that change continuously due to technology improvements and maturing.

The procedure is based on present knowledge and technology, but includes some indication of trends and possible future solutions as today almost mature technology becomes commercially available.

The report has provided a high-level overview intended for a broad group of people without necessarily a background in electrical engineering, making it useful for those wanting to understand the electrical design process without going into great detail.

6 APPENDIX: ALGORITHMIC OPTIMISATION OF CABLE ROUTING

Shortest distance optimisation – can be formulated as MILP problem, but quickly becomes computationally demanding to solve with increasing wind farm sizes.

The problem of finding the interconnection of turbines which results in the shortest total cable length is a computational problem that can be solved as an integer linear programming problem. An outline for specifying such a problem is outlined below. This example has two types of variables. The first is an integer/boolean variable saying whether or not a potential connection should be realised or not. The other is the power flow, which essentially keeps track of how many turbines are connected to the same feeder. It is necessary in order to implement the cable capacity constraint.

Procedure

- Specify all potential cable routes. Label this set of branches B , and let the distance of branch i be d_i .
- Specify state variables. These are $\mathbf{X} = [y_i, p_i]$, where y_i is an integer equal to 1 if the branch is realised and 0 otherwise, and p_i is the power flow along this same branch.
- Define the objective function F , which is the total cable length:

$$F = \mathbf{C}^T \mathbf{X} = \sum_{i \in B} d_i y_i \quad (\#)$$

- Specify constraints. See below.
- The optimisation problem is then to find the state variables which give the minimum value of the objective function, subject to certain constraints.

Constraints

1) Power balance at each node n (except substation node):

$$\sum_{j \in B(n)} s_j p_j + P_{wind} = 0, \quad s_j = \begin{cases} +1 & \text{for branch directed into node } n \\ -1 & \text{for branch directed out of node } n \end{cases} \quad (\#)$$

Here, $B(n)$ is the set of branches connected to node n .

2) Power flow on branch i is limited by cable capacity (C_{max}), and by whether the cable is realised or not (y_i):

$$-y_i C_{max} \leq p_i \leq y_i C_{max} \quad (\#)$$

3) Topology – Sum of branches connected to a node n (except substation node):

$$\sum_{j \in B(n)} y_j \begin{cases} = 2, & \text{for ring topology} \\ \leq 2, & \text{for string topology} \\ < \infty, & \text{for unconstrained topology} \end{cases} \quad (\#)$$

Here, $B(n)$ is the set of branches connected to node n .

4) Branch intersection constraint – Sum of intersecting branches (constraint for each group of intersecting branches):

$$\sum_{j \in S(i)} y_j \begin{cases} \leq 1, & \text{if intersections are not allowed} \\ < \infty, & \text{for unconstrained topology} \end{cases} \quad (\#)$$

Here, $S(i)$ is the set of branches intersecting with branch i .

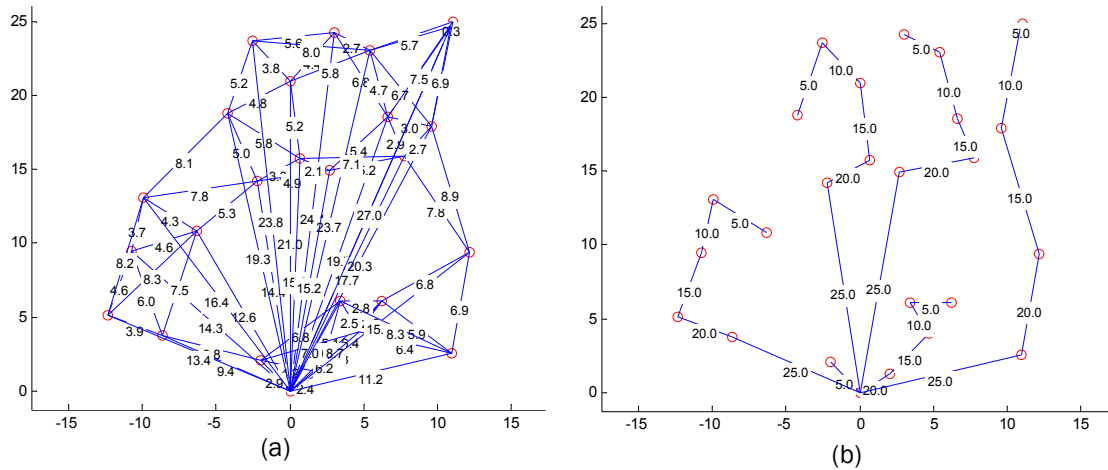


Figure 6-1: Example of cable routing optimization based on minimized cable distance and string topology; a) all potential branches with distances indicated; b) optimal solution. The node at position (0,0) is the substation.

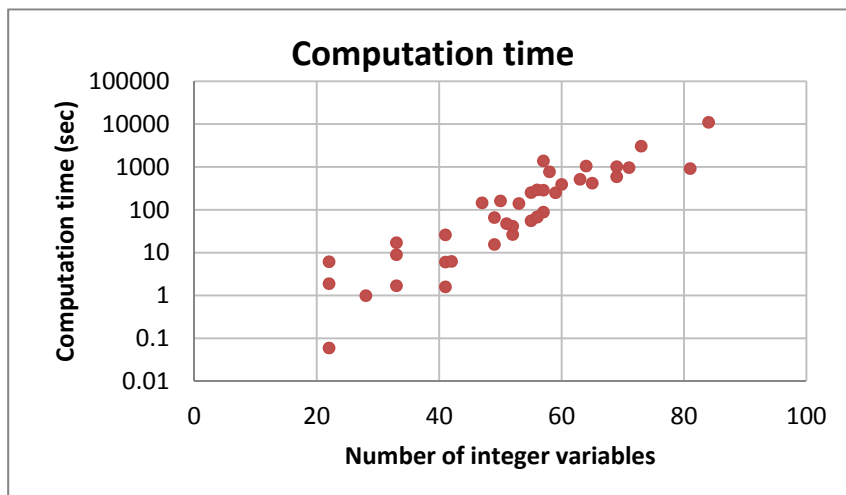


Figure 6-2: Computation time for cable length optimization using a normal laptop computer. Number of integer variables equals number of potential branches, and is about three times the number of nodes.

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