



# BEST PRACTICES FOR OFFSHORE SUBSTATION BUSBAR SCHEMES

INDIA-DENMARK ENERGY PARTNERSHIP (INDEP)

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**Centre of Excellence**  
for Offshore Wind and Renewable Energy

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## Disclaimer

This study was jointly prepared by the Danish Energy Agency (DEA) and COWI A/S (COWI) after consultations with the Ministry of New and Renewable Energy (MNRE) in India. The assumptions and opinions expressed in this study do not necessarily reflect the view of the Government of India and its related agencies on offshore wind development and/or policies. This study does not propose or indicate any ownership or responsibility of power evacuation assets in India. The document is primarily for use within the bilateral energy partnerships and does not have any legal status and is not an official and legally binding DEA document.

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## Foreword

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India is taking bold strides toward its target of achieving 500 GW of non-fossil fuel capacity by 2030. India is also working on tendering out up to 37 GW of offshore wind in the same timeframe. Consideration must be given to the offshore electrical infrastructure required to connect the country's inaugural offshore wind projects to consumers.

Denmark, a global leader in offshore wind, is proud to support this transformative journey through its strategic collaboration with India. The Centre of Excellence for Offshore Wind and Renewable Energy—established by the Ministry of New and Renewable Energy (MNRE) of India and the Danish Energy Agency (DEA)—continues to serve as a platform for sharing knowledge, building institutional capacity, and fostering a sound enabling environment for offshore wind.

This report, written by COWI, builds upon earlier studies on conceptual planning of power evacuation infrastructure, delving deeper into this critical aspect of offshore wind development. A key objective of this study is to strengthen the technical understanding of international approaches to offshore substation design—particularly the configurations used for internal electrical systems. This knowledge transfer is intended to support well-informed decision-making as input to the electrical design for offshore wind projects.

This work represents another important step in translating India's offshore wind ambition into reality—one grounded in international collaboration, technical excellence, and shared commitment to a clean energy future.

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## Executive summary

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This study builds upon earlier work on the cost impact of power evacuation infrastructure on installation and operational costs, with COWI serving as the implementation consultancy. The overall aim is to reduce risks for developers interested in constructing and operating offshore wind farm projects off the coast of India and to lower the cost of offshore wind power by utilising best practices in planning and cost-reducing measures, thereby supporting the continued implementation of ambitious targets.

The solutions proposed in this study offer a balanced approach between cost, reliability, and availability. It includes assessments of the required redundancy in electrical systems based on component reliability and potential cost efficiency, while examining the trade-off with initial expenditure. The intention is to balance technical requirements with the associated capital and operational expenditures to allow a well-informed decision should be made regarding the optimal configuration of the offshore substation.

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## Abbreviations

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[AC]	Alternating Current
[CAPEX]	Capital Expenditure
[DEA]	Danish Energy Agency
[EAT]	Earthing and Auxiliary Transformer
[EMC]	Electromagnetic Compatibility
[EMF]	Electromagnetic Field
[GIS]	Gas Insulated Switchgear
[HV]	High Voltage
[HVAC]	Heating, Ventilation and Air Conditioning
[HVDC]	High Voltage Direct Current
[IAC]	Inter-Array Cable
[INDEP]	India-Denmark Energy Partnership
[LV]	Low Voltage
[MNRE]	Ministry of New and Renewable Energy
[MPT]	Main Power Transformer
[MV]	Medium Voltage
[MW]	Megawatt
[NER]	Neutral Earthing Resistor
[OEM]	Original Equipment Manufacturer
[OPEX]	Operational Expenditure
[OSS]	Offshore Substation
[OSP]	Offshore Substation Platform
[OTM]	Offshore Transformer Module
[PCC]	Point of Common Coupling

[PoB]	Persons on Board
[RAM]	Reliability, Availability and Maintenance
[SCADA]	Supervisory Control and Data Acquisition
[UPS]	Uninterruptible Power Supply
[WTG]	Wind Turbine Generator

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## 1. Introduction

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Following the announcement of the first offshore wind tenders in India, consideration must be given to the construction of the offshore electrical infrastructure for the initial offshore wind projects in the country. The Danish Energy Agency (DEA) is currently offering additional support to enhance the capacity of its partner the Ministry of New and Renewable Energy (MNRE) of India, through further technical documentation and is also seeking support from COWI.

As part of the establishment of the centre, the DEA and MNRE released a report on the financing of offshore wind, two reports on marine spatial planning for the coasts of Gujarat and Tamil Nadu, and a port study to identify suitable ports for offshore wind project construction. These studies were aimed at reducing risks for developers interested in constructing and operating offshore wind farm projects off the coasts of Tamil Nadu and Gujarat. To further mitigate risks, the MNRE and DEA have conducted a study on the cost impact of power evacuation infrastructure on CAPEX and OPEX, with COWI serving as the implementation consultancy.

The current engagement aims to lower the cost of offshore wind power by utilizing best practices in planning and cost-reducing measures, thereby supporting the continued implementation of ambitious targets

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## 2. Objectives of the Assignment

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The objectives of the assignment can be summarized as below:

*To showcase examples of the best practices in Europe on different busbar schemes that are used on offshore substations for offshore wind projects. This knowledge will be crucial in determining the design of the busbars for the OSS for offshore wind projects in India.*

### 3. Scope of Work

The tasks of the assignment can be summarized as below:

*“Preparation and presentation of a memo, that showcases best practices for busbar design and configuration implemented on existing offshore wind farm projects in Europe and come up with recommendations on the busbar scheme of an OSS (Offshore Substation) designed for an offshore wind project in India with 500 MW capacity”*

Figure 4.1-1 provides the general overview for the offshore wind farm system, where the offshore substation & its HV & MV switchgear busbar schemes are our focus of discussions in the subsequent sections.

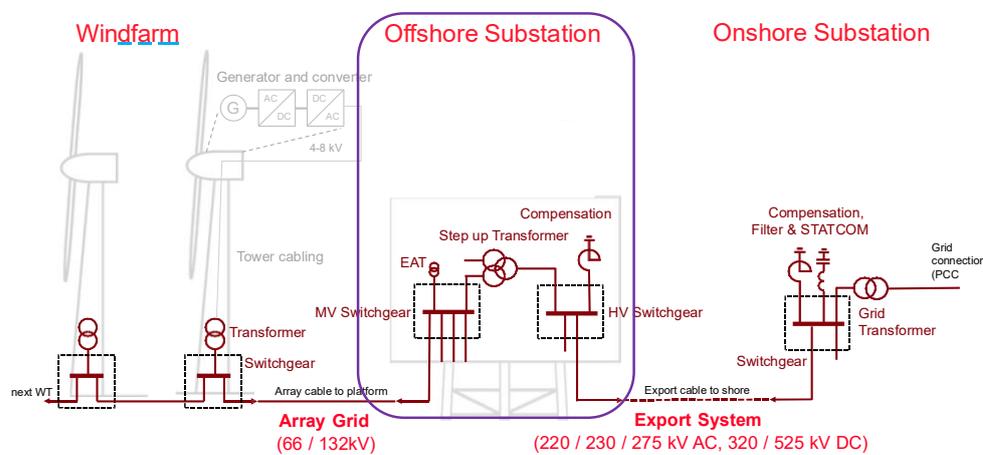


Figure 4.1-1 Overview of power infrastructure for OWF

## 4. Design Inputs for Offshore Substation

Understanding the design basis for offshore substations is crucial before deciding on the busbar scheme for the AC offshore substations. This section aims to address the critical aspects and parameters that impact the selection of electrical equipment for offshore substations.

It is also important to note that when the wind power plants are located further offshore, for longer cable route lengths, HVDC transmission becomes a viable option. The cable length above which HVDC transmission becomes more economic than AC transmission referred as the AC/DC break-even point. Figure 4.1-1 represents the break-even point which is currently between 60 and 80 km depending on wind power plant size and several other factors. For wind power plants above around 200 MW in size & more than 60km (general range is withing 60-80kV) from shore, the HVDC option tends to have the fewest cables connecting the wind power plant to shore. Therefore, for long distances, HVDC will be cheaper in terms of investment costs.

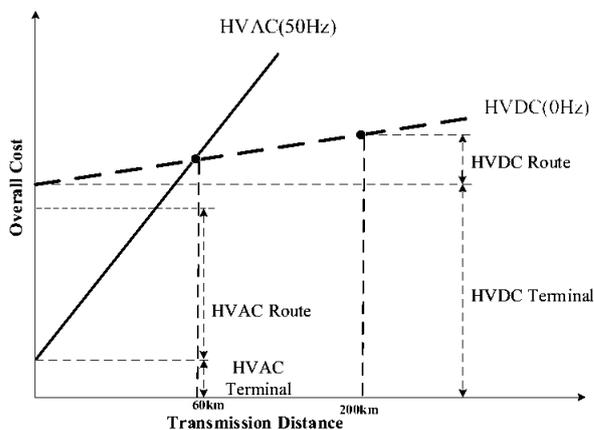


Figure 4.1-1 Relationship between cost and distance between AC & DC transmission for Offshore wind farm. Source-“CIGRE 483”

Based on the previous power evacuation infrastructure studies, it has been established that the distance between the offshore substation and shore does not exceed 50 km. Consequently, an AC transmission can be selected as the method for connecting the offshore and onshore substations in the project.

The design of the AC offshore substation will have to be considered in the context of the total system including the cable, the wind power plant itself and the onshore grid situation.

Wind power plants located more than  $\approx 25 \text{ km}^1$  from shore are typically equipped with one or more offshore HV substations, where transmission voltage step up from 66kV/132kV to 220/275 kV facilitating more efficient power transmission to the shore.

<sup>1</sup> Relates to 66 kV WTGs. The distance will almost double up for 132 kV WTGs.

The challenges encountered when designing an offshore substation can be summarized as follows:-

- › The primary electrical equipment resembles the equipment in an onshore substation but will require proper adaptation. The specific adaptations needed for the harsh marine environment and the modular approach required to minimise the maintenance intervention time.
- › Offshore substations demand more from their secondary equipment in terms of reliability. Secondary equipment is a vital part of the offshore platform and must be well designed.
- › The physical aspects i.e., issues related to the physical environment an offshore platform is exposed to and the challenges of building a substation offshore and the precautions taken to protect people and equipment.
- › The offshore substation will tend to be on the critical path of the project timeline in respect to design, fabrication and installation / commissioning.
- › Ownership Boundary. In the UK, the generator is responsible for constructing all assets, while the connection assets from the 132kV or 66kV side of the OSP transformer to the onshore substation are handed over to an Offshore Electricity Transmission Operator (OFTO). In countries like Germany and the Netherlands, it is the responsibility of the Transmission System Operator (TSO) to construct the offshore platform and export cables, with the generator being accountable for supplying the 132kV or 66kV switchgear

In subsequent sections various design considerations explained in brief, aimed at addressing the challenges outlined above.

## 4.1 Assessment of the Number of Offshore substations

In wind farm developments, the decision between a single large offshore substation platform or multiple smaller platforms is a critical factor. Listed below, the advantages and disadvantages associated with each approach, with the ultimate objective of providing valuable insights to inform the decision-making process.

### *Single Offshore Substation Platform*

#### *Advantages:*

- › Cost effectiveness – A large Offshore platform required upfront capital investment but reduces construction, installation & maintenance cost and overall project timeline.
- › Space Optimisations – A single platform consume less space compared to multiple platforms, optimized use for limited offshore area.
- › Operational efficiency – Single offshore substation simplifies operational and maintenance activities, streamline the coordination of personnel, equipment & supplies.

- › Redundancy – Having multiple feeders in single platform provide inherent redundancy in the export system in the event of major failure such as transformer or cable, also beneficiary in terms of control and protection system.

#### Disadvantages:

- › Size & weight – The increase size and weight of a single offshore substation platform reduces the supply chain options and installation options. Which could lead to increased costs or delays.
- › Cable Length of Array Cable and Export Cable – A single substation may require longer cable lengths due to its singular location within the wind farm, leading to higher electrical losses
- › Increase Risk – Concentrating all the transmission infrastructure and equipment in a single platform increases the risk of a single point of failure. A significant failure in the substation could lead to a complete shutdown of the entire wind farm.

#### Multiple Offshore Substation Platforms

##### Advantages:

- › Standardised design – Standardised design for smaller offshore substation platforms, with potential to reduce costs.
- › Increased Efficiency – Smaller platforms can be strategically located closer to the wind turbines, reducing transmission distances and minimising electrical losses.
- › Scalability and Phased Development – Multiple smaller platforms offer scalability advantages, facilitating phased development of the wind farm. New platforms can be added as the project expands, allowing for easier integration of additional turbines without overburdening a single substation.

##### Disadvantages:

- › More capital Investment – Having multiple smaller platforms involves higher upfront costs due to additional construction, installation, and maintenance requirements.
- › Space Utilization – Multiple platforms require a larger offshore area compared to a single platform. This aspect could pose challenges and may lead to potential conflicts with other marine activities.
- › Complex Planning – Managing and coordinating multiple offshore substation platforms demands more extensive planning and logistical efforts. It requires careful synchronization of maintenance schedules, personnel deployment, and supply chain management.

A summary of windfarm projects of similar capacity to current projects in consideration within the Europe is presented in the Table 4-1.

Table 4-1 Windfarm Projects Capacity and No. of OSP

Name of Wind Farm	Commissioning Year	Country	Generation Capacity	No. of OSP
Hornsea One	2020	England	1218 MW	3 +1 RCS (midpoint Reactive Compensation station Platform)
Hornsea Two	2022	England	1356 MW	1 + 1 RCS
Moray East	2022	Scotland	950 MW	3
Triton Knoll	2022	England	857 MW	2
Inch Cape	2027	Scotland	1080 MW	1
Seagreen Phase 1	2023	Scotland	1075 MW	1
Beatrice	2007	Scotland	588 MW	2
Moray West	2022	Scotland	882 MW	2
Seamade (Mermaid + Seastar)	2021	Belgium	487 MW	2
Deutsche Bucht	2020	Germany	252 MW	1
Thor	2026	Denmark	1080 MW	1

Most wind farms are developed with 1-OSS platform configurations having multiple circuits or with 2- OSS configurations. For instance, projects like Hornsea Two offshore wind farm feature single offshore substations with multiple export circuits, each rated up to 400 MW at 220 kV per circuit. These offshore substations are designed with the principle of one main transformer per circuit. In contrast, wind farms like Hornsea One and Moray West incorporate multiple smaller offshore substations, each rated up to 400 MW at 220 kV. These substations follow a single transformer design with a single export cable per substation. It is worth noting that the maximum export capacity per circuit is limited by the export cable design rather than the substation design. Beside technical factors, cabling cost is also one of the important drivers for the no. of offshore substations i.e. lifetime cost associated with electrical losses(array & export cables) versus the capital investment for the platforms.

## 4.2 Open Deck and Close Deck Substation Platform Design

The terms "open deck" and "closed deck" refer to two different configurations or designs of offshore substation. Each is explored below:

### *Open Deck Offshore Substation*

An open deck offshore substation is characterized by its exposed platform or deck area on the top of the substructure or jacket. This design facilitates flexible operations, as it can accommodate various equipment and components required for the substation's functioning. The power transformers and shunt reactors are installed outdoor whereas HV/MV switchgear and auxiliary/control/SCADA systems are installed in individual containers. Generally, the transformers used on this style of platforms have enhanced corrosion protection. Figure 4.2-1 represents the same.

#### Advantages:

- Simple Design approach
- Flexibility
- Accessibility
- Cost effectiveness

#### Disadvantages:

- Exposure to marine and harsh environment
- Required enhanced protection and treatment
- Safety Risk associated to it



*Figure 4.2-1 Open Platform Design (HSM Offshore Energy Thor 1 GW)*

### *Closed Deck Offshore Substation*

A closed deck offshore substation is designed with a fully enclosed or covered deck area up top. Closed deck substations often have centralised HVA/C(Heating, Ventilation and Air Conditioning

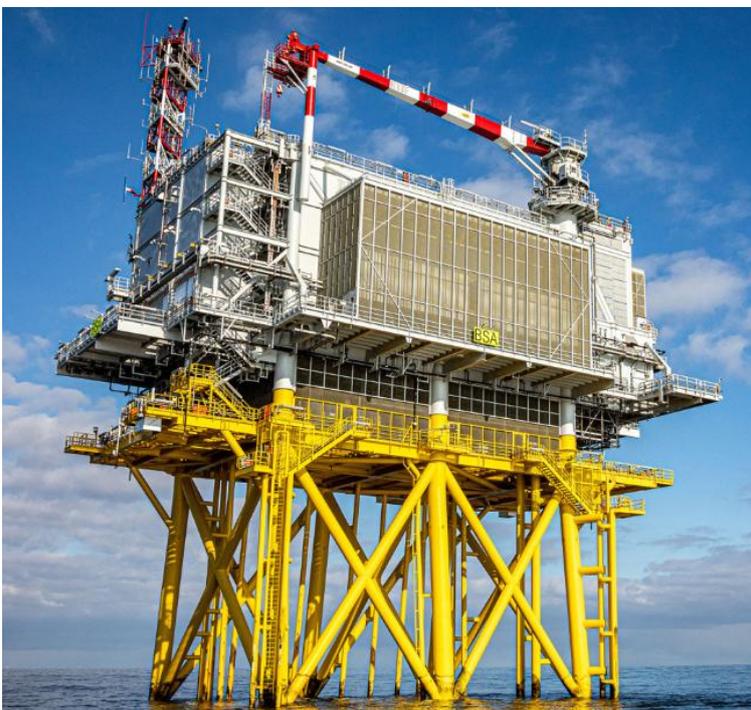
systems to regulate temperature and humidity within the enclosed space, ensuring optimal operating conditions for the equipment but also adding a level of complexity and maintenance needs. Figure 4.2-2 represents the same.

**Advantages:**

- Closed equipment protections
- Controlled Environment
- Reduced interference

**Disadvantages:**

- Complex design & Constructions
- Increase of cost
- Limited Flexibility



*Figure 4.2-2 Closed Platform Design (HSM Offshore Energy 700 MW Borssele Alpha)*

Below Table 4-2, presents insights on different European wind farms and the selection of either closed or open deck design for offshore substations.

Table 4-2 Wind Farm, Operating Country & Deck type

Wind Farm name	Commissioning Year	Operating Country	Offshore SS Type
Westermost Rough	2015	England	Closed
Gwynn y Môr	2015	Wales	Closed
Humber Gateway	2015	England	Open
Burbo Bank Extension	2007	England	Closed

Dudgeon	2017	England	Closed
Race Bank	2018	England	Closed
Galloper	2018	England	Closed
Rampion	2018	England	Open
Walney Extension	2018	England	Closed
Beatrice extension	2019	Scotland	Open
East Anglia One	2020	England	Closed
Hornsea One	2020	England	Closed
Moray East	2020	Scotland	Open
Hornsea Two	2022	England	Closed
Triton Knoll	2022	England	Open
Near Na Gaoithe	2025	Scotland	Open
Seagreen	2023	Scotland	Closed
Moray West	2022	Scotland	Open

Based on previous power evacuation infrastructure study for Gujrat Offshore Wind farm, total capacity of the wind farm is of 1GW, consisting of 2 x 500MW offshore substation, both with closed deck design concept suggested.

### 4.3 Risk & Hazard Management

It is essential to continuously identify, assess, and mitigate risks by using effective risk management and assessment processes in the offshore substation design. Table 4-3 highlights the associated risks in offshore substation design that are taken into consideration during the design process.

Table 4-3 Associated risk with offshore substation design

Risk Category	Equipment associated with the Risk
Electrical Design	High voltage stresses - High overvoltage exposure of equipment - Plant ratings
Physical Environment	Main Transformers & Reactors - Transformer failure, fire hazard and explosion - Gas Insulated Transformers (GIT) Equipment arrangement - Load handling and dropped object damage to systems and structures - Location of storage area - Safe operating and access ways for personnel

Systems	<p>Inter array cables</p> <ul style="list-style-type: none"> <li>- Minimum cable length, optimal configuration</li> <li>- Access for cables into electrical plant</li> <li>- Reactive compensation for cable systems</li> </ul> <p>Harmonic Performance</p> <ul style="list-style-type: none"> <li>- Interactions between cable resonances, existing harmonics, and control systems</li> </ul> <p>Earthing transformers</p> <ul style="list-style-type: none"> <li>- Effective grounding</li> <li>- Platform earthing systems e.g., cathodic electrodes</li> </ul>
Operational Aspects	<p>Maintenance of Offshore substations</p> <ul style="list-style-type: none"> <li>- Unplanned maintenance</li> <li>- Oil management</li> </ul> <p>Health and Safety</p> <ul style="list-style-type: none"> <li>- Access to and egress from substation</li> <li>- Fire and explosion hazards</li> </ul>
Environmental	<ul style="list-style-type: none"> <li>- Oil handling &amp; spillage</li> <li>- Rainwater management</li> <li>- Diesel spillage</li> <li>- Bird guano</li> </ul>

Further, below is a list of key risks aspects, identified that have an impact on the physical design of the offshore substation:

- › Personnel Safety, aspects include
  - Access of personnels, on and off platform normal and in emergency
  - Transportations of personnel
  - Emergency evacuations
  - Hazards area classifications
  
- › Assets Safety aspects include.
  - Fire
  - Explosion
  - Security
  - Ship Collision
  
- › Operational Safety aspects include,
  - Control and protection of Electrical Equipment's
  - Safe operation of plant and equipment
  - Heating, ventilations and cooling systems
  - Spare part availability
  - Defective Equipment
  
- › Commercial aspects include,

- Regulatory consideration
- Equipment repair cost
- Maintenance cost (active and reactive)
- Loss of Productions
- Insurance cost/claims for accidents
- › Maintenance aspects include,
  - Equipment Identification & Tagging
  - Reliability centred Maintenance
  - Planned & unplanned maintenance
  - Overdesign & redundancy of system
- › Verifications & Certifications during,
  - Engineering Design studies & Design Basis phase
  - Electrical equipment's, structures, foundations & system fabrication; construction phase
  - External certification and verification bodies e.g., DNV GL
  - Transportation & installation phase
  - Commissioning Phase
  - Operations & maintenance phase

#### 4.4 Reliability, Availability & Maintenance (RAM)

During the design phase of an offshore substation, it is crucial to consider the implications of the design on upfront capital investment costs, operational costs, and overall power system availability for the full power infrastructure between the WTGs and the grid substation connection busbars (PCC). Striking a balance between minimizing capital investment and operational costs while ensuring the required system availability is essential. To optimize revenue generation, the following general guidelines are recommended:

- Exclude redundancy of costly and/or reliable components.
- Reliability of communications links associated with SCADA and control systems.
- Minimize offshore installation and maintenance work.
- Minimizing electrical losses of plant and equipment.
- Incorporate predictive maintenance planning.
- Maximize availability in energy transmission terms.

RAM analysis is performed generally with below assumptions for any design approach:

- Failure data of various equipment, historical data, OEM's data
- Repair initiated at first failure (i.e. at reduced production capacity)
- Common 1–60-day mobilization time for any repair mission (*spare available within mobilization period and will be different offshore vs. onshore*)
- Consideration of strategic spares
- Production capacity impact
- Simplified wind speed / power generation distribution

- Statistical failure rate and mean time to repair assessment on the outage of main power transformers and export cable systems. (*E.g. 2–4-month repair time for an offshore export cable should be considered*).

Failure mode and effect analysis (FEMA) is one of the key procedures in RAM analysis. This method provides valuable insights into the production availability percentage, downtime over the lifespan, the number of repairs required during the lifespan, and the probability of repair-free operations for either the entire wind farm or individual equipment

#### 4.4.1 Reliability and Availability

In the design of an offshore wind power plant substation, the system reliability is determined by the expected failure rates and repair times of its components. Availability is often measured in relation to time. When evaluating the availability of the substation, it is advisable to express it relative to production. This approach raises an important question: What percentage of the energy generated can be effectively transmitted? Making availability assessments in this manner significantly impacts considerations related to redundancy and maintenance philosophy.

#### 4.4.2 Redundancy & Overloading

In grid systems, redundancy is often mentioned as (N-1) or (N-2), indicating that one or two components in a system of  $n$  components can fail without affecting system performance. However, achieving complete (N-1) redundancy in a wind power plant substation can result in significant additional investment costs.

Alternatively, instead of implementing complete redundancy with two components at 100% nominal capacity, it is possible to install two components at 50% or 70% each. This approach still results in a loss of capacity when one component fails, but not all capacity is lost. Choosing two components at 70% capacity can also reduce operational stresses and extend the lifespan of substation components, as they won't be fully loaded during operation.

It is important to consider different redundancy approaches for wind power transmission systems because achieving complete (N-1) redundancy can be prohibitively expensive, considering factors such as extra equipment costs, increased platform weight, and limited space availability.

Based on operational wind farms, it has been observed that actual power production is typically less than 50% of the maximum production for about 70% of the time. This suggests that installing less than 100% nominal system capacity may be economically feasible. For example, transformers or cable systems can handle temporary overloading, allowing peaks in wind power to be transmitted for limited periods using the overloading capacity of system components. However, overloading components will reduce their life expectancy. This concept is often referred to as (N + 'a little bit') redundancy.

In practice, most systems are not designed with complete redundancy but only critical components, such as HV equipment, secondary equipment and communications, and HVAC and cooling systems, are considered (N-1) redundant. Nevertheless, it seems to be worthwhile to provide built-in overloading capacity to the offshore equipment rather than applying (N-1) rule or overdesigning the equipment by providing spare capacity needed only in rare cases.

#### 4.4.3 Maintenance, Manning & Type of Platforms

Offshore maintenance, like all offshore work, is expensive and should therefore be minimized. Offshore maintenance involves a hazardous working environment, long travel times and is highly dependent on the prevailing weather conditions. When developing operation and maintenance plans, it may be more appropriate to increase levels of planned maintenance to reduce the risk of costly unplanned maintenance.

Platform installation are commonly preferred as Type A as per DNV-ST-0145 i.e. Normally unmanned platform with power equipment. Persons are only expected to be present for inspection and maintenance activities during daytime working hours. This is often chosen for AC offshore substations.

The manning level for each phase of substations lifecycle are:

- Installation
- Commissioning
- Initial Operational phase
- Normal Operations
- Inspections & Maintenance

The manning procedure include:

- Maximum persons on board (PoB)
- Methods of access to and egress from the substation
- Weather condition limits allowing approach of transfer to/from and departure from the substation
- Including wave height, tides, wind speed, visibility, temperatures and daylight
- Monitoring of the weather situation before and while the substation is manned
- Means of communication.

Minimum and Maximum number of Person expected to be in substation at any time should be defined for all relevant types of work and foreseeable emergency situations. Furthermore, careful consideration should be given to the mode of transportation for personnel to and from shore, whether by helicopter, boat, or a combination of both. These factors have a design impact on offshore substations and should be included in the design considerations.

## 4.5 Grid Code Compliance & Requirements

Compliance to grid code and requirements is highly dependent on the regulatory bodies of the respective countries. Ownership boundaries and areas of responsibility for compliance also needs to be considered, this will form part of the regulatory framework. Adhering to this grid codes have significant impact on offshore substation design and equipment selections.

The grid code requirements provide the necessary controls for the system operator to maintain stable grid operation while considering the specifics of wind power plants' power generation. The point where the grid codes apply is commonly referred as Point of Common Coupling (PCC/POC) its location will affect the form and location of reactive compensation and other equipment and can therefore introduce extra costs.

Listed below are common grid code requirements for wind power plant installed in Europe countries:

- Fault ride through
- Fault level; infeed from grid system & infeed from wind turbine
- Frequency response
- Voltage and reactive power
- Active power control and remote operations
- Harmonic performance and filters

Each requirement is analysed by in-depth power system studies and suitable equipment's and rating are chosen in compliance to grid code.

## 4.6 System Studies

To design large offshore wind power plants effectively, various system studies must be conducted. These studies encompass essential aspects such as

- Grid code compliance.
  1. Reactive power,
  2. Harmonic performance,
  3. Static and dynamic stability performance,
  4. Protection co-ordination,
- Wind power plant and export circuit component ratings, and
- Protection and safety.

It should be noted that the depth and type of studies will vary depending on factors such as the developer, installation country, local utility or system operators, and regulatory bodies. However, addressing these aspects through comprehensive system design studies is crucial, and each study should have its own set of objectives.

Listed below are basic system studies that are usually important for all wind farm for proper equipment selection, sizing and configurations:

#### 4.6.1 Power System Philosophy & Black Start Philosophy

Power system philosophy documents outline the design and operation of the electrical power supply and distribution systems. It includes overall power system, hardwired or serial electrical interlock / intertripping principles throughout the electrical power system, an overview of the control philosophy, general principles for the power distribution control systems (if relevant), power management functions, operating requirements and interface between control facilities and electrical equipment.

Black start philosophy study<sup>2</sup> includes:

- O&M procedure for stepwise start-up from black site condition to island mode, and from island mode to normal operation connected to grid
- UPS recharging, diesel refuelling, temporary power alternatives
- Black start from UPS and diesel generator
- In case of cable from other independent unit this alternative method of black start also included

Black site condition is meant as the initial scenario where:

- Site is unmanned
- Installed back-up power is depleted (fuel for diesel generator, energy stored in batteries incl. diesel generator start batteries)

A site is in “island mode” when electrical connection to external grid is not available but emergency and essential power is established, i.e. running of diesel generator.

#### 4.6.2 Total Load & Load Flow Study

This study determines the auxiliary consumption of the OSS, to correctly size the auxiliary system in general and sources of power such as auxiliary transformers, diesel generator and UPS system.

The study shall identify the maximum load demands for different operating configurations and modes:

- Normal operation
- Island mode (loss of grid)
- UPS mode (loss of grid and local generation capability)
- The study shall also include sub-modes as relevant to optimize sizing of diesel generator and UPS system.

The load flow study determines the voltage drops and the necessary feeder and equipment capacity for various operating scenarios. The load flow study presents:

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<sup>2</sup> Please note, no offshore substation can operate in island mode, unless it has some supporting infrastructure e.g. batteries, UPS i.e. energy storage.

- Confirmation of primary equipment ratings Bus-bar voltages and percentage voltage drops and active/reactive load
- Active/reactive flow and losses in lines, cables, and transformers, including percentage loading
- Currents in feeders/incomers
- Recommended tapping and tap size for transformers

#### 4.6.3 Dynamic Stability Study

The purpose of the dynamic study is to study the impact any condition in the complete system could have on the design and operation of the windfarm itself.

- Study the behaviour and dynamic response of the windfarm to external faults
- Study the behaviour and dynamic response of the windfarm to internal faults; also including faults at the IAC collector levels.
- Study windfarm dynamic response
- Manual and automatic operation of breakers
- Any special protection schemes
- Adjustment of setpoint on equipment (transformers, shunt reactors, SVC/Statcom)
- Determine FRT behaviour (voltage, frequency) and capability for various faults

The simulations covers the voltage and reactive power stability, fault ride through and voltage dip requirements.

#### 4.6.4 Short Circuit Study

Short circuit calculations are done to determine the electrical stresses during fault conditions. The results are used for specifying rating of equipment and to determine setting of operation.

Calculations include:

- Different fault scenarios (3-Ph short circuit, ph-ph fault, earth fault, ph-ph-earth faults)
- All relevant modes (normal, island, parallel operation with diesel generator and UPS mode)
- Different network configuration (especially those configurations giving the extreme fault levels, both minimum and maximum levels)

#### 4.6.5 Harmonic Study

A harmonic study is carried out to identify the harmonic sources in the system and to determine the effects on the electrical equipment and on the quality of the power generated by the windfarm at the point of connection to the onshore transmission network. The calculations verifies that the harmonic distortions in all operating modes and network configurations are within defined limitations and does not exceed equipment capability.

The following shall be documented:

- Harmonic spectrum of each significant source of distortion
- Driving point impedance as function of frequency seen from the main harmonic sources
- Calculated harmonic currents in main feeders.
- Calculated harmonic voltage spectrum for selected points at the OSS
- Calculated voltage THD in % of fundamental voltage component for all main distribution boards and sub-distribution boards.
- Calculations with and without mitigating actions

#### 4.6.6 Transient switching/equipment insulation coordination study

The objective of a transient switching and insulation coordination study is to specify the correct equipment insulation levels based on the type of equipment in use and to determine if additional protections are required.

- The objective of transient switching and insulation co-ordination study includes:
  - The insulation withstand level for all the primary HV components within the complete windfarm.
  - The study identifies the locations for overvoltage protection of equipment.
  - To identify the required protective measures such as surge arresters (location and characteristics) to protect the high voltage components from overvoltage's and where switching voltage may exceed the insulation level.
  - To determine number of WTGs that can be energized simultaneously during inter array string energizations.

This study also determines other protection like point on wave switching and pre-insertion resistor requirements and shall thoroughly investigate phenomena like delayed current zero crossing (DCZ), transient recovery voltage (TRV) and rate of rise of re-striking voltage (RRRV).

#### 4.6.7 EMC & EMF studies

An electromagnetic compatibility (EMC) analysis is carried to plan and perform EMC measures in various equipment's. The study shall minimum contain:

- EMC requirements
- EMC input data
- EMC analysis
- EMC measures
- EMC verification

The resulting EMC mitigation plan is then included in the procurement of equipment and installation procedures.

An electromagnetic field (EFM) study is carried out to ensure levels are within acceptable limits as per applicable to local and international standards. Based on the results, proper mitigation procedures that need to be adopted and should be documented with relevant EMF levels, before and after mitigations.

#### 4.6.8 Earthing & Lightning Protection studies

The earthing philosophy includes protection against lightning and induced over voltages due to lightning stroke and accumulation of static charge. The study includes:

- Design philosophy
- Touch and step voltage calculations.
- Static voltage and bonding considerations.
- Protection of high points and structures.

The earthing study and eventual lightning arrestors reduces the possibility of damage caused by lightning to an acceptable limit. Location of lightning arrestors according to IEC and/or IEEE standards.

#### 4.6.9 Protection Coordination Study

An overall protection and discrimination philosophy document for the windfarm will need to be developed, providing the basis for performing the individual relay settings includes:

- Protection principles and discrimination throughout the windfarm
- Principles per system (system protection) and operational mode if applicable
- Principles per equipment type (equipment protection)

The protection coordination study is essential to both personnel and equipment safety. The study shall be based on the short circuit study data models and the focuses on:

- Safety of personnel and safety to the plant and equipment
- Maintaining stability and integrity of the power system
- Minimising damage to equipment and systems due to faults
- Ensuring max continuity of power supply to non-faulted equipment
- Selectivity of series connected protection, ensuring discrimination during fault conditions
- Correct discrimination for all currents up to maximum prospective fault currents, while the thermal effect of the fault current should not exceed the thermal withstand capability of any circuit component.

For each equipment, an individual or combined protection setting document is prepared and maintained, includes time diagram and selectivity from source to Point of common coupling (PCC), often referred as as-built settings.

### 4.7 Electrical Equipment Considerations

All the design inputs discussed in above sections goes into deciding criteria for electrical equipment selection, sizing and configurations for an offshore substation, referred to as the Topside.

Major electrical equipment for a wind farm which impacts the topside design can be categorized in two parts:

#### *Primary Equipment- Heavy & Expensive:*

- Main Power Transformer (MPT)
- MV/HV Switchgear (GIS), consisting of both Array cable (MV) and export cable (HV)
- Offshore Reactors (SR), if required
- Earthing & Auxiliary Transformer (EAT)
- Neutral Earthing Resistors (NER)

#### *Secondary Equipment- Auxiliary & support system:*

- Control, Protection & SCADA Panels
- LV panels
- Battery Bank, charger & UPS
- Telecom & Security system
- HVA/C Units
- Fire Protection System
- Diesel Generators

In the subsequent sections, this will be focusing mainly on primary equipment, discussing various configurations, the most followed design practices and recent improvements in design practices.

#### **4.7.1 132kV Array System-Step Changes**

Currently, it is common practice for wind farms to have a 66kV array voltage level. Before the adoption of 66kV as the array voltage, 33kV was the most commonly utilized output voltage from wind turbines.

Average Offshore Wind Farm (OWF) size has doubled from 310MW in 2010 to 620MW as of 2019. Hornsea project 1 (1218MW) & Hornsea project 2 (1386MW) are the largest offshore project operational globally as of now. As the technology develops, larger sizes are expected in the future e.g. Yorkshire, England, 3.6 GW Dogger Bank A, B & C, due to be operational by 2026.

Industry trends towards larger and more powerful wind turbines. Larger turbines can achieve higher capacity factors at same site conditions, i.e., they run more often. Siemens Gamesa launched a 14MW wind turbine (commercially available in 2024), which is a direct drive turbine with a 222-meter rotor & reaching 15-20 MW wind turbine sizes are expected by 2030. Table 4-4 provides a perspective of wind turbine physical sizes and output capacity.

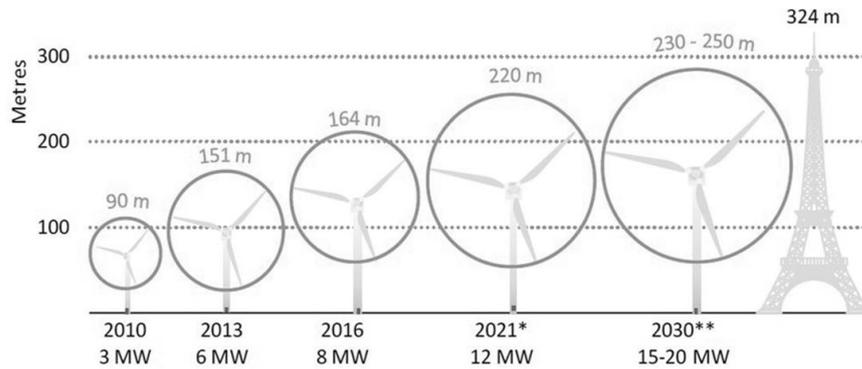


Figure 4.7-1 Wind turbine sizes and output power trends.

With the above development, industry-wide consensus for the optimal array operating voltage is likely to be above the current 66 kV standard, in order to accommodate wind turbine generators larger than 14 MW. Through extensive engineering analysis, in conjunction with life cycle cost-benefit studies, it was concluded that 132 kV is the optimal array operating voltage ( $145 \text{ kV } U_{\text{max}}$ ) for the larger wind turbines. It was found that 132 kV offers significant cost saving potential over 66kV, even for wind turbines with a capacity of 14 MW, and that the benefits increase with increasing turbine size.

Table 4-4 Wind power rating Vs Array Voltage provides a rough perspective of relation between wind turbine power rating, Array Voltage and No of turbines per string

Table 4-4 Wind power rating Vs Array Voltage

Wind turbine Power Rating	Array Voltage Level	No. of Turbines per String
3-6 MW	33 kV	15-7
6-12 MW	66 kV	15-7
12-24 MW	132 kV	15-7

Based on the previous power evacuation infrastructure studies, 66 kV is the array voltage level, which defines the MV switchgear configurations and design, will be discussed in the next sections.

#### 4.7.2 Export Cable System

The export cable connects the offshore substation to the onshore substation to transmit the power from the wind farm to shore. It also provides the auxiliary power to the offshore substation and the wind farm when it is not generating and also provides the fibre communications.

AC transmission export cables are now typically rated at 220 kV ( $245 \text{ kV} = U_m$ ), allowing the export of approximately 400-450 MW per three-core subsea cable. Overall, export cable technology is relatively mature and no significant change in design is expected by 2027. While single core 275 kV ( $300 \text{ kV} = U_m$ ) is first installed in 2024, but no 3 core export cables have yet been installed, they are currently in production and scheduled for installation in 2024. The voltage chosen balances the cost of the cable, the number of circuits required, and the number

of offshore substations required. Wind farms tend to have more than one export cable circuit per OSP for redundancy.

Based on the previous power evacuation infrastructure studies, 220 kV is the export cable voltage level, which defines the HV switchgear configurations and design, will be discussed in upcoming sections.

### 4.7.3 HV & MV Switchgear

When developing a 66/220 kV step-up offshore substation, developers may be interested in evaluating various technologies available in the market, mainly:

- Air insulated Switchgear (AIS)
- Gas Insulated Switchgear (GIS)
- Hybrid Switchgear (HIS)

While each of these technologies has its inherent advantages and disadvantages, the main determining factor is the space requirement and its impact on the topside size and weight. The increase in topside size and weight has a significant impact on the steel requirement and can result in substantial cost implications.

To have the most cost-effective solution and without compromising on operational efficiency and security, all wind farm have topside built with GIS switchgears. The adoption of GIS as an alternative to AIS has led to significant cost reductions when assessed over the lifetime of the asset. The classic reason to use a GIS instead of an AIS is that there is a limited installation footprint available. GIS systems are more expensive in terms of their initial cost (CAPEX), but when considering the total cost (CAPEX plus OPEX) of an offshore substation during its lifespan, it will be more cost effective because of its smaller offshore footprint.

A proposal has been provided to COWI for an OSS SLD as shown in Figure 4.7-2 with the array cable voltage 66kV and export cable voltage 220 kV.

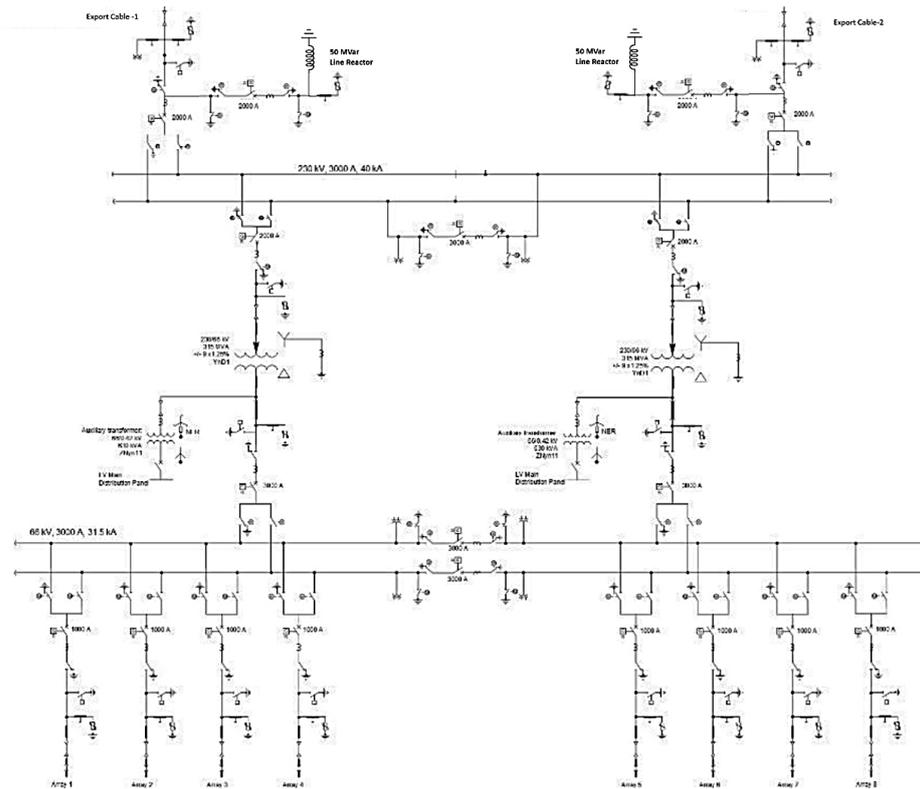


Figure 4.7-2 Input provided to COWI for 500 MW OSS SLD

Based on Figure 4.7-2 the OSP can be equipped with

- › **66kV GIS switchgear will have:**
  - 8 Array Feeders
  - 2 Trafo Feeders
  - Based on Busbar Schemes either 1 or 2 sectionalizer feeder, (will be discussed in detail in subsequent sections)
  
- › **220kV GIS switchgear will have:**
  - 2 Export Cable Feeder
  - 2 Trafo Feeder
  - Based on Busbar Schemes either 1 or 2 sectionalizer feeder, (will be discussed in detail in subsequent sections)
  - Interconnector feeders (if a BoP concept with two OSS, two export cables and one HV interconnector is designed).

For a 66kV system voltage, there are options to consider based on the OEM selected. One option is to adopt a 72.5kV rated GIS with a continuous current rating of 2500 Amp. Another option is to choose a 145kV rated GIS with a higher continuous current rating of 3150 Amp. If the required ampere rating exceeds 3150 Amp, a 170kV rated GIS can be selected, which offers continuous current rating of 4000 Amp with short circuit rating of 50kA.

Similarly, for a 220kV system voltage, the choice of GIS depends on the OEM selected. Two options can be considered: a 245kV rated GIS or a 300kV rated GIS. Both options offer a continuous current rating of 4000 Amp along with a short circuit rating of either 50kA or 63kA.

In the subsequent section of the report, a detailed discussion will be presented regarding GIS switchgear busbar schemes. This discussion will include various examples from executed offshore wind farms, particularly in the European region. Also, busbar schemes depend on Transformer type (2 winding or 3 winding) selections and the level of redundancy expected from the system.

About GIS technology, it is also important to understand the latest industry trend and paradigm shift towards the clean gas as medium of insulation. The revision of the EU F-gas regulation has called for tighter restrictions on F-gases. In October 2023, a provisional agreement was passed on the phasing out of F-gases ( $GWP \geq 1$ ) in new high-voltage switchgear by 2028/2032. In January 2024, the European Parliament and the European Council have formally adopted their provisional agreement.

Table 4-5 provide a brief insight on the EU F-gas regulations March 2024, switchgear restrictions.

Table 4-5 Prohibition of F-gases when putting new switchgear into operations

Medium Voltage		
≤ 24 kV	All F Gases	01.01.2026
> 24 kV - ≤ 52kV	All F Gases	01.01.2030
High Voltage		
> 52 kV - ≤ 145 kV	F- Gases $GWP \geq 1$	01.01.2028
> 145 kV	F- Gases $GWP \geq 1$	01.01.2032

Following these restrictions, European Offshore wind farm developers have already shifted design considerations towards SF6 Free GIS right from concept design stage. Table 4-6, provide a consolidated timeline for various SF6 Free Gas Switchgear availability for three major OEMs:

Table 4-6 Consolidated Timelines for SF6 Free GIS Availability

Proposed Date	2024	2025	2026	2027	2028	2029	2030
GE (g3 – Using Novec 4710)	72.5kV, 145kV, 420kV GIL, 420kV	245kV 170kV	362kV				
Hitachi (EconIQ – Using Novec 4710)	72.5kV, 145kV, 420kV, 550kV		245kV	170kV			

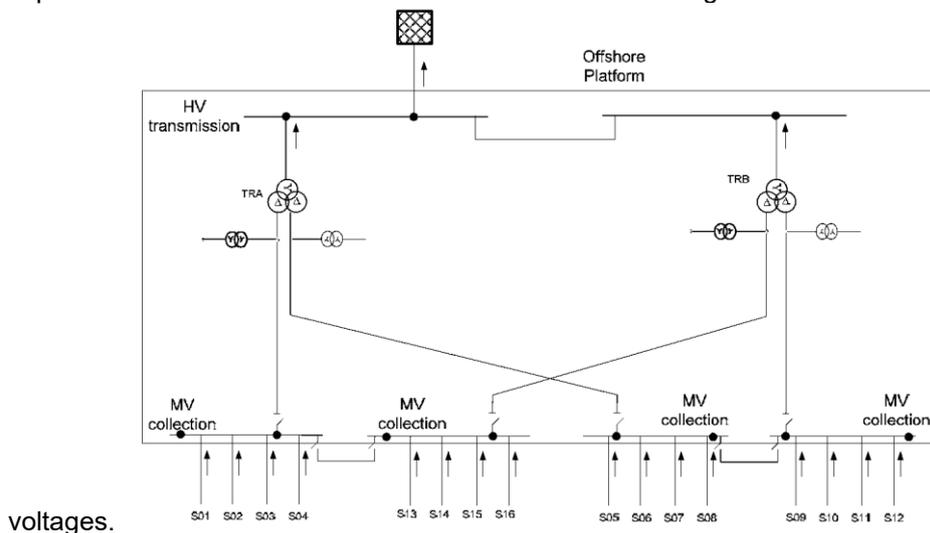
Siemens (Blue – Using Clean Air)	72.5kV, 145kV 420kV GIB & Back parts		420kV CB		245kV		550kV
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There are currently only slight variations in dimensions between the SF6 & SF6- free solutions as well as an increased bay separations (approx. +1m) for the SF6-free option due to the technology being new to the market so suppliers are building extra tolerances into their design and erring on the side of caution.

#### 4.7.4 Main Power Transformer (MPT)

Offshore substations require the collector circuit voltage to be stepped up for transmission to shore. In wind power plant design, there are two options for step-up transformers: 2-winding or 3-winding. A 2-winding transformer is simpler and cheaper than a three-winding transformer. It allows for easy incorporation of transformer tapping on the HV winding, enabling adjustment of the LV voltage to 1.0 p.u.(nominal rated voltage) if necessary. However, this design usually results in the highest available fault duties on the MV collector busbar and also requires larger dimensions of the internal windings.

On the other hand, a 3-winding transformer offers the advantage of splitting the collector circuits between the two secondary windings. Although the parallel impedance of these windings can be similar to a two-winding transformer, it increases when the windings are split. This helps reduce fault levels at the collector circuit level. Additionally, a 3-winding configuration provides improved redundancy, as shown in the Figure 4.7-3. When using transformer taps for voltage control, it is important to have balanced loads on each of the LV windings to ensure balanced secondary



voltages.

Figure 4.7-3 Typical Three winding connection arrangement

Based on data provided by Hitachi “Grid\_eXpand\_AC\_Offshore\_factsheet” document, the Figure 4.7-4 represents break points by power rating for their offshore grid solutions.

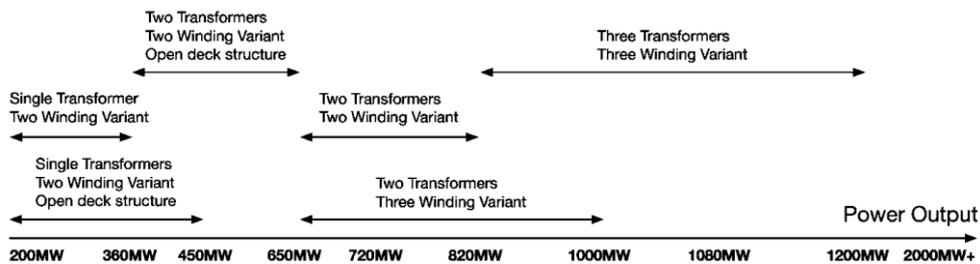


Figure 4.7-4 Transformer 2 winding & 3 winding w.r.t Offshore substation output power.

The *Princess Amalia Dutch wind farm* offshore substation is having a Single Transformer-Two Winding-Closed Deck design, and the *Thorton Bank Belgian Wind Farm* offshore substation is having Two Transformer-Two Winding Closed Deck Design which are being developed by Hitachi Solutions.

*It is safe to infer that single project phase of 1000 MW that the platform configuration would be of a single platform with 2 off 3-winding transformers. If the project is developed in two phases of 500 MW, then it could be achieved with two platforms each with 2 off 2-winding transformers.*

It is often seen that the limitation for the platforms is usually the export cable as the transformers themselves are designed and built to the project requirements. Previous experience has shown that export cables of 132 kV could only transmit 250MW-350MW efficiently. The way around this is to increase the export voltage to 220 kV or above.

Offshore Transformer Modules (OTM) from Siemens are one-third smaller in size and weight compared to a conventional AC platform. Focusing on the core electrical equipment and removing a number of optional ancillary systems made this space and weight reduction possible, which also results in a reduced maintenance regime.

#### Benefits of the OTM:

- Ultra-compact offshore transformer (lower weight and reduced platform cost)
- Built-in earthing transformer (weight reduction) – 100 percent assembled and tested in the transformer factory
- Heavy-duty ONAN design (no sensitive fans)
- Use of synthetic ester reduces platform cost especially for oil collecting facility

For the *Beatrice wind farm*, Siemens offered, two units of its modular OTM concept, that saves space, weight, and cost. The technical specifications for the three transformer units were to deliver 310 MVA units for the 220-kV level in heavy-duty design with ONAN cooling. Siemens OTM modules were special coated for C5-M corrosion category withstanding harsh marine environment. The insulation medium used is ester oil, thus achieving high flash and flame point along with environmentally friendly. The compact design of a 310 MW Transformer has the dimension of only 13.1 x 7.3 x 7.7 m and weighing only 326 tons.

It is quite evident that the OTM design concept streamlines the topside by minimizing its components and placing them on a smaller substructure. To achieve the required capacity,

multiple modules are used instead of a single unit, providing a similar operational capability to that of a traditional topside. This approach reduces the necessity for large, heavy-lift installation vessels for foundation and topside installation.

#### 4.7.5 Earthing & Auxiliary Transformer (EAT) & Neutral Earthing Resistors (NER)

As the MV (66 kV) winding of the Main Power Transformers (MPTs) is delta ( $\Delta$ ) connected, there is no system neutral pathway available, and hence no path for the unsymmetrical fault currents (zero sequence currents) to flow. Consequently, a 66/0.4 kV zigzag auxiliary earthing transformer (EAT) is required on the Offshore Substations (OSPs). This transformer will create a neutral point, thereby providing a path for the unsymmetrical fault currents on the 66 kV system.

The EATs are also used to provide auxiliary supply voltage within the offshore substation at service voltages of 0.400 kV or 0.420 kV, based on the respective country's distribution voltage standards. Each EAT is generally rated between 500 kVA to 800 kVA. The number of EATs depends on the number of bus sections created on the MV array string side. Each bunch of array string feeders connected to a specific bus section should have a dedicated EAT connected at all times. Typically, the EAT connection is tapped from the MV transformer feeder with a T-connection, avoiding the need for a dedicated feeder.

The earthing system for the Offshore Wind Farm can be assumed to be a low resistance earthing system via an NER connection to the HV-Zigzag winding of the earthing and auxiliary transformer.

This method of low resistance earthing is the preferred method for:

- Limiting the transient voltages during switching of long (capacitive) export cables.
- Achieving a defined level of fault currents (more than the total system capacitive current).
- Achieve a proper coordination (selective tripping) of the earthing fault protective equipment.

The sizing of the NER depends on the following:

- Charging currents or zero sequence capacitances of cables (i.e. dependent on cable types chosen)
- Zero sequence capacitance of the transformer and GIS switchgear
- The transient over voltages and insulation level of the equipment
- Fault current withstand time for the NER (defined for assumed fault duration)
- The energy to be dissipated in the NER (expected temperature rise in resistor elements).

The EAT combined with a Neutral Earthing Resistor (NER) facilitates fast and selective fault clearing. At the same time, it effectively limits temporary over-voltages in the healthy phases.

Therefore, a phase-to-ground fault in the offshore wind power plant must not lead to cascade tripping of the wind turbine generators or endanger other offshore network components.

## 5. General Substation Configurations & Busbar Schemes

The main design guideline for an offshore substation is not only keeping a continuous power flow but also to achieve a high level of availability for the installation to be ready to transmit the available power from the WTGs to the PCC.

Following the basic principle of the power distribution business: security of supply for the clients, offshore substations use redundant configurations and automatic transfer systems for a quick adaptation and response of the installation to fault conditions, always in order to provide a continuous power flow according to each utility quality standards.

The medium voltage busbar arrangement should be approached considering the general design philosophy of the whole installation regarding functionality and redundancy. The switchgear itself should be defined according to the voltage rating but mainly according to current ratings both for continuous and short circuit operation.

For the first offshore substations, the preferred medium voltage configuration has been a single busbar to which are connected all the array circuits by means of breakers, even for wind power plants with moderate installed power like Horns Rev 1 (160 MW) or Lillgrund (110 MW); Refer Figure 4.7-1. This type of configuration usually required a large gen-set to power up the OSS if the MPT is out of operation.

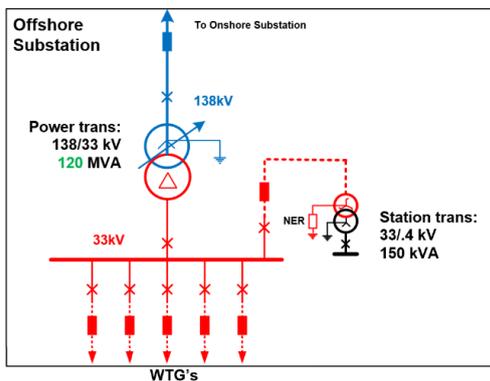


Figure 4.7-1 Lillgrund Offshore Wind Farm

In the following examples for offshore wind power plants, like UK's or German projects, the power has been increased to more than 1GW and this has called for a more elaborated design of the electric layout for the substation, including the medium voltage system.

Many of these new substations are equipped with two power transformers, so the single busbar has been divided into two parts for the connection to the two transformers and, in some cases, the transformers have two secondary windings so each one of the medium voltage semi-busbars has been again divided into another two parts for connection to the two windings.

Figure 4.7-2 represents West of Duddon Sands Offshore wind farm developed by Ørsted & Scottish Power Renewables, with 33 kV as array voltage and 155 kV as the export voltage with 2 x 240MVA trafo capacity.

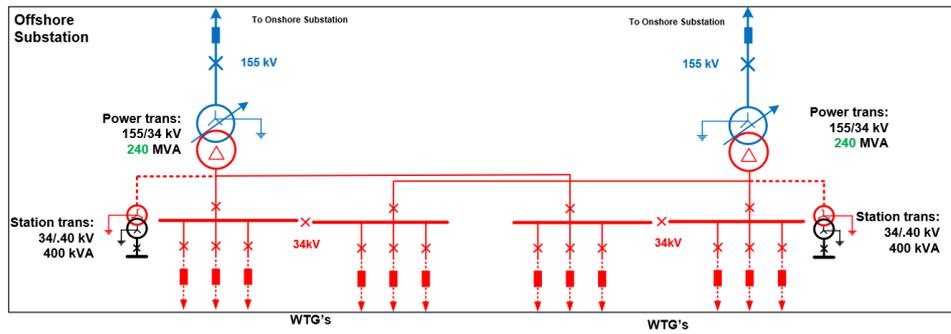


Figure 4.7-2 West of Duddon sands Offshore Wind Farm

Below are a few more example from different offshore Wind Farm:

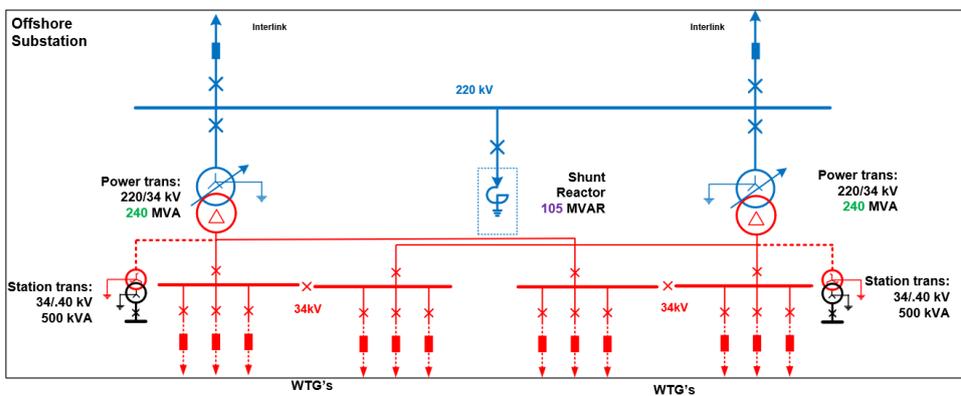


Figure 4.7-3 Hornsea 1 Offshore Wind Farm

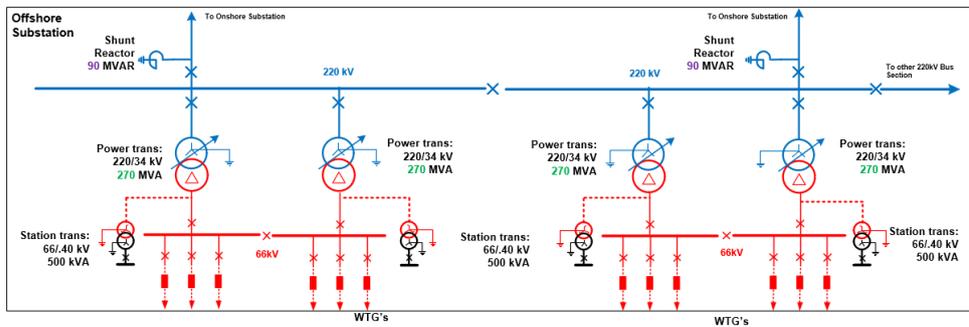


Figure 4.7-4 Hornsea 2 Offshore Wind Farm

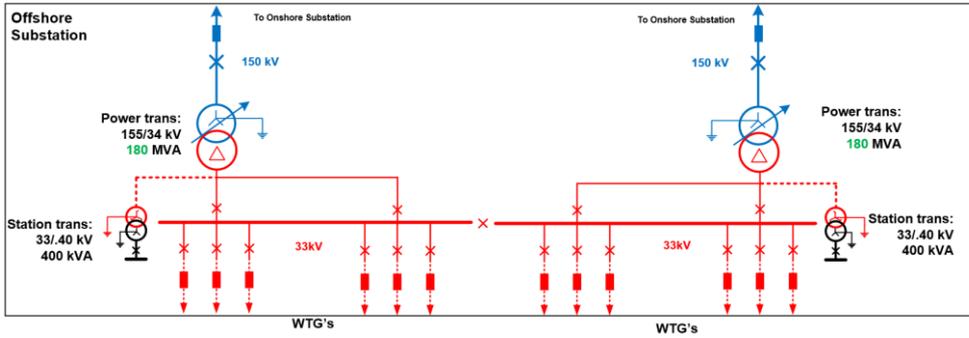


Figure 4.7-5 London Array Offshore Wind Farm

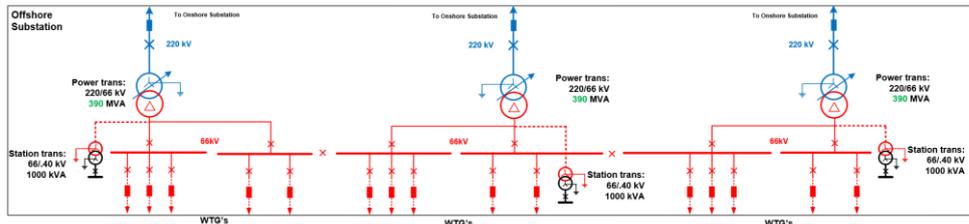


Figure 4.7-6 Seagreen Offshore Wind Farm

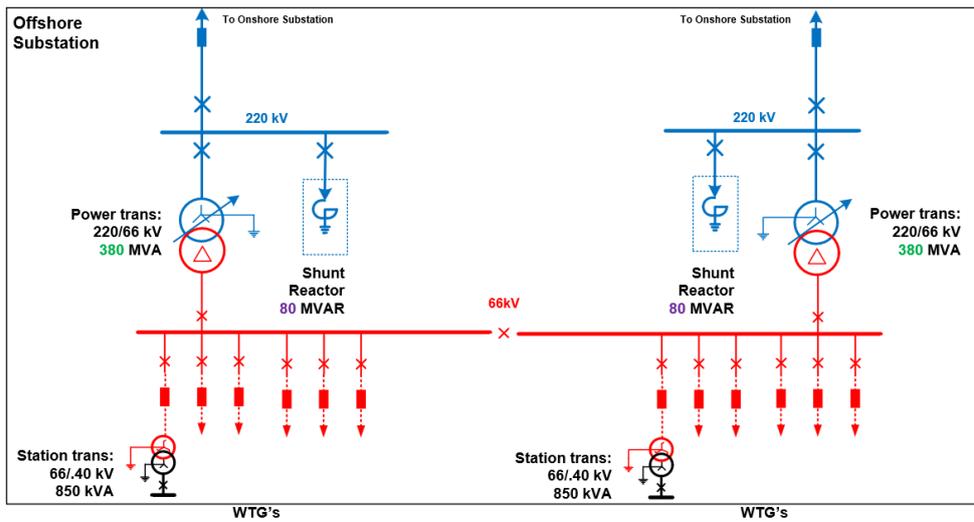


Figure 4.7-7 Baltic Eagle Offshore Wind farm

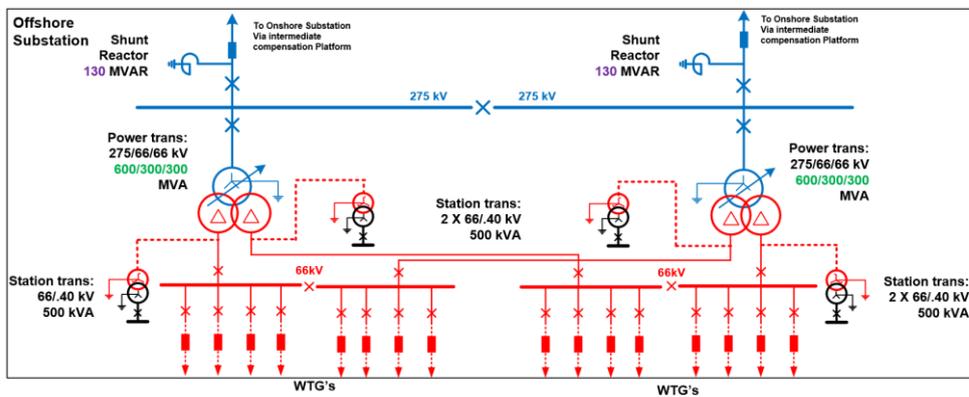


Figure 4.7-8 Hornsea 4 Offshore Wind farm

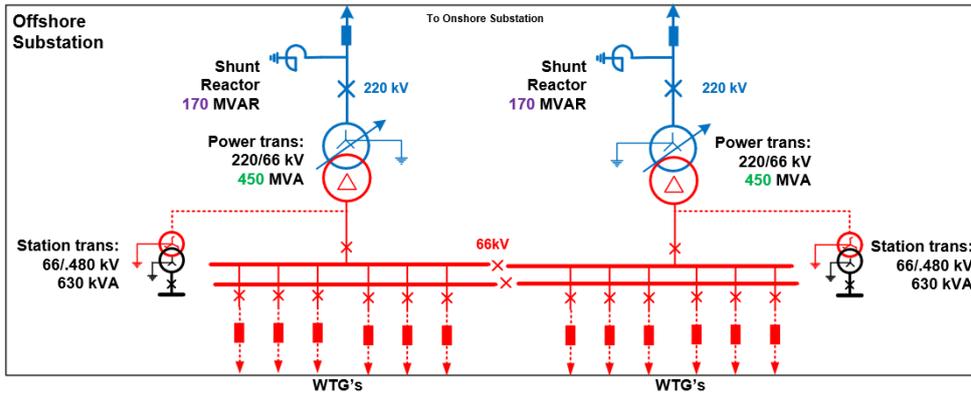


Figure 4.7-9 Vineyard-Wind Offshore Wind Farm

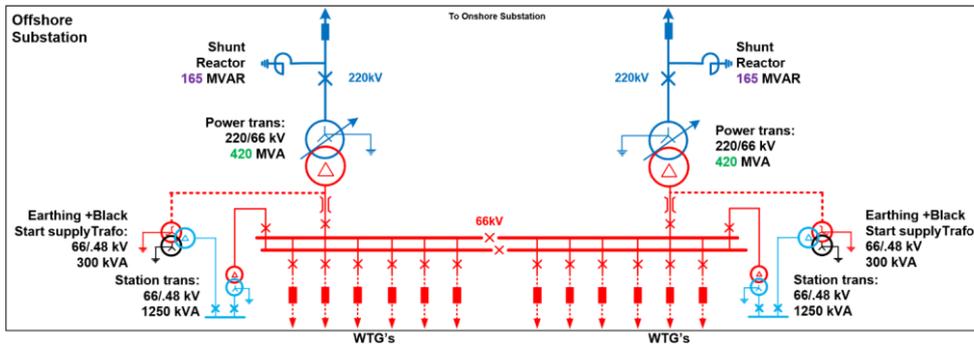


Figure 4.7-10 Empire-Wind Offshore Wind Farm

Apart from above examples, we have explored additional offshore wind farms, listed in Table 5-1

Table 5-1 Wind Farm List

Wind Farm name	MW Installed	Developer
Galloper Wind Farm	353MW	RWE
Greater Gabbard Wind Farm	504MW	SSE
Gwynt y Môr Wind Farm	576MW	RWE
Moray East Wind Farm	952.5MW	MOWEL
Thanet Wind Farm	300MW	Vattenfall
Triton Knoll Wind Farm	857MW	RWE
Walney 1 Wind Farm	183.6MW	Ørsted
Walney 2 Wind Farm	183.6MW	Ørsted
Walney Extension Wind Farm	659MW	Ørsted
Hornsea 3 Wind Farm	3,000MW	Ørsted

Wind Farm name	MW Installed	Developer
Rampion Wind Farm	400MW	RWE
Borkum 2 Wind Farm	450MW	Ørsted
Gode 1 and 2 Wind Farm	582MW	Ørsted

Studying all the above wind farm layouts, it can be inferred that windfarm developer, by means of dividing the busbars into switchable sections (normally disconnected) for three winding transformers. This makes it possible to reduce the short circuit ratings both for the busbars and for each one of the connected bays given the increased impedance of this configuration. For this configuration to provide better availability in case of failure, one could oversize both the power ratings of the transformers and of the export cables. In this way, when a transformer fails, it is physically possible to connect the whole wind power plant to one of the transformers, although the maximum power will be limited by the rating of the windings.

It is also true that 3 Winding Trafo solution is good for the case where the array cable voltage rating is limited to 33 kV, however with increase of array cable voltage to 66k V and 132 kV, a 2 winding trafo seems more feasible because of higher current handling capacity of the GIS switchgear.

In Table 5-2 simple calculated co-relations is presented between trafo rating and MV voltage of 66kV for selecting 2 winding or 3 winding trafo.

Table 5-2 Trafo Winding w.r.t LV Current and GIS Rating

Options	Trafo MVA (max)	LV Rated Voltage	LV A (max)	GIS modules	Trafo Design
A	350	66 kV	3150	145kV GIS	2 Winding
B	450	66 kV	4000	170kV GIS	2 Winding
C	550	66 kV	5000	5000 A GIB +	2 Winding
D	>550	66 kV	>5000	2 no of 4000 A 170kV GIS Busbar 2 no of 4000 A 170kV GIS Busbar	3 winding Trafo i.e. 2- 66kV Winding (LV) 1-220kV Winding (HV)

To realise better, the above options are represented below from Figure 4.7-11 to Figure 4.7-14.

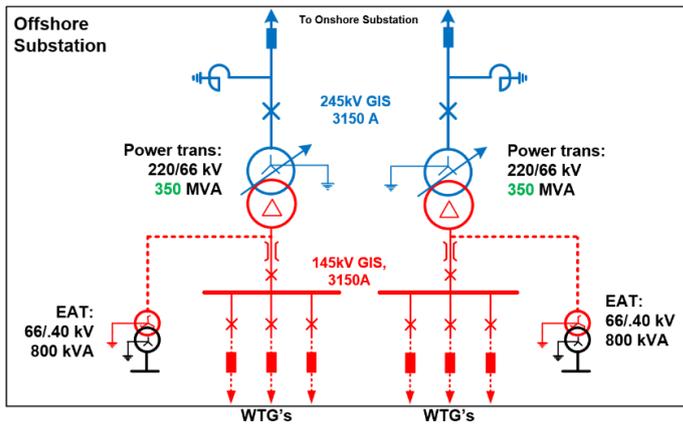


Figure 4.7-11 Option A

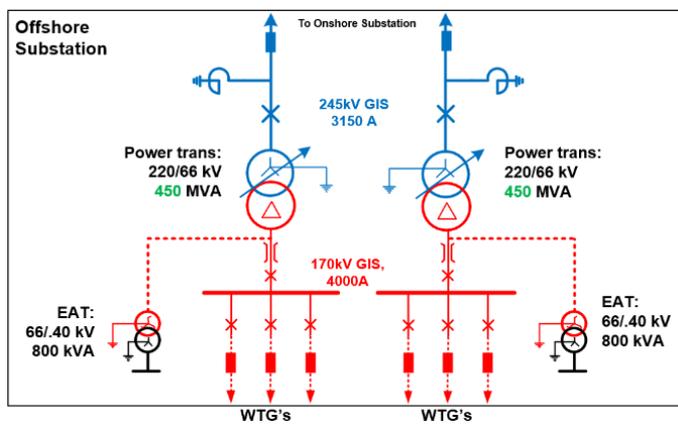


Figure 4.7-12 Option B

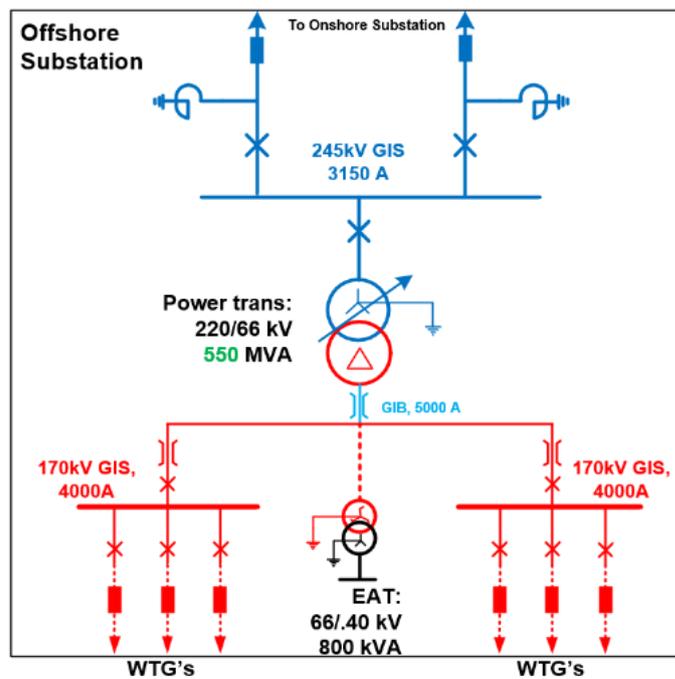


Figure 4.7-13 Option C

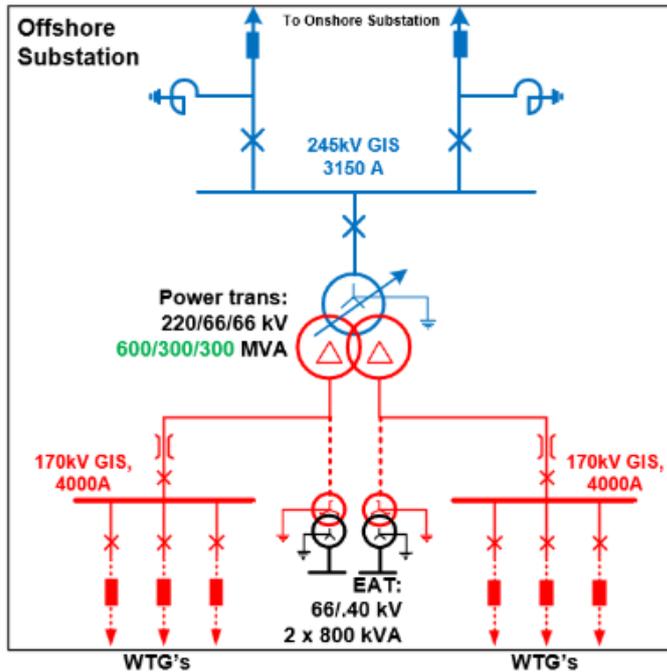


Figure 4.7-14 Option D

For HV switchgear, the design concept for the earlier offshore substations in Europe has been driven by simplicity. Therefore, the single busbar or even transformer-export cable joint bays have been the most common configurations in offshore substations. Although this is the cheapest option, it is necessary to guarantee in each case that the onshore breaker is able to interrupt the reactive currents of both the export cable and the offshore transformer. If the onshore network can be managed correctly with such configurations, then these could be the most cost-effective solution for small wind power plants.

Figure 4.7-15 & Figure 4.7-16 represents this concept.

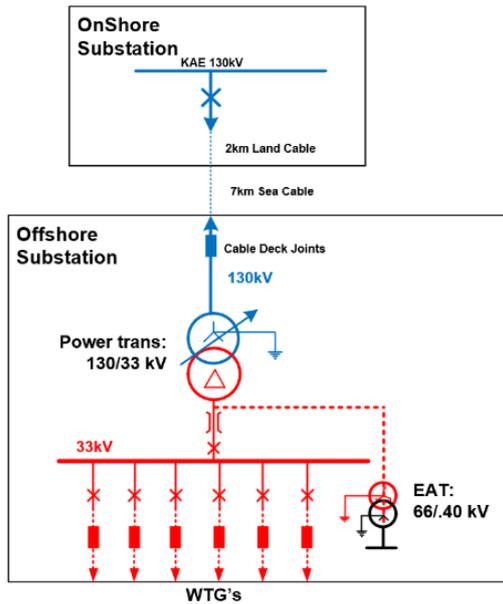


Figure 4.7-15 Lillgrund Offshore Wind farm, Sweden

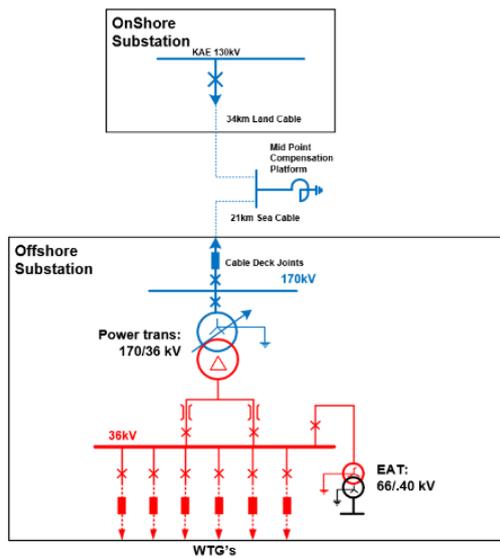


Figure 4.7-16 Horns Rev I Offshore Wind Farm, Dutch

It is evident that such schemes do not provide optimum solutions regarding flexibility in switching operations, redundancy, and selective protections. By this reason, recent projects involving several transformers on the same platform, different configurations *are* considered, like two semi-busbars separated with circuit breaker or a double busbar or ring for projects with more than one export line.

When multiple export cables are necessary, some redundancy can be provided by placing a number of breakers between the cables and the transformer and between the cables. The configuration in the Figure 4.7-17 enables you to isolate either a cable or a transformer separately. In case of a cable failure, one could utilize, maybe even overload, the other cable without overloading the transformers.

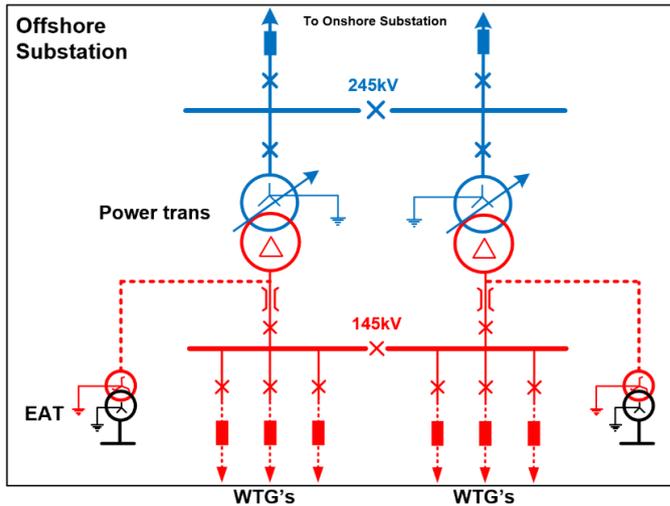


Figure 4.7-17 High Flexible HV Configurations

With respect to all the discussion above, for HV busbar configuration, it is advisable to have some redundancy considering the total output power. It is logical that with higher rating offshore substations i.e. a single point for large power evacuations, a double busbar may be justified as the installation will involve three or more transformers and two or more export lines. It provides more reliability and availability in case of failures. For smaller power installations with two transformers and their corresponding export lines, the semi-busbars could be the best option.

In recent developments, some offshore wind farm developers are adopting the Offshore Transformer Modular approach (OTM) for the topside design and with multiple smaller offshore substations interconnected to have one or two export cable to the onshore substation.

Figure 4.7-18 Represents a design concept for small standalone OTM offshore substation.

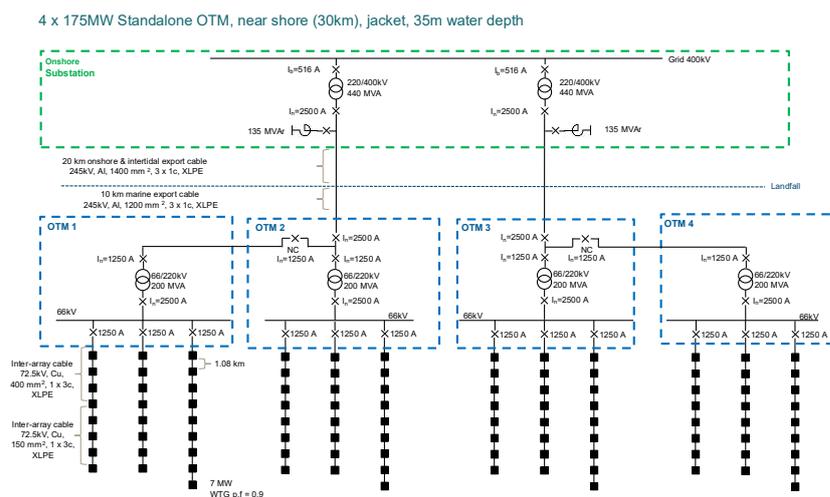


Figure 4.7-18 4 x 175MW standalone OTM Concept

Figure 4.7-19, represents design concept with integrated Offshore substation with one of the Wind Turbine foundations platforms.

4 x 175MW Integrated OTM, near shore (30km), jacket, 35m water depth

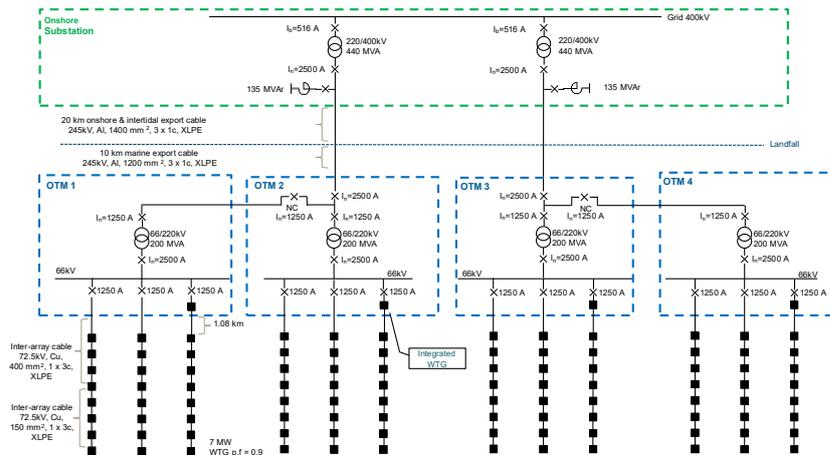


Figure 4.7-19 4 x 175MW with Integrated OTM Concept

The above design offers cost advantages due to the utilization of one of the wind turbine foundations to accommodate the Topside equipment. This approach proves feasible considering the smaller size and weight of the equipment, attributed to the low rated power of only 175 MW.

From the above discussion, it is evident that developers have various options for configuring the offshore substation. However, when undertaking the design process, it is vital for developers to prioritize reliability and availability, considering that this approach may result in increased weight and size of the Topside. Such modifications can significantly impact the overall capital expenditure (CAPEX) of the project. Therefore, striking the right balance between reliability and size becomes imperative to optimize the costs associated with the design of the offshore substation.

## 6. Recommendation

The development of an AC offshore substation requires addressing five key aspects. These include:

- Economy
- Complexity
- Reliability, Availability & Maintenance
- Feasibility

Hence, with this basis, COWI recommends the following two configurations for 500MW offshore substations:

### Option A

Assuming the transmission of 500MW, which is the full capacity of the Offshore Substation, with both the Main Power transformer and Export Cable fully rated at their 100% capacity, and minimal redundancy at the switchgear level, the equipment rating of the Offshore Substation would be as follows:

- 2 Main Power Transformer- 275MVA
- 2 Export Cable-250MW
- 1 Interconnecting Cable<sup>3</sup>
- 66kV Array cable Voltage
- 220kV Export Cable Voltage
- 2 x 600 kVA EAT

### Proposed System Configuration:

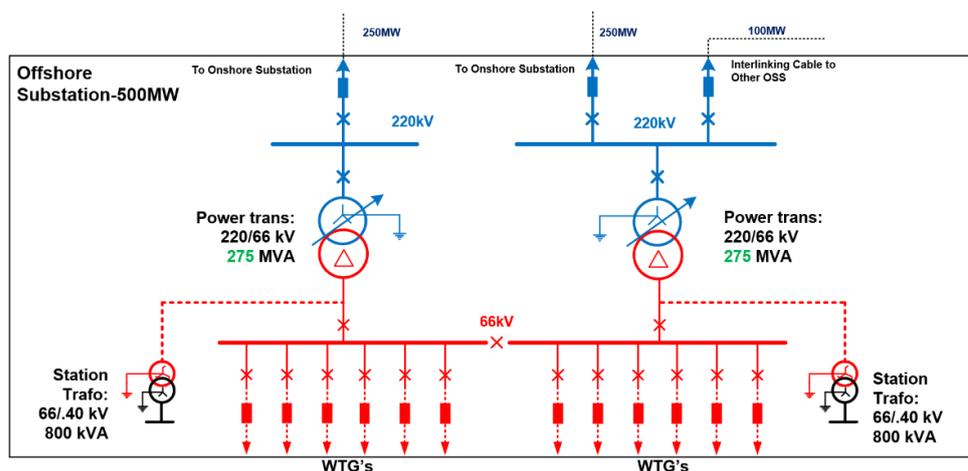


Figure 4.7-1 Option A Proposed Configuration of Offshore Substation

<sup>3</sup> Interconnecting cables can be considered for connection of a future 500 MW OSS. Consequently, the number of HV cable feeders will depend on the planned number of OSS for a given area for allowance of WTG installed power. This also will impact the export cable sizing.

### Advantages:

- Simpler Configurations
- Less Topside Weight
- More economical
- Simpler Control and Protection Design
- WTG's can share load equally via the MPT.

### Disadvantages:

- Less redundant Design
- No over capacity of MPT or Export Cable to share load
- No sharing of load at the 220KV Bus Side.

### Option B

For same above configuration, if 20% more capacity is considered only for MPT and Export cable i.e.

- 2 Main Power Transformer- 275MVA + 20%
- 2 Export Cable-250MW +20 %
- 1 Interconnecting Cable<sup>4</sup>
- 66kV Array cable Voltage
- 220kV Export Cable Voltage
- 2 x 600kVA EAT

### Proposed System Configuration:

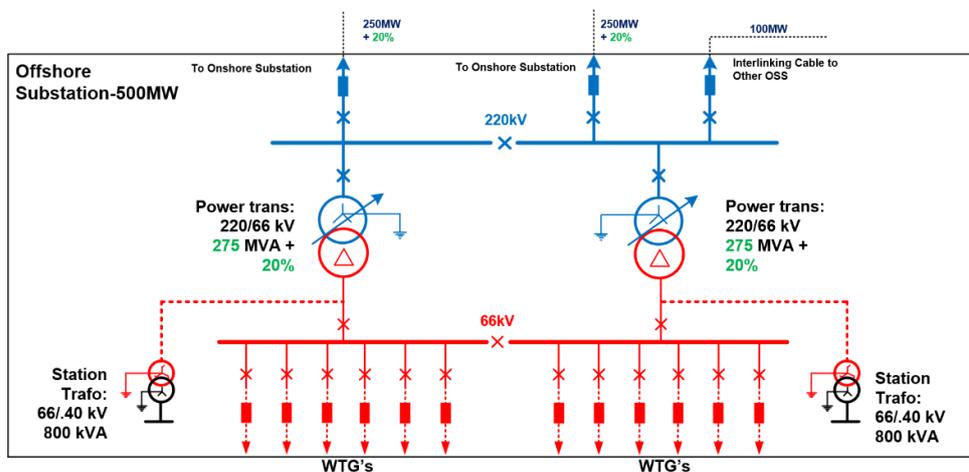


Figure 4.7-2 Option B with 20% more Capacity for MPT & Export Cable.

<sup>4</sup> Interconnecting cables can be considered for connection of a future 500 MW OSS. Consequently, the number of HV cable feeders will depend on the planned number of OSS for a given area for allowance of WTG installed power. This also will impact the export cable sizing.

**Advantages:**

- Simple Configuration
- WTG's can share load equally via the MPT
- MPT & Export cable are design with overcapacity and can carry overloaded during N-1 operation conditions
- Less power losses will prevail in normal operation resulting in larger energy delivered to PCC.
- Simpler Control and Protection Design

**Disadvantages:**

- More Weight of Topside
- More Costly w.r.t to Option A

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## 7. Conclusion

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Both solutions proposed in above section offer a balanced approach between cost, reliability, and availability. However, Option B is slightly more expensive than Option A but with improved redundancy and availability for the power transfer to BoP since more energy can be transmitted during N-1 operation with a MPT or EC out of operation.

While it can be argued for increasing redundancy at the switchgear busbar level, it may not be necessary due to the inherently low failure rate of GIS. Therefore, the additional cost associated with having double busbars at both the HV and MV levels may not be justified in terms of redundancy. This can be determined by a RAM as discussed in section 4.4.

Before finalizing the OSS topside configuration, it is essential for the developer to adopt a lean design philosophy, which involves a Design to Cost approach. This approach should be complemented by conducting a comprehensive power system study that complies with all relevant standards and codes, including adherence to local utility grid codes.

This analysis helps strike a balance between technical requirements and the associated CAPEX and OPEX. By considering both the technical aspects and the financial implications, a well-informed decision should be made regarding the optimal configuration of the offshore substation.

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