Offshore Wind Farm Integration using HVDC: Brief Introduction to System Configuration, Control and Protection

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Outline

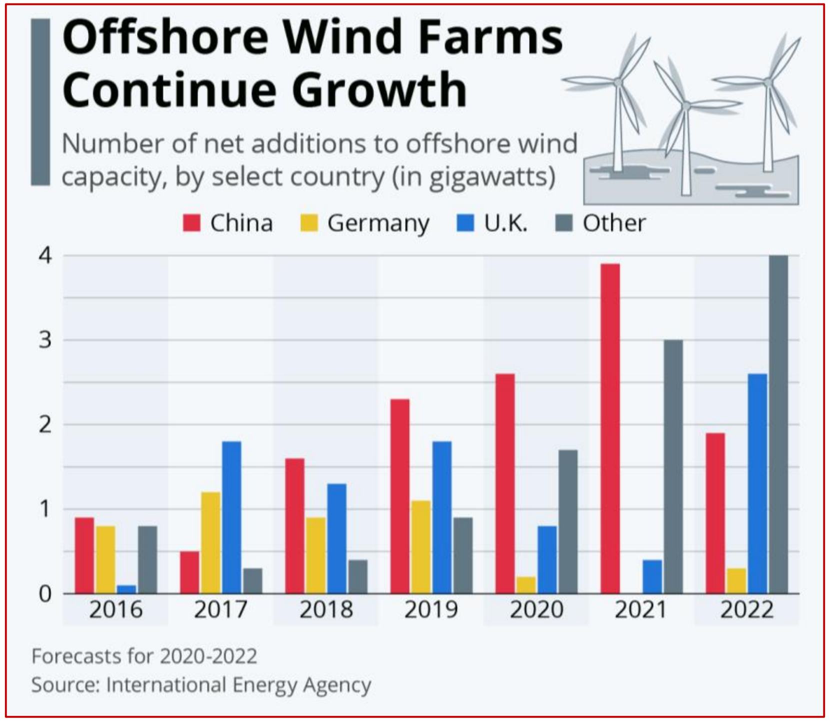
- General introduction to offshore wind generation development and HVDC connection.
- HVDC configuration and control for connecting OWFs
- System control and protection during faults
- Summary

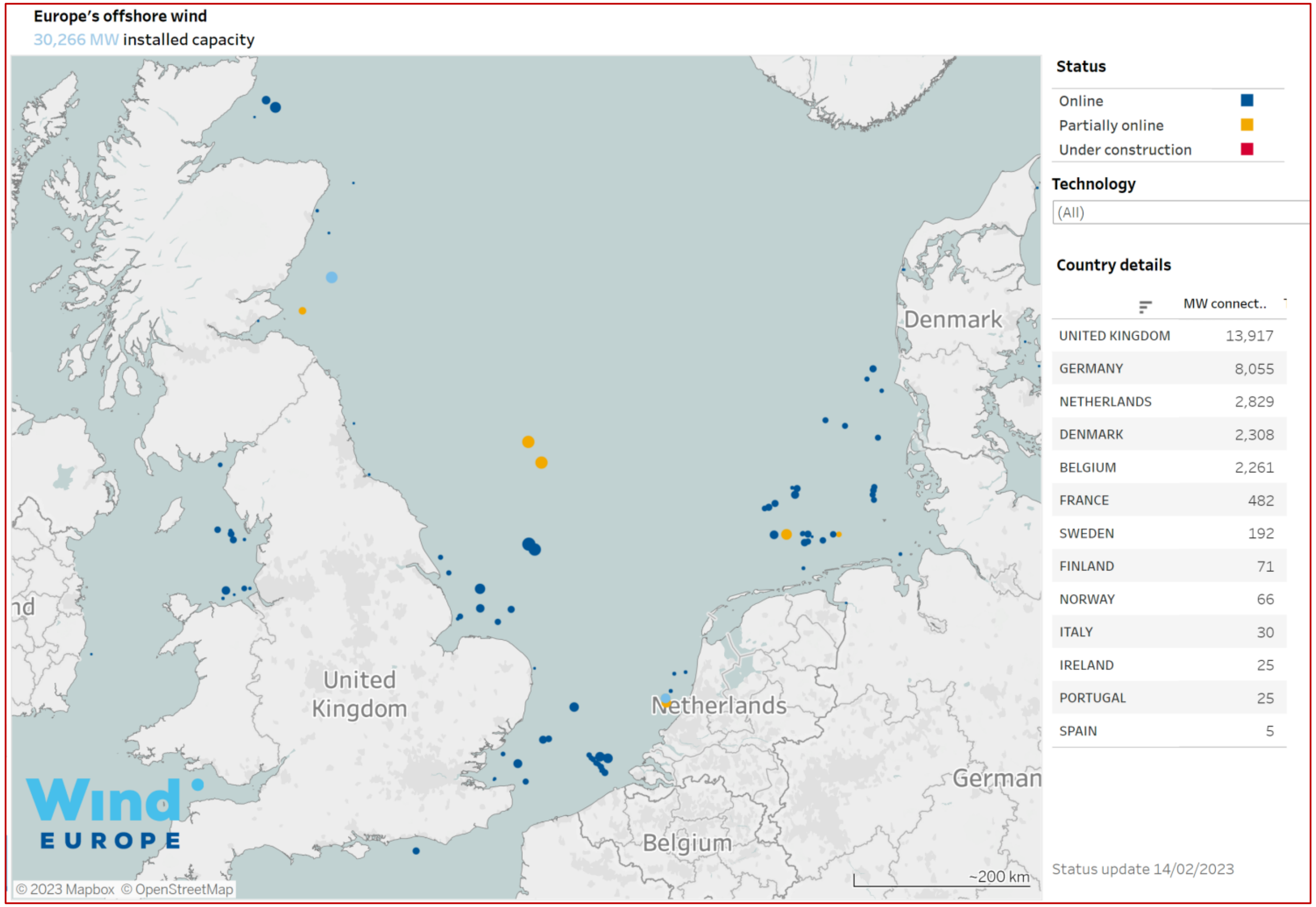
General introduction

Offshore wind development

EU: 60 GW of offshore wind by 2030, and 300 GW by 2050.

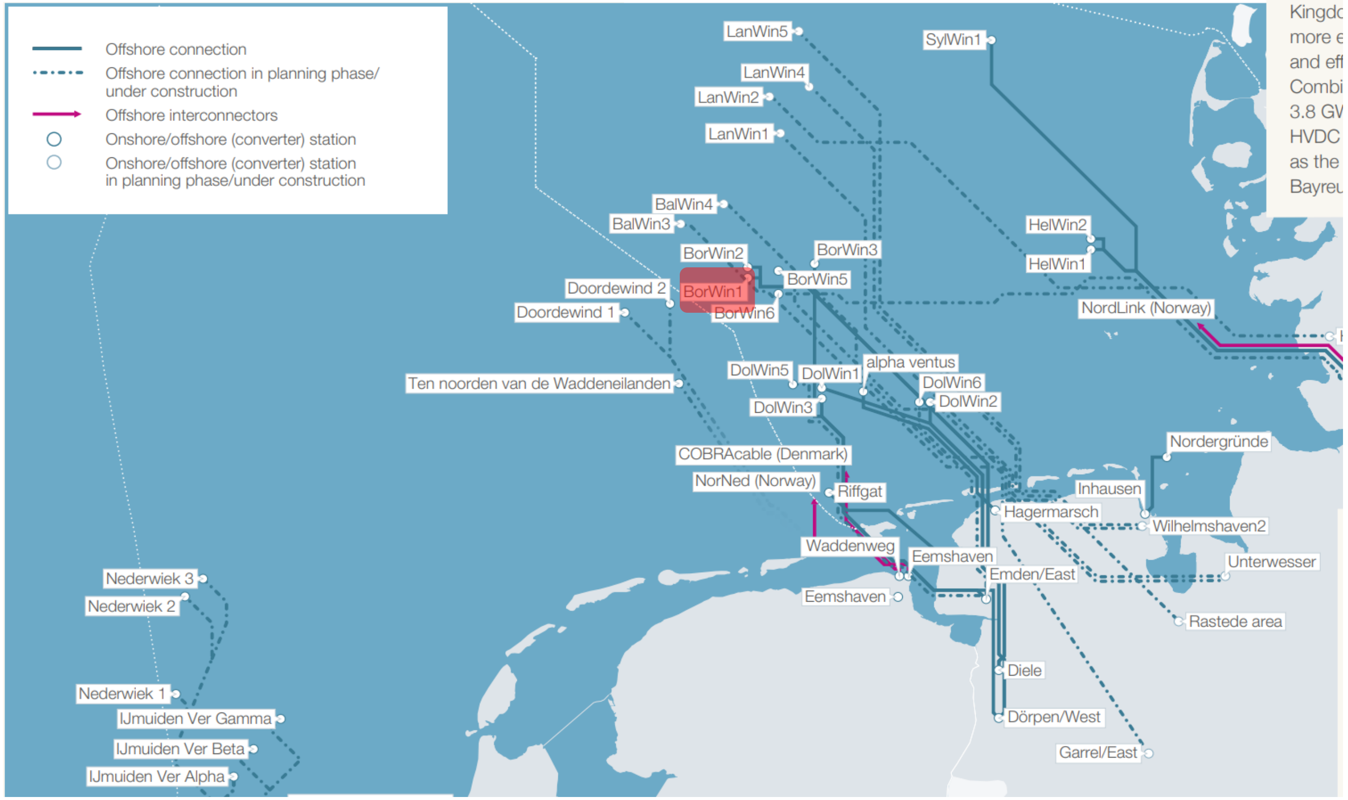
UK: 40 GW by 2030 and 85 GW by 2050





General introduction

OWF development in Germany & HVDC connection



HelWin 2:

690 MW / ± 320 kV DC

Commissioned: 06/2015

Source: www.tennet.eu
www.siemens.com

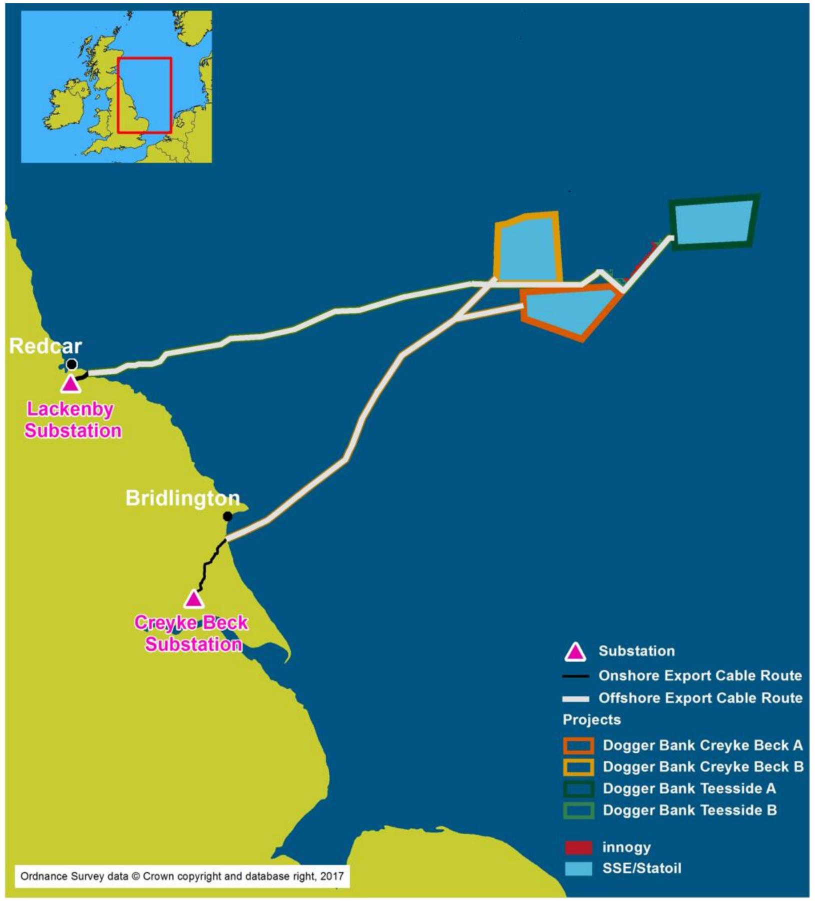
General introduction

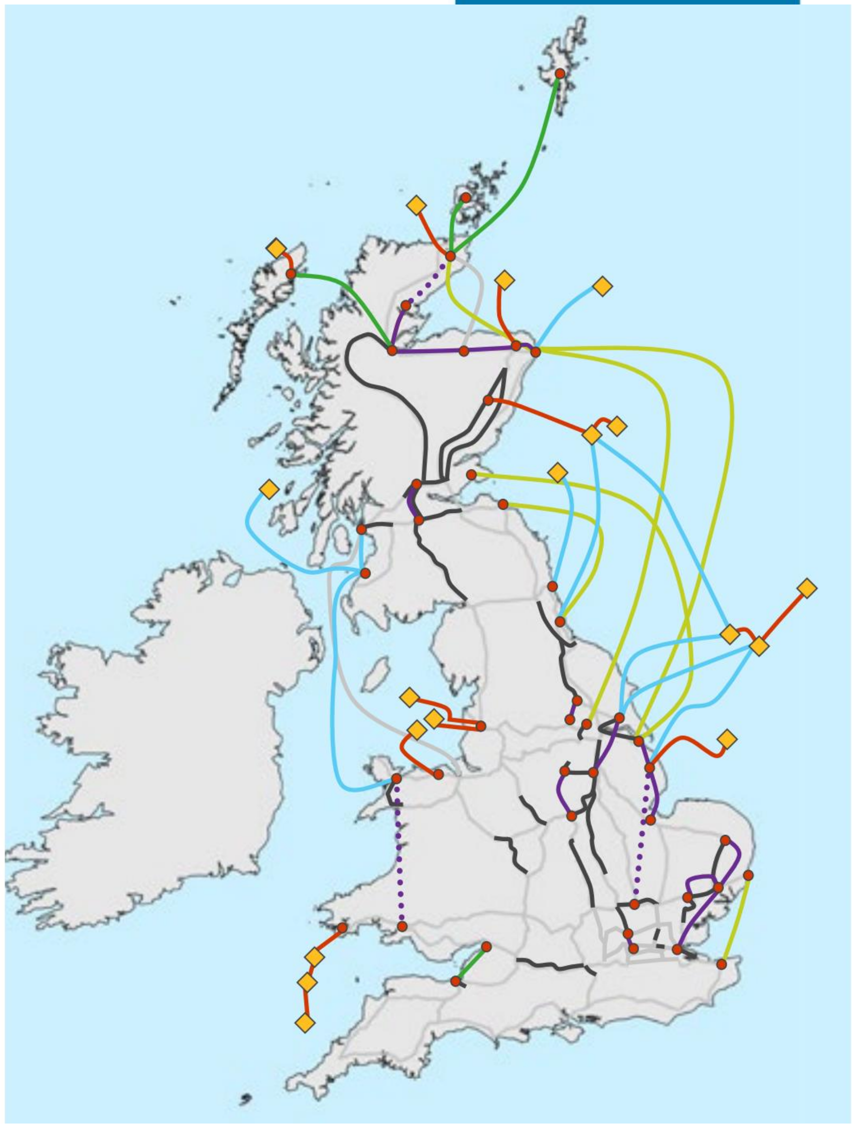
Dogger Bank wind farm in the UK

Dogger Bank A & B: each at 1.2 GW, 131 km to Creyke Beck substation in the East Riding.

Dogger Bank C: 1.2 GW, 196 km to Lackenby Substation at Teesside

Source: https://doggerbank.com/





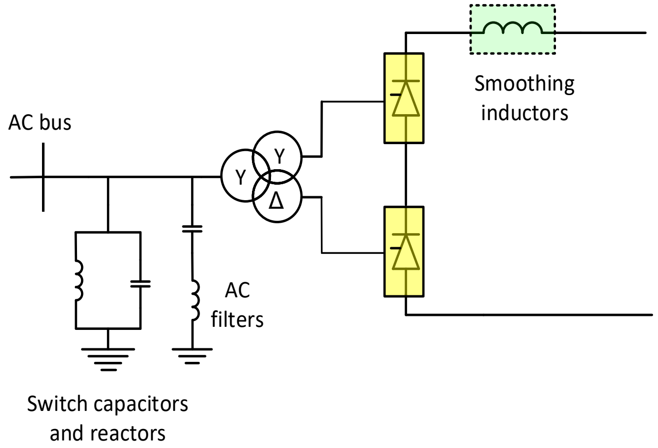
Source: https://www.nationalgrideso.com/future-energy/pathway-2030-holistic-network-design/holistic-network-design-offshore-wind

HVDC configuration and control for connecting OWF

Brief introduction to HVDC system

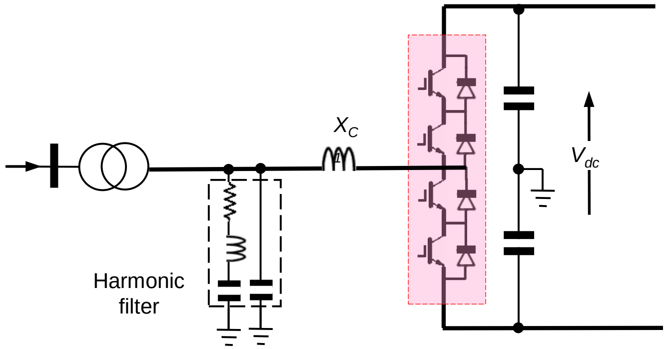
CSC (using Thyristors):

- DC current remains constant and converter is controlled to synthesize sinusoidal current on the AC side. Also called line-commutated converter (LCC).
- CSC was the first configuration for HVDC using mercury arc valves in the 1950s.
- Large numbers of devices in series to support high DC voltage.



VSC (using IGBTs):

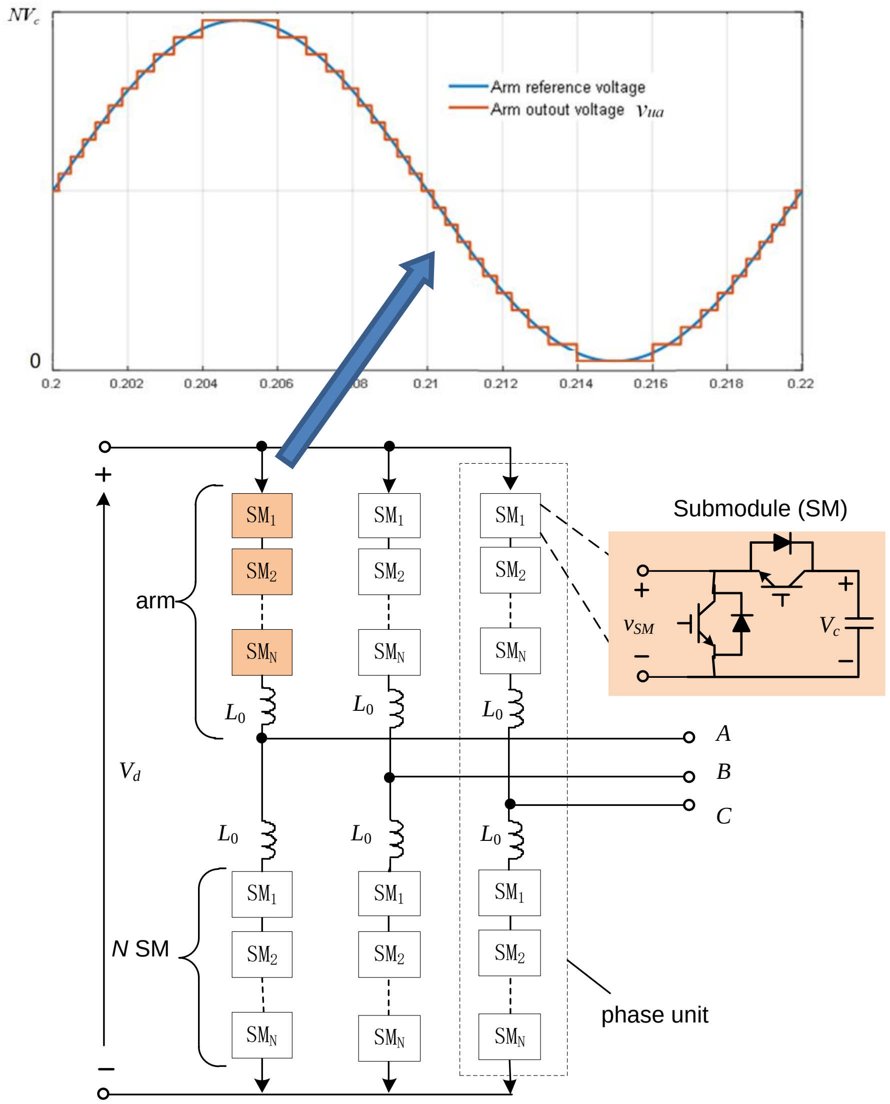
- DC voltage remains constant and converter is controlled to synthesize sinusoidal voltage on the AC side.
- First developed by ABB in 1990s.
- Full control of active and reactive power flow, no need for external voltage for commutation – suitable for OWF connection.
- When using 2- and 3-level converter topologies, large numbers of IGBTs need to be connected in series.
- Also high switching frequency (e.g., around 1 kHz) has to be used, resulting in high power loss.



Brief introduction to HVDC system

Brief introduction to modular multilevel converter (MMC)

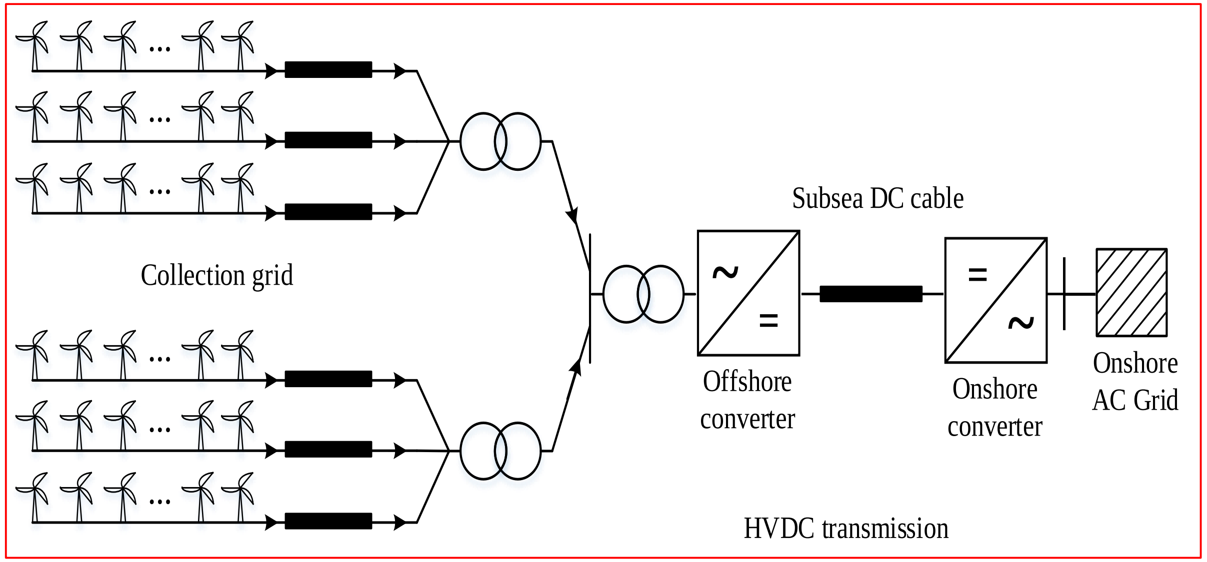
- First developed in 2000s.
- Each phase has two arms, one upper arm and one lower arm.
- Each arm uses modular structure with series connected sub-modules (SM) (also called cell), typically rated at a few kVs.
- Series connection of IGBTs is avoided.
- By selecting the number of SMs to be switched in (Vc state) at any particular period, the total voltage formed by each arm can be controlled.
- Low switching frequency and near sinusoidal voltage output (with large number of SMs).
- MMC (and its variations) is now the only topology being used for VSC based HVDC system.

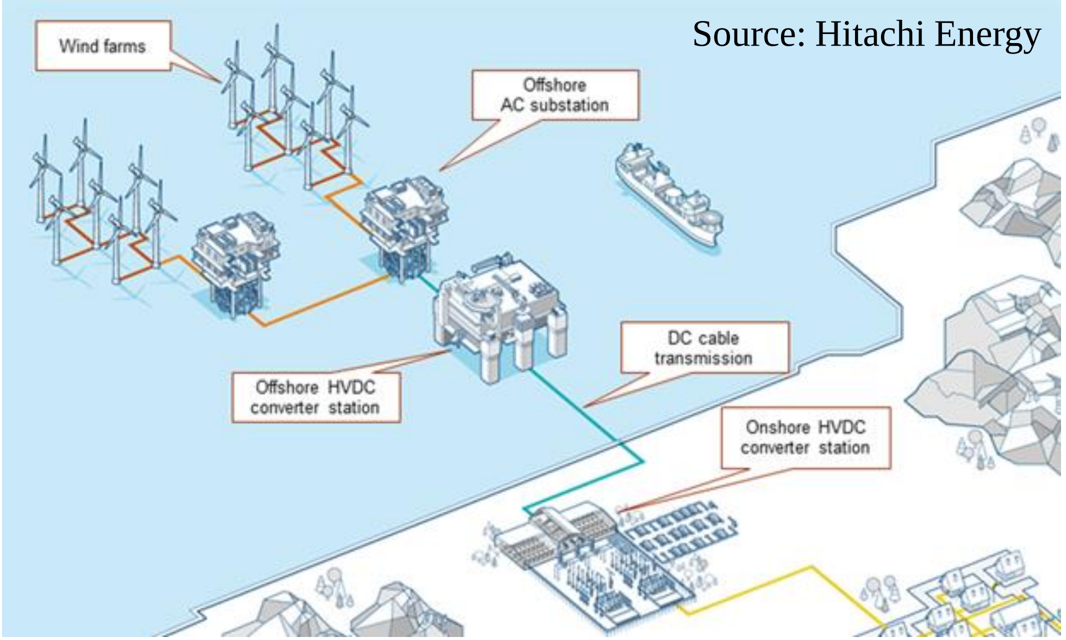


HVDC configuration and control for connecting OWF

VSC-Based solutions: point-to-point HVDC system

- For all the HVDC connected OWFs in Europe, point-to-point VSC based HVDC systems have been used.
- One offshore HVDC converter and one onshore HVDC converter.
- It usually contains one big offshore platform for housing the HVDC station and a number of small offshore platforms for housing the AC substations.

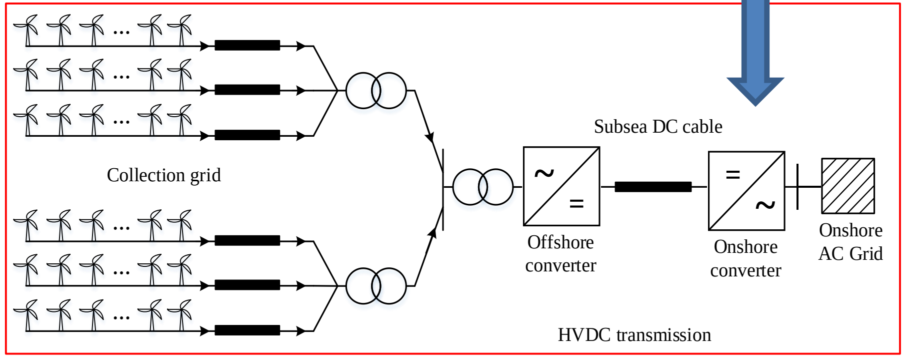


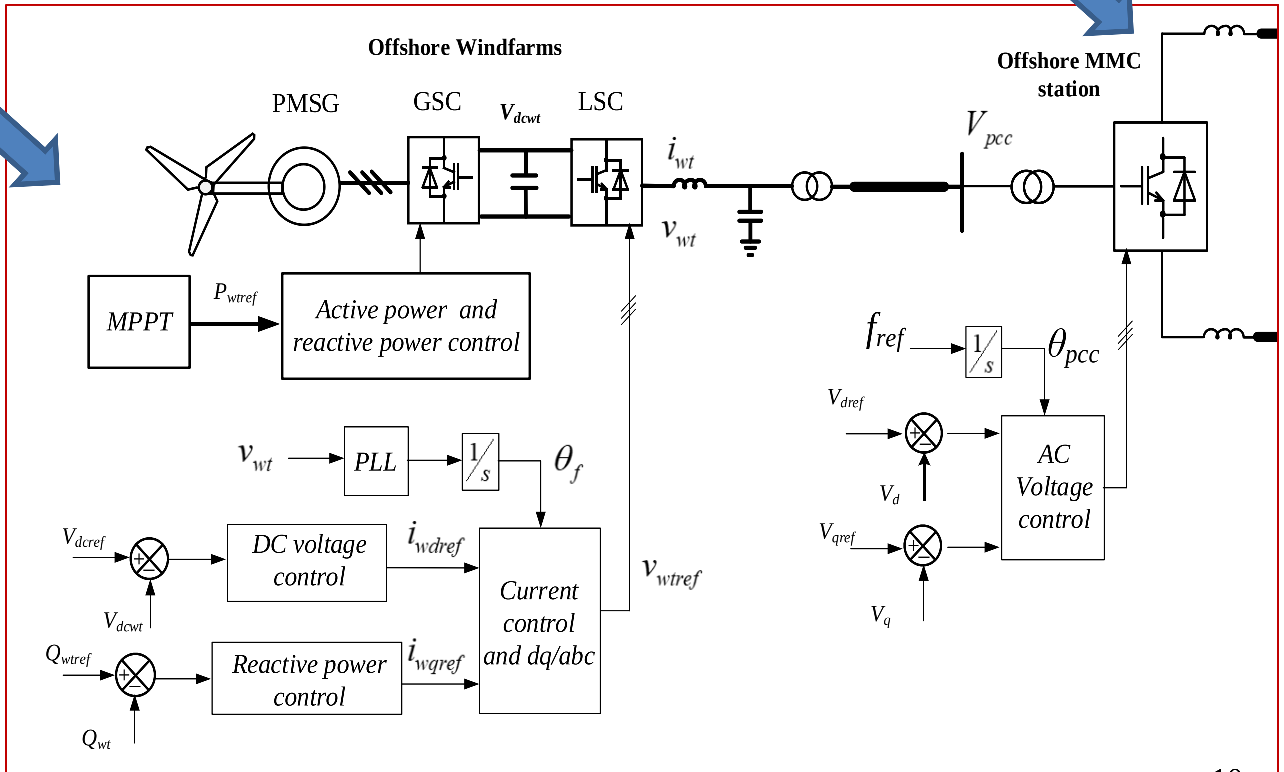


HVDC configuration and control for connecting OWF

VSC-Based solutions: main control structure

- Offshore HVDC station establishes the offshore AC network with constant voltage and frequency (constant V / f control)
- OWTs operate in a similar way as AC connected WTs – generate P and Q as required.
- Onshore HVDC station adopts DC voltage control to balance the power DC power transmission

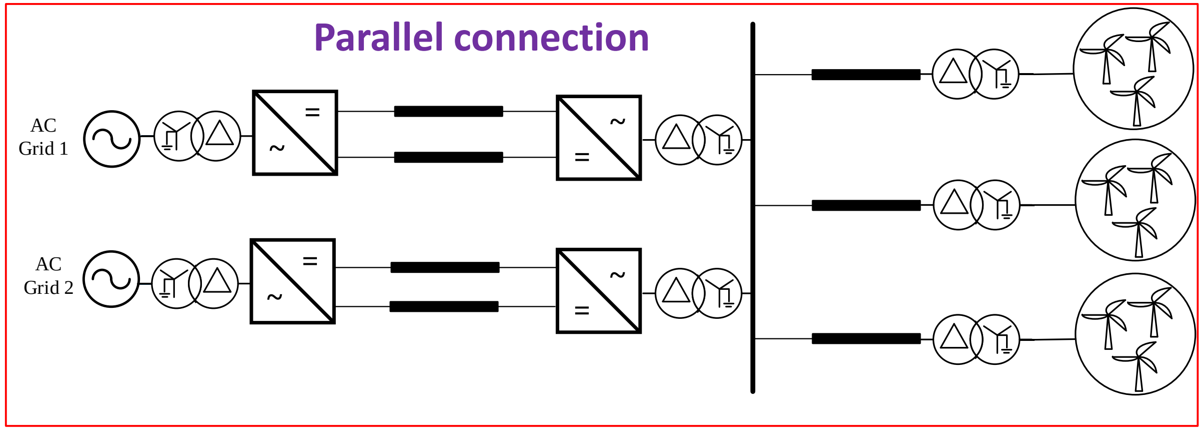


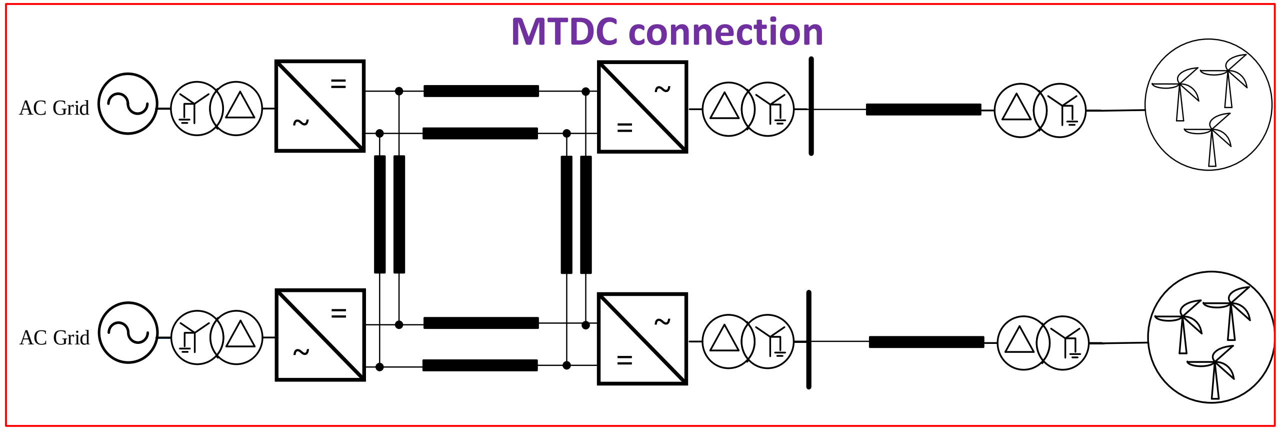


HVDC configuration and control for connecting OWF

Hybrid solutions : Parallel & MTDC connections

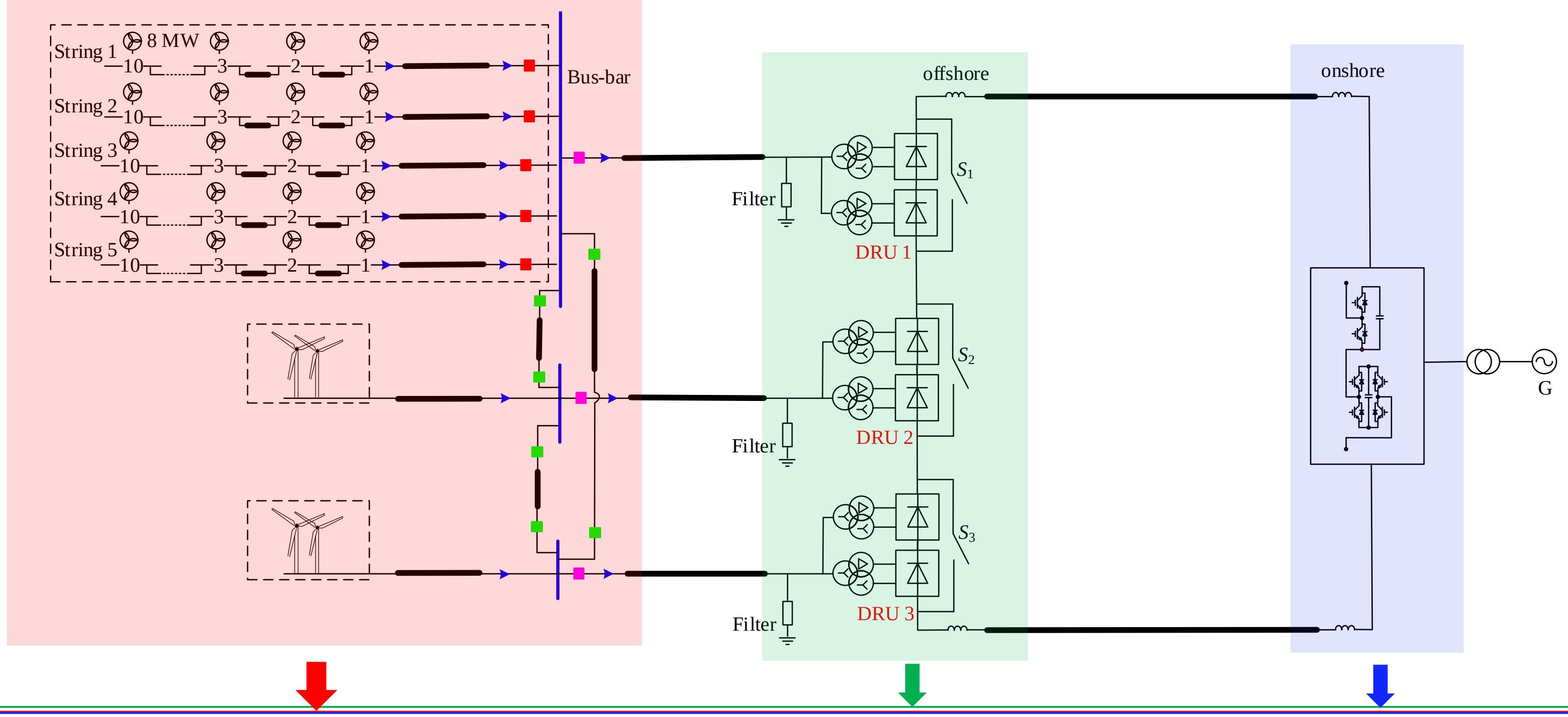
- For large OWFs, where multiple converters are required, parallel connection of offshore windfarm systems may be adopted.
- The OWF is connected to the offshore AC collectors through offshore AC cables and transformers, and parallel HVDC links are used to transmit the generated wind power to the onshore sites.
- The availability of the system can be improved, e.g., when one HVDC link is out of service due to faults, the majority of the generated power can still be exported to onshore through the other link.
- To further improve power exchange flexibility between multiple areas and provide better system redundancy, multiterminal HVDC (MTDC) system may be adopted.





HVDC configuration and control for connecting OWF

DR based solution: operating principle



Diode-rectifier:

- Uncontrollable, unable to control offshore frequency and voltage.
- Receive active power from offshore network and inject power to HVDC link.
- Exchange reactive power with offshore network.

Onshore MMC:

- Receive active power from HVDC link and inject power to onshore grid.

HVDC configuration and control for connecting OWF

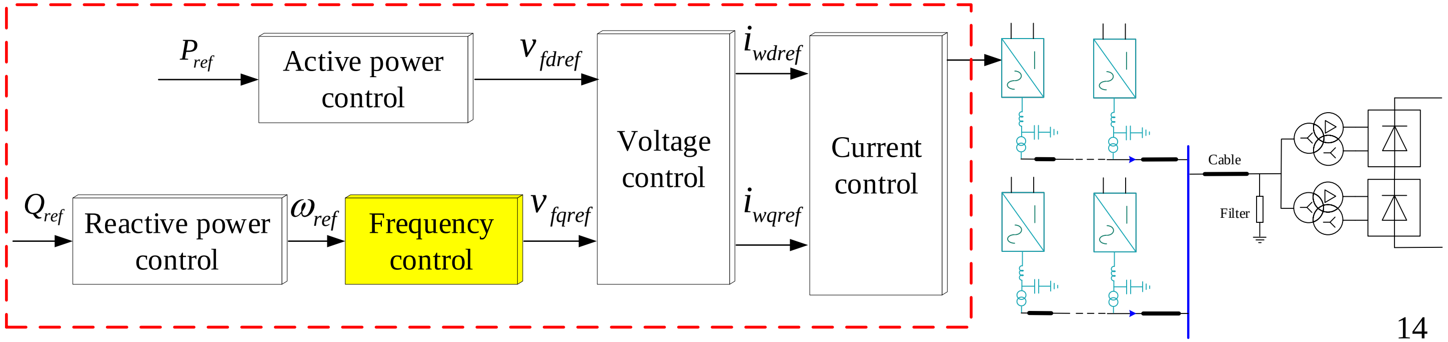
DR-HVDC system control

- Onshore HVDC station adopts DC voltage control to balance the power DC power transmission.
- DC voltage at the offshore DR terminal is dependent on the offshore AC voltage magnitude.
- OWTs has to establish the offshore AC voltage and control the power flow through the DC system.

Main OWT functionality:

- Offshore AC voltage / frequency control.
- Wind turbines control active power (by regulating AC voltage magnitude), control/share reactive power.
- Fault ride-through capability (AC faults, DC faults).
- **OWT has to adopt special control**

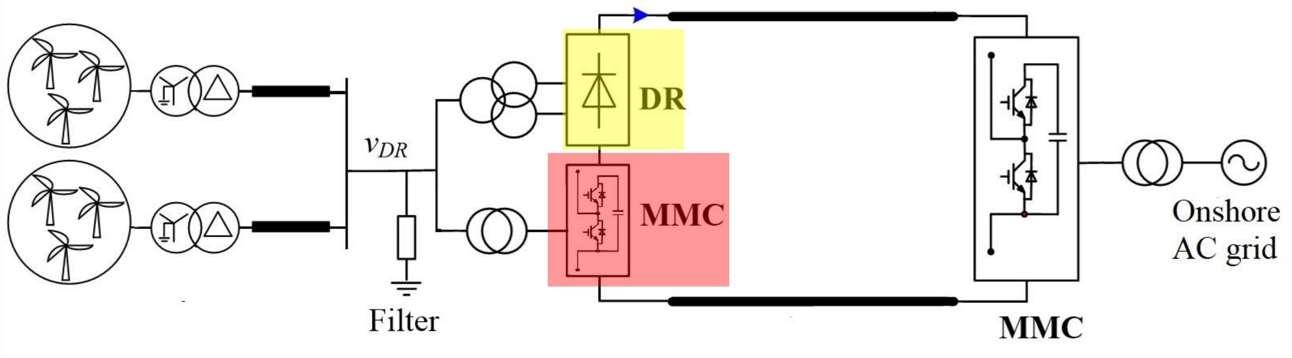
$$V_{dcr} = 2(1.35 V_{AC\_off} - \frac{3}{\pi} X I_{dc})$$



HVDC configuration and control for connecting OWF

Hybrid converter solutions: Series connection

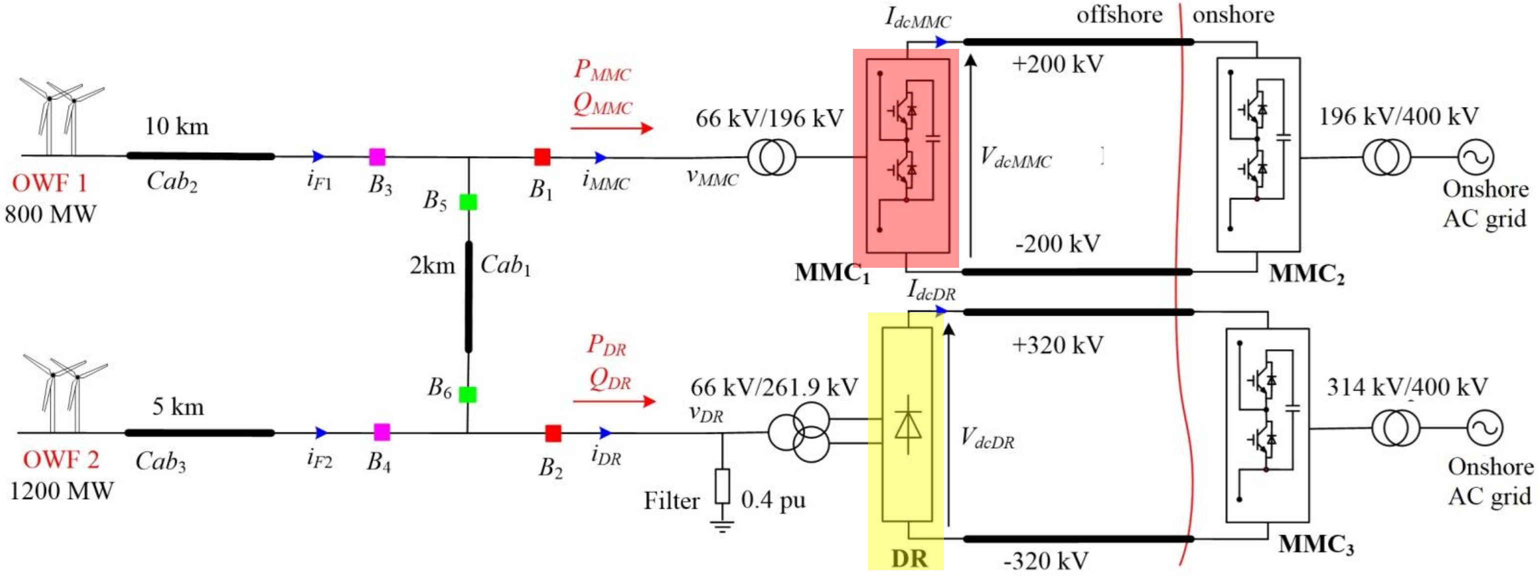
- Series connection of different converter technologies for the offshore station (e.g., DR and a **small** MMC), to take the potential advantages offered by the different technologies.
- MMC establishes the offshore AC network and controls power transmission (by controlling the offshore AC network voltage magnitude).
- OWTs operate as in conventional AC connection – no need for special design.
- MMC may also provide harmonic/reactive power compensation – reduce the size of the passive AC filter for the DR.
- Overall cost and power loss may be reduced (compared to full MMC solution).



HVDC configuration and control for connecting OWF

Hybrid converter solutions: Parallel operation

- Parallel operation of DR-HVDC and MMC-HVDC.
- MMC established the offshore AC network.
- OWTs operate as in conventional AC connection – no need for special design.
- DR potentially offers lower power loss and cheap construction.



System control and protection during faults

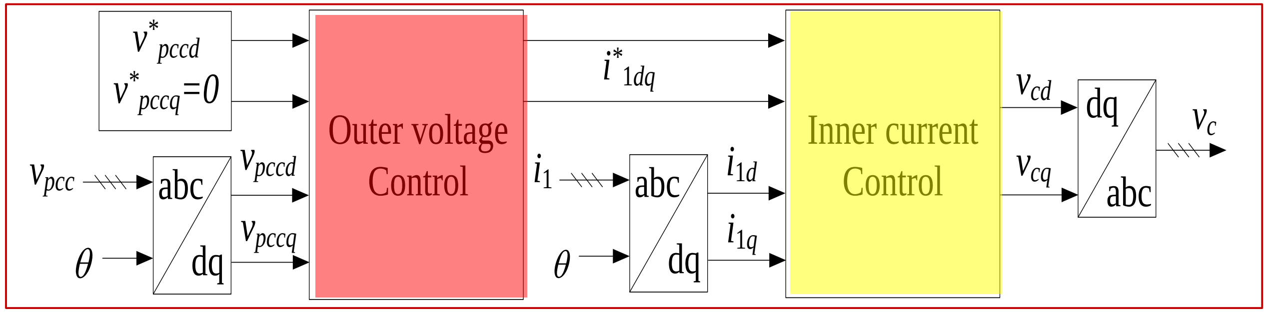
- HVDC connected offshore wind farm system is mainly constructed with power electronics converters, which are vulnerable to over-current and over-voltage in the event of a network fault.
- Thus, system control and protection during various faults, including offshore and onshore AC faults, DC faults, etc. need to be carefully considered, to ensure safety of the equipment and reliability/availability of the ensure generation and transmission system.
- With large offshore wind penetration, the control, operation and protection of HVDC connection OWFs during and after faults can significantly affect the onshore system operation.

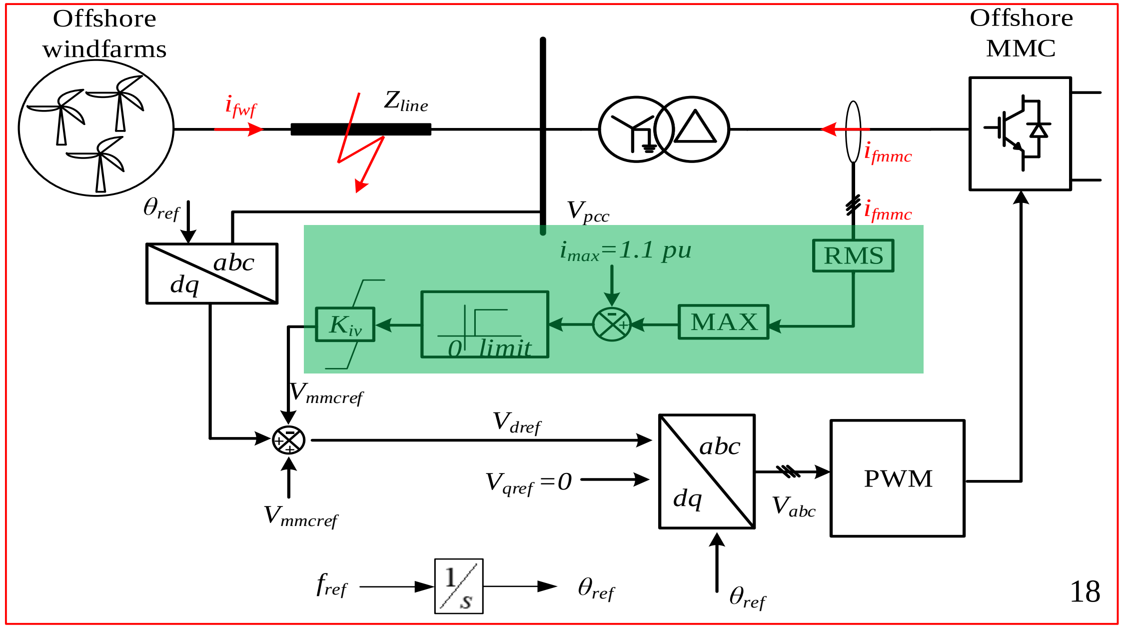
System control and operation during faults - offshore AC fault

During offshore AC faults, the main issues are:

- Converter over-current protection
  - Usually not a major issue due to the use of dual voltage (outer) and current (inner) control loops for the offshore MMC.
  - Current-voltage droop method may be adopted, which adjusts the output voltage reference according to the measured offshore three-phase current to limited the over-current (and prevent the saturation of the outer V loop – helping recovery process).

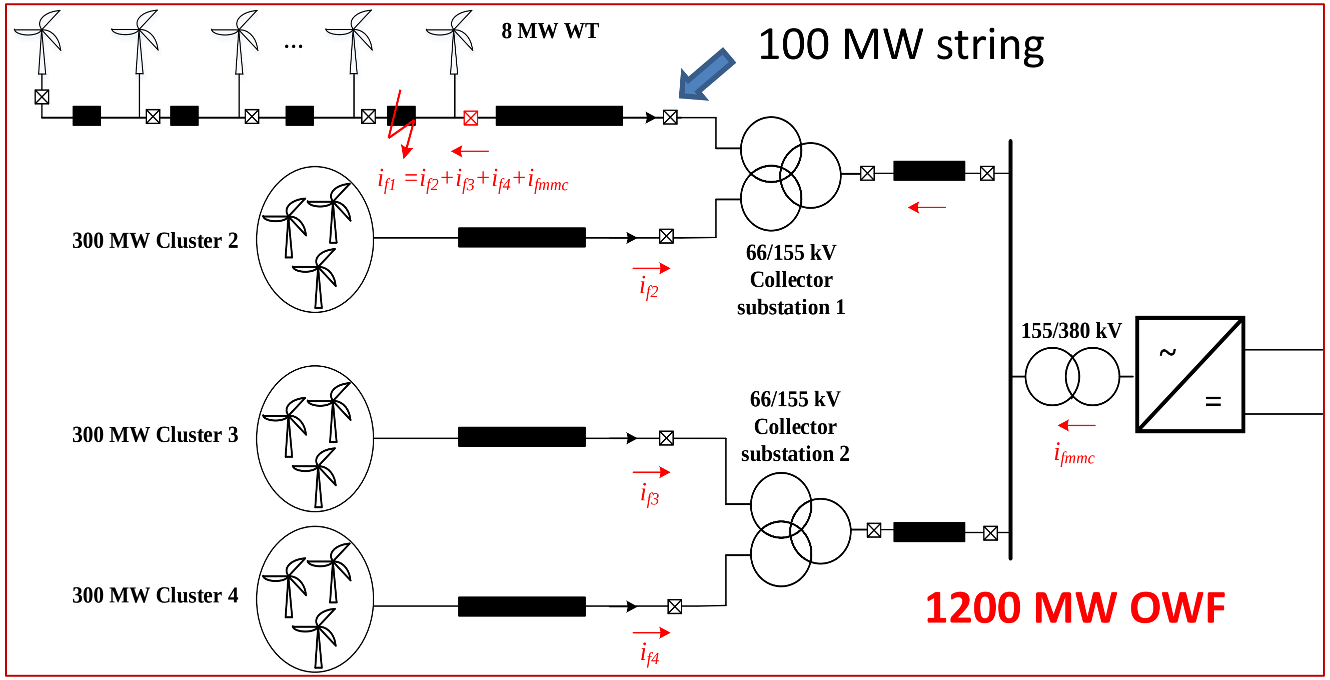
- Fault isolation

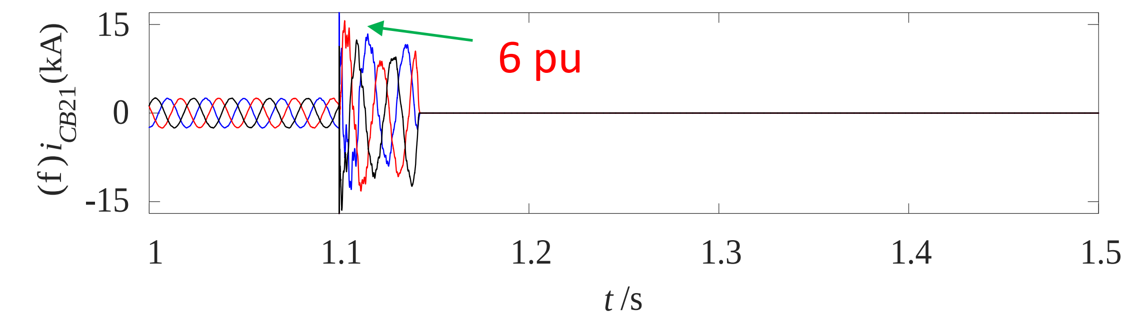


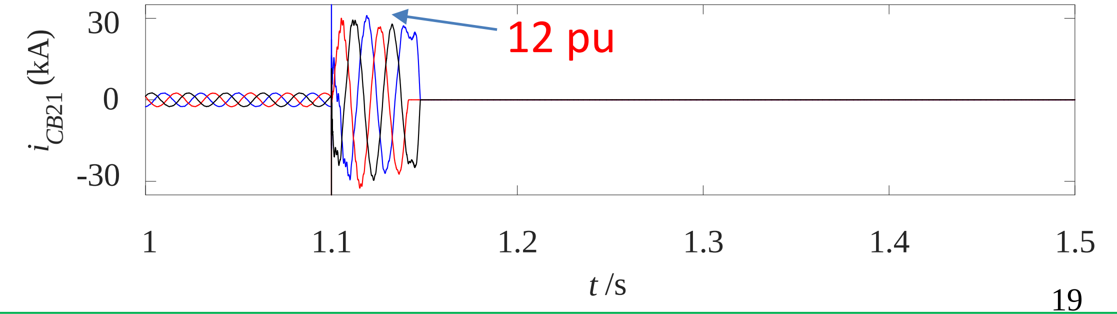


System control and operation during faults - offshore AC fault

- **Fault isolation**
  - Although converters have limited over current capability (e.g., 1.2 -1.5 pu), large numbers of converters (including OWTs and MMC) contributing maximum fault current may lead to too much fault current for protection relays.
  - Fault current may be gradually ramped up (rather than jumped to the current limit instantly).

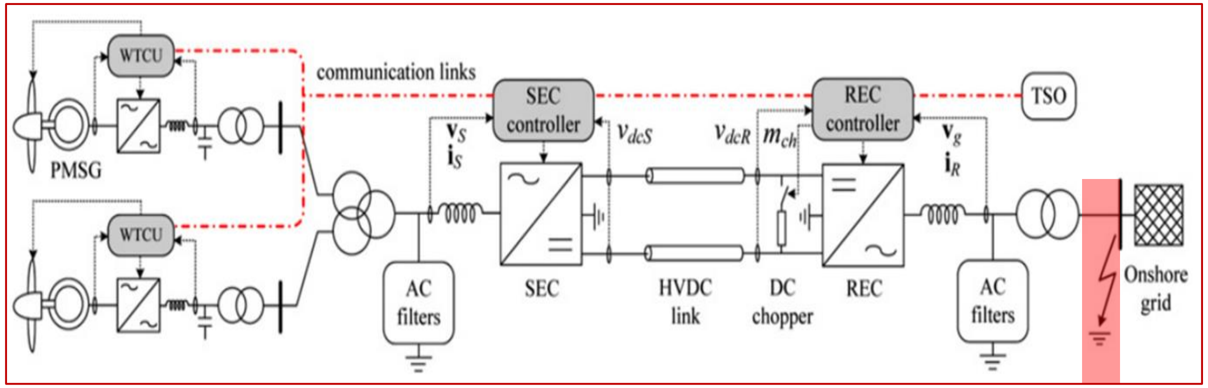


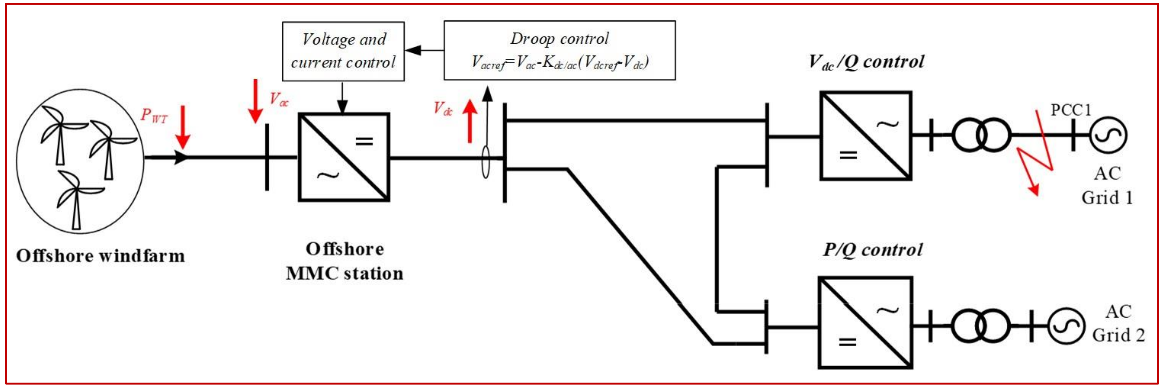




System control and operation during faults - onshore AC faults

- During onshore AC network faults, the power transmission capability of onshore converter is reduced.
- The continuous power export from the OWF to the HVDC link leads to power imbalance, resulting in rapid DC voltage rising of the DC link.
- To avoid shutdown of the entire system, the excess power has to be dissipated:
  - ❑ **DC choppers or dynamic braking resistors connected at the onshore HVDC terminal can be used.**
  - ❑ **Power reduction control with the aid of fast communication system - relies on communication reliability and speed, which reduces the robustness of system.**
  - ❑ **Offshore HVDC converter reduces offshore AC voltage magnitude according to the raised DC voltage. OWTs enter FRT mode resulting in reduced power generation.**



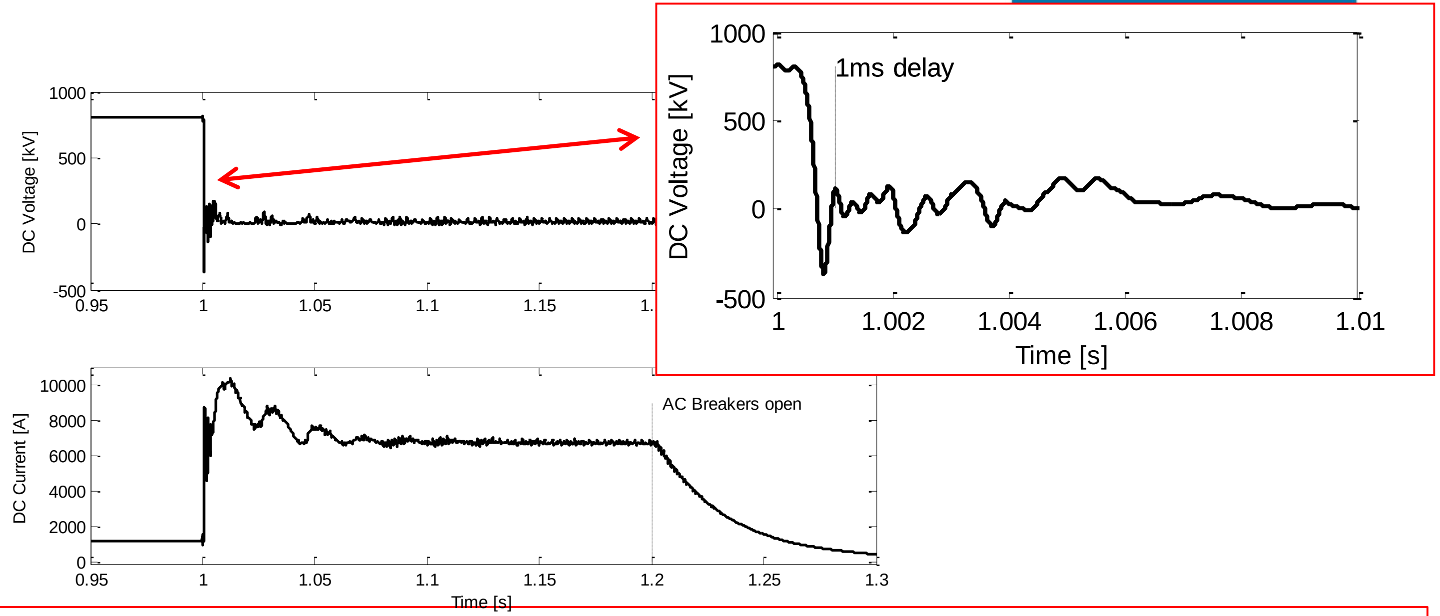


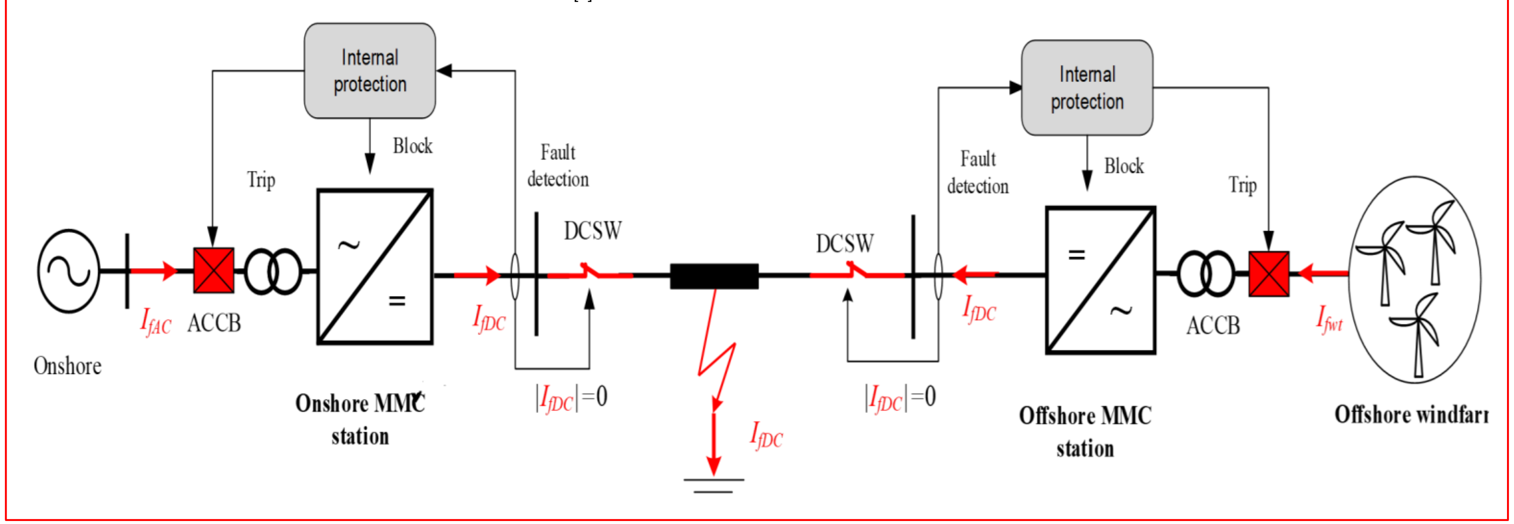
S. Nanou and S. Papathanassiou, "Evaluation of a communication-based fault ride-through scheme for offshore wind farms connected through high-voltage DC links based on voltage source converter," *IET Renewable Power Generation*, vol. 9, pp. 882-891, 2015.

System control and operation during faults – DC faults

- Due to the low DC impedance, a DC fault can result in the collapse of DC voltage and large DC fault current within a few ms.
- In addition, DC fault current does not have zero crossing, so fault breaking (DC circuit breaker) is challenging.
- DC protection speed required for DC fault shall be much faster than that in AC fault.
- The cooperation of ACCBs and fast DC switches (DCSWs) is one of the options used to clear DC fault.

- DC Fault ➔DC over current ➔MMC blocking / Open ACCB ➔ DC current decays to 0 ➔ open DCSW ➔ fault isolation.

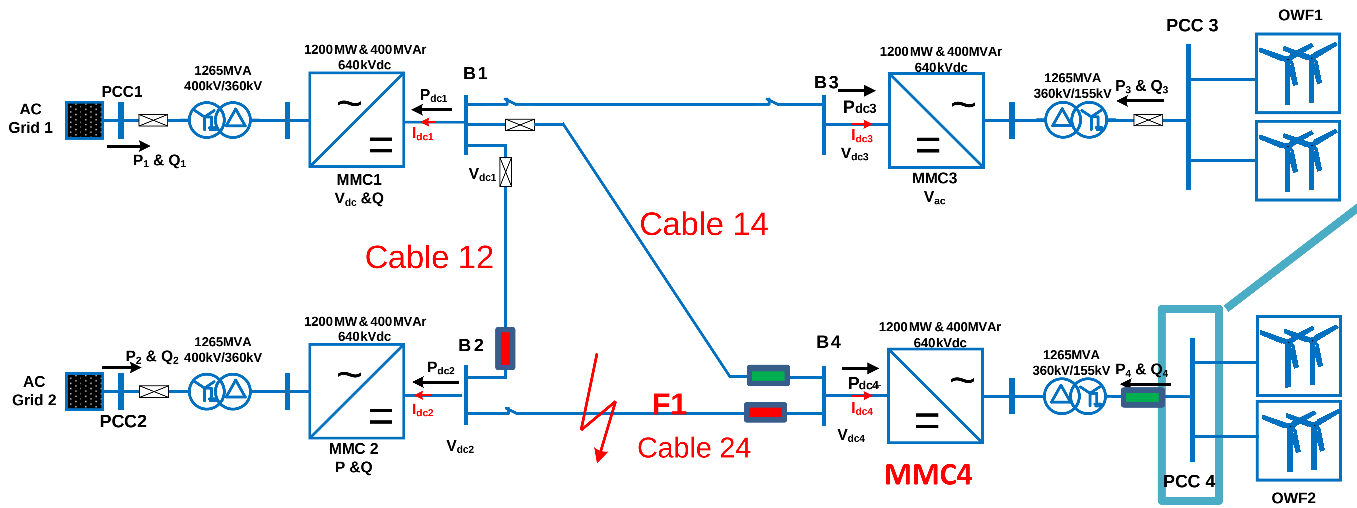


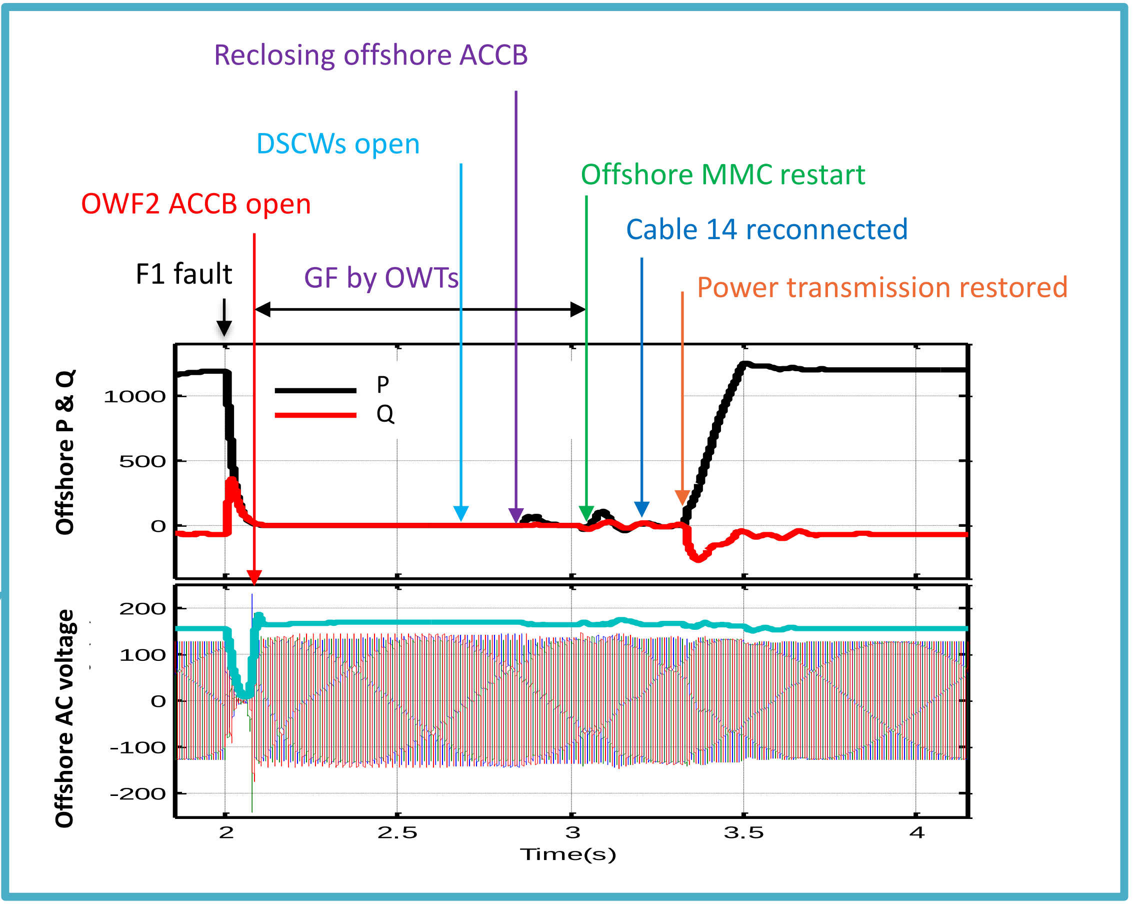


System control and operation during faults – DC faults (example)

University of Strathclyde Engineering

- System overview: two MMC connected OWFs, two onshore MMCs
- Partially selective DC fault protection, Cable 24 protected using DCSW, Cable 12 and 14 protected using DCCB
- Pole-to-pole DC fault at 2s at Cable 24, MMC 2 & 4 are immediately blocked
- Cable 12 and 14 quickly disconnected by opening the DCCBs
- Cable 24 can only be isolated by DCSW after de-energization





Concluding Remarks

- HVDC will see increased development in integrating Europe’s large offshore wind farms.
- Existing schemes use point-to-point HVDC connections (largely with MMC)
- Multiterminal HVDC (MTDC) grids for OWF integration and interconnection have been planned in Europe.
- DC circuit breaker (DCCB) is likely to be an important part of future MTDC grids and is currently under active development.
- Other technologies, e.g., DR-HVDC system, are unlikely to see immediate adoption in Europe (probably due to commercial OWF development model, supply chain constraints, etc)