POWER CONNECTIONS FOR OFFSHORE WIND FARMS

Diploma Thesis

From

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Josef Schachner

Leoben, January 2004

I declare in lieu of oath that I did this diploma thesis in hand by myself using only literature cited at the end of this volume.

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Josef Schachner

Abstract

The objective of this thesis is to show, analyze and compare the options for connecting offshore wind farms (OWF) to shore, the infield power collection and the physical installation procedures of the turbine connection in order to provide recommendations for future developments. For the offshore wind farm near Egmond (Netherlands) specific solutions for the infield power collection were developed.

The power connection for the entire OWF was divided in three sections, the shore connection transporting the electricity from the farm collection point to shore, the infield power collection which deals with the connection of the turbines to the shore connection point and the turbine connection describing the required physical installation procedures to connect the turbines to the infield power collection.

The first step was to give an overview of the options to connect an OWF to the onshore grid connection point where the produced electricity is handed over to the integrated power grid. The options for the shore connection are alternating current at infield power collection voltage level, which is usually in the medium voltage range, alternating current at high voltage and high voltage direct current. At 100 MW transfer power the coverable distances with medium voltage are 15 km, 100 km for high voltage and high voltage direct current for distances larger than 100 km. For the Egmond OWF a shore connection at infield power collection voltage level was a starting guideline.

For the infield power collection at Egmond OWF several connection schemes were developed and applied for a given geometrical layout. Their implications on the electrical infrastructure were investigated and compared in respect to cable dimensions, required switchgear and redundancy aspects. The layout schemes can be divided in string and loop layouts. String layouts are simpler, require less switchgear than loops, but have low redundancy possibilities. Loop layouts require extensive switchgear equipment, but have high redundancy capabilities. The number of turbines per string or loop determines the required cable dimensions. A medium voltage cable can transport about 50 MW of load, limiting the maximum number of turbines per string or loop. To optimize the cable dimensions for specific loads per string or loop a thermic model of the cable was developed. The model showed that the installation parameters like laying depth, soil type and surrounding temperature have a high influence on the actual power transport capacity of the cable and therefore close investigations of the actual conditions on site are required to optimize the cable dimensions. The number of strings or loops at a specific layout determines the required switchgear at the shore connection point. With the developed connection scheme it is possible to house the shore connection switchgear in an additional standard container at one turbine; an additional platform offshore is not required. This is valid for shore connections at infield power collection voltage. The cable failure rates determine the required redundancy and selectivity of the cable layout. Redundancy can be obtained with multi string or loop layouts with extensive switchgear (3 power switches per turbine). But with currently used failure rates (1 cable fault in 25 years) the extensive switchgear is not justified by the gain in energy production. With the before stated parameters a 3 string layout with simple switchgear (1 power switch per turbine) is the optimal layout for the OWF near Egmond.

The physical turbine connection for OWFs was investigated for monopile foundations. The basic installations steps are laying the cable close to the turbine with a cable installation vessel, inserting the cable into a cable riser (J-Tube) at the seafloor and pulling the power cable to the turbine connection point above sea level. In standard installation procedures used by the offshore oil industry this process is supervised by divers or remote operated vehicles (ROV). Scour protection is also an issue that has to be considered, as ether scour protection has to be applied around the monopile or additional precautions have to be undertaken to cover the scour hole, for example with an horizontal extended J-Tube. To bypass the need to either apply scour protection or cover the scour hole directional drilling can be used to drill a well inside the monopile and resurface it at a scour save distance from the monopile. This installation approach has promising aspects, but needs further development to become a standard procedure.

1. Introduction

1.1. Offshore Wind Energy

Wind energy converter systems producing electricity are nowadays subject to a growing interest as they provide a safe, clean and competitive alternative for conventional sources of energy. Most European countries have plans for increasing the production of electricity by wind power. However, wind farms occupy a large amount of space compared to conventional power plants and produce noise as the major emission. Therefore placing the wind farms offshore is an alternative, even gaining advantage over land based systems as with higher annual wind speeds offshore a higher energy yield is obtained. Countries like Germany, the Netherlands, United Kingdome, Denmark and Sweden are currently operating offshore wind farms or have offshore wind farm projects in development.

1.2. Problem description

Offshore wind farms consist of arrays of turbines linked together. The energy produced by the farm is collected within this array of turbines and transported to shore to a grid connection point where the electricity is handed over to the integrated public grid. A typical layout is shown in Figure 1.

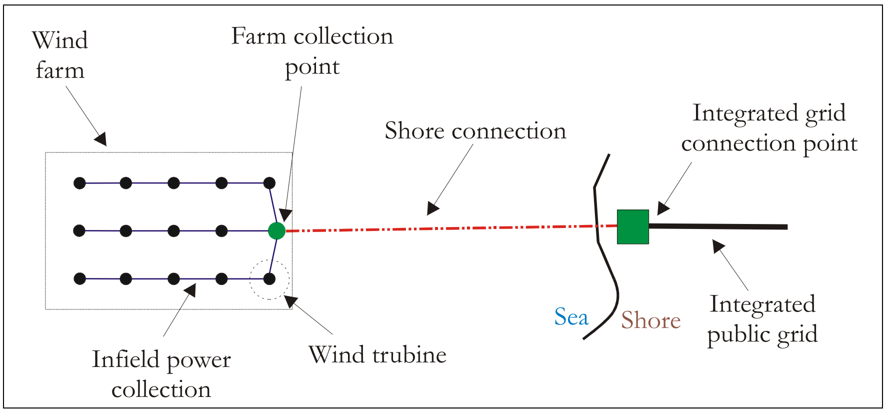


Figure 1 Offshore wind farm

An offshore wind farm involves numerous cable connections, most of them for the infield power collection. These connections have impact on the annual produced power, the operation, the reliability and the installation of the wind farm. The concept of offshore wind farms is relatively new, many of its aspects are yet to be optimized in order to guarantee a successful future. Construction is mostly done with knowledge and expertise of the offshore oil industry, but connecting a huge amount of single turbines is a task not similar done in recent offshore operations and therefore only little knowledge about the implications of different set-ups is existent.

1.3. Objective and set-up of the thesis

The objective of this thesis is to show, analyze and compare the options for connecting the wind farm to shore, the infield power collection and the physical installation procedures of the turbine connection in order to provide recommendations for future developments. According to this the support structures for the cables (J-Tubes) should be investigated. The first step of this thesis is to give an overview of the options to connect an offshore wind farm to the shore grid connection point where the produced electricity is handed over to the integrated power grid. The different electrical options will be discussed and rated. The next step is to analyze the different infield power collection possibilities and develop a connection scheme based on a case study for the Dutch near shore wind farm (NSW) at Egmond. The location is given in Figure 2.

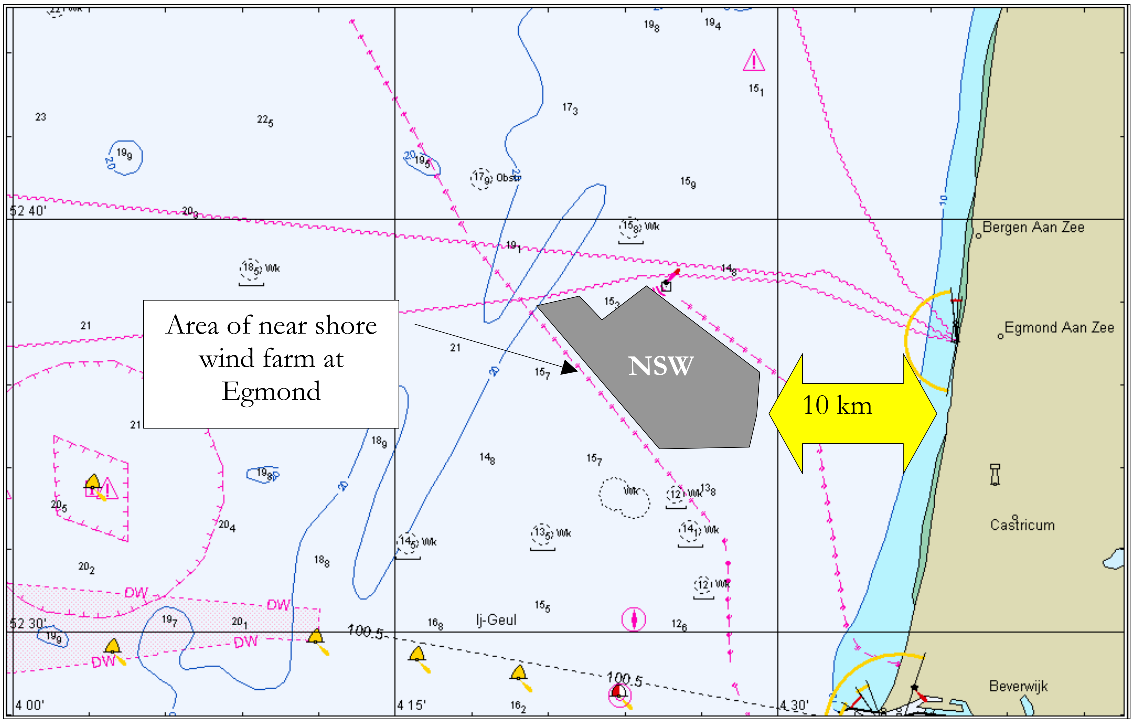


Figure 2 Near shore wind farm at Egmond

The offshore wind farm at is located 10 km west of the shore near Egmond. The output is planned to be 100 MW, gained with 36 turbines of 2,75 MW each. As third step a physical connection scheme for the turbine connection has to be developed, covering the installation process of the cables connecting the turbines to each other. The installation work done at the Danish offshore wind farm located at Horns Rev will be used as a reference procedure for that objective. The conceptual outline of the thesis work is illustrated in Figure 3, showing the general perspective on the structure of the work.

1.4. Thesis concept

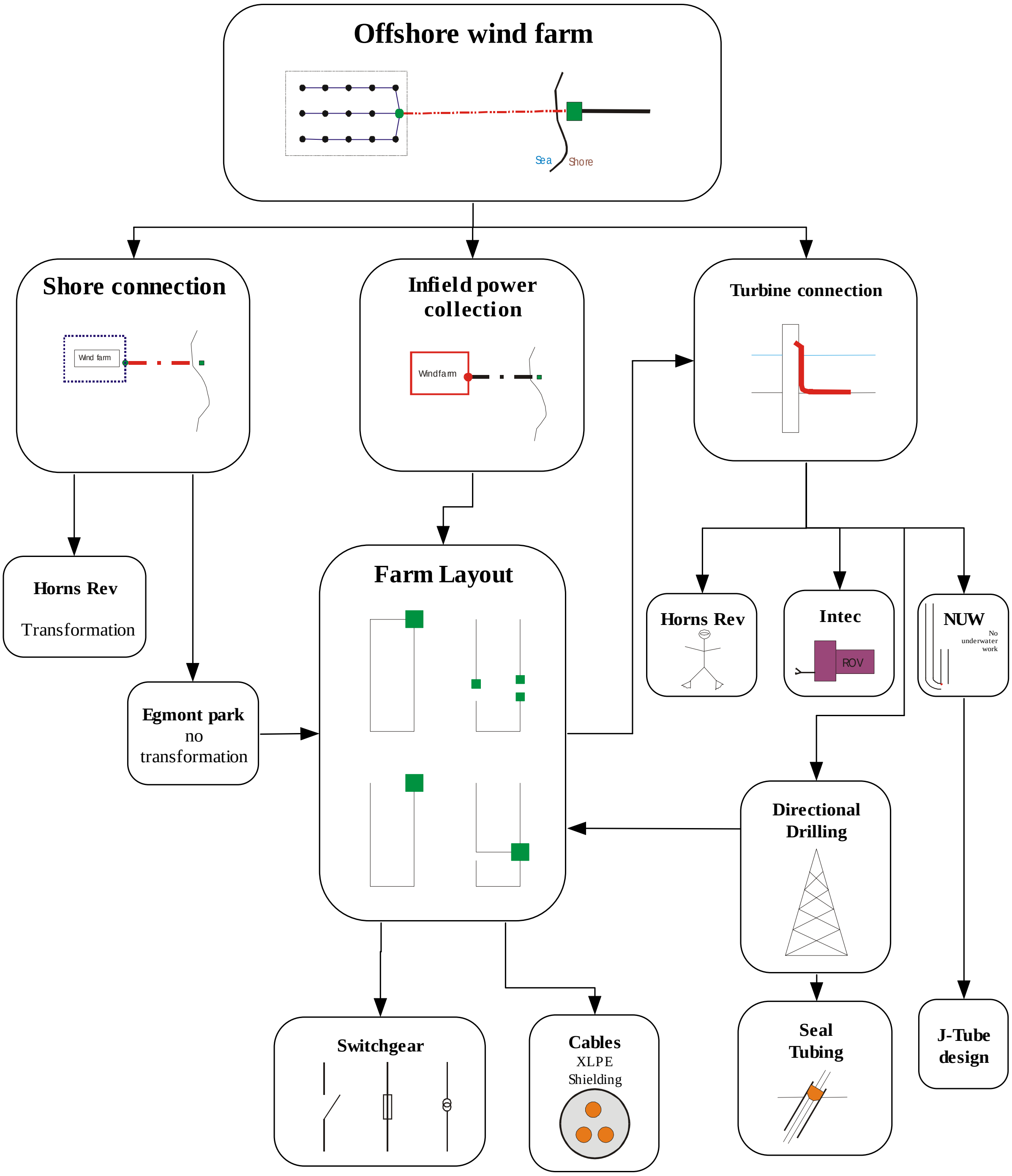


Figure 3 Thesis concept

2. Shore connection

2.1. Introduction

The electrical energy produced in an offshore wind farm has to be transported to a connection point to the local grid onshore. The wind farm and the onshore grid are using AC for production as well as transportation. The only possibility to transport electricity is currently by the use of cables or wires. Overhead transmission lines are not considered in this study as the reasonable span between masts is an average of 700 to 1200m, resulting in the need of several offshore structures, which are expensive to build and require costly installation works. The common way to transport electrical energy across the sea is via sub-sea power cables. In Figure 4 the system configuration of an offshore wind farm is shown, where the wind farm system is connected with a shore connection cable to the onshore grid system.

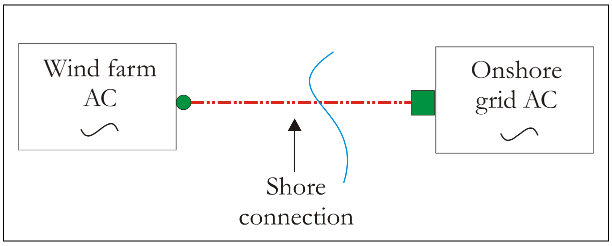


Figure 4 OWF System

Two technologies can be used to transport electrical energy and connect wind farms to the grid: alternating current (AC) and direct current (DC). The next sections discuss these two options and compare their suitability for the connection of offshore wind farms.

2.2. AC connection

2.2.1. AC connection at wind farm voltage level

The obvious solution to connect an AC producing wind farm to an AC onshore grid is to use AC transmission. In recent wind farms the single turbines are connected with medium voltage (MV; 1kV to 50 kV, usually 22 kV or 34 kV). To avoid the need of placing a transformer offshore the internal wind farm voltage can be used for transmission. In Figure 5 a schematic overview of the required facilities is given. The local grid usually operates at the high voltage (HV) level (>50 kV), making transformation to the grid voltage at the onshore connection point necessary.

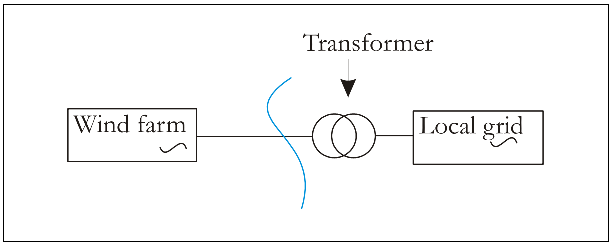


Figure 5 AC connection at wind farm voltage level

Main advantage of this arrangement is that no offshore transformation gear is needed, resulting in lower costs for the wind farm installation. A problem is the limited transportation capacity of MV cables, at 34 kV approximately 50 MW, making multiple cable connections to shore necessary for large wind farms as shown in Figure 6. Multiple cable connections require more installation work and more electrical infrastructure, but in case of cable failure benefit from the ability to load switch between different cables, which can be an economic advantage over single connections. [4]

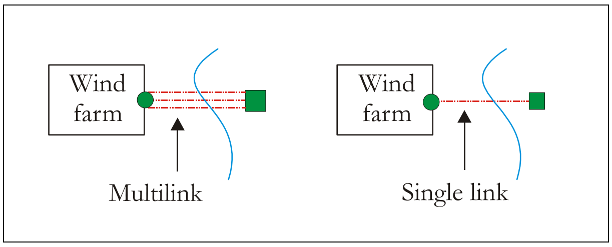


Figure 6 Multilink and single connections

The limiting factor for the length of MV connections is the electrical loss, which increases with distance. The sensible distance for MV cable connections is about 10 to 15 km mainly inflicted by the Ohmic resistance of the cable.

2.2.2. AC connection with offshore transformation

To reduce losses in power transportation the common way is to step up the voltage, as the Ohmic losses are depending on the square of current, shown in Equation 1.

$$P_\Omega = R_{ac} I^2 \qquad (1)$$

P_Ω ....Ohmic losses [W/m]
R_{ac} ....AC resistance [Ω/m]
I ....Current [A]

By stepping up the voltage with constant resistance the current decreases according to the Ohmic law, Equation 2, resulting in significantly lower losses for high voltage transmission.

$$U = R_{ac} l I \qquad (2)$$

U ....Voltage [V]
R_{ac} ....Resistance [Ω/m]
l............................Length [m]
I ....Current [A]

To step up the voltage level for transmission a transformer is required as shown in Figure 7. With this arrangement the transmission losses are lower than with the MV connection, but an expensive offshore transformation station is needed to host the HV transformer.

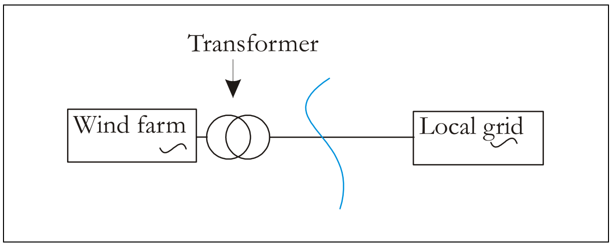


Figure 7 AC connection with offshore transformation

As example for an AC connection with high voltage transmission the 160 MW wind farm at Horns Rev is mentioned. The wind farm is located at the Danish west coast and is sited 14-20 km offshore in the North Sea, connected to shore with AC at 150 kV. For power transportation a single 150 kV sub sea-power cable is in operation. Since the turbines are connected with 34 kV, an additional platform with the 34 to 150 kV transformer was necessary. The erection of the station is shown in Figure 8. The platform also contains 34 and 150 kV switchgear, monitoring and maintenance facilities. A layout of the transformer station is shown in Appendix E.

Figure 8 Transformerstation at Horns Rev

Due to the reduced effect of Ohmic resistance for high voltage cables, the transmission length of this system is no longer limited by Ohmic resistance, but by the electrical characteristics of insulated cables. The dielectric insulation acts as capacitor when subjected to alternating current. Each time the voltage direction changes, the electric dipoles have to be realigned. The current required to effect the realignment of electric dipoles produces heat and results in a loss of active power. Equation 3 shows that the dielectric losses depend on voltage and frequency.

$$W_d = 2\pi f C' U^2 \tan\delta \qquad (3)$$

W_d .... Dielectric losses [W/m]
C´ .... Cable capacity [F/m]
f .... Frequency [Hz]
U .... Voltage [V]
$\tan\delta$ .... Insulation loss factor [-]

Power transmission with high voltage AC is economically limited to distances up to 100 km [2]. To cover distances larger than that and with an eye on Equation 3 a transmission with a frequency of 0 Hz, equal to direct current, would not have any dielectric losses and allow longer distances. Notice that for high voltage AC compensation of the capacitive current is required.

2.3. High Voltage Direct Current (HVDC)

To cover distances longer than feasible with medium and high voltage AC, it has to be converted to DC at an offshore converter and transformer station and backwards from DC to AC at the onshore grid connection point, see Figure 9.

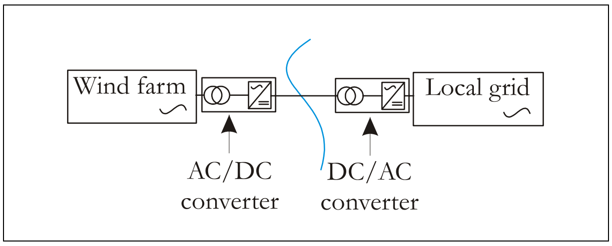


Figure 9 HVDC shore connection

Two different systems of conversion are currently in operation, conventional HVDC with line commutated converters and HVDC plus with voltage source converters. Conventional HVDC is used to transport electrical energy over huge distances, for example the "Pacific Interie DC link" with 1300 km length and a rating of 3100 MW connecting the south of California with the Seattle area. The conventional HVDC technology has a proven track record and is used since 50 years worldwide for sub-sea power transmission, but needs large converter stations both offshore and onshore, built tailor made. With HVDC plus being the newer technology based on a new type semiconductors (IGBT) the gear is modulized and allows a high grade of prefabrication of the converter transformer station. An example of such a station is given in Figure 10. Nevertheless a converter transformer station needs a platform with about 800 m2 and is itself a costly part of equipment.

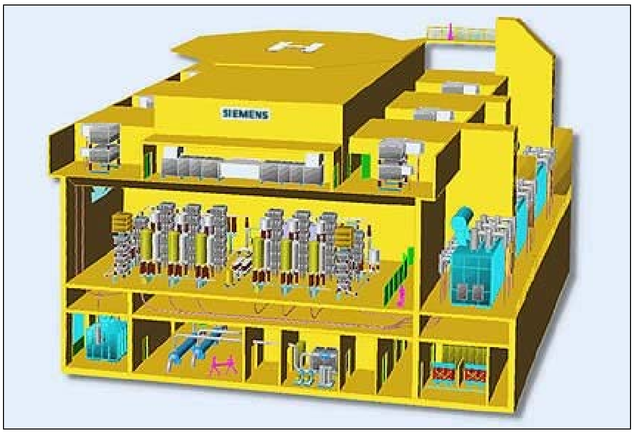


Figure 10 Converter transformer offshore station [1]

Currently an onshore wind farm rated 6 MW at Tjaereborg Denmark is connected to the grid with VSC based HVDC. A distance of 4,4 km is covered. [2] See Figure 11 for the electrical layout of the Tjaereborg connection. The direct connection in this scheme allows back up operation (AC) in case of testing purposes on the HVDC link. In Gotland (Sweden) a 50 MW wind farm is connected over a distance of 70 km to the grid.

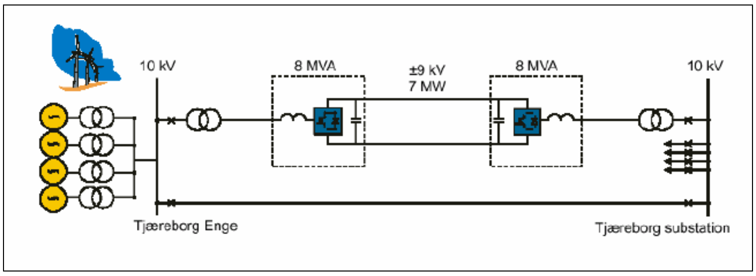


Figure 11 Tjaereborg HVDC light connection [2]

The reasons for that connection are both political and technical, as it was not possible to get permission for overland power lines and with HVDC plus it is possible to control voltage level and reactive power of the grid, compensating problems caused by the electrical behaviour of wind turbines.

HVDC connections for offshore wind farms are not used until now and no offshore wind farms are projected in the next 2 years with HVDC connection.

2.4. Comparison

In Table 1 a comparison of the shore connection options discussed before is given, as it is not possible to give exact numbers not knowing the whole wind farm system. Weak points are indicated by – and strong points by +. As reference the Horns Rev design with offshore transformation is rated neutral.

	AC transmission with farm voltage	**AC transmission with offshore transformation (Horns Rev)**	**Conventional HVDC transmission**	**Voltage sourced conversion HVDC**
Gear size	++	0	--	-
Coverable distance	--	0	++	+
Cost of transmission system	++	0	-	--

Table 1 Comparison of shore connection options

As can be seen the only weak point of the AC transmission with farm voltage is the small coverable distance, making it the option of choice for wind farms close to the shore meaning distances in the range of 10 km. If large distances (> 100 km) have to be covered, according to

Figure 12, it comes down to Conventional HVDC and HVDC plus, giving HVDC plus the advantage with modularized gear and the better controllable grid influence. Only at very large distances the conventional HVDC gets an advantage with decreased losses by the possibility of higher voltage than HVDC plus (conventional HVDC up to 500kV to up to 150 kV with HVDC plus).

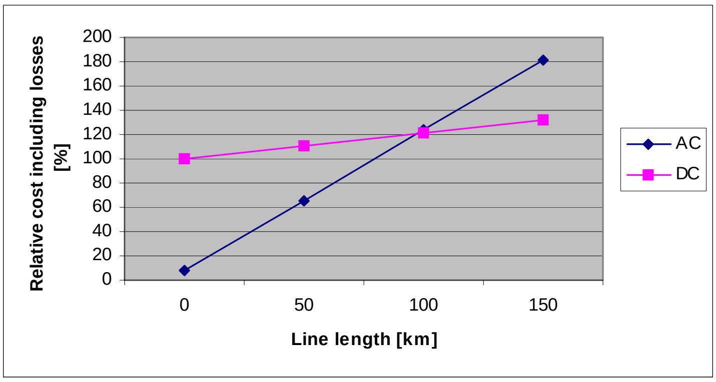


Figure 12 Relative cost of an AC and DC connection including capitalised power losses, with a 0 km DC connection (including capitalised power losses) as reference [3]

In Figure 13 the necessary gear size for the different options is visualized, where only the AC transmission with farm voltage needs no offshore structure for transformation and or rectification. It should also be considered that when using a HVDC option the conversion back to AC at grid connection terms has also to be done by the wind farm operator so the same type of converter has to be placed onshore too.

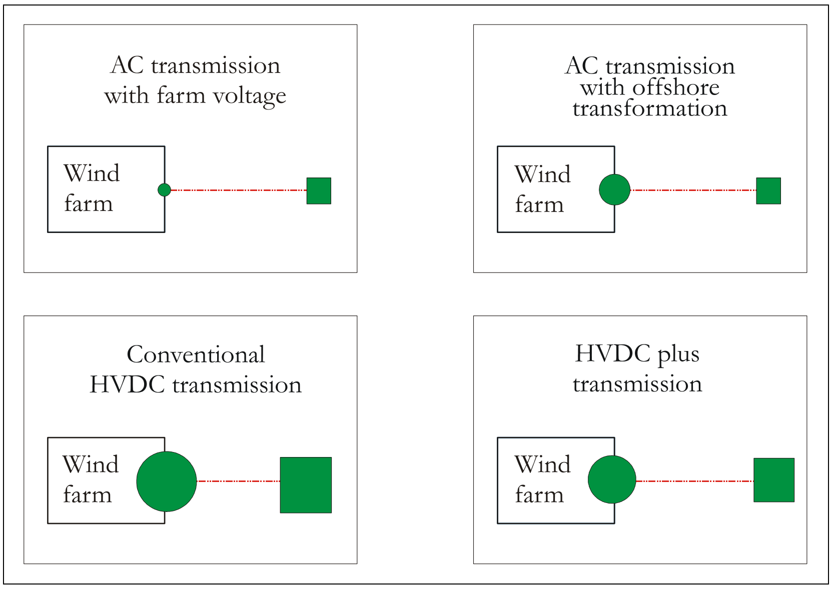


Figure 13 Shore connection options gear size

Figure 14 shows the overall power losses for medium voltage and high voltage shore connections at different OWF power outputs. It can be seen that for higher power outputs MV connections becomes uneconomic due the high losses. The break even points for HV connections are depending on the additional costs for HV transmission gear and the monetary value of the losses.

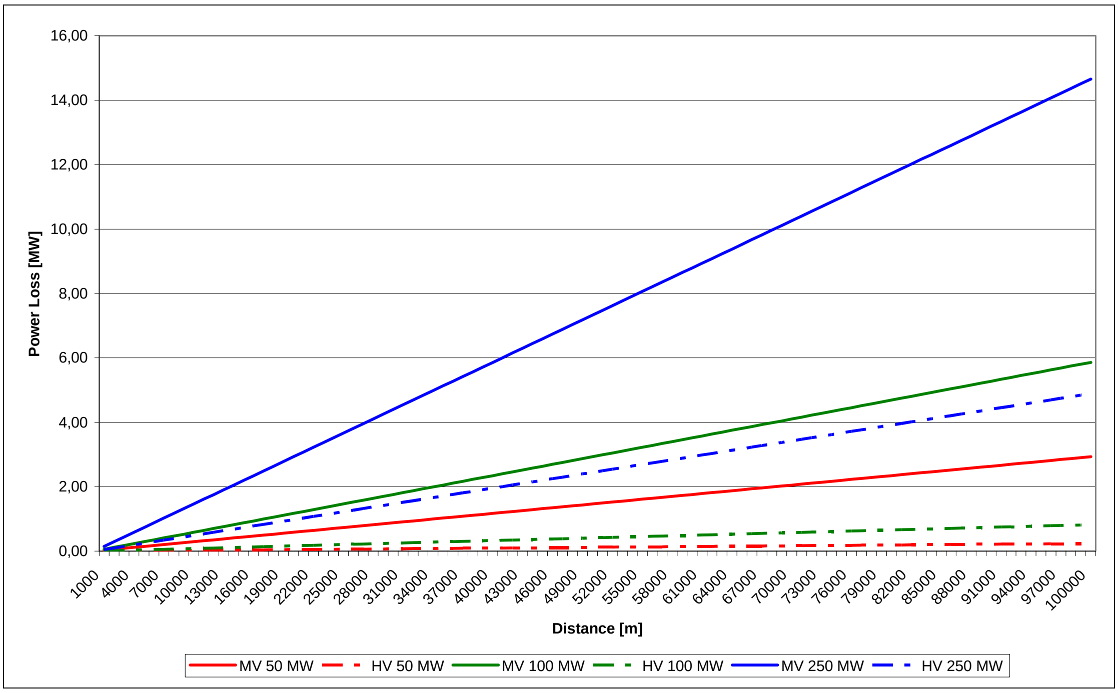


Figure 14 Power losses for HV (132kV) and MV (34 kV)

In Figure 15 the approximately sensible distances for the different connection options are given, showing that any type of AC connection is preferable for offshore wind farms with 100 MW and closer to shore than 100 km. For higher power outputs the AC connection with farm voltage is not an option, and due the increasing losses the break even point for HVDC is closer to shore. Exact distances have to be calculated with actual costs and are out of the scope of this work.

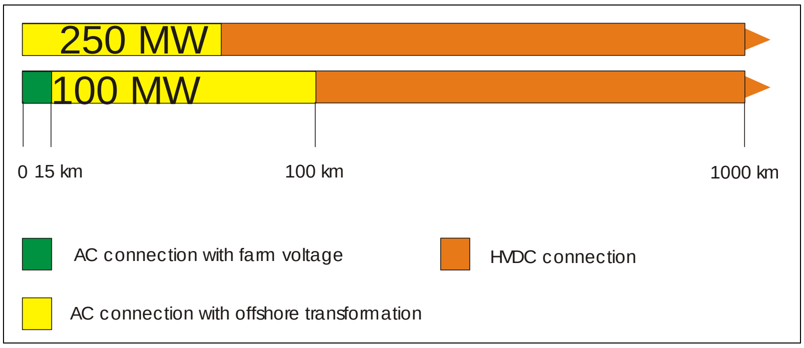


Figure 15 Sensible connection distances for offshore connection

2.5. Egmond near shore wind farm

With an Output of approx. 99 MW and a distance to shore of 10 km an AC connection with farm voltage is according to Figure 15 the most sensible solution. With [4] a multilink connection as shown in Figure 6 is the best fit, given a cable load of 33 MW each resulting in a 3 cable connection to shore.

3. Infield power collection

3.1. Introduction

This chapter deals with the different layout and connection options suitable for offshore wind farms (OWF). It gives basic knowledge of the impacts on cable dimensions by applying selected power collection options to a specific OWF. The near shore wind farm at Egmond will be used to show the impact of power collection options on cable dimensions where applicable. The OWF at Horns Rev is used as a reference design where applicable.

Several factors have to be considered when planning the layout. The geometrical arrangement and turbine spacing is likely to be determined by available space of the site and wind wake effects. The distance to shore of the farm has to be taken into account, as the necessary electrical setup is depending on the shore connection type, mainly if transformation of the infield voltage to a higher level is necessary for transmission to shore or if an AC to DC conversion station has to be placed and connected to the OWF offshore for HVDC transmission. The variations on several layouts are depending on the size of the wind farm determined by the number of turbines and the single turbine rating.

3.2. Fundamental layout options

The standard solutions for the collection and transmission of the electrical power of wind farms are the string collection and the star layout shown in Figure 16, I and III. Both options can be equipped with an additional transformation station to allow high voltage shore connections, shown in options II and IV. However, it has to be considered that these options are most likely to require an additional platform to house the transformer.

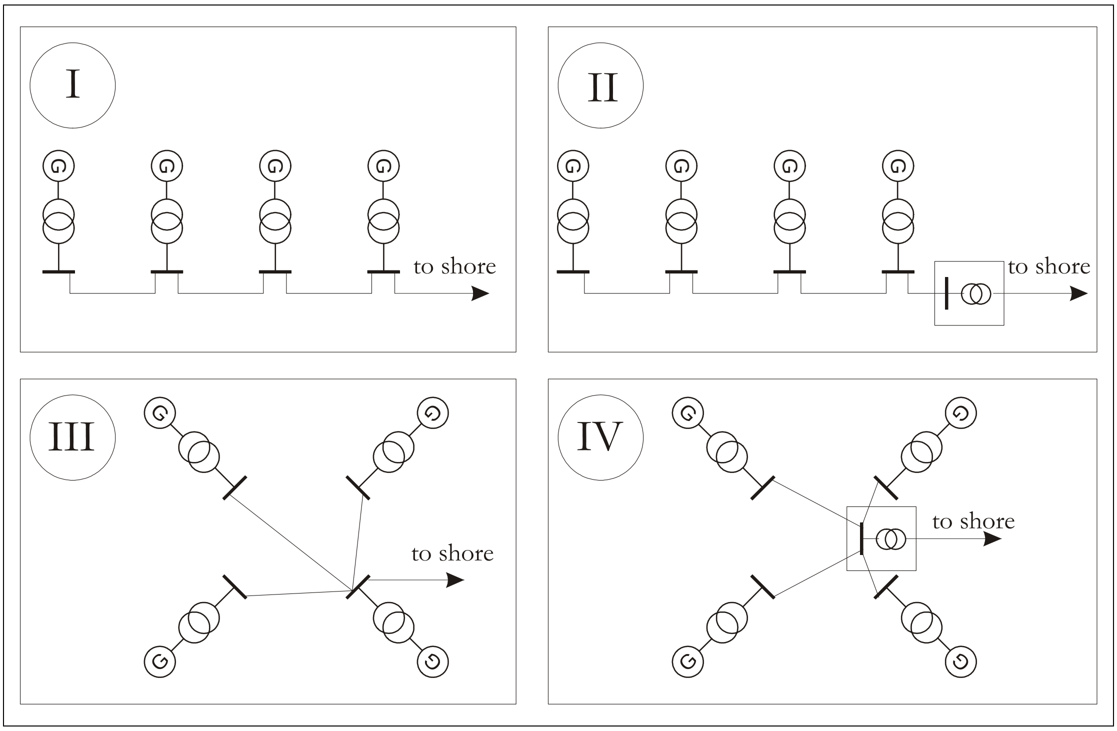


Figure 16 Star and string layout

For large scale OWFs a combination of these basic layouts is commonly used, where several strings of turbines are connected to the shore connection point. Its advantages are the simpler cable laying pattern and the shorter cable lengths compared to a strictly star layout. The disadvantages occur with cable failure, because all the turbines upward the failure site on a string have to be switched off and cannot be connected to the grid until the failure has been repaired. Especially during periods of harsh sea conditions in winter the required repair time can be months. Also the number of turbines which can be connected to a string is limited by the power carrying capability of the cable used. With growing turbine power output, the star connection offers the possibility to reduce cable losses by clustering small groups of turbines to high voltage transformer stations as shown in layout IV. Also in case of cable failure at a turbine connection only the single turbine where the failure occurred has to be switched off, the remaining turbines connected to the transformer platform can stay in operation. The big disadvantage is the required transformer platform. As example for a currently used infield power collection the OWF at Horns Rev will be described.

3.3. Horns Rev

As stated in section 2.2.2 the wind farm is located at the Danish west coast and is sited 14-20 km offshore in the North Sea. Figure 17 shows the location. Water depth in this area is approximately 10 m.

Figure 17 Horns Rev map

At Horns Rev 80 turbines of 2 MW are used, resulting in a nominal farm output of 160 MW. The datasheet of the used turbines can be seen in Appendix B and Appendix C. The turbines are placed in 10 rows with 8 turbines each. 2 rows are connected to a “Radial feeder” which itself is connected to the transformation station. A sketch is given in Figure 18. The support structure used is a monopile, with a transition piece grouted on top. On the transition piece a flange is located to which the turbine tower is bolted [5].

The voltage level for the infield power collection is 34 kV, transformed to shore connection voltage level of 150 kV at the offshore transformer station. This station (20 x 28 m) contains the following grid relevant facilities:

- 36 kV switch gear
- 36/150 kV transformer
- 150 kV switch gear
- Control and instrumentation system, communication unit
- Emergency diesel generator, incl. 2 x 50 tonnes of fuel

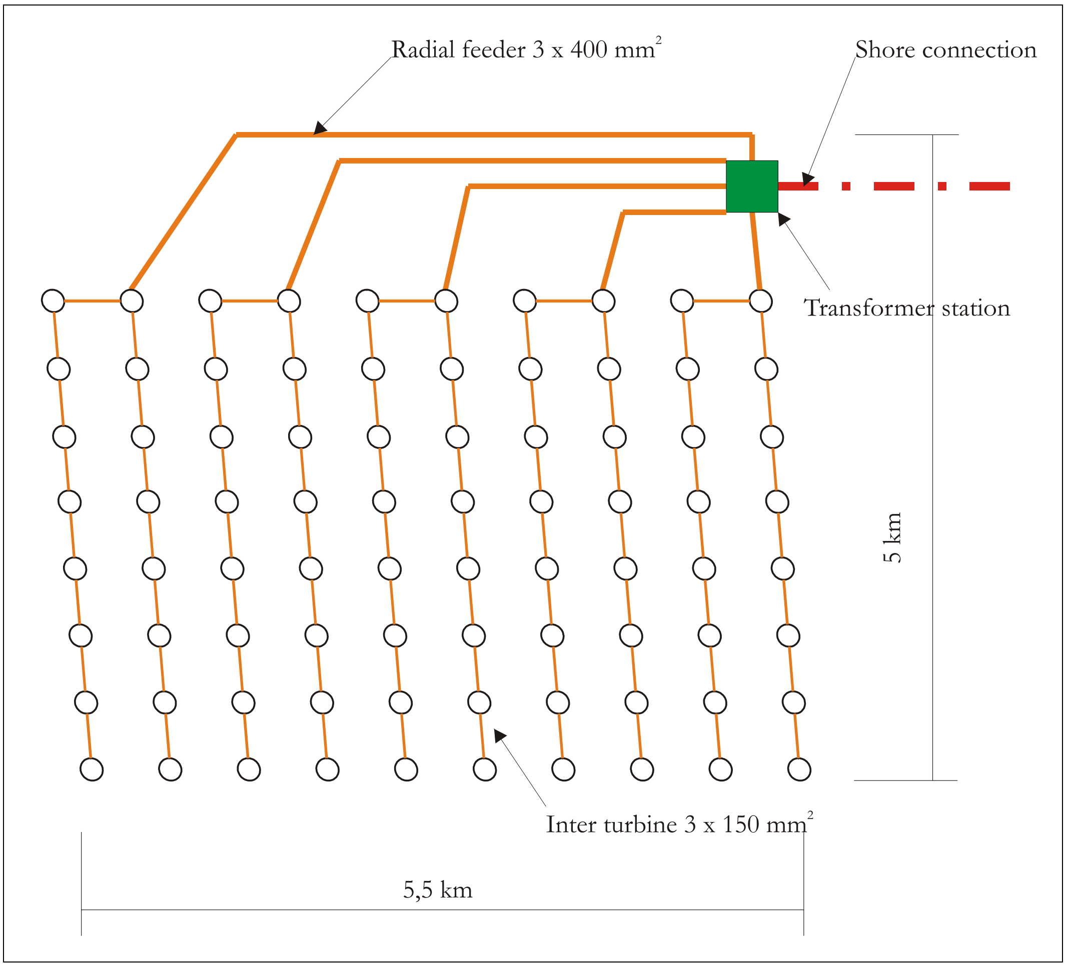


Figure 18 Horns Rev layout

A similar concept will be developed for the OWF near Egmond. The distance to shore is smaller, the geometrical placement of the turbines is different and the power output is rated lower than at Horns Rev. The implications of these differences will be investigated in the next section.

3.4. Egmond OWF

3.4.1. General description of the wind farm

The OWF will be located 10 km west of Egmond, the location can be seen in Figure 2. The nominal power output is rated with 99 MW. The chosen turbine rating is 2,75 MW, requiring 36 turbines to gain the required nominal power output of 99 MW. The shore connection consists of three 34 kV connections.

For the purpose of this study, the turbines are located in two rows, with a horizontal spacing of 6 x D and a vertical spacing of 8 x D, with D being the diameter of the rotor of 92 m. With the distance to shore of 10 km according to section 2.2.1 a connection at farm voltage level is reasonable. A sketch of the geometrical layout of the turbines is given in Figure 19.

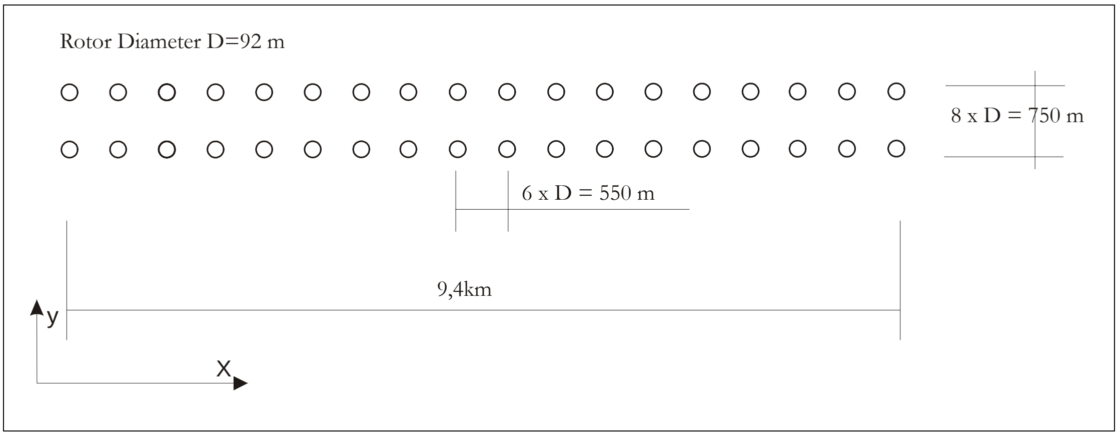


Figure 19 Egmond layout

For this geometrical pattern of turbines an infield power connection scheme has to be developed. To be able to investigate several layout options the given turbine parameters of this setup will be described and their influence on the infield power connection determined.

3.4.2. Single turbine electrical infrastructure Egmond

3.4.2.1. Components of the wind turbine

Figure 20 shows the functional components of a wind turbine, which are: Rotor (Wind is converted into rotation)

- Gear (Rotation is stepped up to generator level)
- Generator (Rotation is converted to electrical energy)
- Transformer (Voltage level is stepped up to transmission level)
- Switchgear (Connecting the turbine to the infield power collection)

The structural components like foundation and tower are not mentioned here.

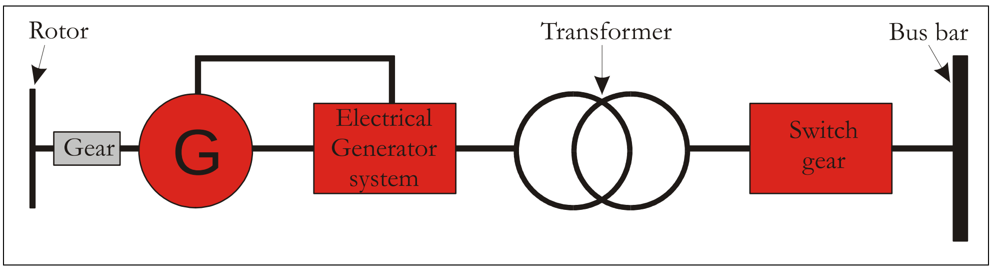


Figure 20 Single turbine scheme

The main electrical compartments of the single turbine are the generator where the electrical power is produced, the transformer where the generated voltage (usually 690 V) is transformed to a higher voltage level for transmission and the switchgear. This setup covers most of the currently used turbines and will be applied for the specific turbines used at Egmond OWF.

3.4.2.2. Turbine specifications

The turbines are manufactured by NEG Micon, Type NM 92 offshore. The electrical relevant turbine data is given in Table 2. A complete datasheet for this turbine is shown in Appendix D.

Nominal output	2750 kW
Output regulation	PRVS*
Rotor diameter	92 m
Number of blades	3
Generator Type	Double-fed asynchronous
Voltage – stator	960 V
Voltage – rotor	690 V
Nominal frequency	50 Hz

Table 2 NM 92/2750 data sheet [6]

The choice of turbines has by far the widest influence on the infield power collection layout. The nominal output determines the required number of turbines for a given OWF rating. The type of generator and the output voltage level influences the choice on transformation and the required switchgear devices. As first component of the turbine the generator will be described.

3.4.2.3. Generator and converters

The generator is a double fed asynchronous (induction) machine. A sketch of the electrical components is given in Figure 21.

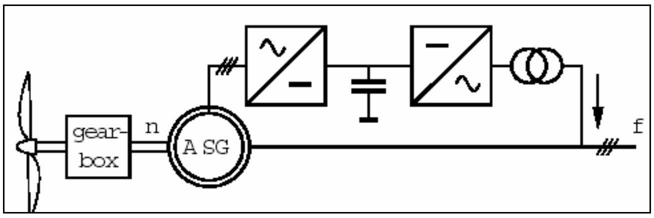


Figure 21 Double fed asynchronous (induction) generator and back-to-back converters [7]

Asynchronous or induction machines have a variable ratio between rotation speed and the generated frequency. The difference between the rotation frequency and generated frequency is called "slip" and usually about 2 % for a standard induction machine. The relation between rotation and frequency is given in equation 4.

* Pitch Regulated Variable Speed

$$f_{gen} = \frac{pn}{(1-s)} \tag{4}$$

f_{gen} .... Electric frequency of the generator [1/s]
p .... Number of pole pairs [-]
n .... Rotations per second [1/s]
s .... Slip [-]

To be able to use a generator with variable rotation speed in the region of 20 %, electronic power devices are used to alter the frequency (and with that the slip) that is fed to the rotor windings. This is done with so-called AC-DC back-to-back converters. The AC-DC back-to-back converters are connected in line to the rotor windings and parallel to the stator windings, which is why this set up is called doubly-fed generator. This allows to dimension the converters to a fraction of the rated generator power, P_{rating}= s*P_{nom}, where s is the maximum slip and P_{nom} is the nominal power of the turbine

With this type of generator it is also possible to control the power factor cos φ, which is usually 0,90, but can be altered to ~1,00. This allows to use the rated power output of the turbine as total power output.

3.4.2.4. Current per phase

The power output of turbines is usually given as effective power P_{eff}. To calculate the current with given voltage equation 5 is used. It can be assumed that when operating at nominal output the power factor cos (φ) is regulated to be ~1,0 for the double fed asynchronous generator.

$$I_{eff} = \frac{P_{eff}}{\sqrt{3} \times U \times \cos\varphi} \tag{5}$$

P_{eff} .... Nominal power [W]
U .... Voltage per phase [V]
I_{eff} .... Effective current per phase [A]
φ .... Phase angle [°]

These are rough assumptions to get an overview of the impact of farm layout on cable sizes and as a result of installation devices needed. For actual cable dimensions an electrical simulation of the electric grid, grid connection and electrical devices used in the farm is highly recommended.

3.4.2.5. Transformer

The output voltage of this type of generator is to low for economic transmission. To step up the voltage a transformer is required. For offshore applications, a dry type transformer is used as conventional oil filled transformers are not allowed for safety reasons by IEE offshore regulations.[8] Here casted coils are used to transform the voltage, as opposed to oil filled conventional transformers. This type has not to be placed in an oil tight compartment and therefore can be build smaller than a conventional oil filled transformer. Also the environmental risk of oil leakage is not present. An illustration of a 3-phase dry type transformer is given in Figure 22.

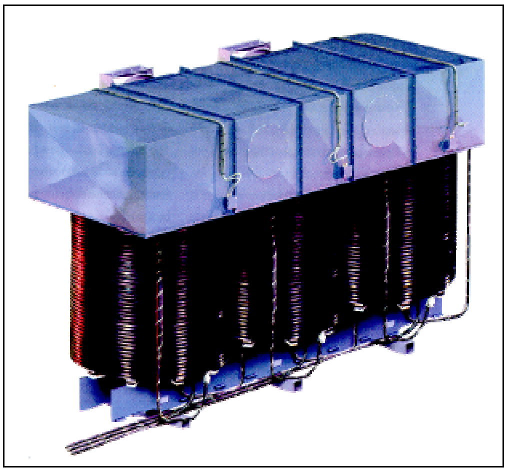


Figure 22 Cable wound dry type transformer (ABB)

The transformer is usually not included in a standard turbine package and has to be chosen according to the infield power collection voltage level. For the NM 92 the transformer is placed in the tower on a level above the switchgear. For reduced losses it is sensible to place the transformer as close to the generator as possible.

3.4.2.6. Switchgear

Switchgear is needed to operate the OWF. The switchgear enables and disables the connection of the turbines to the infield power collection and the connection of several strings of turbines to the shore connection point. The ability of a switchgear arrangement and in combination with a cable layout to isolate failures and maintain operation of the remaining parts is called "Selectivity". It can be calculated according to Equation (6.

$$S = \frac{n-m}{n} \tag{6}$$

S ....Selectivity [-]
n ....Number of Turbines [-]
m ....Number of Turbines out of operation in case of one "worst case" cable failure [-]

The highest grade of selectivity is the "n-1" criterion, meaning that in case of a failure only the faulty turbine or cable connection has to be switched of, the remaining parts of the OWF can be kept operational. Two approaches are possible for OFWs:

- Low failure probability of the cables, short repair times resulting in a low required selectivity
- Medium to high failure probability of the cables, long repair times resulting in a high required selectivity

The switchgear shown in Figure 23 can only maintain a low selectivity, meaning that in case of a cable failure the whole string of turbines has to be switched of until the failure is repaired. Its advantage is that only one power switch is needed per turbine. (Horns Rev is equipped with that turbine switchgear configuration.)

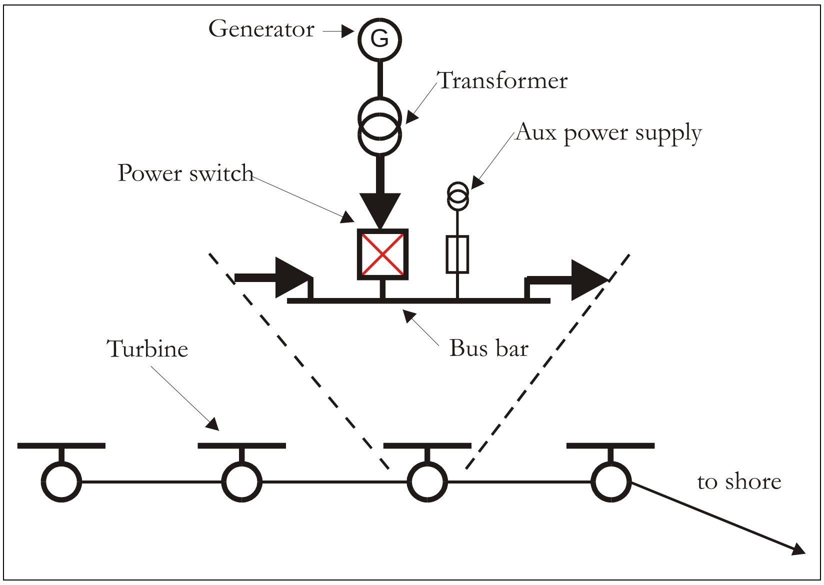


Figure 23 Turbine switchgear low selectivity

High selectivity requires a switchgear configuration which is able to switch parts of a string in case of cable failure, therefore every cable connected to the bus bar at the turbine is connected with a power switch. The disadvantage is obvious; three power switches are needed and have to be placed inside the turbine.

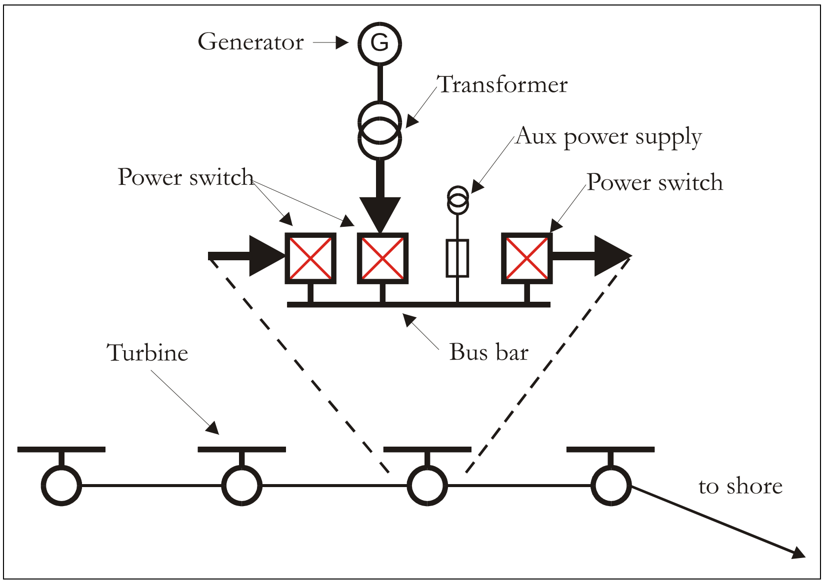


Figure 24 Turbine switchgear high selectivity [9]

The electrical elements used in Figure 23 and Figure 24 consist of:

- A power switch, which is able to switch under load and disconnect the cable in case of a short circuit
- A bus bar, which is a collection conductor to where all switches or cables are connected

- An aux power supply, which provides low voltage (220 V/380 V) supply for devices like cranes, hydraulic pumps, navigation lights…..

In case of malfunction of any part of the OWF the switchgear has to be able to disconnect the relevant parts from current or voltage carrying lines. For maintenance or repair it has to ensure that the relevant parts are free of voltage and current and cables are connected to ground. As OWFs require special care concerning the size of the gear, reliability and safety a special type of switchgear is generally used.

Gas Isolated Switchgear (GIS)

If a MV carrying conductor is switched an electric arc is drawn between the two contacts. This arc has to be blown out as soon as possible to break the circuit. This is done by a special gas, SF6. It has a high dielectric isolation coefficient compared to air, is chemically inert, thermally stable and non toxic. Caused by the big molecule size, SF6 can be kept pressurized up to 40 years without significant losses. SF6 is used as circuit breaker medium and as isolation gas between conductors. As can be seen in Figure 25, for a voltage of 34KV the critical distance in air is about 20 mm, but in SF6 about 3-7 mm, depending on pressure. As a result the switchgear can be built compact and modular.

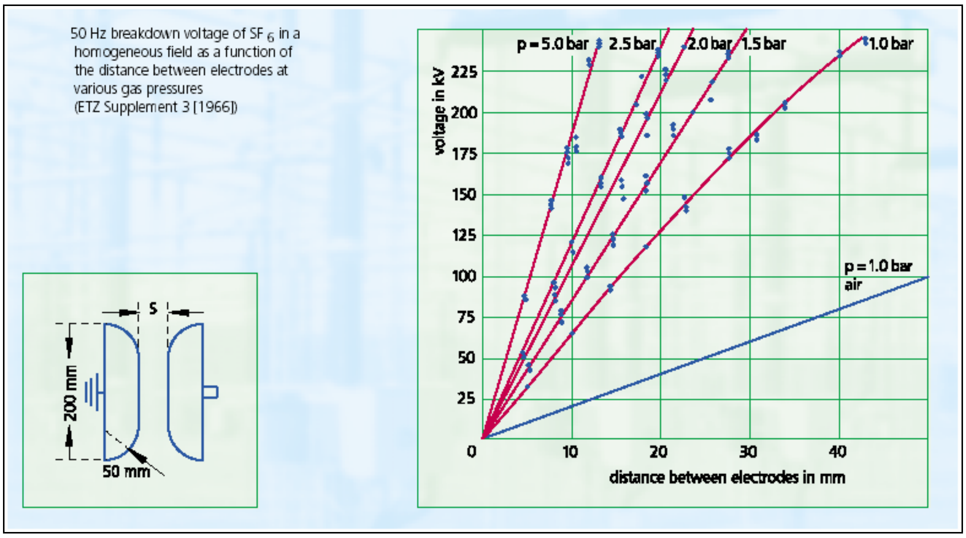


Figure 25 SF6 Breakdown voltage [10]

3.4.3. Power cables

3.4.3.1. Dimensioning approach

When electricity is transported over a cable, the limiting factor for the maximum transportable power is the generated heat in the cable. Basically heat is generated by the Ohmic losses and the dielectric losses in the cable. The two main sources of heat will be discussed. As the produced heat in the cable is depending on the cable properties, the calculation is done by first estimating the cable cross section and then calculating the corresponding current carrying capacity exactly for a certain cable type. Depending on the cable laying parameters a new cable cross section is chosen. The necessary calculation steps are described next.

3.4.3.2. Type of cable

As for the calculations it is necessary to use cable specific parameters, a certain type of cables is chosen to be used for the infield power connection. The type is called XLPE; named after its insulation of Cross linked PE. In Figure 26 the typical structure for a medium voltage XLPE submarine power cable is shown, including fibre optics to transfer data via the cable. This data line can be used to monitor and control the turbines and their electrical equipment. XLPE cables are widely used for medium and high voltage transmission project, offshore and onshore and have proven their reliability.

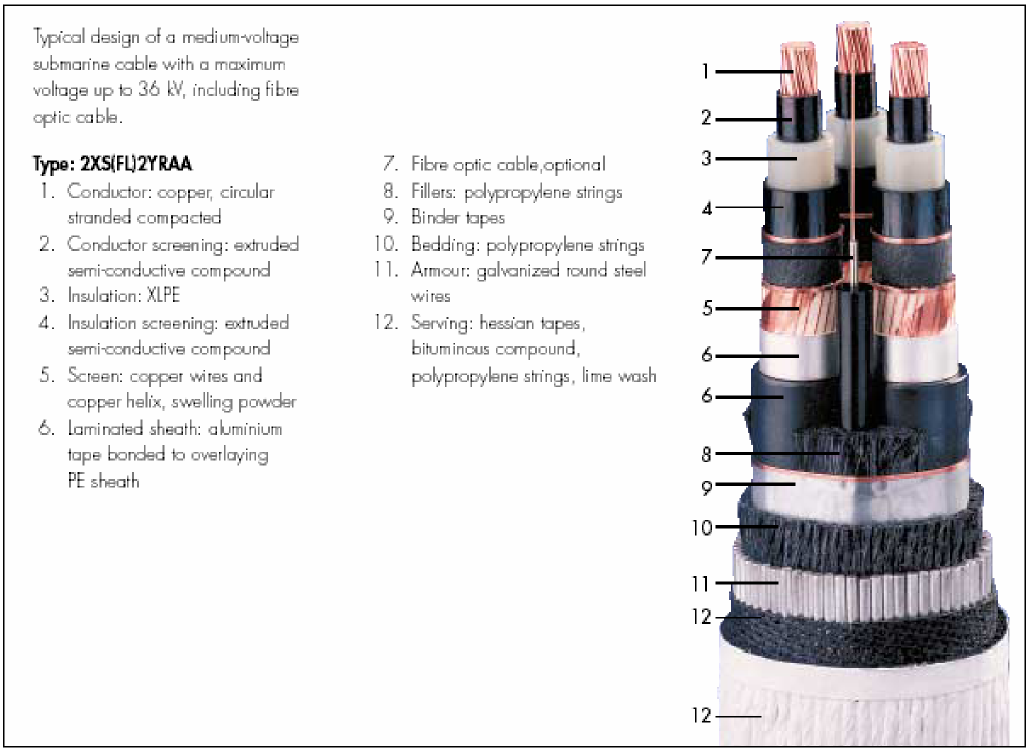


Figure 26 XPLE MV submarine cable [15]

Compared to standard oil filled cables with copper conductors, XLPE cables offer the following advantages:

- XLPE is a solid dielectric. It is maintenance free, requiring no supervision and control of the oil level in the cable system is necessary.
- XPLE insulated cables are usually supplied without a lead sheath. The construction is therefore of lighter weight permitting longer continuous delivery lengths and easier handling during transportation and laying.
- The minimum allowed bending radius is small. The solid dielectric and the heavy steel wire armouring are superior to the paper insulated and lead sheath cables and are much less sensitive to severe stresses to which submarine cables are subject during transportation, laying and operation.

The main electrical and thermical characteristics of XLPE compared to paper-oil insulated MV cables are given in Table 3. The data in Table 3 shows that with XLPE insulation it is possible to build cables which can carry more power with smaller cross sections than a paper oil insulated cable would be able to. The reasons for this are the higher operating temperature for a higher current carrying capacity and the higher insulation resistance allowing to use thinner insulation layers for the conductors.

	Dielectric loss factor: tan δ	Dielectric constant: ε	Insulation resistance [Ω cm]	Operating temperature [°C]	Short circuit temperature [°C]
XLPE	0,0004	2,3	10^{17}	90	250
Paper-oil	0,003	3,7	10^{14}	60-70*	140-170

Table 3 XPLE cables general data *Depending on type of oil used [11]

3.4.3.3. Electric cable model

For electrical short connections the simplified cable model can be developed, where the distributed capacity, inductance and resistance are treated as accumulated (integrated) components. Figure 27 shows the so called "π circuit" or simplified cable model for a power cable. Notice that this model represents a single phase of the cable.

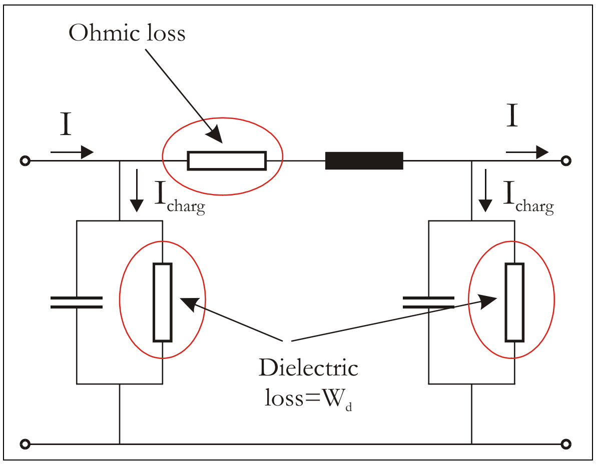


Figure 27 Electric cable model [12]

With this model the maximum transfer length for a cable can be determined, notice that at that length the whole current is used to charge the cable, meaning that no power can be transfered. When an open cable is connected to an AC voltage source, a current will flow into the cable according to Equation 7:

$$I_c = U \times \omega \times C' \times l \qquad (7)$$

I_c..........................Charging current [A]
U ....Voltage per phase [V]
ω..........................$2\pi f$ [s^{-1}]
C'.........................Capacity per length [F/m]
l............................Cable length [m]

It can be seen that with increasing cable length the charging current increases until it has reached the maximum allowable current in the cable. It is noted that the capacity of a cable increases with the cable cross section. The typical transmission length for an AC cable is about of 150 km. This distance can be extended with the application of compensation devices to reduce the charging current. However, for the infield power collection where the distances are a fraction of the maximum transmission length compensation can be neglected.

To perform the next calculation steps, specific cable data is required for resistance, capacity and insulation loss factor. As those values are specific for every cable type and diameter, different cables were chosen according to their operational current rating [13] Appendix A gives the data of the used cables.

3.4.3.4. Ohmic losses

The Ohmic losses are caused by the resistance of the cable. As AC is used for transmission, the corresponding AC resistance (R_{ac}) has to be used in calculations. As R_{ac} is depending on temperature, usually values are normalized for the operation temperature of the cable and are given in [Ω/m]. The losses are calculated according to Equation 8:

$$P_\Omega = R_{ac} I^2 \tag{8}$$

P_Ω ....Ohmic losses [W/m]
R_{ac} ....AC resistance [Ω/m]
I ....Current per phase [A]

3.4.3.5. Dielectric losses

The characteristics of dielectric losses are described in section 2.2.2. Where cable capacity is given in [F/km] and has to be multiplied with the cable length. The losses can then be calculated with Equation 9:

$$W_d = 2\pi f C' U^2 \tan\delta \tag{9}$$

W_d ....Dielectric losses [W/m]
C' ....Cable capacity [F/m]
f ....Frequency [Hz]
U ....Voltage [V]
$\tan\delta$ ....Insulation loss factor [-]

For electrical short connections at full transmission power the capacitive losses are nearly negligible. But as the OWF operates significant times at partial load, and the transmission voltage is constant, the percentage of the dielectric losses to the total cable losses is increasing with decreasing overall power output of the OWF.

3.4.3.6. Generated heat

During operation cables suffer electrical losses which appear as heat in the conductor, insulation and metallic components. The current rating is dependent on the way this heat is transmitted to the cable surface and then dissipated to the surroundings. A maximum temperature is fixed, which is usually the allowed operating temperature of the insulation. See Table 3 for a comparison of operation temperatures for different insulation materials. The other important factor is the temperature and thermal resistance of the surroundings [14].To be able to calculate the allowable current for a specific application the model in Figure 28 is used.

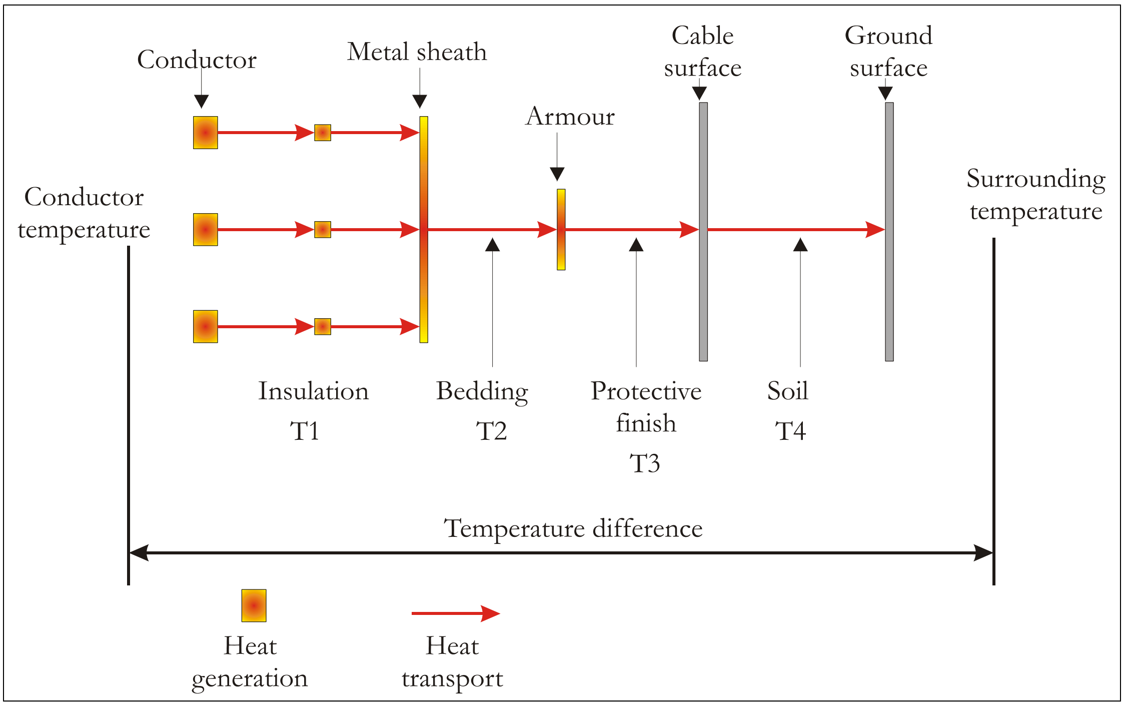


Figure 28 Heat model 3 core cable

The fundamental cross section of a XLPE medium voltage submarine cable is given in Figure 29 and developed to the cross section of the thermic model in Figure 30.

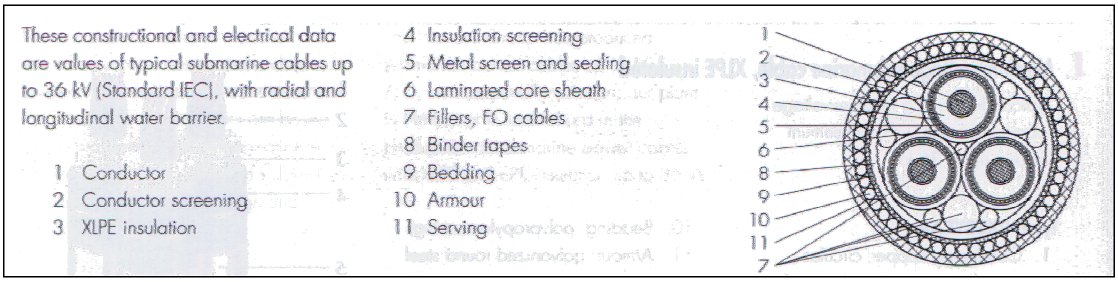


Figure 29 Cable data XPLE [15]

In this model the thermal resistance of the screen and the amour is neglected as the thermal resistivity of steel or similar materials is 1/100th the resistivity of the insulation material and the transfer length is small so it is not likely that the heat transport through the cable is influenced. The effective thickness of the bedding and the fillers has to be estimated and the results cross checked with known parameters for the resulting current carrying capacity.

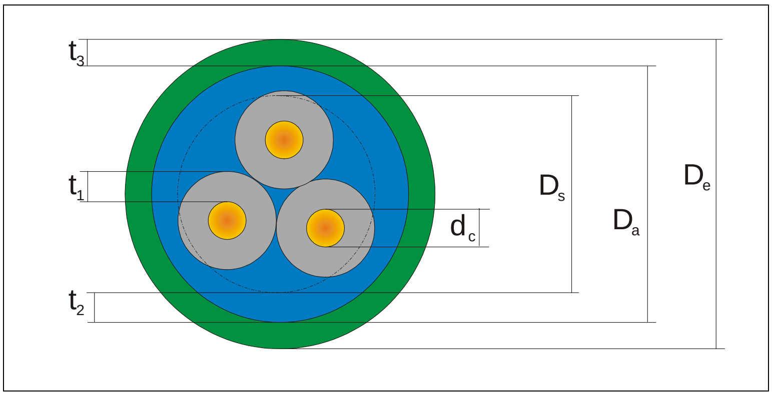


Figure 30 Heat model cross section

The heat is generated in the conductors (I^2R), in the insulation (W_d) and in the sheath and armour (λI^2R). Each of these sources is multiplied with the thermal resistance of the layers it has to pass (T_1; T_2; T_3; T_4). For the model in Figure 28 this can be formulated as Equation 10:

$$\Delta\Theta = \left(I^2 R_{ac} + \frac{1}{2} W_d^l \right) T_1 + \left(I^2 R_{ac} (1+\lambda_1) + W_d^l \right) n T_2 + \left(I^2 R_{ac} (1+\lambda_1+\lambda_2) + W_d^l \right) n (T_3 + T_4) \tag{10}$$

$\Delta\Theta$ .... Conductor temperature rise [°K]
I .... Current flowing in one conductor [A]
R_{ac} .... AC resistance per unit length at operation temperature [Ω/m]
W_d^1 .... Dielectric loss per unit length for the insulation [W/m]
T_1; T_2; T_3; T_4 ..... Thermal resistance per unit length [m°K/W]
n .... Number of load carrying conductors in the cable [-]
λ_1 .... Ratio of losses in metal sheath to total losses in cable [-]
λ_2 .... Ratio of losses in the armouring to total losses in the cable [-]

Equation 10 can be rewritten to obtain the permissible current rating, forming Equation 11

$$I = \sqrt{\frac{\Delta\Theta - W_d^l \left[\frac{1}{2} T_1 + n(T_2 + T_3 + T_4) \right]}{R_{ac} T_1 + n R_{ac} (1+\lambda_1) T_2 + n R_{ac} (1+\lambda_1+\lambda_2)(T_3+T_4)}} \tag{11}$$

To be able to calculate allowable currents for different cable options the factors T_1; T_2; T_3; T_4 “Thermal resistance” need closer investigation. These factors are restricting the transportable heat over a certain cross section of cable.

The factor T_1 is only influenced by the cross section of the conductor and the type and thickness of insulation. As the main property of the insulation is to prevent short circuits in the cable its dimension is determined mainly by the applied voltage and can not be reasonable be altered for heat transfer improvement.

$$T_1 = \frac{\rho_I}{2\pi} \ln\left(1 + \frac{2t_1}{d_c}\right) \tag{12}$$

T_1 ....Thermal resistance between conductor and sheath [m°K/W]
ρ_I ....Thermal resistivity of insulation [m°K/W]
t_1 ....Thickness of insulation [mm]
d_c ....Diameter of conductor [mm]

T_2 represents the thermal resistance in the bedding of the 3 insulated conductor cores and has only small influence on the rating of the cable. It is calculated similar to T_1.

$$T_2 = \frac{\rho_b}{2\pi} \ln\left(1 + \frac{2t_2}{D_s}\right) \tag{13}$$

T_2 ....Thermal resistance between sheat and armour [m°K/W]
ρ_b.........................Thermal resistivity of bedding [m°K/W]
t_2..........................Averaged thickness of bedding [mm]
D_s ....Diameter of bedding [mm]

T_3 represents the thermal resistance of the outer coverings and has also only small influence on the cable rating. It is calculated according to:

$$T_3 = \frac{\rho_c}{2\pi} \ln\left(1 + \frac{2t_3}{D_a'}\right) \tag{14}$$

T_2 ....Thermal resistance of outer coverings [m°K/W]
ρ_b.........................Thermal resistivity of covering [m°K/W]
t_3..........................Thickness of covering [mm]
D_a' ....External diameter of armour [mm]

T_4 represents the thermal resistance of the soil where the cable is buried. This is the main influence factor together with T_1 on the current rating of the cable. It is depending on the outer diameter of the cable, the buried depth and the thermal resistivity of the covering soil. For single buried cables T_4 is calculated according to Equation 15 and Equation 16:

$$T_4 = \frac{\rho_s}{2\pi} \ln\left[\mu + \sqrt{\mu^2 + 1}\right] \quad (15)$$

$$\mu = \frac{2L}{D_e} \quad (16)$$

T_4 ....Thermal resistance of the soil [m°K/W]
ϱ_s ....Thermal resistivity of the soil [m°K/W]
L..........................Distance from ground
D_e........................External cable diameter [mm]

Table 4 defines the standard values for specific conditions; in this case the conditions are according to IEC 287/IEC 60287.

Conductor temperature [°C]	Ground temperature [°C].	Ground thermal resistivity [m°K/W]	Laying depth [m]
90	15	1,0	0,80

Table 4 Standard conditions for current ratings of buried cables

3.4.4. General options

3.4.4.1. Introduction

In the next section a range of layout options for the OWF at Egmond will be discussed. With the location, the geometrical layout and the turbine specifications several layouts are possible. As first step the voltage level has to be determined.

3.4.4.2. Voltage level

The voltage level influences the type of transformer, switchgear and cables. The voltage level of the infield power collection will be 34 kV for the following reasons:

- No additional transformer is needed between shore connection and infield power collection.
- 34 kV is a “Standard Voltage Level” used in medium voltage (MV) power supply.
- Standard equipment i.e. transformers and switchgear can be used, being cost efficient and available.
- The size of the used gear is likely to fit in the tower or in a compartment that can be fitted to the tower, avoiding an additional offshore structure.
- Balance between low transfer loss and size of the equipment. Above MV sizes and costs grow rapidly.

The aim of the connection scheme is to connect the entire wind farm to shore without need of an additional support structure containing switchgear and transformers.

3.4.4.3. Transformer

For a 2,75 MW turbine with controllable cos φ and an output (secondary) voltage of 34 kV a transformer rated with 3 MVA would be a sensible choice. The overrating allows some reactive power at full load. The weight of the transformer in this power class is about 6 t. Sizes are variable, an example being the Siemens GEAFOL 3150 with 2,30m x 1,28 m x 2,06 m (LxWxH). At this type of turbine the transformer is fitted in the tower. A sketch of the placement is given in Figure 31.

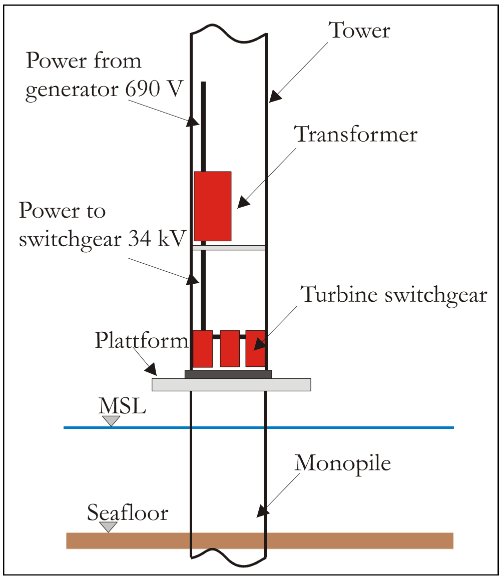


Figure 31 Transformer and switchgear placement

The transformer can be installed in the tower onshore and then transported to the offshore location. Special care has to be taken to avoid damaging the transformer during transport and erection of the tower.

3.4.5. Cable connection schemes

3.4.5.1. Analysed options

With the geometrical setup given in Figure 19 the following different layouts have been developed and will be discussed:

- Double string, no redundancy; Option A;
- Triple string, central connection point; Option B;
- Three single strings, local connection point; Option C;
- Looped string, single redundancy; Option D;
- Two looped strings, double redundancy, Option E
- Four strings with interconnections, partial redundancy, Option E II

In the following work these will be referred as A, B, C, D E and E II. A drawing of the layouts with power ratings for each string can be seen in Figure 32. In Option E II the dotted line shows that the loop can be closed between turbines in case of cable failure.

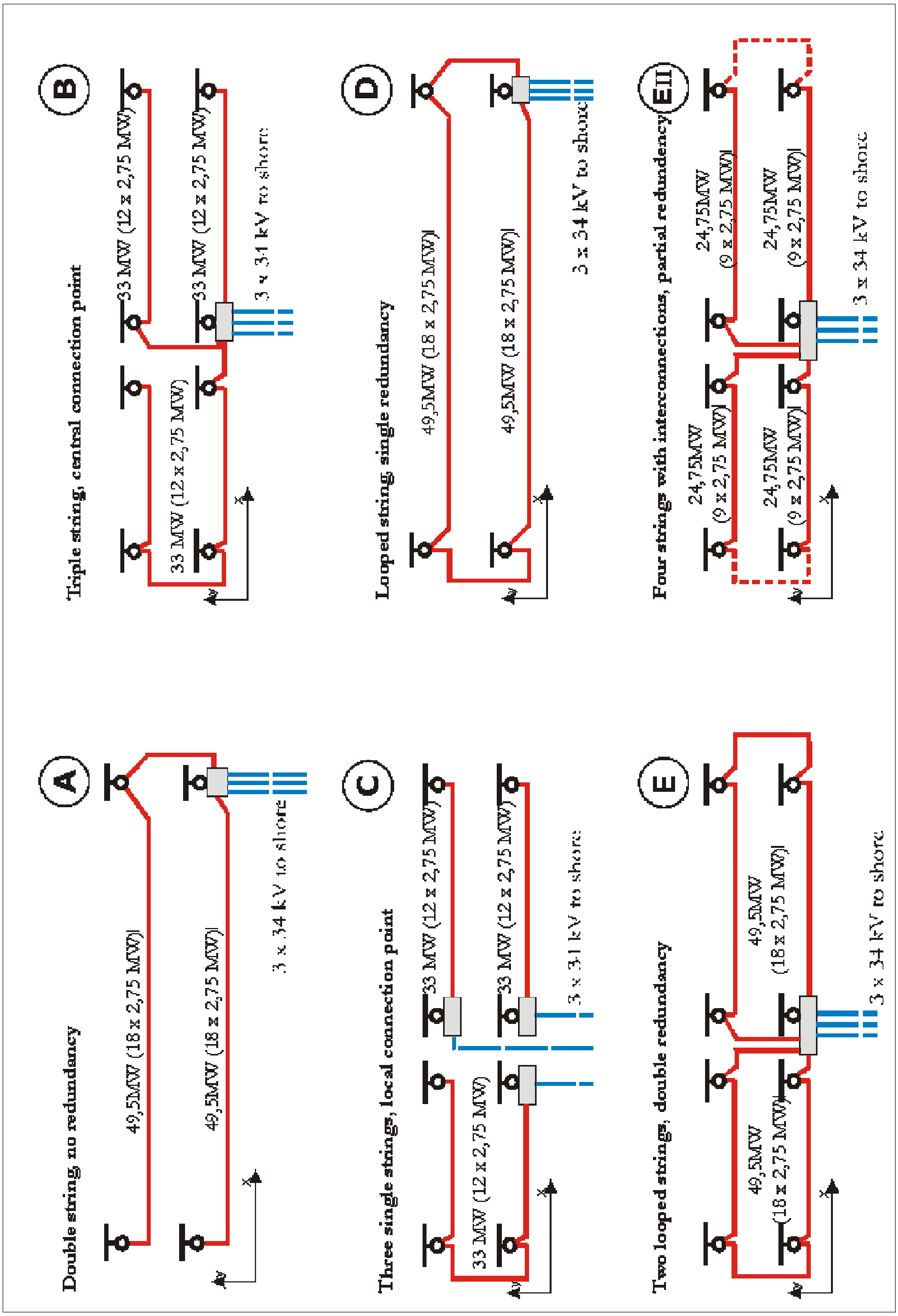


Figure 32 Layout options

3.4.5.2. Geometrical data

The cable lengths for the options A to E II are given in Table 5. The spacing in x direction is 550 m and the spacing in y direction is 750 m. The distance from seabed to the connection rail at the turbine is assumed to be 25 m. The cable lengths are calculated for the infield power collection, the shore connection is not included. The longest string is also calculated, showing the longest cable length for a single string in the layout, relevant for the calculation of the cable rating. The power rating is the power which has to be transported over the longest string.

	A	B	C	D	E	E II
Cable length [m]	21200	21400	21400	22000	23190	23190
Longest string [m]	11000	7375	7375	22000	11938	5790
Power rating [MW]	49,5	33	33	99	49,5	24,75

Table 5 Cable lengt

3.4.5.3. Results of first estimation

With the above mentioned equations the results in Table 6 were calculated. The cables were selected from the table of standard cables given in Appendix A, using the current rating specified by the manufacturer. The data for the physical properties of the cables are from Nexans Germany [15] and BICC Cables UK [16]. With the calculated current per phase a cross section according to the maximum allowable current is chosen. Options B, C and E II have the lowest losses, mainly due the smallest current. For Option D an estimation of the required cross section could not be done, because the current is too high for commonly used 3 core MV cables. It should be also mentioned that with a cross section above 630 mm² usually single core cables are used, requiring the installation of 3 cables for every connection making this option not likely to be used because of the required installation work. Option D will therefore not be considered in the following investigations.

	A	**B**	**C**	**D**	**E**	**E II**
Current per phase [A]	842	561	561	1687	842	421
Cross section [mm²]	3x630	3x400	3x400	n.a.	3x630	3x240
Ohmic losses [W]	608250	423484	397974	n.a.	821538	410036
Dielectric losses [W]	11395	9326	8738	n.a.	11453	7747
Overall losses [MW]	0,62	0,43	0,41	n.a.	0,83	0,42

Table 6 Results cross section and losses

3.4.5.4. Soil influence

To quantify the influence of the burial of the cable and the soil conditions several options will be calculated and compared for the cable cross section in Table 6. The thermic model and the procedures described in section 3.4.3.6 are applied for the calculations. For different soil types the according heat resistivity is given in Table 7. The typical soil in the north sea area at the OWF site is wide graded dense sand which is highlighted in the table.

	Heat resistance
gravel layers typical	0.05 [m°K/W]
coarse sand typical	0.10 [m°K/W]
wide graded dense sand typical	0.50 [m°K/W]
fine silty sand typical	0.8 [m°K/W]
clay typical	0.9 [m°K/W]

Table 7 Heat resistivity of different soils [17]

For variations of different heat resistivities of the covering soil the allowable current was calculated for standard conductors. The results are drawn in Figure 33.

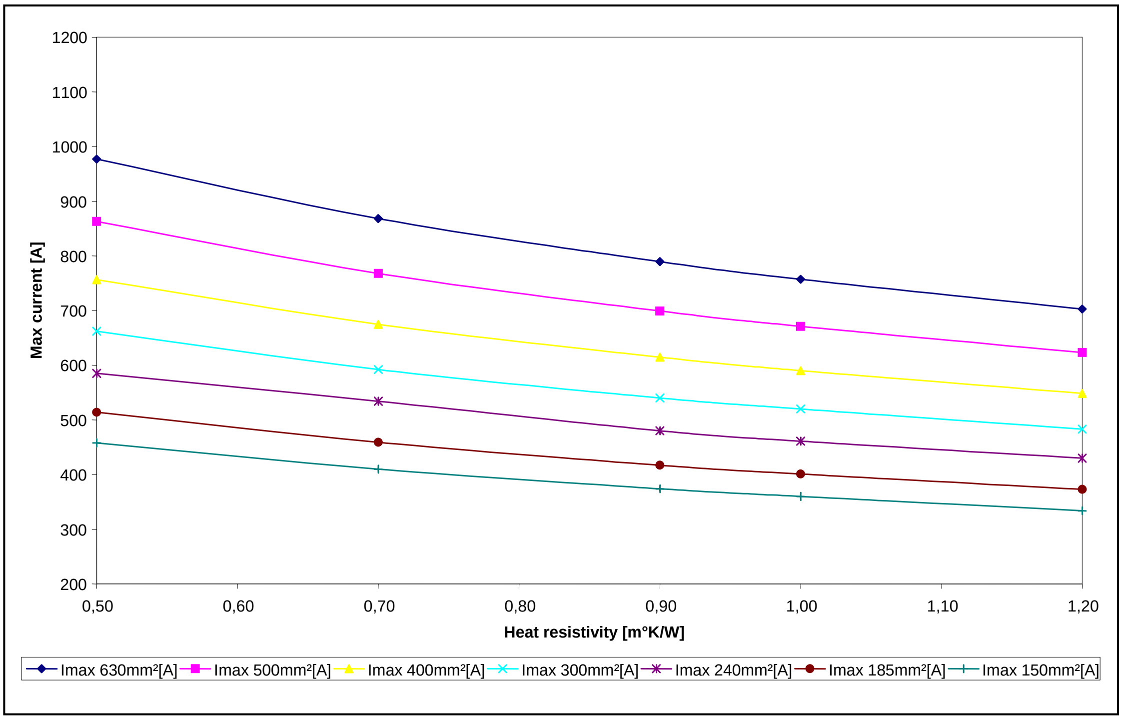


Figure 33 Allowable current with variation of soil heat resistivity

It can be seen that soils with low heat resisitvity allow a significantly higher current carrying capacity in the same cross section. In the example above, a covering with gravel layers would require a 3x240 mm² cable to transport 585 A, where with standard conditions a 3x400 mm² cable would be required for the same current.

3.4.5.5. Laying depth influence

With the model in Figure 28 it is also possible to predict the influence of the depth of trenching on the current carrying capacity of the cable. Usually submarine cables in areas with ship traffic and trawler fishing activities are trenched to the seabed to an approximate depth of 0,80 to 1,50 m. An alternative to trenching the cable would be rock dumping on the cable path. Anyhow the highest current carrying capacity can be obtained with unburied cables, shown in Figure 34. A not trenched cable is assumed with 0,10 m laying depth as the cable sinks into the seabed by its own weight.

The impact on the current carrying capacity of the cables is relatively low in great laying depth, but increases with more shallow installation. Between a depth of 1,50 m and surface laying is an increase of capacity of nearly 50%. Unfortunately the threat to cables by trawling gear and anchors is high in that area and repairs of the cable require costly operations. It is recommended to trench the cables to at least 1,00 m.

As the cables have to be trenched to avoid damage to them, the influence in laying depth is not taken into account for the connection schemes in this report, but should be considered for future OWFs farther offshore where hardly any trawling activities take place.

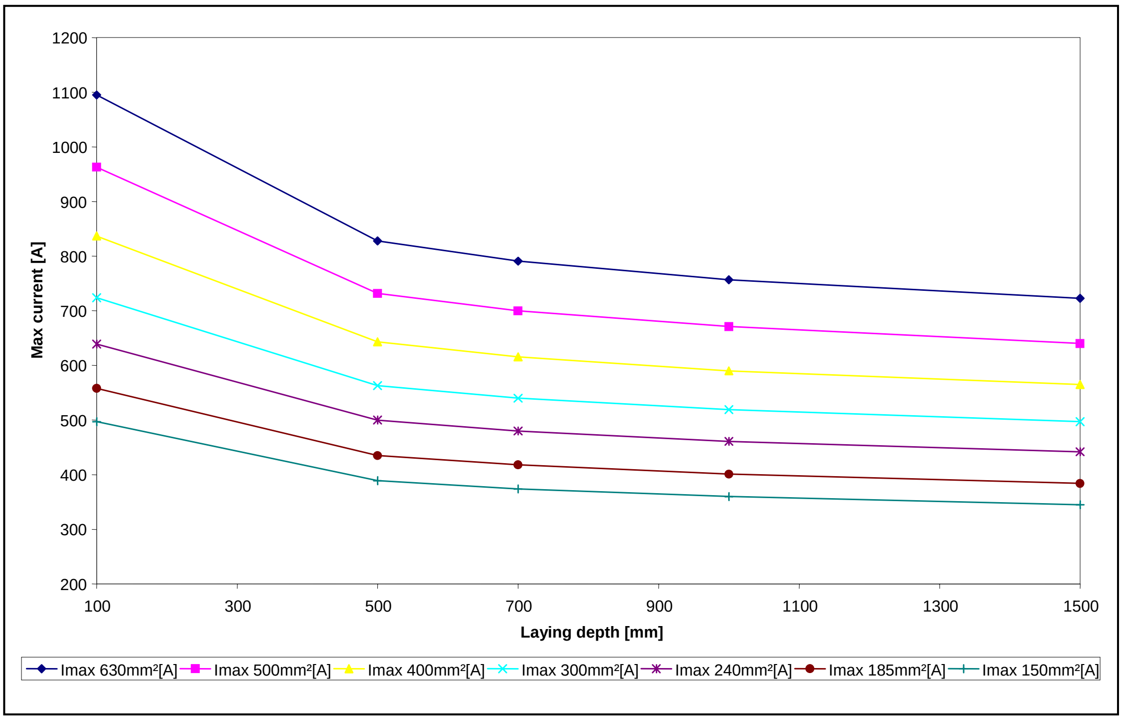


Figure 34 Allowable current with variation laying depth

3.4.5.6. Final cable dimensions

With the implementation of Figure 33 and Table 7 the cables for the different layout options can be redesigned. The new cable selection is given in Table 8.

	A	B	C	E	E II
Current per phase [A]	842	561	561	842	421
Cross section [mm²]	3x500	3x240	3x240	3x500	3x150
Ohmic losses [MW]	0,75	0,67	0,63	0,82	0,65
Dielectric losses [MW]	0,01	0,007	0,007	0,01	0,006
Overall losses [MW]	0,76	0,74	0,70	0,83	0,71

Table 8 Final cable dimensions

This cable selection is for all options smaller than the initial selection of cables, mainly due the lower heat resistivity of the soil at the OWF location. The losses have slightly increased, but are well below 1 % of the overall power rating for the infield power collection. The potential of better heat transfer from cable to soil has to be developed; one possibility is to enlarge the cable surface with cooling ribs. But as such devices alter the handling of the cable it has to be considered that the infield power collection requires numerous cable handling operations and an advantage with smaller cables can be easily wasted with complicated or time consuming installation methods.

3.4.5.7. Switchgear at the single turbine

The switchgear at the turbine has to be chosen according to the infield power collection scheme. For collection schemes without redundancy (loops) the switchgear according to Figure 23 is suitable, as a scheme with low selectivity can not be altered to high selectivity with extensive switchgear usage. This gear is referred as "Simple" in Table 9.

For connection schemes with loops redundancy can only be maintained with switchgear that is able to isolate a cable failure and keep the remaining functioning parts of the OWF in operation. Therefore, a switchgear arrangement as shown in Figure 24 is suitable for this application. In Table 9 this is referred as "Extensive". In "Number of power switches" the power switches for the shore connection are not considered, as the shore connection point is treated in the next section.

	A	B	C	E	E II
Switchgear type	Simple	Simple	Simple	Extensive	Extensive
Number of power switches [-]	36	36	36	106	106

Table 9 Power switches for different connection schemes

3.4.5.8. Switchgear at shore connection point

For the different cable connection schemes the required switchgear is shown in 3.4.5.7. The switchgear required for each shore connection cable is a power switch and a conventional melting fuse. To ensure the operation of the OWF during maintenance or sequential fault each connected string or loop can be switched to the shore connection bus bar separately with an additional power switch.

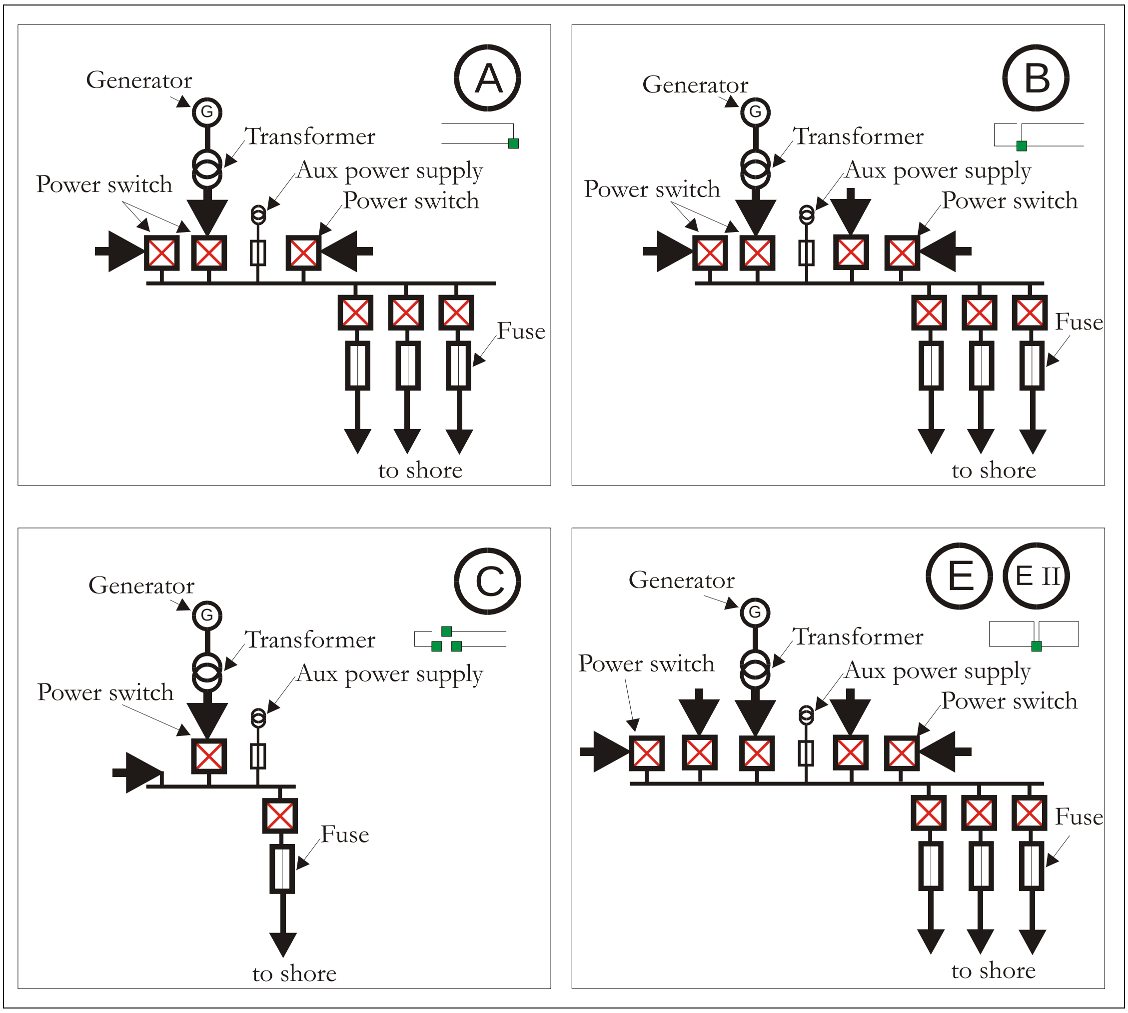


Figure 35 Switchgear at shore connection point

As stated before in chapter 3.4.2.6, Gas isolated switchgear (GIS) is required. GIS is produced by various suppliers, for reasons of availability and future development Siemens devices are selected. GIS provides the smallest gear size available and is currently used in OWFs, for example in the OWF Mittelgrunden and at Horns Rev, both Denmark.

For every shore connection cable a fusible cut-out and a circuit breaker power switch is needed. As an example the NX plus series of switchgear by Siemens was selected. These are SF6 GIS and as can be seen on the datasheet in Figure 36 capable of switching the voltage and current at Egmond OWF. Given a pattern of 600 mm, at least 1200 mm of space per shore connection cable is needed for a power switch and a fuse (2 units). For additional power flow control metering units can be added without additional space requirements as digitalized monitoring units can be integrated in the casing. The weight of a unit is assumed to be 900 kg.

Rated values

Single and double busbar switchgear

		12 kV	24 kV	36 kV
Rated voltage	max.	12 kV	24 kV	36 kV
Rated frequency		50 Hz [1])	50 Hz [1])	50 Hz [1])
Rated short-duration power-frequency withstand voltage		28 kV	50 kV	70 kV
Rated lightning impulse withstand voltage		75 kV	125 kV	170 kV
Rated short-circuit breaking current	max.	31.5 kA	31.5 kA	31.5 kA
Rated short-time withstand current, 3 s	max.	31.5 kA	31.5 kA	31.5 kA
Rated short-circuit making current	max.	80 kA	80 kA	80 kA
Rated peak withstand current	max.	80 kA	80 kA	80 kA
Rated normal current of busbar	max.	2000 A	2000 A	2000 A

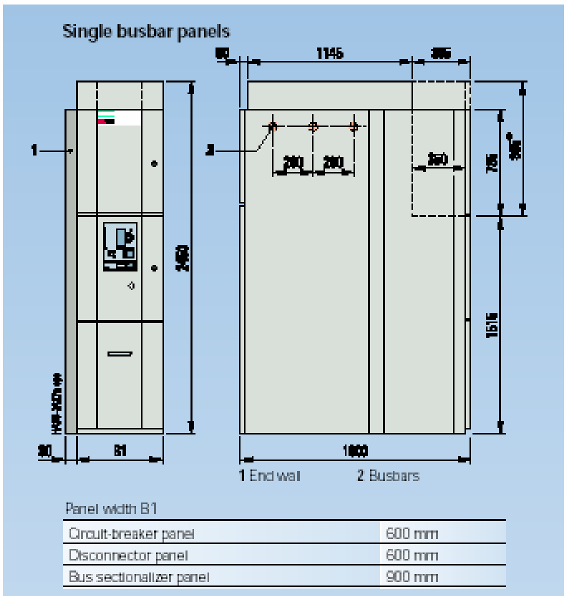


Figure 36 Siemens NX Plus GIS [18]

In Figure 37 the requirements for the available space for the switchgear are given. With this dimensions and installation pattern the placement of the switchgear for the cable connection schemes was developed.

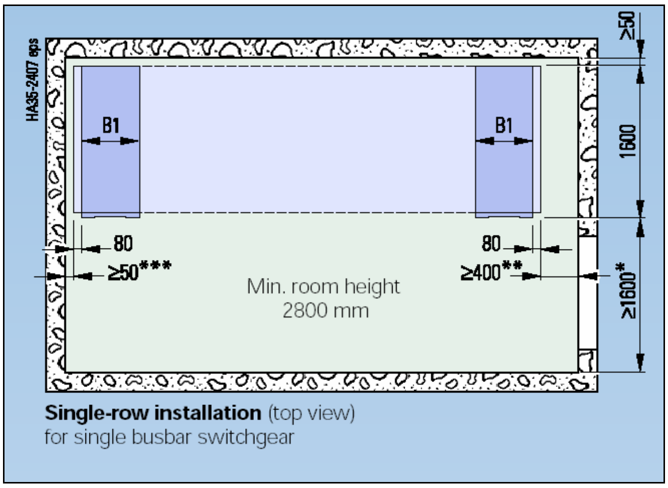


Figure 37 Installation pattern NX Plus[18]

3.4.5.9. Geometrical data

The drawing in Figure 38 is to scale, showing that the required space outside the tower is approx. the same size as available in one tower level. The external space is only required at the shore connection points, as the switchgear at the other turbines fits in the towers The switchgear can only be placed in a straight line in a standard arrangement due to the requirements for the mutual connections. Therefore, the space occupation in the tower is not very economic. (The rectangular box in a round room problem). Notices that the bus bars inside and outside the tower have to be connected, making an additional opening in the tower necessary. The geometrical placement of the J-Tubes on the tower must match the required cable connections, as the bending radius of the cables is restricted. The switchgear and the external compartment can be preassembled and tested onshore, reducing the offshore installation time. By its nature, the cable connections to the bus bar and the connection testing has to be done after complete installation (offshore). The weight of the external switchgear is no problem for the handling crane vessel.

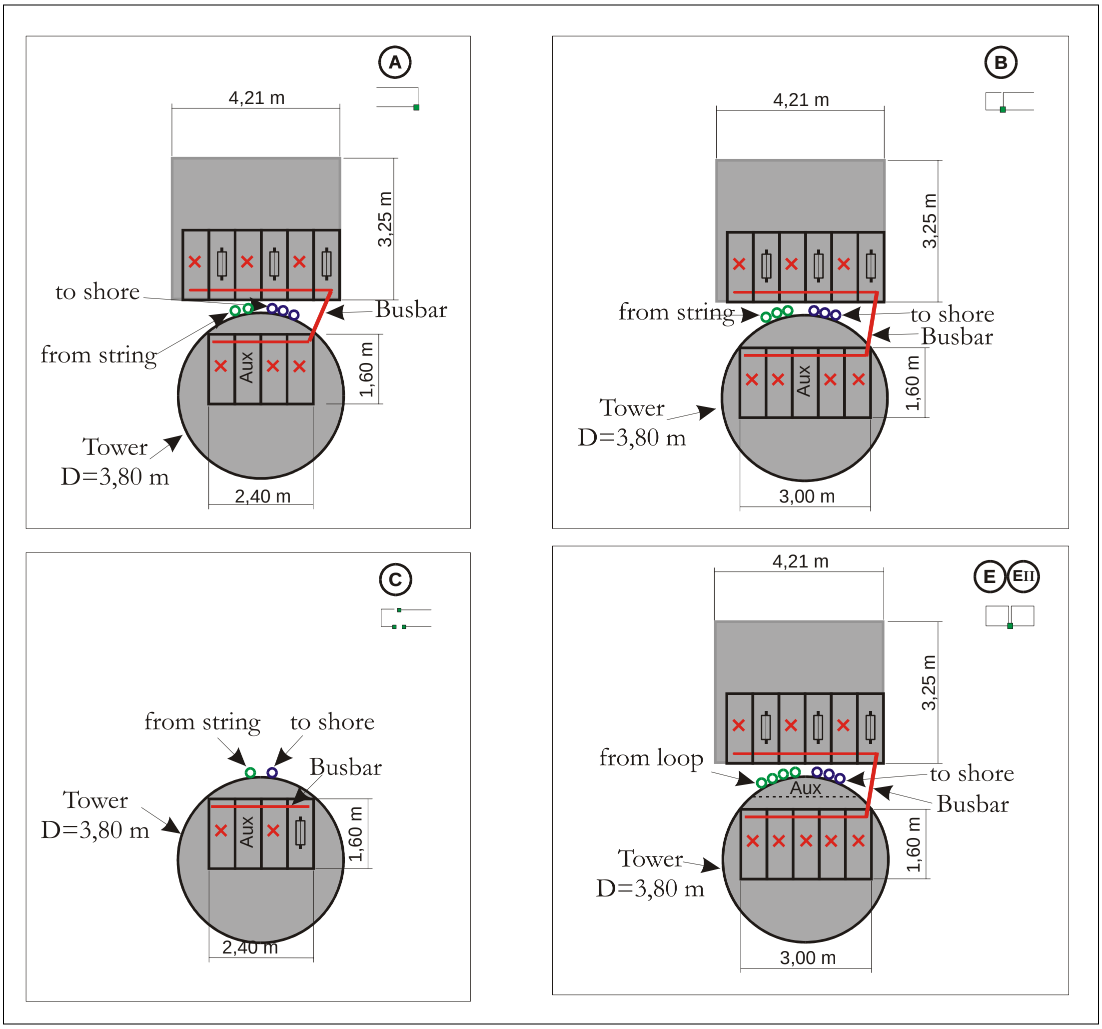


Figure 38 Switchgear at shore connection point placement

In Table 10 the results for the different layout schemes are compared. Option C has by far the smallest requirements, but is de facto a single connection for a 33 MW OWF as can be seen in the drawings. For Option E and Option E II 5 power switches are required inside the tower, therefore the aux. supply for the turbine can not be placed at the same level as the power switches. As the aux supply has to be connected to the bus bar, a possibility is to place it a level above the switchgear at the transformer level and make a separate connection to the bus bar. Notice that therefore a special construction for the aux service compartment is necessary. Options A and B have nearly the same requirements in switchgear, both require external equipment for the shore connection.

	A	B	C	E	E II
Nr. Of Power switches* [-]	5	6	3	5	5
Nr of J-Tubes risers per shore connection point[-]	5	6	2	7	7
Required external space [m²]	13,7	13,7	0	13,7	13,7
Required tower space [m²]	3,8	4,8	3,8	5,8	5,8
Total required space [m²]	17,5	18,5	4,8	19,5	19,5
External equipment weight [kg]	5400	5400	0	5400	5400

Table 10 Switchgear results

3.4.5.10. Selectivity

Selectivity and redundancy are close linked with cable failure rates. A high selectivity (redundancy) pays of with high cable failure rates. To establish cable failure rates it is critical to know the type of marine operations in the OWF area, as different marine activities like trawler fishing, anchoring and so on represent different threats to the installed cables. Cable failure is currently close surveyed by cable installation and operation companies, but the focus of these studies is on long transmission cables in deep water. Figure 39 shows the cable faults per 1000 km for cables installed by Global Marine. It can be seen that the probability for a cable fault increases with a factor 10 for cable installation depths smaller 1000 m.

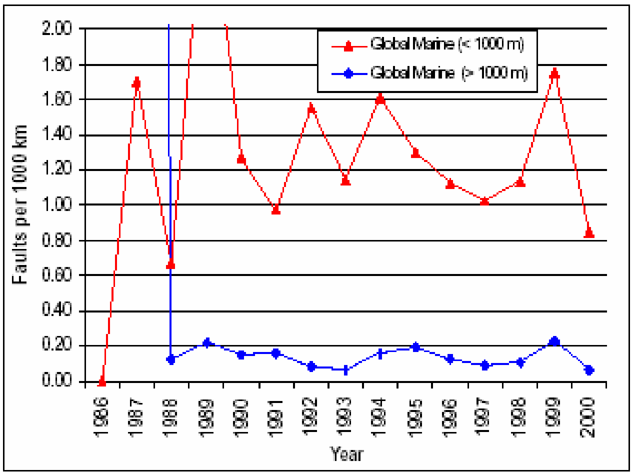


Figure 39 Cable Faults per 1000 km [19]

* Additional power switches at the shore connection point, the standard turbine switchgear is not included.

The highest probability for cable damage is in shallow water, recently more than 70 % of all cable failures occurred in depths < 100 m, where all recent OWFs are located. Figure 40 also shows an increase of cable damage in shallow water for the period of 1997 to 2000 compared to 1986 to 1996, caused by an increase in trawler fishing and the higher density of installed cables.

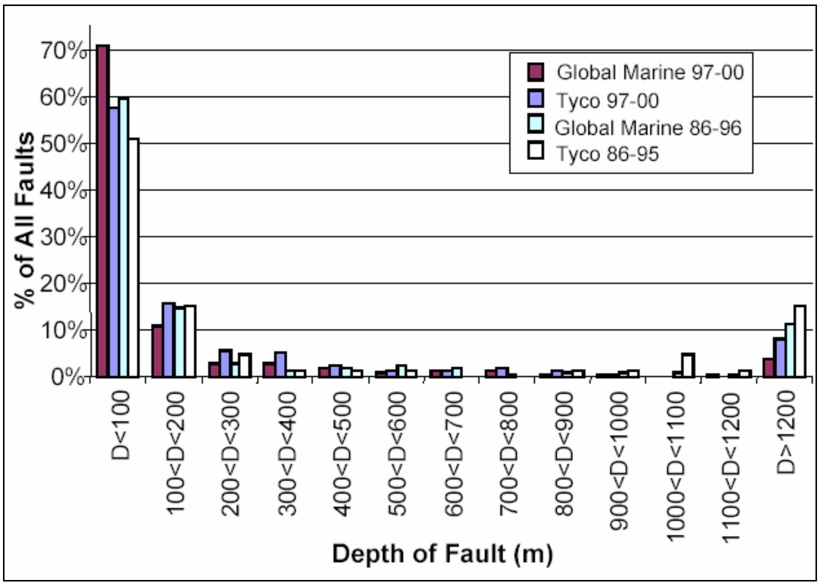


Figure 40 Depth of cable fault [19]

In combination with the cable connection scheme and the comprehensive switchgear in each turbine variable operation in case of cable failure is possible. To estimate the selectivity of a certain connection scheme with the corresponding switchgear the following methods were used:

- OWF operating at nominal power output (99 MW).
- One cable is damaged, multiple failures are ruled out.
- Cable fault at the infield power collection (shore connection fully operational).
- Cable failure at the “worst case” section.
- Fault is detected and isolated, allowing normal operation of the remaining turbines according to the possibilities of the infield power collection scheme.
- Repair time is assumed to be the same for all faults in every scheme so that the loss in power production can be quantified with the reduced power output.

The repair times for OWFs are depending on the weather and sea conditions and can be assumed with 3 months for the North Sea area [4].

The location of the cable failure is given in Figure 41. Generally the worst case location is on the cable connecting an entire string to the shore connection point, where the whole string is disconnected or in case of redundancy (Option E and E II) where the highest cable loads occur.

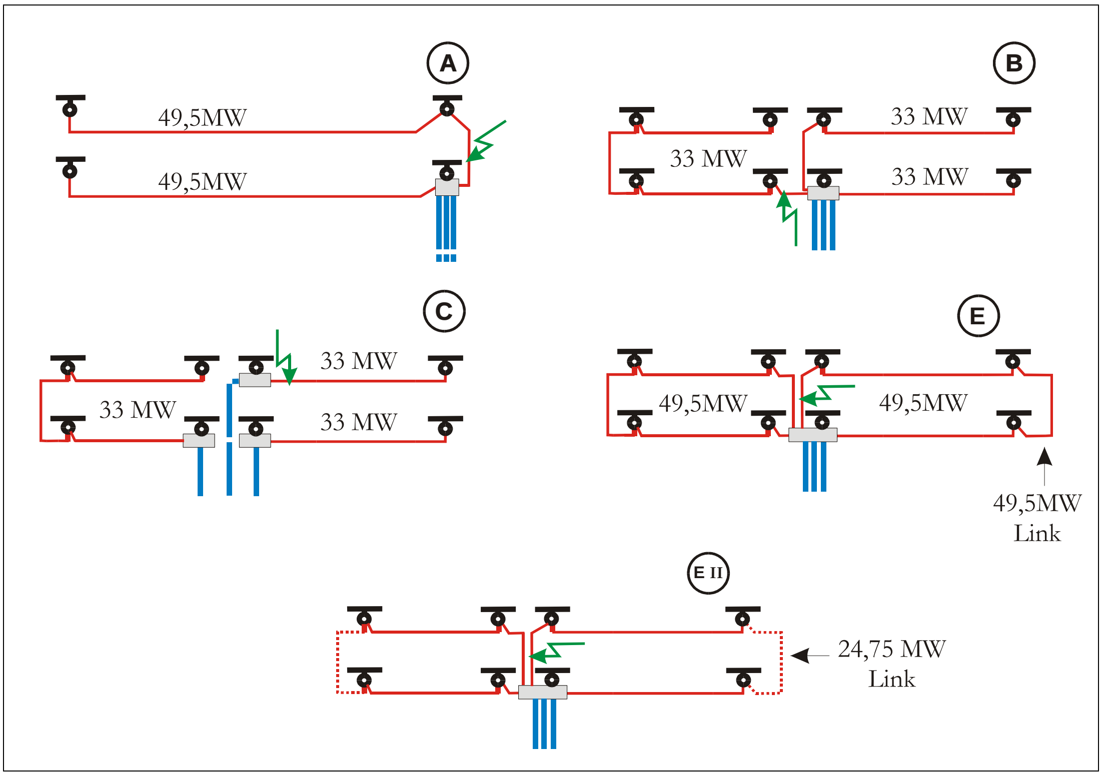


Figure 41 Cable failure location

As can be seen in Table 11 option E has by far the highest capability to handle cable failure, where a single fault at one loop does not inflict the power output at all, even a second fault at the worst case connection for the second loop would not inflict the output, as in the loop with the given switchgear the faulty cable can be isolated without the requirement to switch off turbines. Option B allows operation at one third of the rated output in case of a single cable fault. Option A has the smallest capabilities to handle failure, with one fault the output can go down to 50%. Option C was rated neutral, but when this concept (small autonomic units building an OWF) is developed for large scale projects its simplicity could be advantageous in case of failure.

Option E II has a link similar to Option E, but here the cable is rated for the maximum output of one string only (24,75 MW), opposed to Option E where the link is rated for the entire loop output (49,5 MW). This setup allows to use the significant smaller cable of Option E II (4 string layout) as a cross link between two strings. In case of failure the link can be loaded with the nominal output of one string. If the produced power exceeds the maximum power transfer capability of the link cable, the power output of single turbines has to be reduced or turbines have to be switched off. With Option E II a reasonable redundancy can be obtained, without the drawbacks of full redundant systems where cables have to be dimensioned on the entire loop output. Table 11 shows that Option E II has 75 % of the redundancy capabilities of the full redundant layout Option E and is a reasonable compromise between redundancy and cable size.

	A	B	C	E	E II
Selectivity	0,5	0,66	0*	1	0,75
Lost output [%]	50	33	100	0	25
Production loss over repair time (2160 h) [MWh]	106920	71280	213840	0	53460

Table 11 Cable failure

With the currently established failure rates of approx. 1,8 failures per 1000 km cable and year, and an cable length of ~20 km for the infield power collection a cable failure occurs only every 25 years, which is at the life cycle limit of an OWF. But with increasing cable failures in shallow waters and more OWFs build in close shore areas these rates are likely to increase significantly.

3.4.6. Reactive power compensation

Below distances of 30km, the cable capacitive loading can be counteracted by the turbine. At longer distances, the cable capacitive current is partly supplied by the utility grid. Parallel connected compensation coils or other counter-actions can also be considered. It was not possible to determine if the reactive power supplied by the cable is a curse or a blessing, since it may depend on the local grid connection. If the grid connection point is close to a conventional production unit (electrical motors need reactive power), it possibly is a blessing as reactive power is needed to compensate for inductive loads. If the cable onshore is also a long cable it will be a course as the cable onshore produces also reactive power and adds it to the offshore cable. For a three cable connection as at Egmond it is feasible to disconnect 1 or 2 shore cables with Options A, B and E at low power production. This will lower the reactive energy to 1/3 and make it stepwise controllable.

3.4.7. Results for the infield power collection

In Figure 42 the costs for the different parts of an OWF are given (data for a large scale OWF in the Danish North sea region). These are project specific, but for rating the different connection schemes and layout options the proportions can be taken into account. The main cost drivers are the costs for foundations, turbines and shore (grid) connection. These costs increase with increasing distance to shore and water depth. The electrical equipment (switchgear and infield cables) contributes only about 7% of the overall costs and is nearly independent on distance to shore.

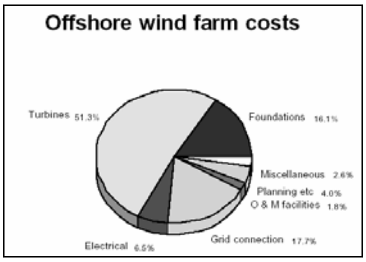


Figure 42 OWF costs [20]

* As the loads between different shore connection strings can not be transferred, each shore connection string is treated separately in terms of net topology, resulting in a selectivity of 0.

The infield power connection and the required switchgear inflict the costs mostly by the required time for installation. The overall rating is compiled with the following factors:

- Number of J-Tube risers
- Number of shore connection points
- Number of power switches
- Switchgear space
- Cable cross section
- Standard or modified gear
- Redundancy
- Overall infield losses

Each of this factors was weighted equal and rated with +/0/-. The rating is shown in Table 12. With this comparison an overview on the impact of different infield power connections is given. A similar scheme can be used to rate several infield power collections.

	A	B	C	E	E II
Number of J-Tube risers [-]	73	73	71	77	77
	0	**0**	**0**	**-**	**-**
Number of shore connection points[-]	1	1	3	1	1
	0	**0**	**--**	**0**	**0**
Number of power switches [-]	41	42	39	113	113
	0	**0**	**+**	**--**	**--**
Switchgear space [m²]	15,36	16,32	4,8	17,28	17,28
	0	**0**	**+**	**-**	**-**
Cable cross section [mm²]	3x500	3x240	3x240	3x500	3x150
	--	**0**	**0**	**--**	**++**
Standard /modified gear [-]	S	S	S	M	M
	0	**0**	**0**	**-**	**-**
Selectivity [%]	0,50	0,66	0	1	0,75
	0	**+**	**-**	**+++**	**++**
Overall infield losses [MW]	0,76	0,68	0,64	0,83	0,66
	-	**0**	**+**	**-**	**+**
Overall rating [-]	**---**	**+**	**0**	**-----**	**0**

Table 12 Summarized results

For this specific OWF at Egmond an infield power collection similar to Option B would be the best choice. It is in none of the categories outstanding, but in exchange has no significant weak points.

Option E II is the best compromise in cable size and redundancy. In case of cable failure a part of the turbines can be kept operational. The smallest cable size of all layouts is also a significant advantage. But similar to Option E with the current cable failure rates redundancy does not pay off.

Option C is also a considerable connection scheme, its advantages in small and simple switchgear, but requiring 3 shore connection points. With the growing output of single turbines, clustering several small "sub wind farms" offshore to a transformer platform becomes sensible when a HV or HVDC link is used for the shore connection. Nevertheless, for direct to shore connected strings the reliability is not as good as for multi shore connections [21].

Option E has a big advantage in redundancy, but requires the most complex installation features. This layout scheme could be considered in a very hazardous environment where cable failure is very likely to occur. But further investigations on the energy gain due redundancy has to be done to be able to quantify up to what failure rate a scheme like this pays of. [4], especially compared to a scheme like option B, which has also redundancy capabilities.

The limiting factor for infield power collections is the maximum transferable power with electrical cables. The actual transfer capability of the cables is depending on the soil condition and the burial depth, but as a rule of thumb much more than 50 MW cannot be transferred with MV cables. With that the number of turbines per string is limited.

4. Turbine connection

4.1. Introduction

In this chapter the installation procedures for cable connections at single turbines will be covered. According to the system described in the previous chapters, cable installation routines for monopile foundations in shallow waters are developed. In Figure 43 the system border (red) of the covered part is given.

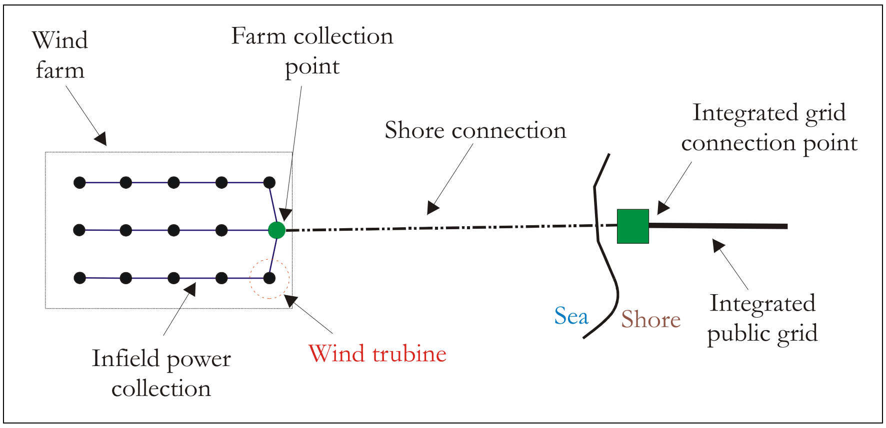


Figure 43 System overview

Installation procedures for cables are well developed by the offshore oil industry, but are focused on installations on a single structure (platform). As a difference OWFs consist of many similar structures and require a high amount of repetitive installation procedures. The cable installation procedures are specific for different foundations; in these script procedures for monopiles as the currently best suited foundation for recent OWF (up to 6 MW per turbine and approx. 25 m water depth) will be discussed.

4.2. OWF System

4.2.1. Elements

For installation procedures it is useful to divide the whole windmill in several elements. Table 13 shows the diversion of a windmill system:

System	Component	Element
Windmill	Foundation	Monopile
		Transition piece
	Superstructure	Turbine tower
		Nacelle
		Rotor

Table 13 System diversion

Figure 44 shows a graphical system diversion. The element relevant for cable installation is the transition piece where cable support and protection devices (J-Tubes) are fitted.

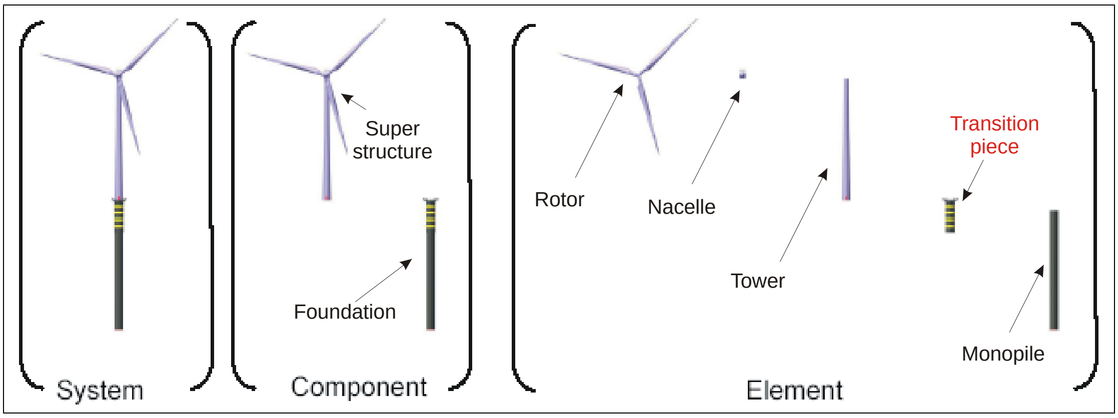


Figure 44 System diversion [22]

- The monopile is a hollow tubular steel pipe and the first part of the foundation structure. It has to provide support for the other parts of the windmill according to the load conditions at the windmill location.
- The transition piece is mounted on top of the monopile and builds the foundation with the monopile. The function of a transition piece is to correct out of alignment of the monopile. The transition piece has to be placed over the monopile in such a way that the connecting flange is exactly horizontal. The transition piece also provides access to the turbine tower. Therefore it is equipped with mooring support and a platform.
- The turbine tower is the support structure for the nacelle
- The nacelle houses the rotor shaft, gearbox, generator and the hydraulic system for the pitch control of the rotor. Monitoring and control equipment is also housed in the nacelle.
- The rotor consists of the rotor hub and the rotor blades

In Table 14 the dimensions of the elements for a 2,75 MW turbine in north sea conditions. are given. [22]

	Monopile	**Transition piece**	**Turbine tower**	**Rotor**
Dimensions [m]	L=60	L=10	L=55	D=92
	D=4,3	D=4,4	D=4,7-2,5	
Weight [t]	300	60	140	75

Table 14 Elements dimensions

4.2.2. Elements installation

The system installation process covers the preparation of the seabed, the erection of the windmill and the power connections and shows the system integration of the infield power collection.

- As first step of the erection scour protection mattress are applied to the seabed at the location of the windmill.
- The monopile is transported to the construction side and hammered trough the scour protection mattress to its final position.
- The transition piece (complete with pre-installed features such as boat landing arrangement, cathodic protection, J-Tubes for sub-marine power cables, turbine tower flange, etc.) are grouted together with the mono-pile.
- The cable ducts are applied on the first layer of scour protection mattress and connected to the J-Tubes. The ducts are then covered with gravel to secure them on their position.
- The remaining parts of the superstructure are transported to the site and erected, depending on the available lifting capacities. Tower, nacelle and rotor can be transported separately and are assembled on location or the whole superstructure can be preassembled on shore and transported the erection site.
- Infield power collection cables are laid out to the windmill and pulled through the J-Tubes. When the final position is reached, the cables are fixed with clamps.
- The cable is trenched into the seabed and the cable exit at the duct is protected with gravel.

Figure 45 shows a graphical illustration of the required system installation steps. Theoretical the cables could be pulled to their position after the transition piece is in place, but to prevent the cables from damage during the superstructure installation the cables are installed afterwards.

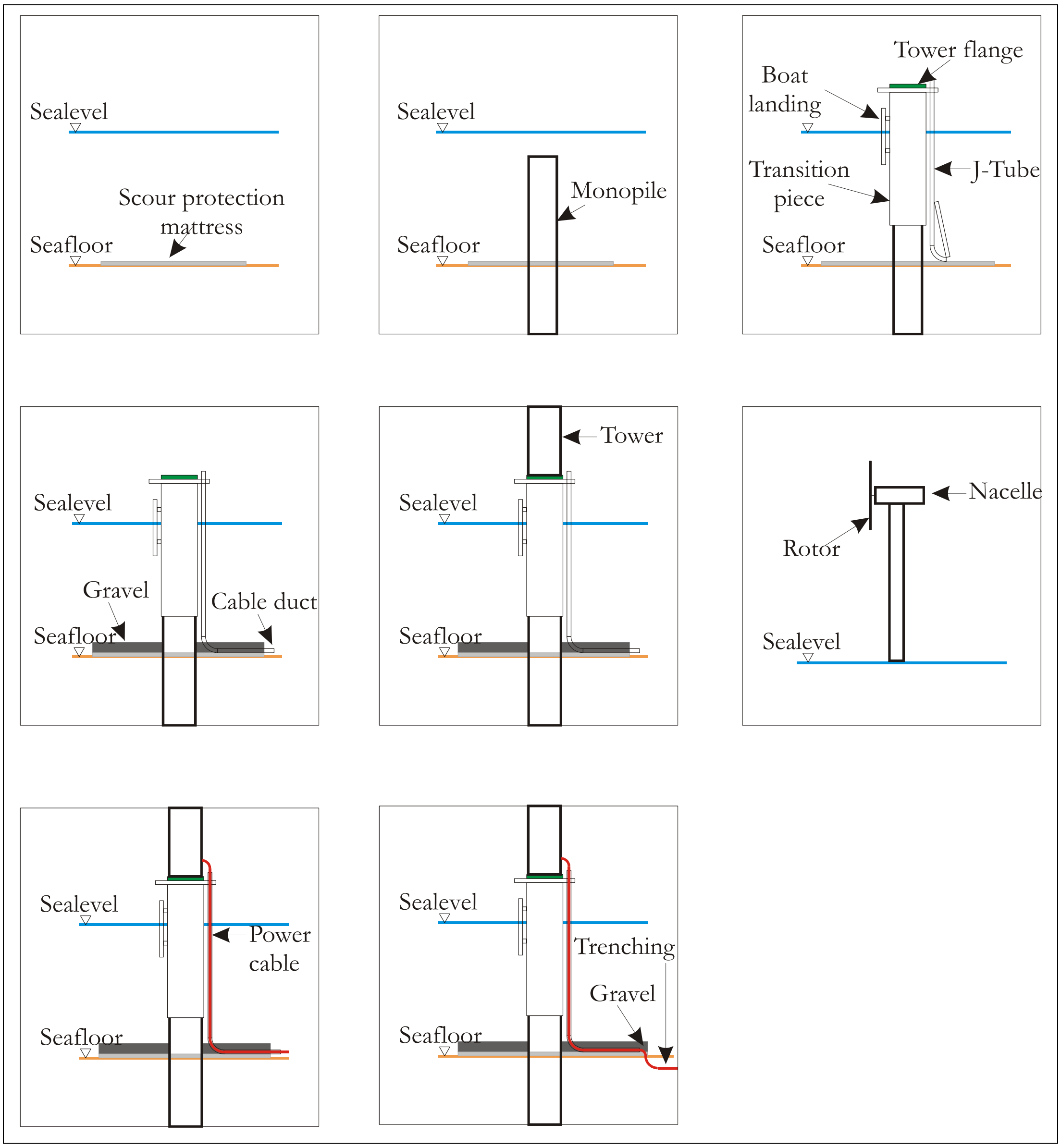


Figure 45 Windmill installation steps [5]

4.2.3. Scour protection

Scour is the removal of granular bed material by hydrodynamic forces in the vicinity of offshore structures. Due to changed currents around the foundation structure, erosion of the seabed will occur. When no scour protection is applied, a scour hole of approximately 1.5 times the pile diameter is expected. The foundation pile has to be adapted to this hole by increasing diameter and wall thickness and increasing pile penetration [23]. The horizontal extend of the scour hole is 4D upstream and 6D downstream (D=monopile diameter) [24] A sketch of the scour hole at a monopile foundation is given in Figure 46. Notice that it takes months or even years until the scour hole is fully developed.

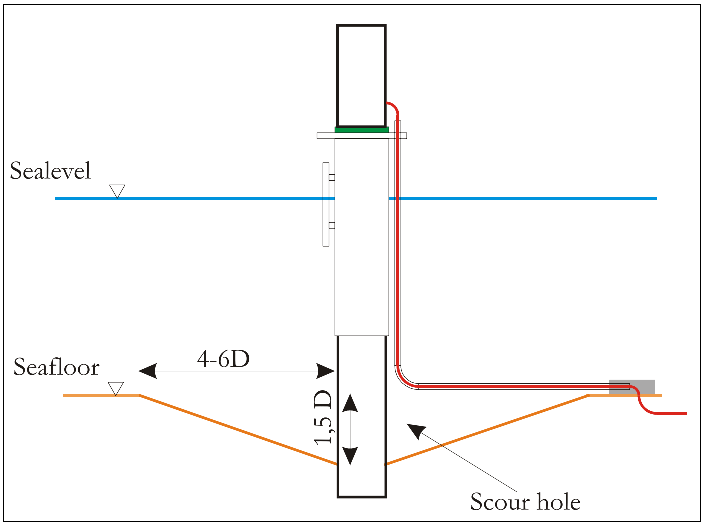


Figure 46 Scour hole

If no scour protection is applied to the monopile location, the scour hole has not only to be taken into account for the design of the foundation; but has also to be crossed with the electrical power cable. This results in additional loads on the J-Tubes and has to be considered for the J-Tube design. To avoid these problems usually scour protection is applied to the monopile. This can be done before installation of the pile with mattresses placed at the pile location, or after the complete installation of the turbine with rock dumping around the monopile.

4.2.4. J-Tubes

The J-Tubes have to be designed to support and protect the power cable during installation and in operation in the marine environment. The J-Tubes have to withstand the applied scour protection methods and make sure that during the pulling process the allowed tension on the cable is not exceeded. A transition piece with J-Tubes used at Horns Rev is shown in Appendix F. J-Tubes can be made of plastic or steel. The advantage of plastic is that no corrosion protection is required. Steel J-Tubes can be coated, which is difficult on the inside, or a seal is attached to the cable, and after installation the J-Tube is sealed watertight. See Figure 47 for a sketch. When the tube is sealed, corrosion inhibiting chemicals are purred into the remaining water in the J-Tube.

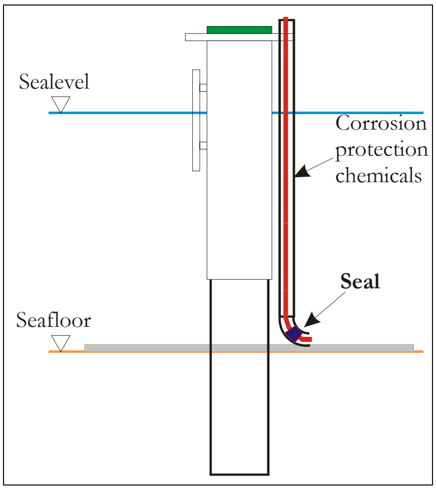


Figure 47 J-Tube Seal

The tension on the cable during the pulling procedure is determined by the following factors:

- Weight of the cable
- Friction inside the J-Tube
- Length of the installed cable
- Turning angle of the bow in the J-Tube

The force on a horizontal pulled cable is calculated according to Equation 17

$$F = \mu \cdot G \cdot l \cdot 10 \qquad 17$$

F..........................Pulling force [N]
G.........................Cable weight [kg/m]
μ..........................Coefficient of friction [-]
l............................Length of cable [m]

The increase in pulling force in bends (J-Tubes) is calculated with Equation 18:

$$F_b = F \cdot e^{\mu\alpha} \qquad 18$$

F_b.........................Pulling force behind the bend [N]
F..........................Pulling force [N]
μ..........................Coefficient of friction [-]
α..........................Angle of the bend [rad]

The maximal allowable force on a power cable is specified by its supplier, for example Nexans allows 50 N/mm² permissible pulling force when a pulling head is used. [25]

The weak point of this calculations is the determination of the friction coefficient. For practical installation a test is recommended. Figure 48 shows the J-Tube pulling force test done for the OWF at Horns Rev. The J-Tube is fixed and the cable pulled through.

Figure 48 J-Tubes pull

4.3. Power cable installation

4.3.1. Installation procedures with scour protection

4.3.1.1. Horns Rev

This installation procedure was used at the OWF at Horns Rev in 2002. A team of divers, who ensured the smooth proceeding of the installation, closely monitored the whole procedure. A graphical illustration of the procedure can be seen in Figure 49.

- The transition piece is placed on the monopile and grouted to its final position. The messenger cable was inserted in the J-Tube before the transition piece was transported offshore. The remaining parts of the windmill are installed according to 4.2.2. When the erection of the windmill structure is complete, the power cables are installed.
- The J-Tube and the cable duct are folded out of their transport position and the cable duct is fixed on the seafloor with diver assistance.
- A second layer of gravel is applied to stabilize the cable duct
- The power cable is connected to a cable pulling head (Chinese stocking) on board the cable laying vessel
- The power cable is laid out and kept floating with buoys
- The floating cable is towed to its installation position and the pulling head is connected to the messenger cable by divers
- The power cable is pulled in with the tower winch and simultaneously lowered to the seafloor by detracting the buoys
- When the power cable has reached its final position, it is fixed with clamps.
- Additional sheeting is placed by divers at the entry point of the cable duct
- The cable is washed into the seabed with a trenching device

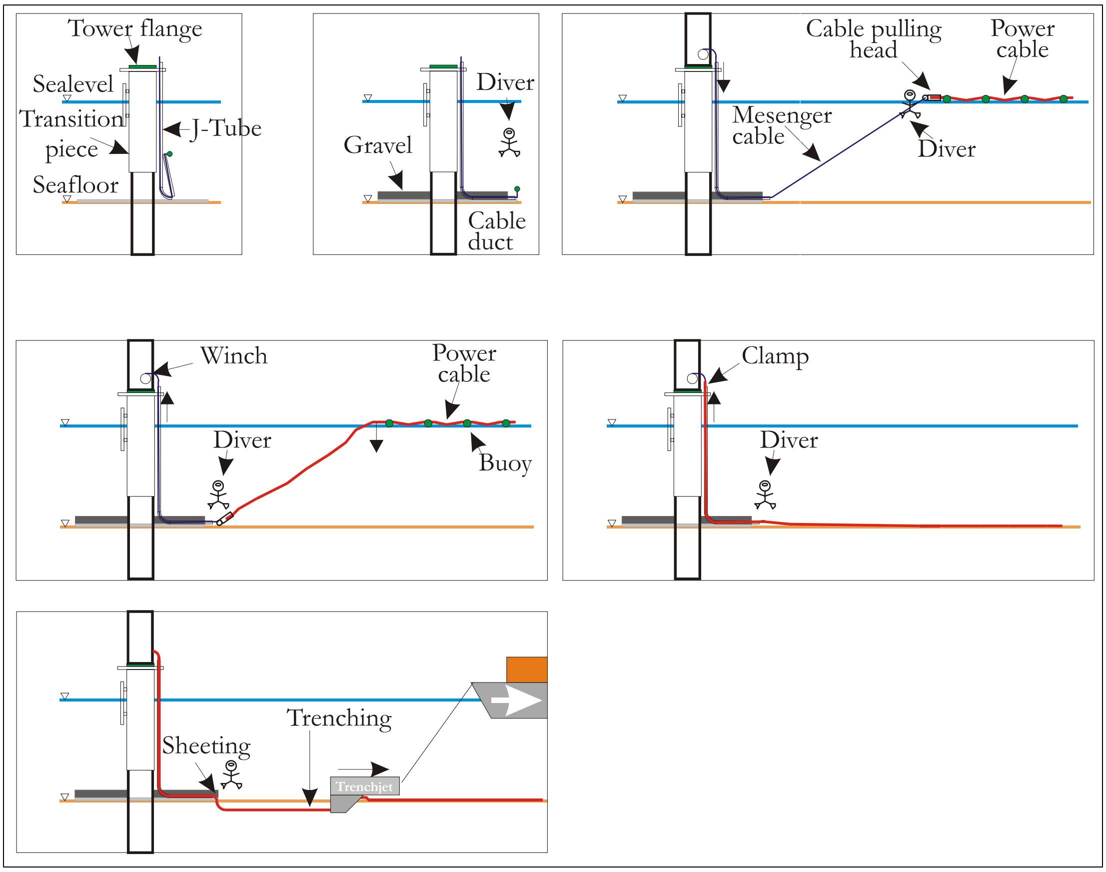


Figure 49 Horns Rev installation

Advantages:

- Well tested and known procedure
- The floating cable can be easily positioned at its correct position by tugs, no dynamic positioning system (DPS) vessel is required
- Smaller forces on the cable during installation due the cable is kept floating during the pulling process

Weak points:

- Scour protection is required for the cable supporting devices
- J-Tubes are required to protect the cable outside the turbine
- Holes have to be drilled into the turbine tower for the cable entry
- Diver operations are costly and dangerous

4.3.1.2. ROV installation

To avoid diver assistance, a modification of the Horns Rev installation procedure was done. The divers are replaced with a ROV (Remote Operated Vehicle), and the cable is installed to its final position with the cable laying vessel, which operates the ROV too. Illustration in Figure 50

- The messenger cable is inserted in the J-Tube onshore, and fixed to the J-Tube mouth with an ROV operational hook
- The transition piece and the remaining windmill structure is installed similar to Horns Rev
- The cable installation vessel lays the cable to the turbine, on approach of the final installation position the cable is laid in "S-shape" on the sea floor to allow pull in of the cable.
- The cable is equipped with a pulling head onboard the cable installation vessel
- The ROV picks up the messenger cable (that's why the ROV operational hook is required) and pulls the messenger cable to the cable installation vessel
- The power cable and the messenger cable are connected to each other onboard the cable installation vessel and picked up by the vessel's crane
- The cable is pulled in with the turbine winch and simultaneously lowered by the cable installation vessel's crane.
- As the power cable has reached its final position, it is fixed with clamps
- The cable is protected by rock dumping and trenched to the seabed.

This installation is an altered procedure by Intec [26], performed on a platform in the North Sea. Within the original procedure the cable was pulled not by a winch but by a crane on the platform.

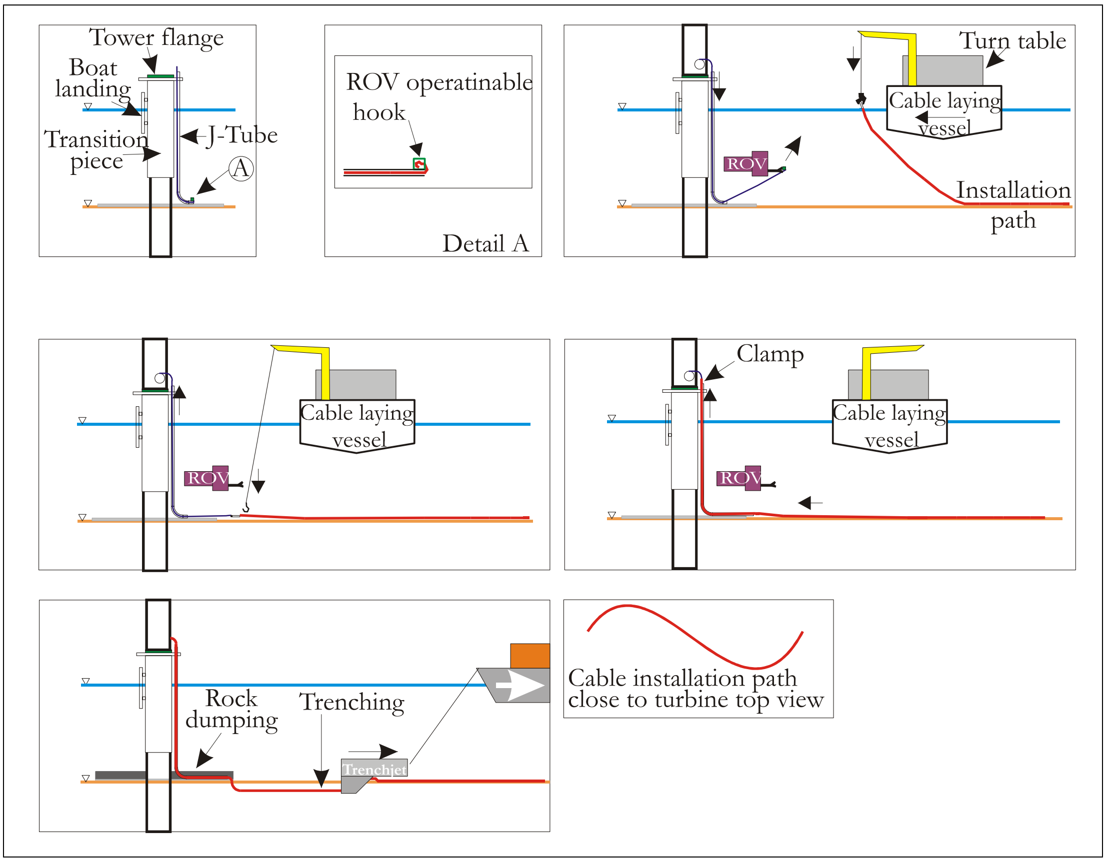


Figure 50 ROV installation

Advantages:

- Standard procedure for offshore oil rigs
- No divers are required
- No additional cable duct is installed

Weak points:

- ROV operations are complex and costly
- A DPS vessel is required to ensure the correct position of the cable on the seafloor and allow the complex "S-shape" laying pattern close to the turbine
- As the cable is pulled along the sea floor, pulling forces are higher than with the Horns Rev procedure

4.3.2. Installation procedures without scour protection

4.3.2.1. Fold out J-Tube

The before stated installation procedures require extensive scour protection around the monopile. To avoid the need for scour protection the developing scour hole can be covered with an horizontal extension of the J-Tube. The extension pipe is folded in during installation of the transition piece, and then folded out and fixed to the sea floor to cover the scour hole that will appear around the pile. (Notice that the scour hole takes months to years to evolve to its final diameter and depth) The actual cable installation can be done according to the Horns Rev or ROV procedures. The fold out sequence is shown in Figure 51.

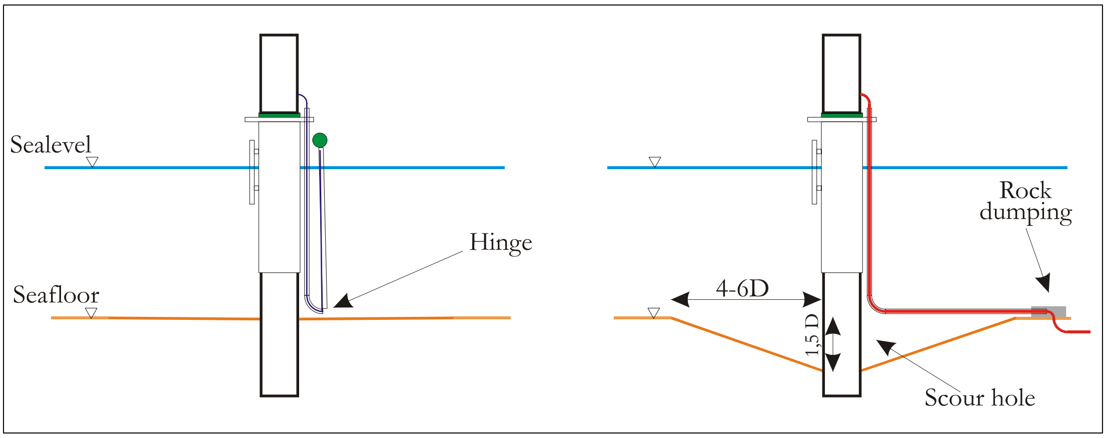


Figure 51 Fold out J-Tube

Advantages:

- No scour protection is needed to enable the cable connection to the turbine.

Weak points:

- High hydrodynamic loads on the J-Tube.
- Exact knowledge on the occurring scour hole is required to design the extension pipe.

4.3.2.2. Directional Drilling

An other possibility to bypass the need of scour protection, directional drilling can be used to drill a well inside the monopile. The well has to take a 180° turn when the monopile is passed and resurface beside the pile. Unfortunately the standard horizontal drilling equipment used for example for shore landings is not suited for this type of well, instead drill rigs used for oil and gas wells have to be used.

The installation steps are:

- Installation of the monopile with the same procedure as for the conventional installation methods, except the scour protection
- Installation of the transition piece; also similar to the conventional procedures
- The drill rig is transported to the site and rigged up at the monopile
- The well is drilled and lined with a PVC or steel tubing
- After completion of the well, the messenger cable is attached to a buoy and pressed through the well. The mud pump used during drilling can be used to do this.
- Rig down, and transport to the next monopile
- The remaining parts of the windmill are installed similar to 4.2.2
- The messenger cable is picked up by the crane of the cable installation vessel and connected to the power cable pulling head
- The power cable is pulled into the well by the turbine winch and lowered simultaneously by the cable vessel crane
- When the power cable is in place, it is fixed on its final position with a clamp
- The cable is trenched into the seabed and the well exit point is protected with rock dumping

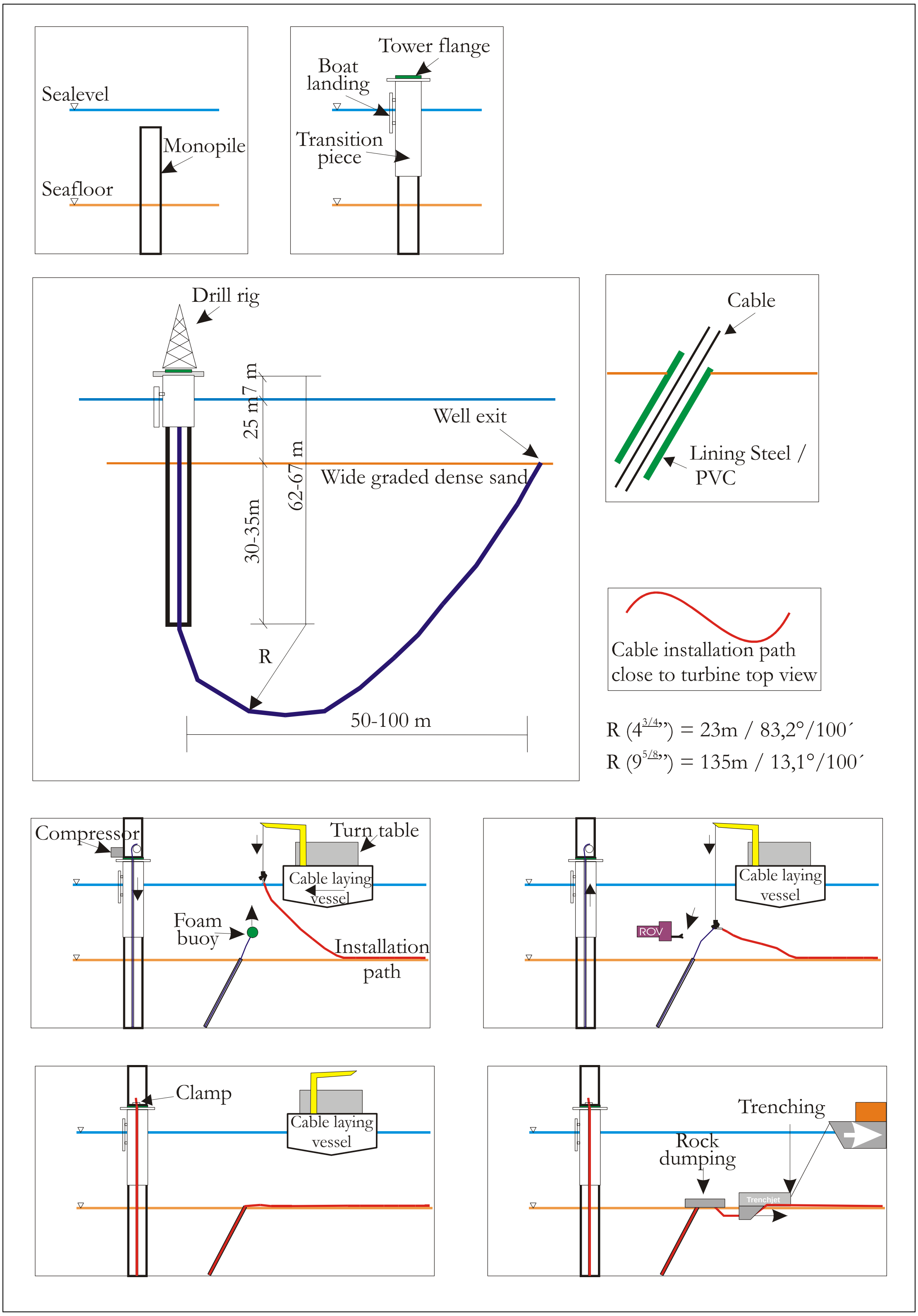


Figure 52 Directional drilling

Advantages:

- No scour protection is needed to enable the cable connection to the turbine

- J-Tubes are not required
- The cable is very well protected inside the monopile, it is not exposed to ice or wave loading

Weak points:

- No experience with a cable installation procedure using a well with 90° intrusion angle
- Horizontal direct drilling units like the "Ditch Witch" cannot be used, because these units are not suited for the required intrusion angle. Offshore oil drilling equipment has to be used instead. The geometrical setup of the well is possible to drill [27], but the rig drillers are not used to resurface their wells, so mud handling problems at the exit point have yet to be solved.
- The power cable installation has to be done right after completion of the well, to avoid soiling of the well exit point with sediments of the seabed.
- The smaller penetration depth of the monopile caused by the scour hole has to be taken into consideration when designing the foundation. [23]

4.4. Installation recommendations

For the cable cross sections used in the infield power collection schemes in 3.4.7, and the cable data in Appendix A the pulling force for installations with J-Tubes and for directional drilling installations where calculated. The allowed force on the cable is specified with 50 N/mm² of copper cross section. For the installation procedures with scour protection the same cable length was assumed.

Installation type	Cross section [mm²]	Weight [kg/m]	Cable length [m]	Angle [rad]	Force horizontal [N]	Force bending [N]	Allowed Force [N]
Convent.	150	17,6	42	1,57	1109	1404	7500
DD	150	17,6	189	3,14	4990	7992	7500
Convent.	240	23,4	42	1,57	1475	1866	12000
DD	240	23,4	189	3,14	6634	10625	12000
Convent.	500	40,7	42	1,57	2564	3245	25000
DD	500	40,7	189	3,14	11538	18480	25000

Table 15 Force on cable during installation

Except for the cable with 150 mm² all installation procedures remains under the allowed pulling force of the cable, but these values are highly depending on the friction coefficient, which is in this calculation an assumption for smooth pipes [25]. For the conventional installation procedures this is not an issue, but for directional drilling this is a problem, so if directional drilling is chosen as installation method, special care has to be taken on the friction behavior of the cable and the J-Tubes.

5. Results and conclusion

5.1. Abstract of Egmond OWF specific results

In this investigation uses the design of the electrical infrastructure for the Egmond OWF as a guideline. Before presentation of the general conclusions and recommendations, this section summarises the design results for this specific case.

A connection with medium voltage level was the starting guideline for this specific OWF, a sketch is given in Figure 5. In this example a multilink is applied.

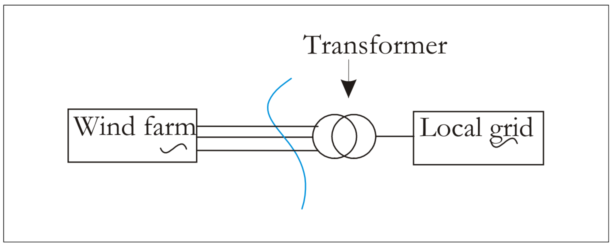


Figure 5 AC connection at wind farm voltage level

The switchgear at the shore connection point of the infield power collection can be seen in Figure 35. The type and voltage rating of the switchgear is determined by the shore connection type.

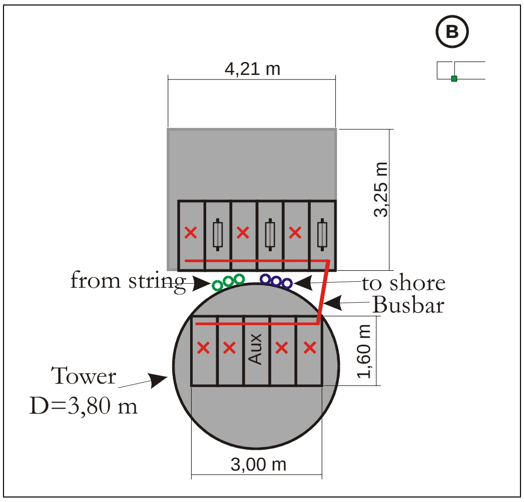


Figure 35 Switchgear at shore connection point

The "Triple string, central connection point" layout is the best choice for the OWF at Egmond, Figure 32 gives a sketch of the connection scheme.

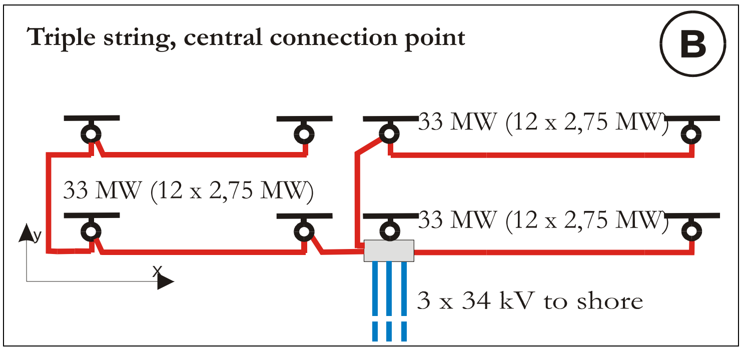


Figure 32 Layout options

For the above recommended infield power collection scheme the appropriate turbine switchgear is shown in Figure 23.

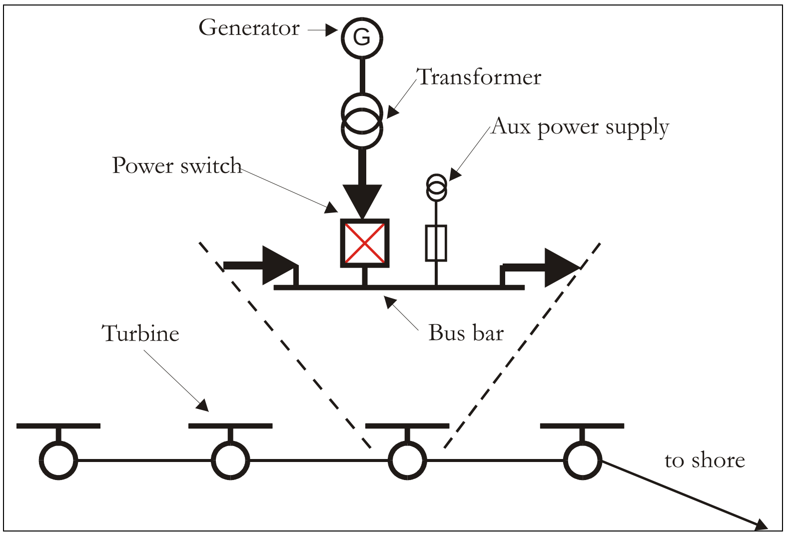


Figure 23 Turbine switchgear low selectivity

The required cable for this layout has the following dimensions. Notice that these dimensions and losses are highly specific for the location and the OWF power output. With that layout a moderate cable cross section can be used. Table 16 shows the cross section and the infield power collection losses.

	Cable for Option B
Current per phase [A]	561
Cross section [mm²]	3x240
Overall cable	0,68

losses [MW]	

Table 16 Option B cable and losses

5.2. Conclusions concerning the design process

The main influence factors on the shore connection are distance to shore and the required transmission capacity, resulting in a specific shore connection type. The type of shore connection determines the required electrical facilities especially the shore connection switchgear and transformation. Figure 53 shows the according flowchart.

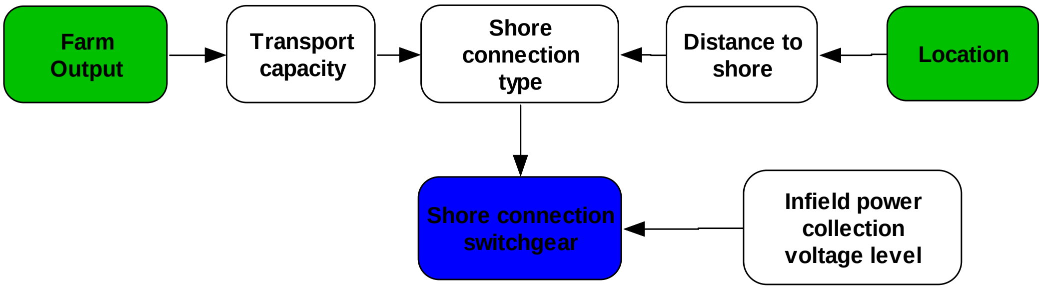


Figure 53 Shore connection flowchart

With distances larger than 100 km HVDC connections are required. The aim of this work was to connect an OWF to shore without an additional platform to house electrical facilities, this can be done only at MV, thus restricting distances to shore to 15 km.

Turbine switchgear and the cable dimensions for the infield power collection together with the shore connection build the electrical layout of the OWF. In Figure 54 the according flowchart can be seen. The main influence factors are again the location of the OWF and the farm power output, but with the available transport capacity as additional factor. Unlike at the shore connection, the transport capacity can not be easily altered by the voltage level of the transmission. The lowest allowable voltage is determined by the required transmission capacity and the maximum cable size, while the highest voltage is limited by the switch gear size, which grows with voltage level. The most sensible solution is to use the medium voltage level, with negligible losses and small switchgear that can be fitted into the tower. The limited cable capacity is a factor that has to be considered in future development. As can be seen in this work, the cable capacity at the infield power collection is on its upper limit, much more than 50 MW can not be transported with 3 phase cable types. A possible solution is to divide multi megawatt OWFs in smaller units and connect them to a transmission point as it is done at Horns Rev, requiring an additional offshore platform. For short distances to shore as at Egmond, an additional platform is not required, but the switchgear has to be placed outside the turbine.

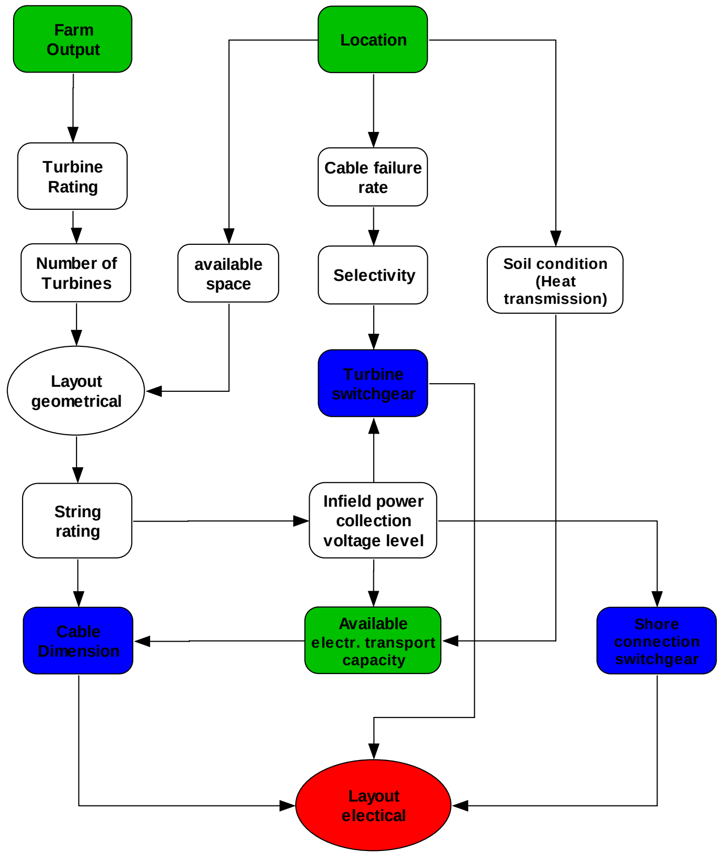


Figure 54 Infield power collection flowchart

The factors for the cable installation procedure at the infield power collection are the J-Tube design, the required scour protection and the cable dimension. The possible installation procedures are also depending on the available cable installation vessels, certain procedures require either a dynamic positioning system or a vessel able to operate a ROV. As repairs are very costly and can only be done with appropriate sea conditions, the aim of the installation procedure should be to establish a reliable and fail safe cable connection. Figure 55 shows the flowchart for this issue.

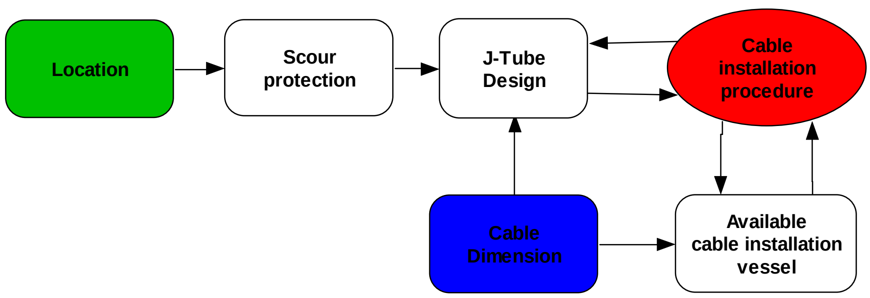


Figure 55 Cable installation procedure flowchart

5.3. Recommendations and further work

For a 100 MW OWF the sensible distances for different shore connection types are:

- up to15 km for MV connections
- up to 100 km for HV connections
- >100 km for HVDC connections

For OWFs with higher power output the HV connection is even sensible at distances closer than 15 km because of the limited power transfer capacities of MV cables.

At MV level a 3 core cable can be used to transfer about 50 MW, for higher power either additional connections or HV have to be used

In this investigation cable failure rates of 1,8 failures per 1000 km and year are used to determine the benefits of redundancy. OWFs are currently planed close to shore in areas of high naval activity. A close investigation of specific failure rates for OWF installations can alter the failure rate and with that the layout of the infield power collection. The cable failure rates currently used are mainly generated from long transmission cables installed in deep water only with a short shore landing opposed to the infield power collection of OWFs, where relatively short cables are installed punctually in shallow water. About 70 % of all cable failures occur in shallow water, therefore a closer statistical investigation of specific failure rates in close to shore areas with heavy shipping activity could alter the monetary value of redundancy.

Grid connections with HVDC and their back to back converters allow influencing vital parameters for grid stability and are therefore valuable instruments for public grid operators. With large scale OWFs connected to the grid the HVDC coupling can help to guarantee the stability of the public grid. At the current point, only very large distances and powers are covered with HVDC technology, but the current development in HVDC technology with small converter modules is likely to decrease the break even distance for HVDC connections. Closer investigations in this technology will be of great value when more OWFs have to be connected to the public grid.

Directional drilling is a common used technology, and has various advantages. To become an approved installation method for OWF cable connections a test well would be the logical next step. Practical problems like the resurfacing of the well, application of the lining and installation of the messenger cable can be solved. Directional drilling is a promising concept for cable installations and with the upcoming OWFs investigations in this area can be of great value for future installation procedures.

Appendix A

Cable data

Cross section A	**Max current I**	**Capacity C**	**Resistance R_{ac}**	**Diameter D_e**	**Weight W**
[mm²]	[A]	[uF/km]	[Ω/km]	[mm]	[t/km]
150	366	0,19	0,16	108	17,6
185	411	0,21	0,13	113	21,0
240	470	0,23	0,10	116	23,4
300	530	0,27	0,0789	119	27,7
400	584	0,31	0,0629	129	34,2
500	760	0,34	0,05	135	40,7
630	850	0,37	0,0405	138	49,1

Table 17 Cable data XLPE [13]

Appendix B

Horns Rev Turbine Type Vestas V80-2.0MW datasheet

Rotor

Diameter:	80 m
Area swept:	5,027 m^2
Speed of revolution:	16.7 rpm
Operational interval:	9-19 rpm
Number of blades:	3
Power regulation:	Pitch/OptiSpeed™
Air brake:	Three separate pitch cylinders

Tower

Hub height (approx.):	60 - 67 - 78 m

Operational data

Cut-in wind speed:	4 m/s
Nominal wind speed (2000 kW):	15 m/s
Stop wind speed:	25 m/s

Generator

Type:	Asynchronous with OptiSpeed™
Nominal output:	2,000 kW
Operational data:	50 Hz/60Hz 690 V

Gearbox

Type:	Planet/parallel axles

Control

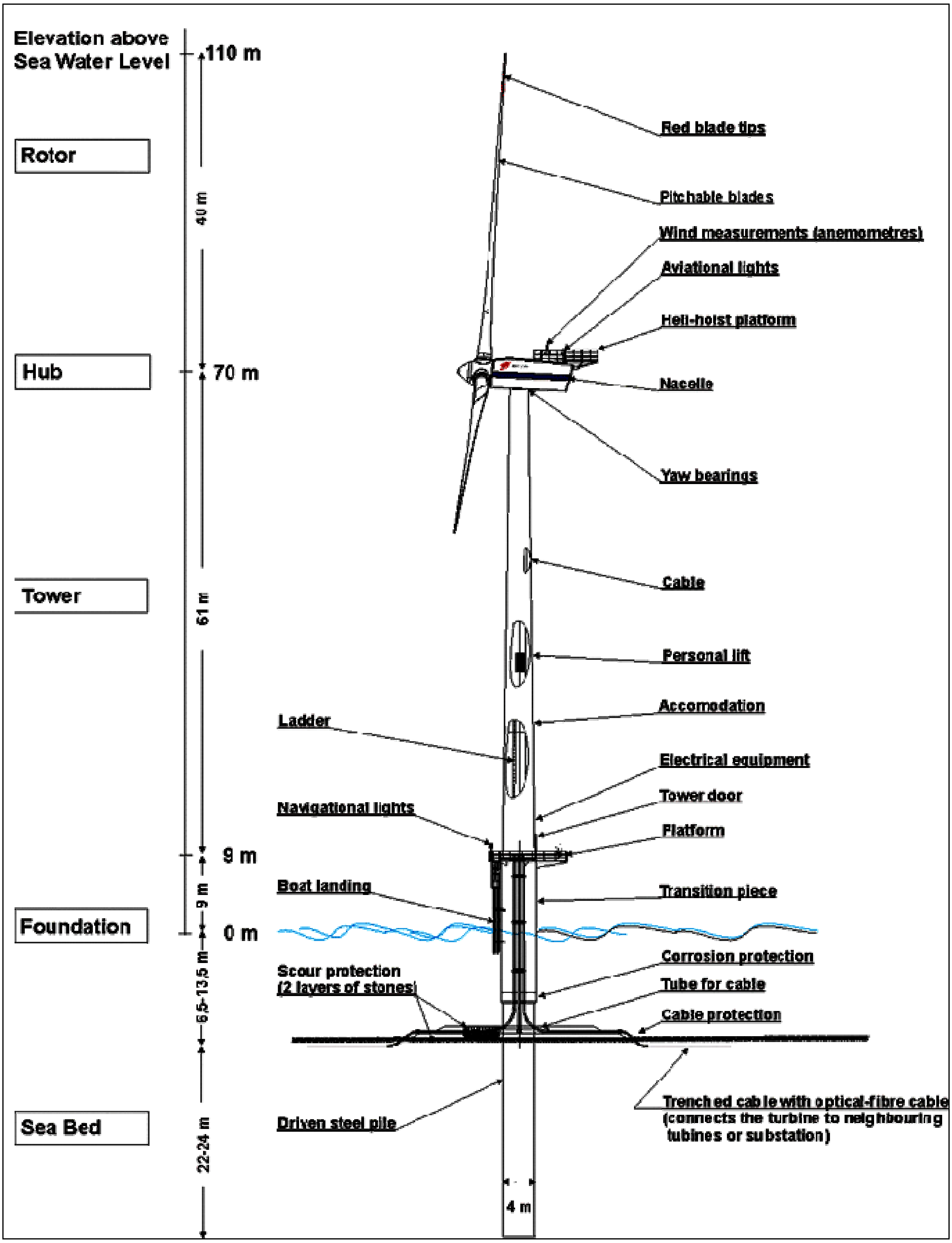
Type:	Microprocessor-based control of all the turbine functions with the option of remote monitoring. Output regulation and optimisation via OptiSpeed™ and OptiTip® pitch regulation

Weight (IEC IA/IEC IIA)

Hub height:	60 m	67 m	78 m
Tower:	140 t/124 t	158 t/142 t	203 t/199 t
Nacelle:	61 t	61 t	61 t
Rotor:	37 t	37 t	37 t
Total:	238 t/222 t	256 t/240 t	301 t/297 t

Appendix C

Horns Rev turbine overview



Appendix D

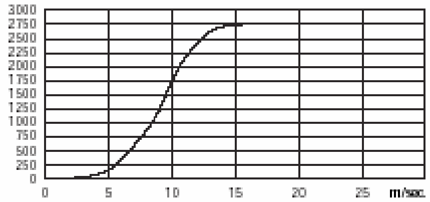
Egmond turbine type NEG Micon NM 92/2750

Technical data

Operating data	**NM92**
Nominal output	2750 kW
Output regulation	PRVS
Nominal wind speed	14 m/sec
Cut-in at	4 m/sec
Cut-out at	25 m/sec
Rotor	
Rotor diameter	92 m
Swept area	6648 m²
Number of blades	3
Rotor revolutions	15.6 rpm
Brake system	
Blade brakes	Each blade can be pitched individually, and each has its own back-up system
Disc brakes	One unit mounted on the high-speed shaft
Drive train	
Gear type	3 step planetary/ helical hybrid
Gear ratio	1:70.65
Main shaft	Forged shaft and flange
Main bearing	Spherical roller bearing
Cooling	Oil cooling with pump
Generator	
Type	Double-fed asynchronous generator
Voltage – stator	960 V
Voltage – rotor	690 V
Nominal frequency	50 Hz
Rated power	2750 kW
Cooling	Water
Yaw system	
Type	Double ball race with internal gearing
Yaw brakes	5 hydraulic brake callipers
Yaw motor/gears	5 electrically driven planetary gears
Tower	
Type	Conical steel tower, painted
Hub height	70 m or depending on location
Control	
Type	Computer controlled
Cut-in system	Soft with frequency converters
Remote monitoring	Modem

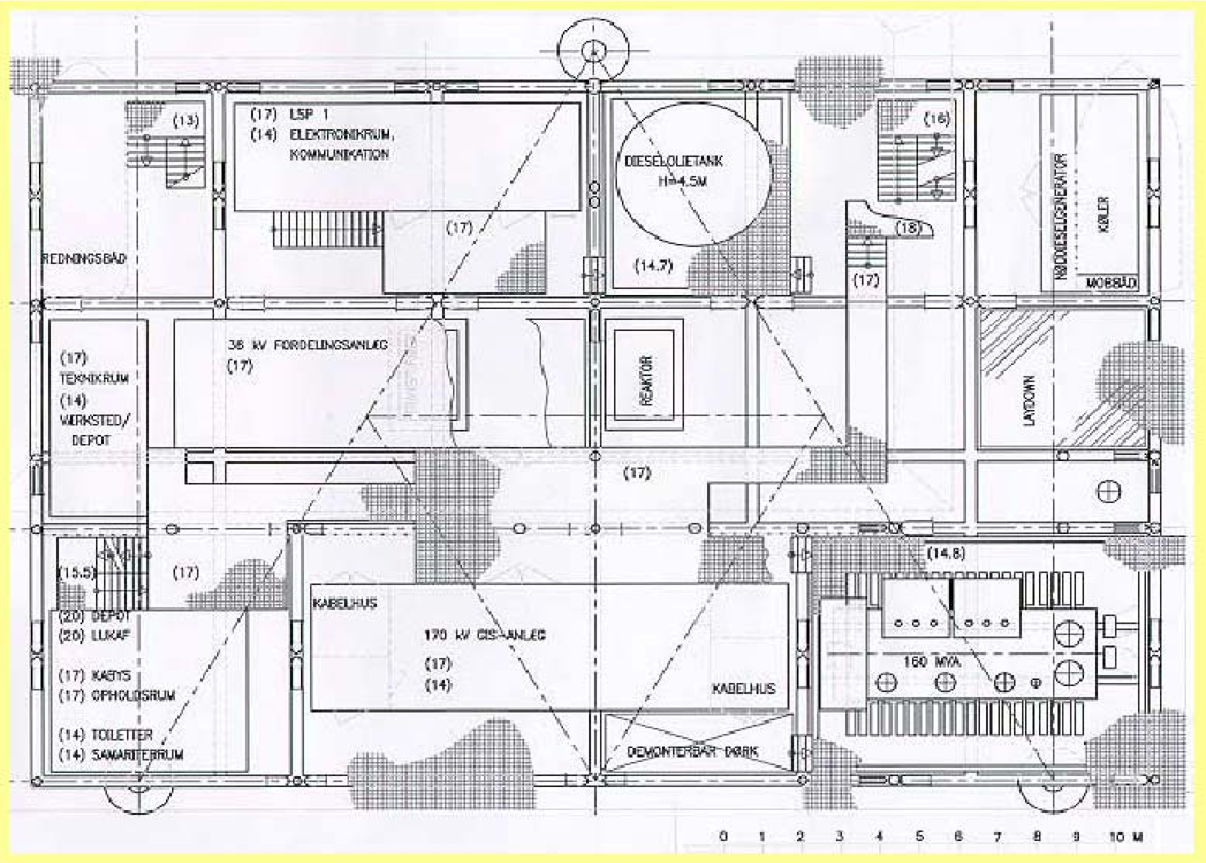
Lightning protection
Superstructure to most recent international norms.

Power curve
kW NM92/2750



Appendix E

Horns Ref transformer station



Appendix F

J-Tube at Horns Rev

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