Hitachi Energy

Grid-Forming HVDC: From Operational Experience to Future DC Grids

The 11th IERE Webinar:
Grid-Forming Inverters (GFMs)
16 October 2026

Public



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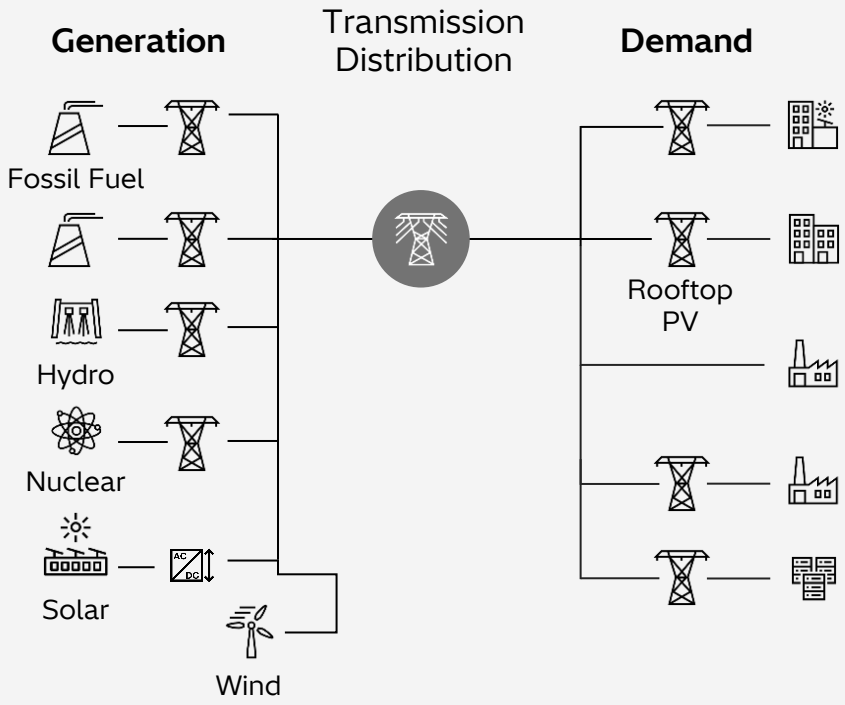


Why Grid-Forming HVDC?

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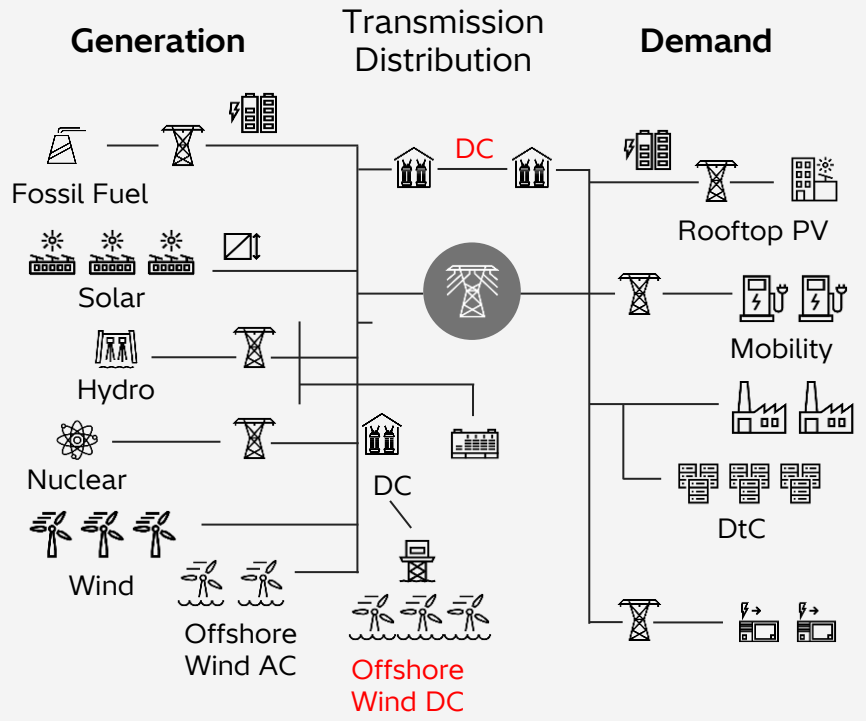
The evolution of the power grid

Legacy grid | 2020



Centralized and Passive Grid

Net-Zero grid | 2050



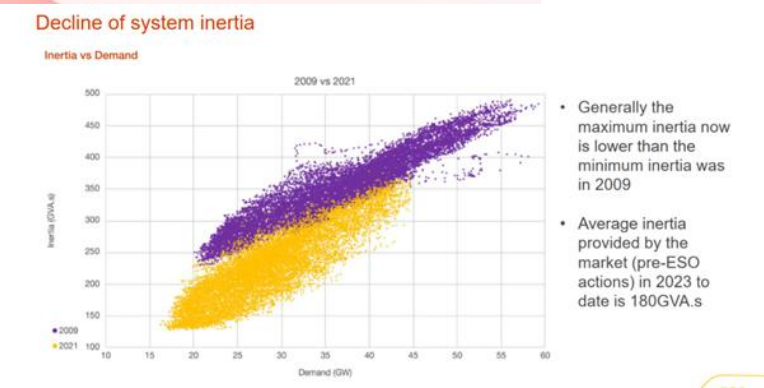
Decentralized and Active Grid

Grid challenges

01	Integrate Remote Renewable
02	Power Imbalances
03	Highly Dynamic Power Flow
04	Rapid Grid Expansion
05	Resilience of Weakening Grid

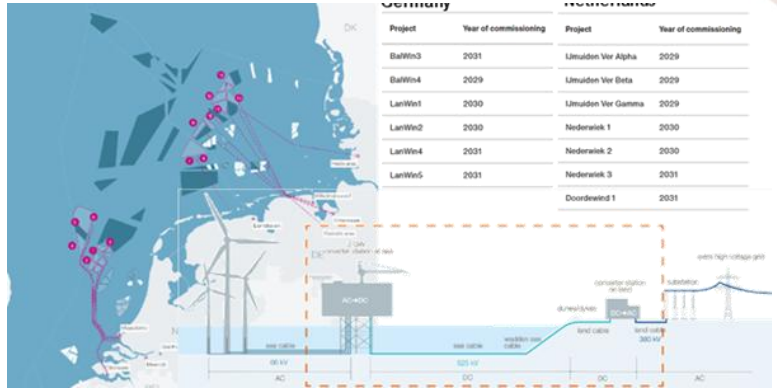
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New grid challenges, today and in future



Weakening of the power systems

- Energy transition toward renewable makes conventional large rotating generators decommissioned
- Lowering of system inertia and short circuit power
- **Need for further development of GFM control strategies**



Remote passive generation grids and power electronics interactions

- Renewable plans represent often situation of weak grids with several power electronics solutions
- Increase risk of interactions and oscillations requiring **new verification methods and models (Software in the Loop)**



New large loads, possibly off-grid

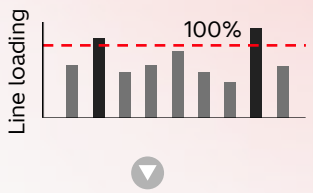
- New upcoming possible applications such as **green infeed** to large-scale electrolyzer, Datacenters and AI factories
- **Passive grids on both sides to be operated and stabilized**
- Co-operation of different PE technologies (HVDC, BESS…)

GFM Grid Forming, BESS Battery Energy Storage System
Left plot from “Low Inertia System Operation, Dr. Xiaoyao Zhou, Operability Policy Manager ESO (Energy System Operator)”

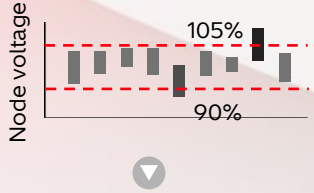
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Operational constraints in AC grids
and how HVDC helps

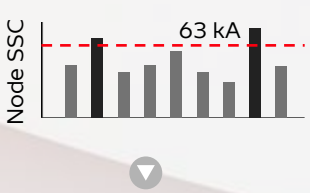
Power system capacity (steady state)



Current limits



Voltage limits

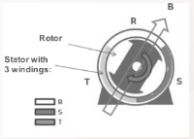


Short-circuit current limits

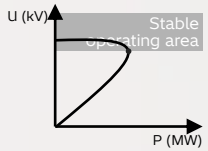
Power system stability (transient state)



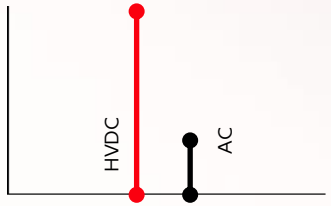
Frequency



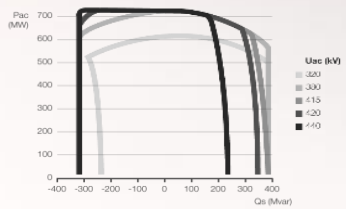
Rotor angle



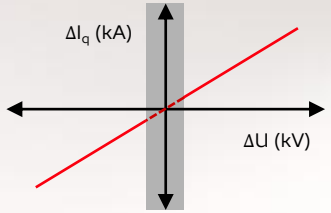
Voltage



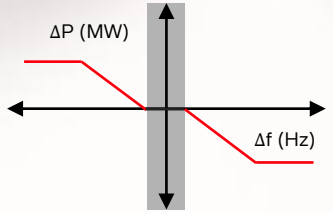
More power
Power flow control



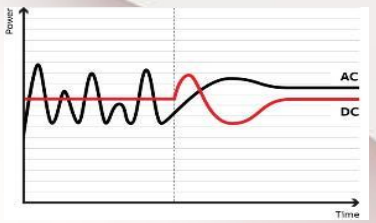
Reactive power control



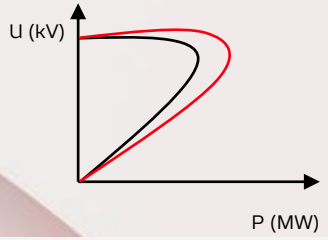
Controlled short-circuit current



Frequency control



Damping control



Dynamic voltage control

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GFM definition and controls for HVDC?

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New requirements for enhanced controllability and grid forming

The term ”Grid Forming” does not yet have a universally accepted definition

Control method adapted to AC grid conditions

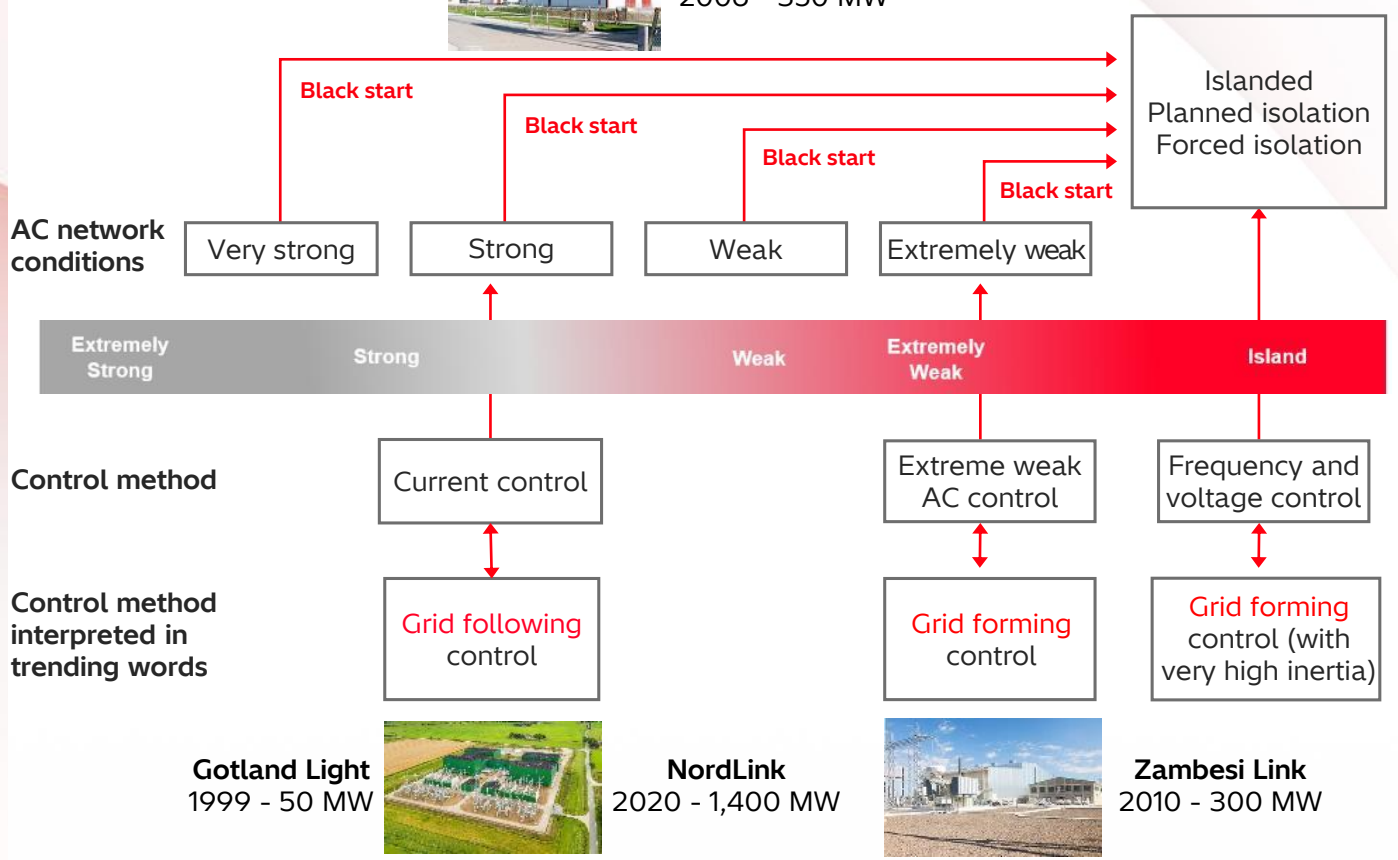
- Respect the need of the grid
- Respect the physical condition of system
- Consider low energy storage
- Sensitive to overcurrent

With energy storage

Operating connected ac grids with zero SCR on both terminals
(100 % renewables, passive loads)



Estlink
2006 - 350 MW



Gotland Light
1999 - 50 MW

NordLink
2020 - 1,400 MW

Zambesi Link
2010 - 300 MW

The purpose of HVDC control is to support the connected AC system with maximized performances, rather than just to emulate a synchronous generator

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HVDC Light® Theory – VSC

01

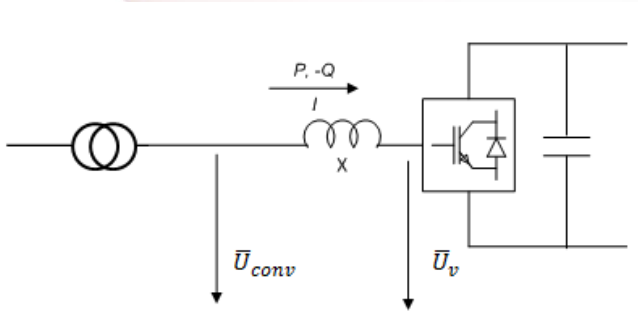
Active power is controlled by the phase angle difference in converter and valve a.c. bus voltage

02

Reactive power is controlled by voltage difference over converter reactor

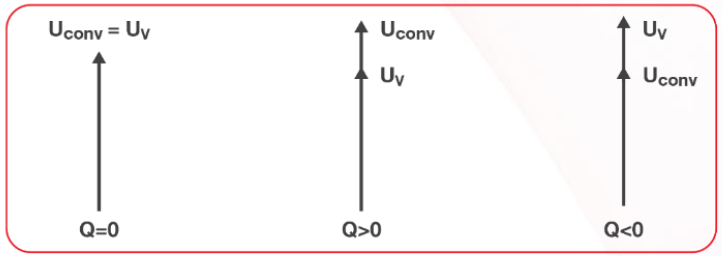
03

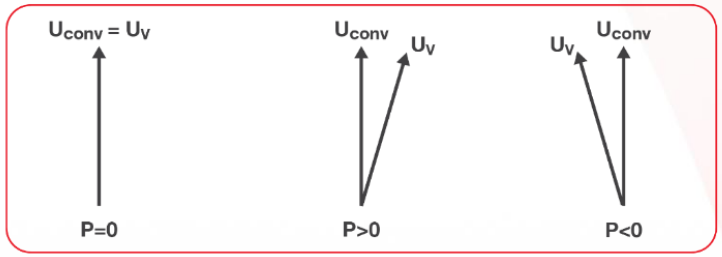
Frequency and phase angle can be fully controlled by the converter



$$P = \frac{U_V * U_C * \sin(\delta)}{X}$$

$$Q = \frac{U_C * (U_V * \cos(\delta) - U_C)}{X}$$





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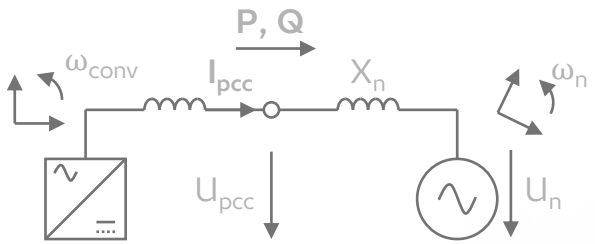
Basic control modes – Grid forming

Grid Following Control

Vector Current Control (VCC)

Current Source Emulation

- **Synchronization** to grid
- **Power** control through **current control**
- **Frequency not prioritized** (only indirectly)
- Voltage limiter
- Current source emulation
- ESCR > 1.5

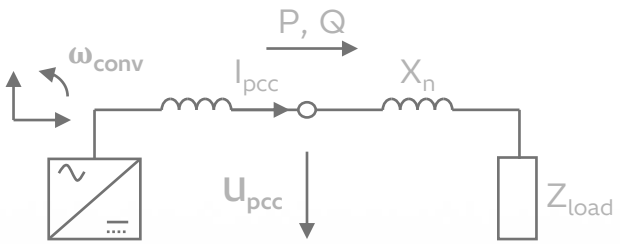


Synchronous Grid Forming

Extremely Weak Network Control (EXWEAK)

Voltage Source Emulation

- **Slow synchronization** to grid
- **Power and frequency** control through **voltage phasor control**
- Both **frequency and power prioritized**
- Current limiter through transient mode
- Synchronous machine emulation
- ESCR < 1.5

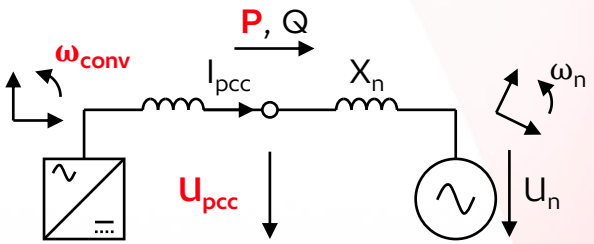


Grid Forming Control (with very high inertia)

Frequency Voltage Control (FVCTRL)

Voltage Source Emulation

- No synchronization to grid
- **Frequency & voltage control (“slack bus”)**
- **Power not prioritized** (except limits)
- Current limiter (direct and transient mode)
- Voltage source emulation
- ESCR=0



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Overview of HVDC dynamic control portfolio

Grid Following Current Control (GFLCC)

Main objective

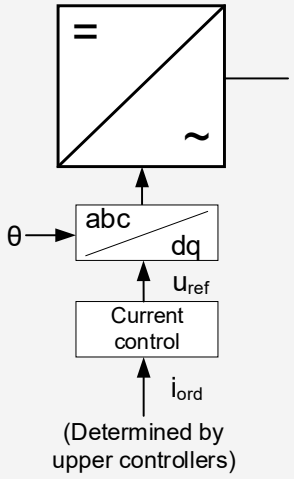
Exchange power with the AC grid by controlling the current and its angle

Main control modes

- UAC/Q-Control
- UDC/P-Control

Main characteristics

- Synchronization with PLL
- Current control limitation



Grid Forming Current Control (GFMCC)

Main objective

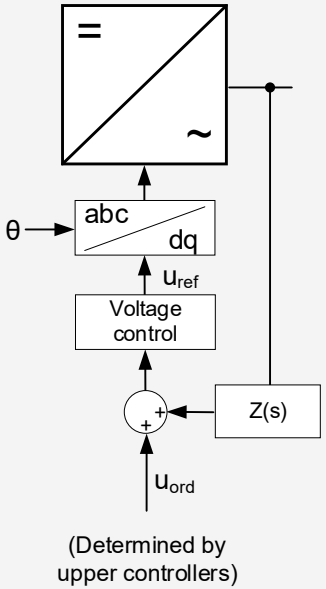
Exchange power with the AC grid by controlling the voltage and its angle

Main control modes

- UAC/Q-Control
- UDC/P-Control

Additional functions

- Virtual admittance
- Virtual inertia
- Current control limitation
- Synchronization with or without PLL



Grid Forming Voltage Control (GFMVC)

Main objective

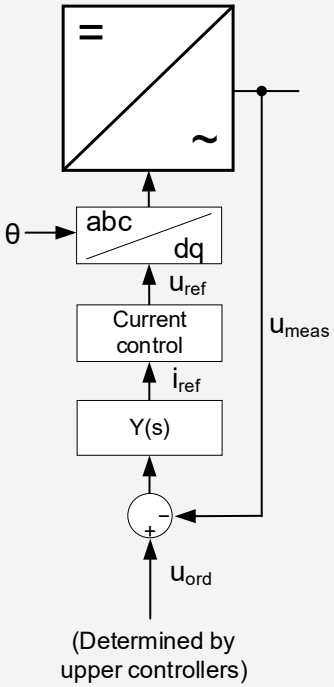
Exchange power with the AC grid by controlling the voltage and its angle

Main control modes

- UAC/Q-Control
- UDC/P-Control

Additional functions

- Virtual impedance
- Virtual inertia
- Voltage control limitation
- Synchronization with or without PLL



Extremely Strong	Strong	Weak	Extremely Weak	Island

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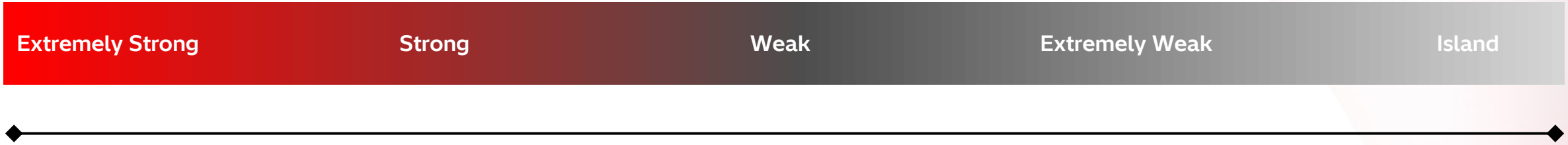
Grid forming as a definition of performances

The objective is to deliver a system with optimized performance under the widest possible range of short circuit power/AC grid conditions defined in Grid Code.

Grid Forming shall not define a specific control strategy; it shall rather define the expected performance in the power system.

Grid Forming capability is required to improve the grid stability and fulfil Grid Code requirements.

Different control strategies may be used depending on the grid the converter is connected to.



Grid Forming Performance	Contribute to grid strength	Contribute to short circuit current injection	Reduces system unbalance	Provide inertial response	Contribute to frequency control	Island operation

Grid Forming as a definition of performances rather than definition of control strategy

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Grid Forming Operational experience since 2006

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Insights from practical applications of grid-forming control

Project examples

Hitachi Project Experience Publications

Estlink (Commissioned 2006)

HVDC with Voltage Source Converters; A Powerful Standby Black Start Facility, IEEE PES T&D conference in Chicago, USA, April 21-24, 2008

Borwin1 (Commissioned 2008)

HVDC with Voltage Source Converters – A Desirable Solution for Connecting Renewable Energies, Energynautics conference “Large-scale integration of wind power into power systems”, Bremen, Germany, 2009. Ride-through methods for wind farms connected to the grid via a VSC-HVDC transmission EPE 2010

Caprivi Link (Commissioned 2010)

Stability Enhancement and Blackout Prevention by VSC Based HVDC Presented at CIGRE The electric power system of the future-Integrating supergrids and microgrids International Symposium in Bologna, Italy September 2011

Kriegers Flak (Commissioned 2020)

Kriegers Flak Combined Grid Solution Commissioning of the Master Controller and the HVDC System, GCC CIGRE 2022

South Fork Wind Offshore (Commissioned 2023)

Cigre Symposium B4 Trondheim 2025

STATCOM Opladen(Commissioned 2023)

Cigre Colloquium B4 Vienna 2023



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Zambezi Link Interconnector

Customer
NamPower, Namibia

Customer needs
- Connect the grid in the northwest with the grid in the central parts of the country

Our response
- Turnkey 350 kV 300 MW HVDC Light®
- Option for another 300 MW
- First HVDC Light® with overhead lines

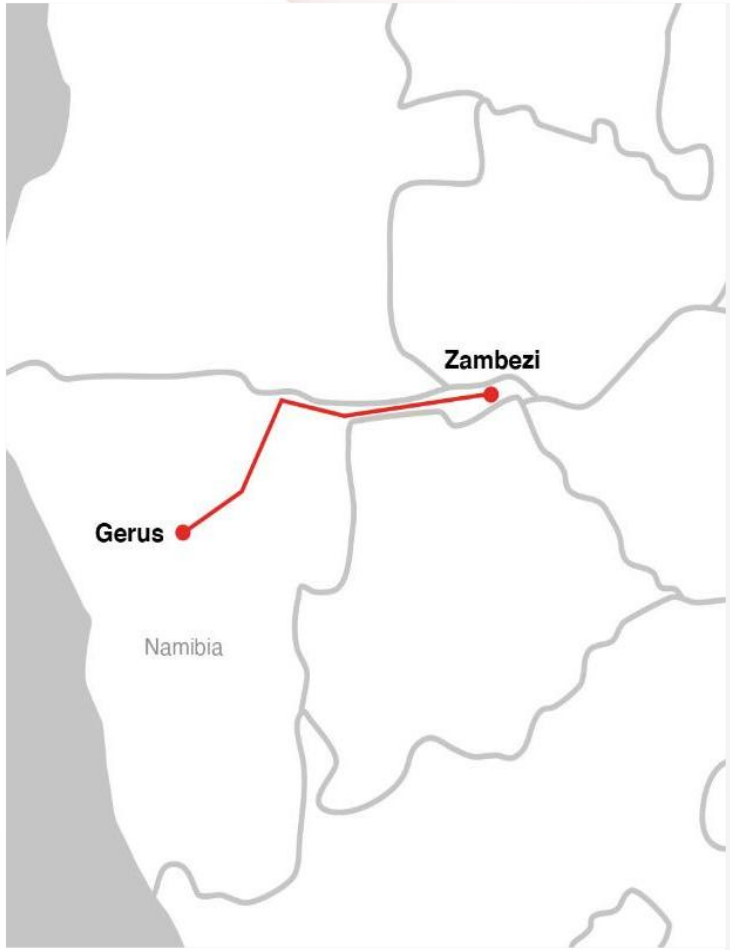
Customer benefits
- Stability in two very weak AC networks
- Enables future power trading in the expansive region of southern Africa

Year
2009

HVDC Light® converter stations

Asymmetrical monopole

System capacity of 300 megawatts (MW)



Stabilizes weak power networks in Namibia and enables power trading in the expansive region of southern Africa

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Grid support provided by HVDC – Zambezi Link Interconnector

Performance under islanded AC network in Namibia

June 3rd , 2010, transmission 80MW from Namibia to Zambia

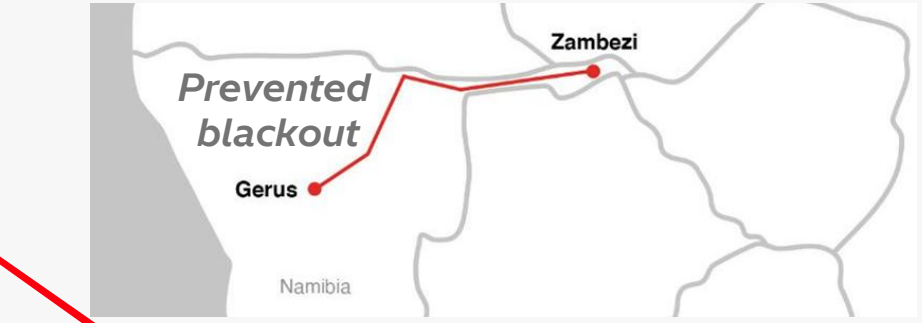
- Zambezi station (Zambia) in **power control mode** & **Gerus station** (Namibia) in the DC voltage control mode

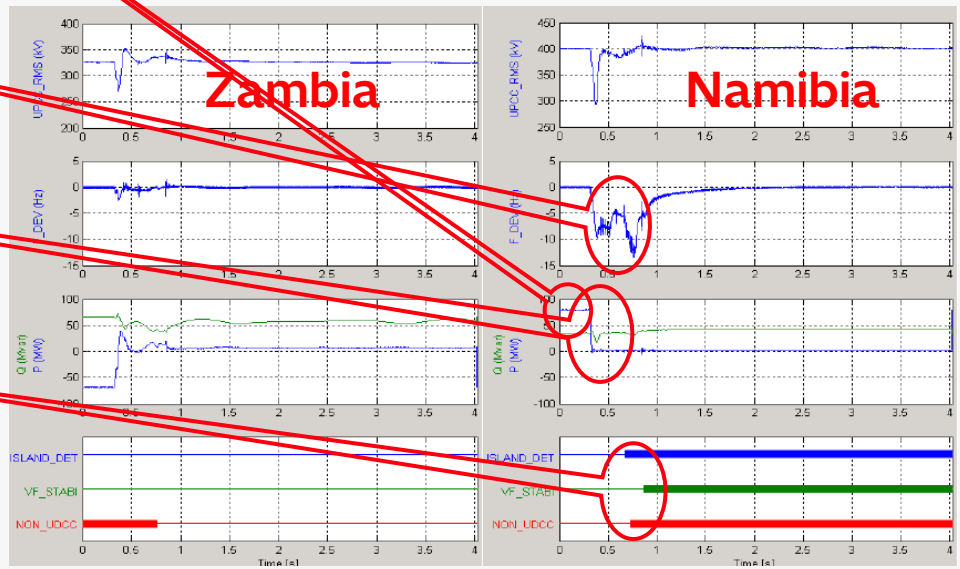
Event

- Trip of 220 kV line during power ramp-up when export from Namibia was 80 MW - sudden island in the Namibian grid
- The sudden outage of the line led to a large frequency dip in Namibian grid

Action

- Power export from Namibia was reduced to zero
- When the Islanded grid was detected:
  - Namibia station automatically switched the DC voltage control mode to Zambia
  - And switched to the voltage and frequency stabilization control (green signal in 4th plot)
- Namibian grid restored the stable AC voltage in both frequency and magnitude





Note: 1st plot: PCC & DC voltage (inst), 2nd plot: PCC voltage (RMS), 3rd plot: frequency, 4th plot: active & reactive power, 5th plot: Islanded condition indication (blue), FV control indication(green), DC voltage control indication (red).

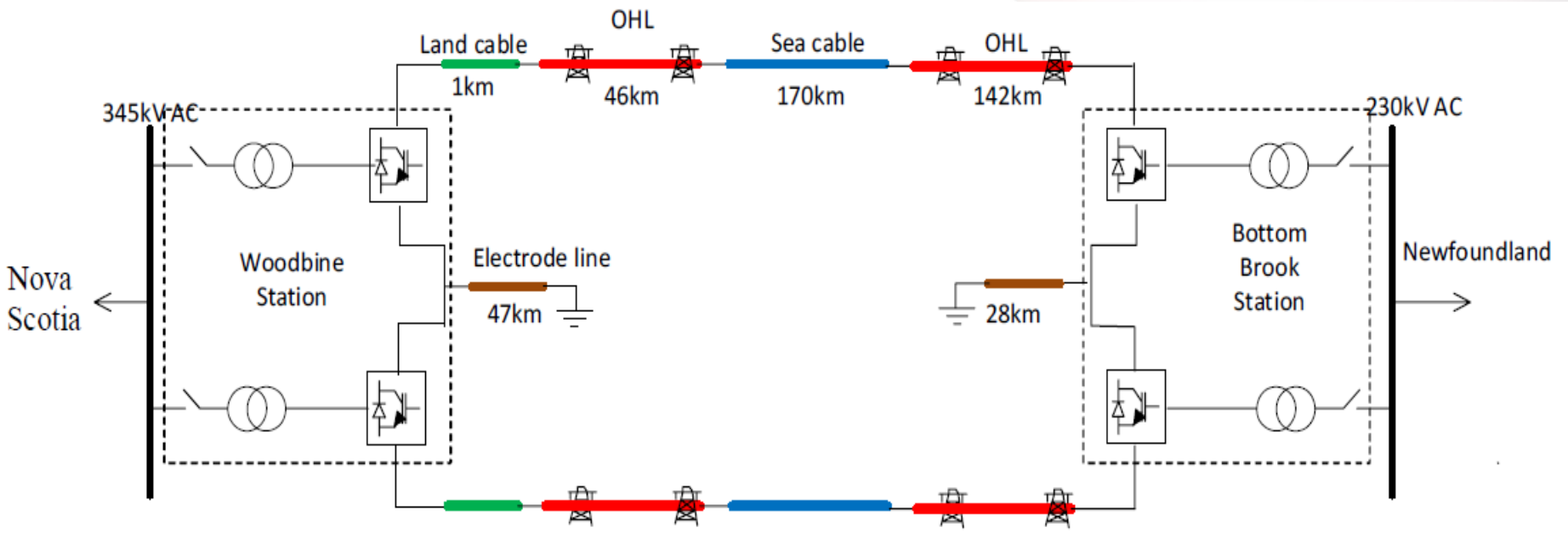
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Grid support provided by HVDC – Maritime Link

±200 kV DC,
500 MW bipolar
HVDC

DC transmission is composed of mixed of overhead lines and DC cable: with 170 km submarine cable, and 142 km & 46 km overhead lines



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Grid support provided by HVDC – Maritime Link

01 The HVDC can be used to support the frequency by automatically adjusting the power transfer

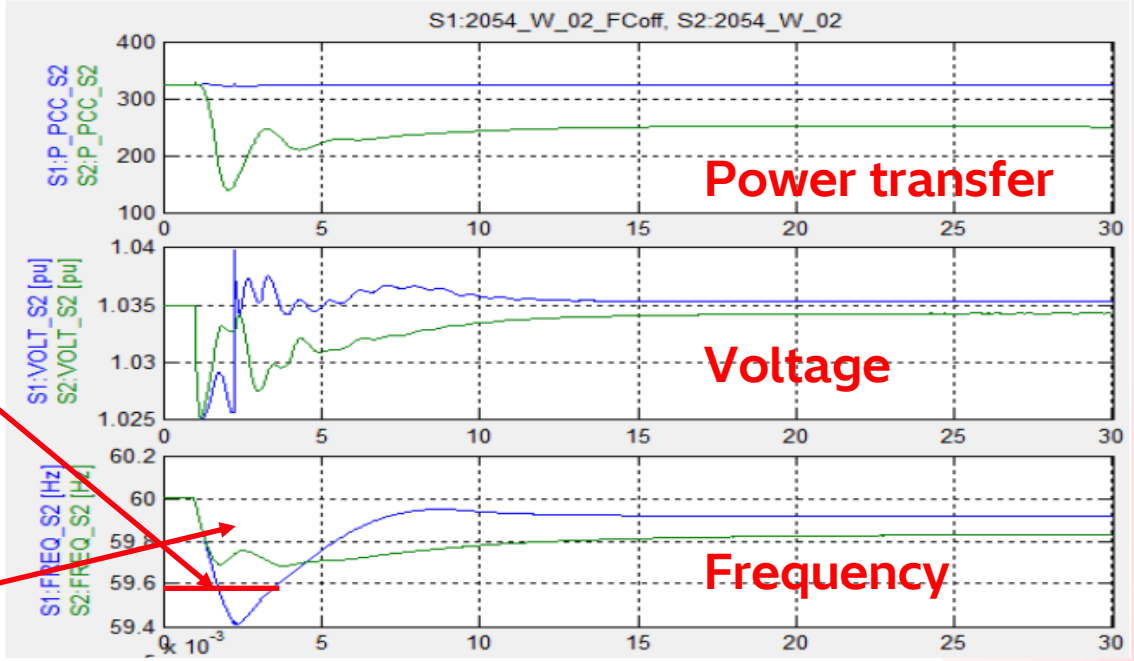
02 To minimize the **frequency deviation**, e.g. in case of loss of generators or loads, a frequency controller has been added

03 **Without a frequency controller** (blue) the HVDC would maintain its dispatched power and frequency would decrease by more than 0.5 Hz (threshold for load shedding) when a large generator trips

04 **With the frequency controller,** the HVDC would automatically adjust the power, and the frequency deviation would be below the load shedding threshold

Effect on AC system without HVDC control response

HVDC response reduces deviations and damps oscillation



Effect of frequency controller (FC) under critical conditions e.g. disturbance led a generator trip: blue (without FC) and green (with FC)

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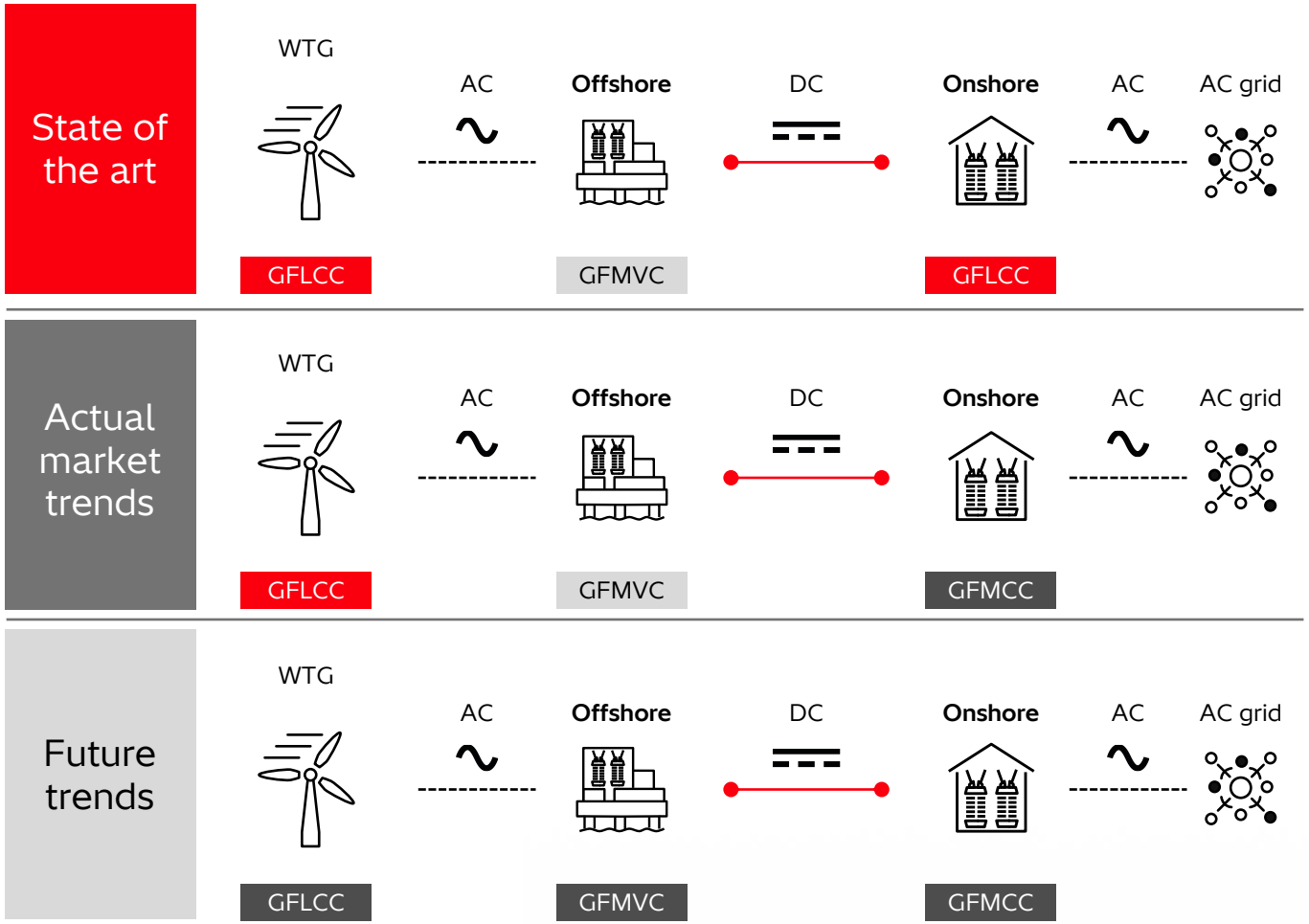
Applications and physical limitations



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Grid forming in offshore wind



01 In offshore wind application, GFMVC fully operational (FU control)

02 Full Grid forming capability can be achieved by deployment of GFM WTG

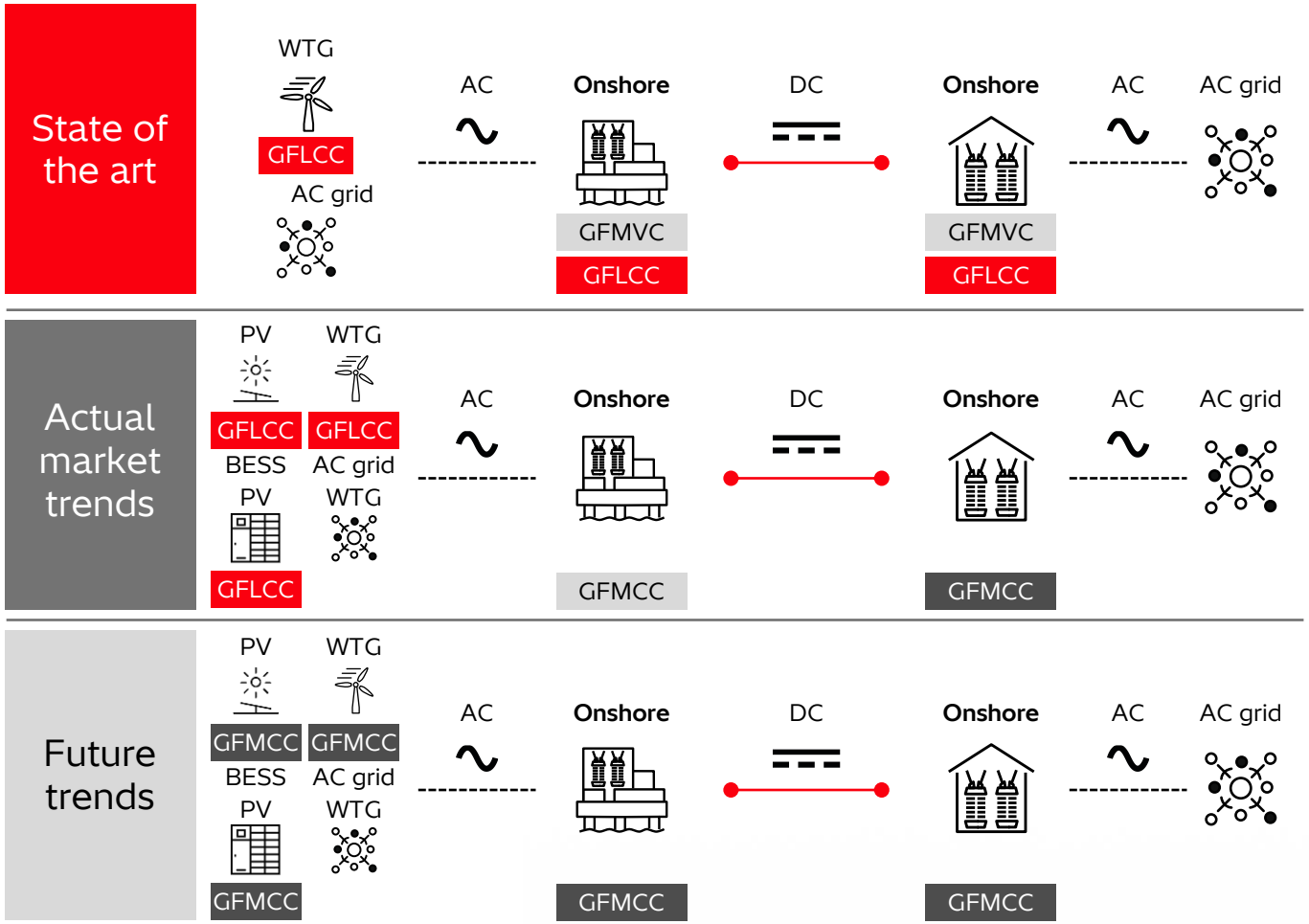
03 Projects are in execution with GFMCC capability (limited Grid forming capability)

GFLCC – Grid following Current Control
GFMVC – Grid forming Voltage Control
GFMCC – Grid forming Current Control

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Grid forming in multi-purpose interconnectors



01 Interconnector applications are fully operational with combinations of GFMVC and GFLCC, operating in different control modes (FU, PQ, PUAC control)

02 Interconnector Projects are in execution with GFMCC capability (limited Grid forming capability)

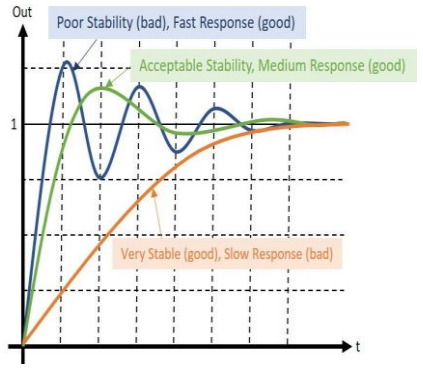
03 Full Grid forming capability can be achieved only by deployment of Grid forming Renewable units (BESS, WTG, Solar ..)

GFLCC – Grid following Current Control
GFMVC – Grid forming Voltage Control
GFMCC – Grid forming Current Control

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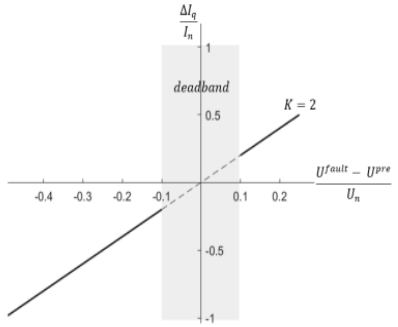
HVDC Grid forming fundamentals

Strong/Weak Grid



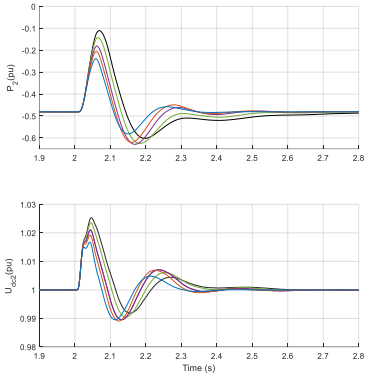
Grid-forming controllers may face limits in strong grid conditions

Reactive Current



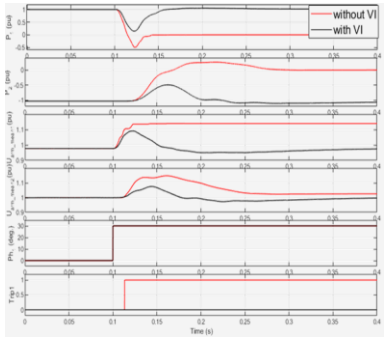
Requirements on reactive fault current during faults conflict with grid forming behavior

Inertia Time Constants



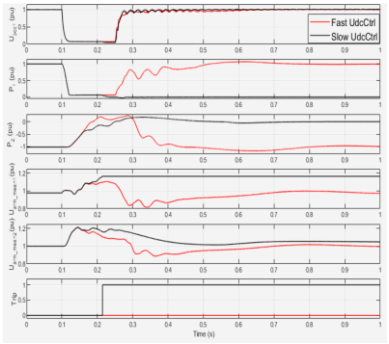
A higher inertia time constant causes slower controller response and increased active power fluctuations

Virtual Impedance



Virtual impedance increases controllability and reducing stress on the converter

UDC-control



Inertia requirements delay UDC control and negatively affect DC link stability during disturbances. Coordination between P-control and UDC-control stations is necessary

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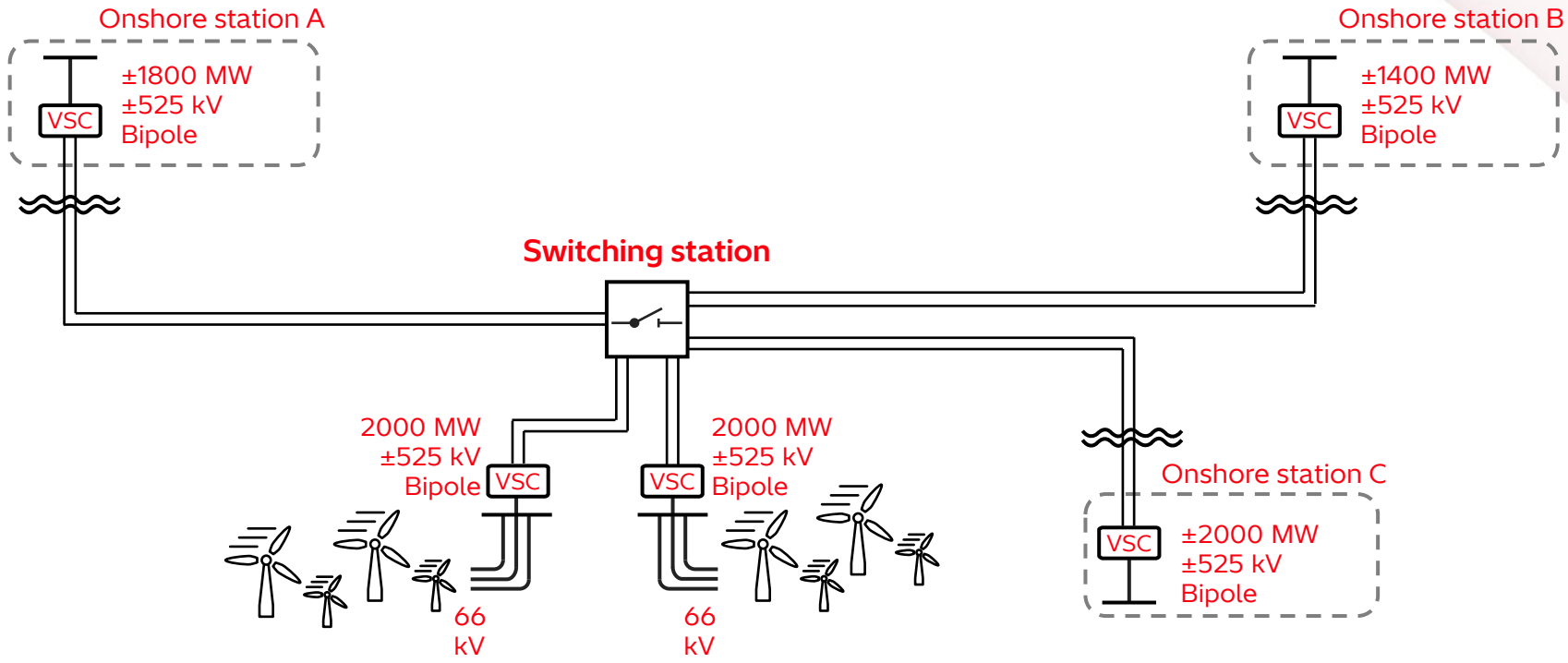


HVDC looking forward?

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Strategic Value of MTDC in Modern Power Grids



An MTDC system is an HVDC network linking three or more converter stations, allowing transfer between several sites via a common DC grid

MTDC Benefits

01 Enhanced Grid Flexibility

02 Improved Reliability and Redundancy

03 Better Support for Renewable Integration

04 Reduced Infrastructure Costs

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Caithness Moray Shetland project

A future-proof solution enabling renewable integration

- Multi-purpose HVDC for up to five converter stations and two solutions for multi-terminal connection point

And enhanced grid reliability

- Blackhillock - stabilizes the DC grid through **DC voltage control**
- Spittal - stabilizes Caithness AC network through **Grid forming control**
- Kergord - stabilizes Viking wind farm on Shetland through **frequency and AC voltage control**
- **Emergency Power Control (EPC)** functions for critical conditions

Early definition of final stage

Detail multi-terminal studies for 5 stations

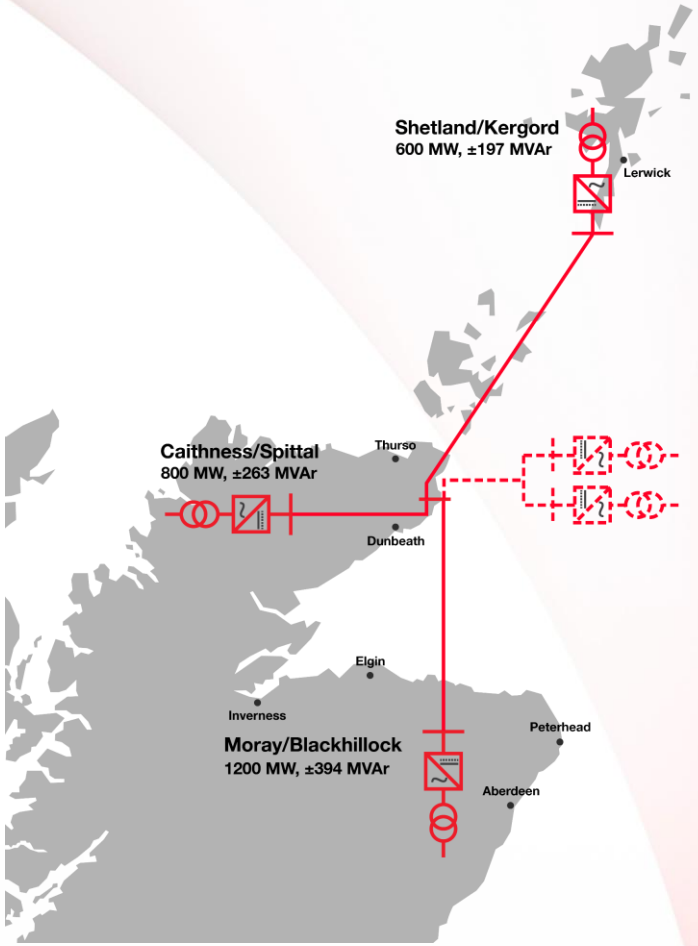
- Exponential modes of operations
- Rating and performance studies using Virtual Control & Protection for accuracy and efficiency

Switching station solution

- For disconnect and reconnect of DC cables and converter stations during power transmission

DC Grid Controller

- To coordinate all signals and sequences, already implemented at stage 1

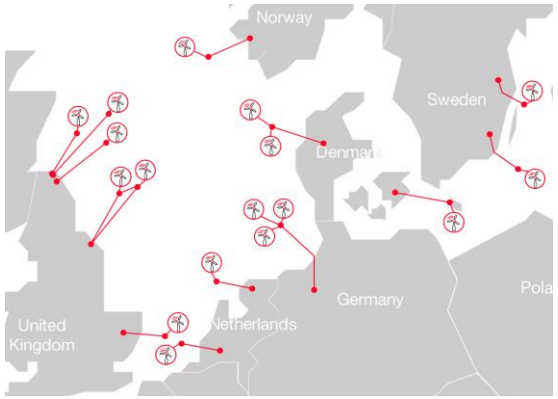


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Future Transmission System – the European example

National Distributed Hubs (NAT)

- TRL 9 – **already in operation** in Germany
- 2 GW bipole links will be required to meet market future requirements – **no major gaps** however

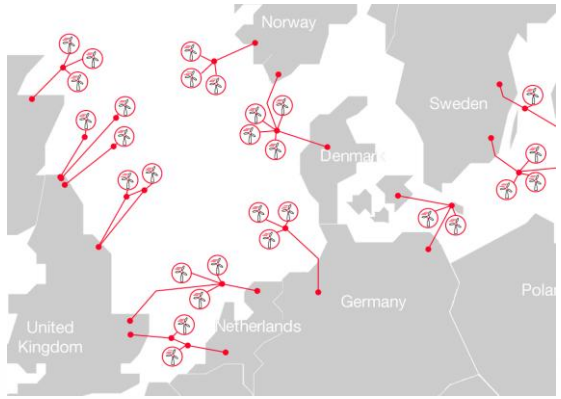


Centralised Hubs (HUB)

Can be built today with

- Single vendor approach
- Multi-vendor solutions with AC connections btw DC links
- More than one protection zone if utilizing the Hitachi Energy's AxoniQ™ Protect (hybrid HVDC breaker)

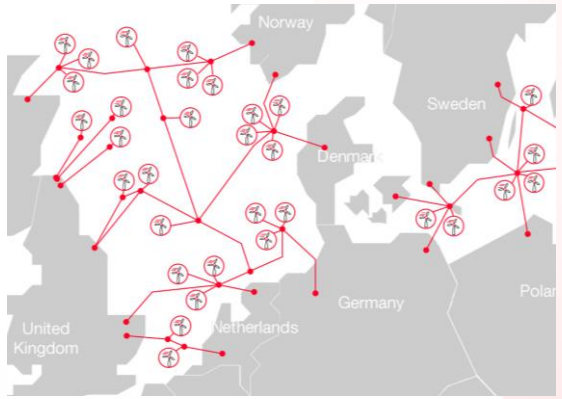
Will require **further development** for **multi-vendor**, multi-terminal approach



Meshed Offshore Grids (MOG)

Will require

- Interoperability
- DC CB
- DC grid codes
- DC grid control and protection



Location of wind farms and transmission links only for illustration purpose
TRL – Technology Readiness Level

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Grid Forming Controls - Way Forward

Hitachi Energy possesses extensive expertise in "Grid forming."

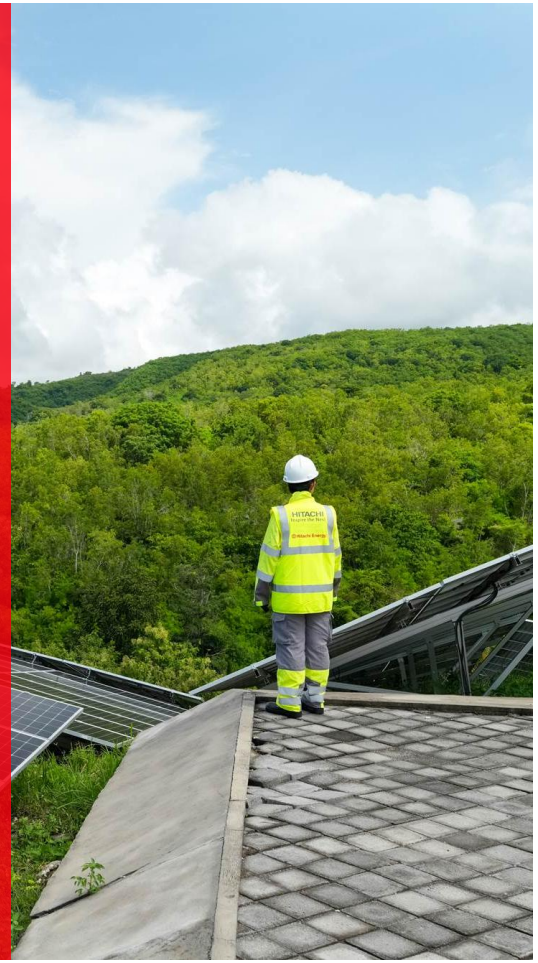
01 Grid forming as the principle of voltage behind impedance is nothing new.

02 New supplementary requirements are arising that need to be considered.

03 It is essential to consider physical limitations.

04 It is preferable for requirements to be specified based on performance.

We are eager to advance the grid forming functionality in our application through close cooperation with industry partners.



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The information given in this document contains general descriptions which may not always reflect those provided by the final system solution developed by considering specific project conditions.

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HVDC

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