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Hornsea Projects One and Two – Design and Execution of the Grid Connection for the World's Largest Offshore Wind Farms

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SUMMARY

Offshore wind farms are currently getting bigger and bigger and being built further and further from shore and have at the same time shorter construction windows compared to earlier projects. This gives several challenges with respect to the design and execution of the projects.

This paper describes some of the aspects of design and execution of the two wind farms: Hornsea Project One and Hornsea Project Two with an installed wind turbine capacity of more than 1200MW and almost 1400MW, respectively. Both Hornsea projects are currently being constructed.

In general, following the state-of-the-art approach for offshore wind farms the active power generated by the wind turbines is transferred via an array cable grid to an offshore substation which transforms the voltage to the export cable level. For the projects described in this paper the export cable voltage level is 220kV between the offshore substation and the onshore substation. At the onshore substation the active power is transmitted to the onshore grid at 400kV level.

Several aspects of load flow, low-order harmonic propagation and switching events (including energization) which are of special concern for long export cables, which in this case is up to almost 200km, are presented in this paper.

In addition, several project execution aspects including the installation of long export cable in a short construction window are presented in this paper for Hornsea Project One.

KEYWORDS

Active filtering, Array cable system, Energization studies, Fault clearance studies, Load flow studies, Low-order harmonics, Offshore wind farm, Resonance frequency, World's longest 220kV export cable system, Zero-miss phenomenon.

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1. INTRODUCTION

Large offshore wind farms are currently getting bigger and bigger and being built further and further from shore and have at the same time shorter construction windows compared to the earlier. Even though the basic design of the large offshore wind farms is like the state-of-the-art known from older wind farms, the significant size and short execution time present a huge challenge. This paper will describe some of the challenges experienced during design and execution of the two biggest wind farms in the world, Hornsea Projects One (aka HOW01) and Hornsea Project Two (aka HOW02) in the North Sea off the coast of England as shown below in Figure 1.

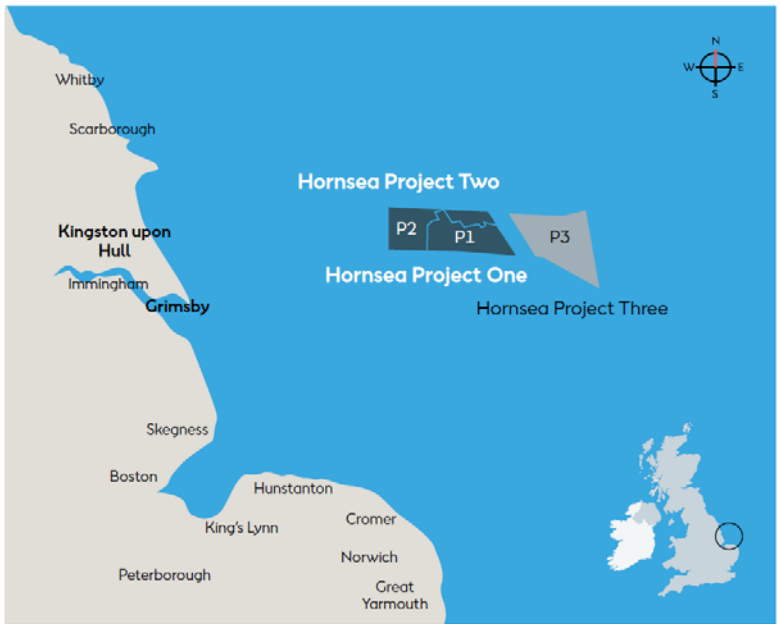

Figure 1 Location of HOW01 and HOW02.

2. HIGH LEVEL ELECTRIC DESIGN OF THE WIND FARMS

From a high level perspective, the two offshore wind farms HOW01 and HOW02 are designed the same way. The active power is generated by the wind turbines (WT's) in the array of the offshore wind farm. The WT's are connected to an offshore substation by the array cable grid. At the offshore substation voltage is stepped-up to the transmission system level of 220kV by transformers. The generated power is exported to the onshore substation by the export cables. At the onshore substation the voltage is further increased to the 400kV level and connected to the two transmission interface points (TIP) at the National Grid's Killingholme substation. To optimize the voltage profile along the export cable a design with a reactive compensation station is used. This also increase the active power transfer capability of the export cable. All the above details are shown in the high-level schematic below in Figure 2.

At the onshore substation several STATCOMs are designed to comply with the reactive power requirement at the TIP. In addition, several harmonic filters are designed to fulfil the harmonic requirement at the TIP and in the export and array cable system. The STATCOMs and harmonic filters are not shown in Figure 2.

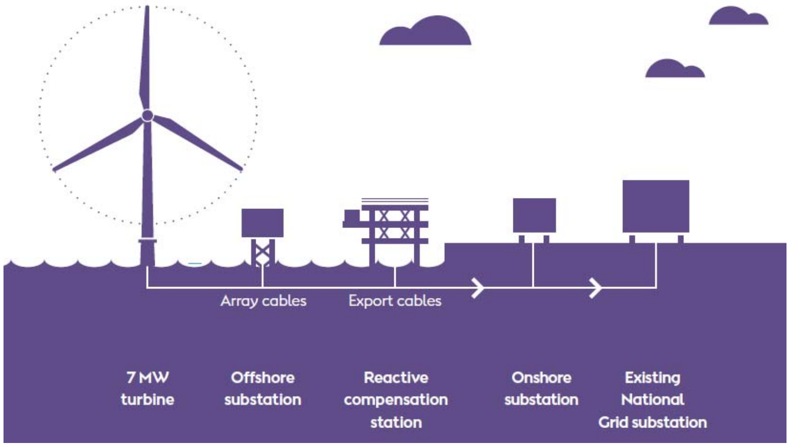

Figure 2 High level schematic of the HOW01 (HOW02 is similar).

2.1. HOW01 base design

The HOW01 wind farm consist of 174 WTs each rated at 7MW connected to the three offshore substations via a large 34kV array cable grid. Each of the offshore substations is connected to the reactive compensation substation by an export cable. In addition, the offshore substations are connected to each other by interlink cables between the substations.

The reactive compensation station is connected to the onshore substation by three parallel export cables.

At the onshore substation the 400kV busbars are connected to the TIP by two 400kV export cables designed to fit the requirement from National Grid with regards to the maximal loading as each connection.

2.2. HOW02 base design

The HOW02 wind farm consist of 165 WTs each rated at 8MW connected to one offshore substation via a large 66kV array cable grid. The offshore substation is connected to the reactive compensation substation by three export cables.

The reactive compensation station is connected to the onshore substation by three parallel export cables.

At the onshore substation the 400kV busbars are connected to the TIP by two 400kV export cables designed to fit the requirement from National Grid with regards to the maximal loading as each connection.

3. LOAD FLOW ASPECT OF THE DESIGN

HOW01 and HOW02 are the perfect examples to describe the complexity level reached in the offshore wind industry with regards to the electrical design when pushing the boundaries of generation capacity and distance to shore. One of the main challenges faced in the design of the electrical infrastructure of the longest HVAC connected offshore wind farms, is to find the optimal solution to transfer the harvested energy from the wind to the network onshore, in a simple, safe and reliable manner. For this purpose, a thorough analysis of the system is conducted to identify the technical limitations, to overcome the bottle necks and to demonstrate compliance with the technical requirements applicable at the point of connection, in this case The Grid Code from National Grid ESO [1].

The export cables of both HOW01 and HOW02 projects are the largest installations of 220kV HVAC submarine cable to date. One of the electrical properties of HVAC cables is that they always generate reactive power, even when fully loaded. The reactive power generated increases as the cable becomes lightly loaded, meaning that the reactive compensation design has to consider the lightly loaded case. With the aim of reducing capital costs, a novel but simple approach is used whereby the voltage is controlled at either end of the export circuits to manage the reactive power generated depending on the load level of the circuit. In practice, the onshore voltage is regulated via the transformer target setting and the offshore voltage is regulated by adjusting the Power Park Controller voltage target setting

The following aspects are considered in this approach:

- At or near full load the reactive power generated is at its minimum value. As there is a desire to maximise the power transferred to shore, a high voltage and corresponding low current levels are used.
- As load decreases the dominant factor becomes the reactive power generated by the cable. In order to optimise the reactive compensation design, a low voltage level is used.

As the cable capacitance decreases, so does the requirement for offshore compensation, and additionally that improves the possibility of being able to reduce the cable cross section increases. Therefore, cables with low capacitance are selected based on the output of the load flow analysis which serves to determine the reactor location and sizes required to compensate the reactive power generated by the cables. These studies also show the needed reactive power compensation to be placed at both ends (onshore substation and offshore substation) and at the mid-point reactive compensation station) of the export circuit in order to transfer the full power generation to shore. Furthermore, to maximise the capacity of the export circuits the wind turbines are not utilised for voltage control at TIP, only the STATCOMs are responsible for the Grid Code compliance with regards to TIP voltage and reactive power control.

This control strategy is captured in Figure 3 with the voltage and current profiles for normal operation and full power generation across the export system of HOW01. It shall be noted that the export system is designed to minimise cable loading at landfall, which is the most thermally constrained portion of the cable.

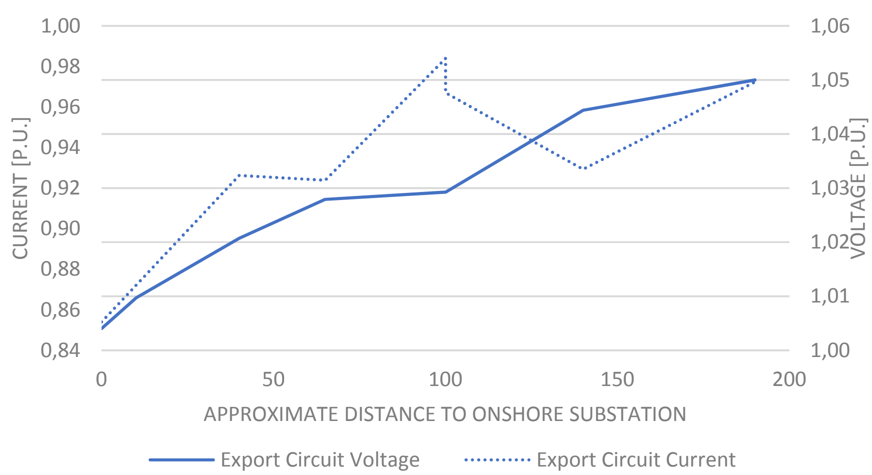

Figure 3 HOW01 export system voltage and current profiles for full power generation.

The operational flexibility of variable shunt reactors is preferred to deal with factors such as the dead-band of the onshore transformers, the different lengths of each circuit and the highly changing power generation. Fixed shunt reactor sizes could result in spillage of reactive power outside the Grid Code requirement if the STATCOM is out of service. Additionally, it means that in normal operation the STATCOMs do not need to compensate for the cable and their size can therefore be reduced. Therefore, the largest possible variable shunt reactors for 220kV are installed onshore. Similarly, the reactive compensation substation reactor sizes are kept the same for all three circuits. Not only does this allow more efficient spare policy, but it substantially reduces the design costs. However, due to the substantially different circuit lengths at HOW01 and the desire for minimising reactive current flow in the array grid (34kV) and hence, power losses, the reactive compensation requirements at the offshore substations are quite different. This results in different reactor sizes at the offshore substations where the limitations on footprint and weight following from the substation design also had to be considered. For HOW02 using only one offshore substation the export cable length of all three circuits is almost the same which means that the reactors are the same for each circuit at HOW02.

Due to the control and operational complexity of these projects, an overall supervisory system is implemented to monitor the configuration of the system and to define the set-points to ensure the maximum availability and minimal losses for the transmission system. Some of the functionalities of this system are to provide voltage target settings to onshore transformers and Power Park Controllers and tap settings to onshore variable shunt reactors based on circuit loadings, tap settings to onshore variable reactors based on the circuit loadings for normal operation and in case of equipment outages.

Another challenge of designing the electrical system with the longest 220kV HVAC export system is handling the harmonic resonances and emissions at the point of connection to grid. The larger the cable capacitance, the lower the resonance frequency. This is another driver to reduce the capacitance of the cable to a reasonable extent. For both HOW01 and HOW02 the lowest resonant frequency fall between the 2nd and the 3rd harmonic depending on the configuration of the wind farm. For this reason, passive harmonic filters are designed and connected to both 220kV and 400kV onshore voltage levels with the objective of damping the wind farm and network resonances and limit the amplification of harmonic voltages to meet the levels allowed at the TIP.

4. ENERGISATION AND FAULT HANDLING AT THE EXPORT CABLE SYSTEM

In addition to the Reactive Power Balance, Voltage Regulation and Harmonics aspects, another challenging issue of the large wind farm design is transient behaviour of the wind farm. Transients are usually generated as a consequence of switching events within the wind farm, switching events on the external grid in the vicinity of the wind farm or due to lightning events. The overvoltage caused by these transient events are classified as slow-front overvoltage, fast-front overvoltage and very-fast-front overvoltage primarily based on duration and frequency of oscillations [2]. This section looks into more details of the switching overvoltages caused within the wind farm. Switching events within the windfarm can be segregated as energisation of various equipment, de-energisation (load rejection) and fault clearance. This paper mainly focusses on the energisation and fault clearance events and details some of the challenges encountered for these wind farm designs.

Due to the long cables considered for these projects, shunt compensation equipment (such as variable and fixed shunt reactors) are located on Onshore Substation, Offshore Substation, and also on the mid-point reactive compensation station. In order to limit the voltage rises caused during the energisation, export cable energisation will be performed in stages. The longest export cable considered for this energisation is almost 200km. The first stage would be energising the first section of export cable from onshore substation to the reactive compensation station along with the variable shunt reactor located in the onshore substation. When both the cable and reactor are energised simultaneously, it is well-known that there could be a zero-miss issue [3] due to the cancellation of capacitive and inductive currents leading to significantly delayed zero-crossing. This delay in current-zero will be up to a number of seconds if the shunt compensation equipment energised along with the cable compensates the cable 100% or nearly 100% and will be completely eliminated or becomes less predominant if the shunt compensation equipment compensates cable less than 40-50%. To avoid zero-miss during energisation of the first section of the cable the variable shunt reactor is tapped to minimum MVAr position which compensates <50% of the cable. Similar issues should also be considered during the further stages of energisation.

Apart from the energisation of export cables, another energisation issue that needs to be considered for a project with long export cable systems is the energisation of large transformers on the offshore substation. Due to the length of the export cables and potential weak grid conditions during low generation, an intra-harmonic resonant frequency between 2^{nd} and 3^{rd} harmonic is observed. Passive harmonic filters are designed to mitigate any amplification of such harmonic voltages, meet the harmonic emission compliance requirements and also to improve the system damping. These filters are essential both during normal operation and during energisation such that sufficient damping is present in the system. However, it is a well-known fact that inrush current of transformer energisation is rich in low order harmonics and especially near to the 2^{nd} order harmonic [4]. As the wind farm resonant frequency is also in the same range, filters tuned to corresponding harmonics may absorb much higher currents than during normal operation. These higher currents may exceed the capability of each harmonic filter. One solution to mitigate this issue will be to increase the filter rating to be suitable for such an energisation event. Alternatively, if more than one harmonic filter is present in the wind farm which are tuned to the low-order resonant frequency, then multiple harmonic filters can be connected for such a switching event such that the low order harmonics in the inrush current is shared between the filters avoiding any overload issues. In addition to these possible solutions related to harmonic filters, a Point on Wave relay could be used for offshore transformer energisation which is expected to minimise the inrush current and hence low order harmonic currents. However, any possible behaviour of ferro-resonant circuit should be checked for in early phases of the design if this solution is adapted.

Another kind of switching event that is crucial for wind-farm design is the fault clearance event and ensuring that transient and temporary overvoltages caused due to these events are within the equipment capability is necessary. These fault clearance events become more critical with the long export cable systems and due to the higher ratings of shunt compensation equipment. Due to its natural behaviour, the reactor feeds a dc current to the fault whenever a fault occurs at the reactor terminals. The only factor that impacts the decay of this dc current is the damping (resistance) of the fault circuit which includes the internal reactor resistance, fault resistance, grounding system resistance etc. Under these circumstances, the normal practice of using an ideal circuit breaker model in the simulations is no longer valid and a detailed energy-based circuit breaker model shall be used to ensure that the circuit breaker is able to clear the fault without causing any damage to the equipment. In addition to the issue caused due to the reactor, due to the amount of energy stored in the export cables, the voltage could persist at significant levels even after fault is cleared. Any potential resonance circuits shall be identified for such islanded systems such that the doubling effect of capacitor (cable) voltage is avoided and hence eliminating the risk of wind farm equipment damage. This situation can be avoided by setting up the inter-tripping scheme within the windfarm to avoid such resonant islanding systems.

5. USING 34KV VS 66KV IN THE ARRAY SYSTEM

One of the main differences between HOW01 and HOW02 is the voltage level used in the array grid. For the HOW01 project, a 34kV array cable system was selected because the 66kV option was not considered to be sufficiently matured at the time of design freeze. However, the development was going fast and at the time of design freeze of the HOW02 array system came, the 66kV system was found to be a feasible option.

It is well known that a 66kV cable can transfer approx. the double amount of installed wind turbines capacity to a platform compared to a 34kV cable assuming cross sections are the same. This brings several benefits such as half the amount of array cables connected to the offshore substation and reduced array cable losses comparing the 66kV with the 34kV array system for the same wind farm.

Among other benefits, using the 66kV array cable enable the use of a single offshore substation at HOW02 compared to the three offshore platforms designed for HOW01

6. ACTIVE FILTERING BY USING THE STATCOM

The electrical infrastructure complexity of offshore wind farms is increasing with the distance to shore and the plant capacity. Nowadays, large wind farms are equipped with power converters installed inside the wind turbines as well as STATCOMs which creates challenges with respect to harmonic emission, propagation and stability [5]. Especially for HVAC connected wind farms, low-frequency resonances created by the combination of large transformers inductance and long power cables capacitance may cause power quality issues [6]. The harmonic distortion due to resonances, nonlinear power system components and emission by the power converters causes on one hand, additional stress as well as heating of electrical components and on the other hand there are potential issues with the Grid Code compliance and overall system stability [7, 8, 9].

To overcome the harmonic challenges, the passive filters together with active filters integrated in STATCOMs are installed at the onshore connection of the wind farm. Due to the fluctuating harmonic content from the wind farm, topology changes and components tolerances the grid the passive filter effectiveness might be affected due its static nature. Therefore, an active filter feature is used in the STATCOMs as a risk mitigation measure [10].

Typically, the STATCOM is required for dynamic voltage and reactive power control at the point of connection to the grid. However, it is also possible to utilize the same STATCOM capacity simultaneously for active filtering to provide damping of fluctuating harmonic distortion thus widening the effectiveness of the passive filter circuits to ensure compliance with the Grid Code [11]. Furthermore, the dynamic voltage and reactive power control is prioritized to maximize the power flow and assure the system stability while the active filtering is utilizing the spare STATCOM capacity to maintain the harmonic content within the defined limits. Using the active filtering provides additional flexibility as the controller can be retuned / adjusted depending on system conditions.

The application of full-scale active filtering in STATCOMs at HOW01 and HOW02 is the outcome of joint research and development efforts. Firstly, the active filtering integration concept with STATCOMs in wind farms was matured to the technology readiness level 4

(TRL 4) within the academic collaboration described in [7, 12]. Secondly, the concept was developed further leading to a small-scale demonstration in an industrially relevant and operational environment, i.e. wind farms [11], at TRL 7. Finally, an integrated active filtering was applied in HOW01 proving the fully functional and matured technical solution at TRL 9 [10] which is now utilized within the offshore wind power project portfolio.

7. THE EXPORT CABLE SYSTEM

The export cable systems for HOW01 and HOW02 are to date the longest 220kV AC systems energized or under construction in the world. The sheer magnitude of cable to be installed has been distributed between three cable suppliers, that were finally chosen to supply the export cable systems for each of the two projects – divided into one supplier onshore and two suppliers offshore.

7.1. HOW01 export cable system

HOW01 has three individual cable systems, each one consisting of the following main subsections:

- Onshore export cables between the onshore substation and the transition joint bay, where the onshore and offshore export cables are jointed together.
- Offshore export cable between the transition joint bay and the reactive compensation substation, where the cables are compensated for the reactive power.
- Offshore export cable between the reactive compensation substation and the offshore substations (three in total in the wind farm).

The offshore substations are connected together through interlink offshore cables (two in total), allowing the power transfer from all parts of the offshore wind farm through any of the three cables systems.

The export cable systems have been optimally designed to comply with the installation and operating conditions, including dynamic loading profiles to be able to reach transmission capacity over 1200MW.

More specifically, the onshore export cable route, from the onshore substation to the transition joints at the landfall, comprises of three thirty-nine (39) km 220kV AC cable circuits of single core cables. The cables were designed to be directly buried in flat formation with delivery lengths of approximately 1500 meters. The bonding scheme on the onshore part was chosen to be direct cross-bonding so that the number of link-boxes could be minimized during the installation of the cables and the phases are transposed in each joint bay as well see below.

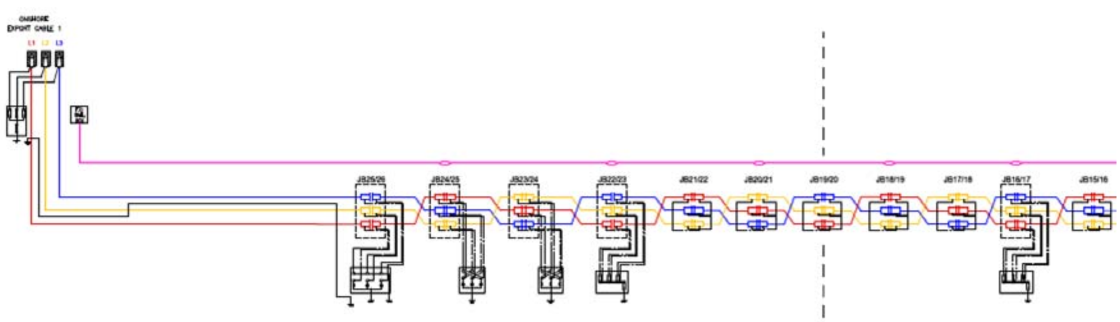

Figure 4 HOW01 Onshore export cable circuit single line diagram part 1.

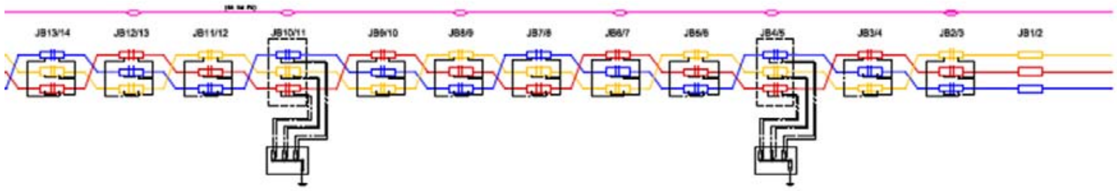

Figure 5 HOW01 Onshore export cable circuit single line diagram part 2.

Two cross-sections of single-core cables were selected for the long onshore part, to ensure the optimal performance under the various installation conditions.

The largest cross section from the onshore route was chosen for all internal cable connections in the onshore substation. The connection from the HOW01 onshore substation to National Grid's Killingholme substation was done by two very large 400kV AC cable circuits.

One leading cable manufacturer was selected for the design and supply of all onshore export cable systems.

The offshore export cable part comprises of three 220kV AC three-phase cable circuits, exporting power from three offshore substations to the transition joint bays via a reactive compensation substation. Four different designs of three-core cables, meeting the latest cable technology standards, have been selected in the offshore sections of the project, ensuring the optimum solution for the execution and operational phase.

The metallic sheath of the offshore export cables has been bonded at both ends; i.e. offshore substations, reactive compensation substation and the transition joints bays, according to standard practice, whereas 220kV AC single-core cables of smaller cross-section have been designed for the internal connections in the offshore substations and the reactive compensation substation.

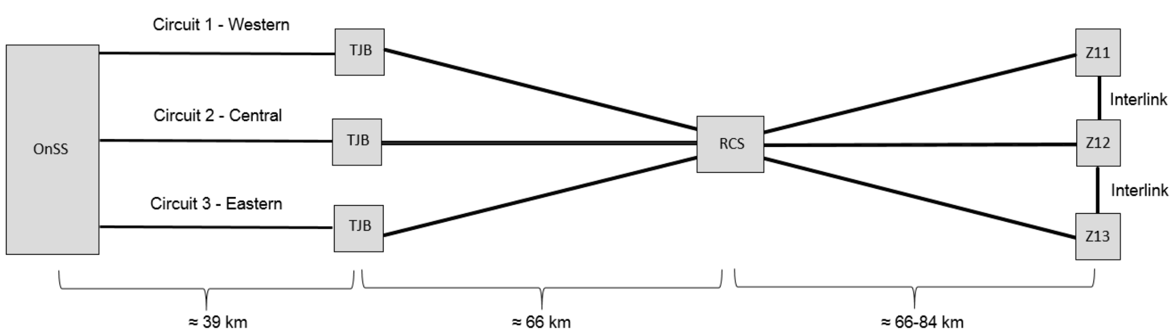

Figure 6 HOW01 export cable layout.

On HOW01, two leading cable manufacturers have designed and supplied the submarine cable systems of nearly 500km in total length, including the interlink cables between the offshore substations.

7.2. HOW01 export cable system

HOW02 is quite similar to HOW01, however there are certain differences; e.g. the offshore cable route is slightly shorter and there is only one offshore substation, where all three individual export cable systems are connected, without any interlink offshore cables. Each offshore export cable system consists of the following subsections:

- Approximately thirty-eight (38) km of onshore export cables between the onshore substation and the transition joint bay, where the onshore and offshore export cables are jointed together.
- Approximately sixty-six (66) km of offshore export cable between the transition joint bay and the reactive compensation substation, where the cables are compensated for the reactive power.
- Approximately sixty-two (62) km of offshore export cable from the reactive compensation substation to offshore substation.

The internal connections on the offshore substation enable the power transfer from all parts of the wind farm through any of the three cables systems.

On top of the differences described above, the onshore export cables are installed in ducts, which are laid in a trefoil formation. Added to this, the power of each circuit has been increased from HOW01 to HOW02 by 10%, meaning that the export cable systems have been optimally designed to comply with the installation and operating conditions, including dynamic loading profiles to be able to reach transmission capacity of almost 1400MW.

8. HOW01 EXPORT CABLE PROJECT EXECUTION

The project has been executed on a multi contract approach, meaning that cables supply and installation were procured separately. Therefore, the amount of interface coordination done in the project by Ørsted is significantly higher and more complex, compared to a turn-key based solution. Especially the interface between offshore export cable supply and the installation of these has been challenging because of the several delivery lengths, installation vessels and windows. Despite of this, all project site activities have been completed on time.

The construction phase of the project has been completed in only two and half years, including the installation, offshore jointing and termination campaigns that has followed the manufacturing and testing activities in the manufacturers' premises. The internal platform cables which are essential for the internal connections in the offshore substations and the reactive compensation substation, were also delivered, installed, terminated and tested onshore, prior to the sail-away of the topsides within approximately one year.

Fifteen offshore export cable lengths have been loaded-out, installed, jointed and terminated within one year, whereas more than 220 single-core cable drums have been delivered, installed, jointed/terminated onshore in nearly one and half year, including successful testing of the numerous joints along the long onshore cable route during the Site Acceptance Tests.

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