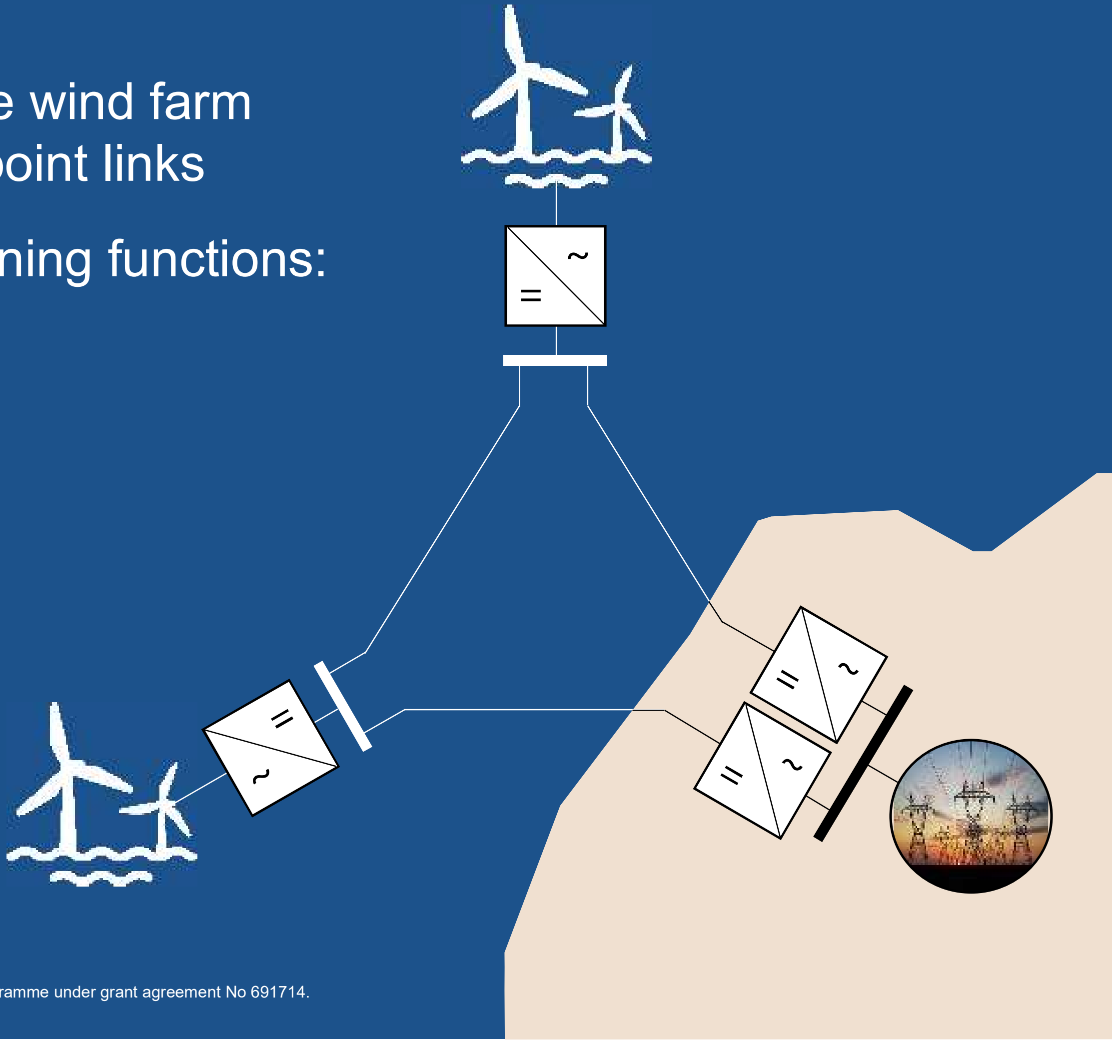
Why do we need meshed HVDC grids?

- Existing HVDC interconnectors and offshore wind farm export connections are all dedicated point-point links
- Improve availability and utilisation by combining functions:
  - Offshore wind export
  - Interconnection
  - AC grids reinforcements



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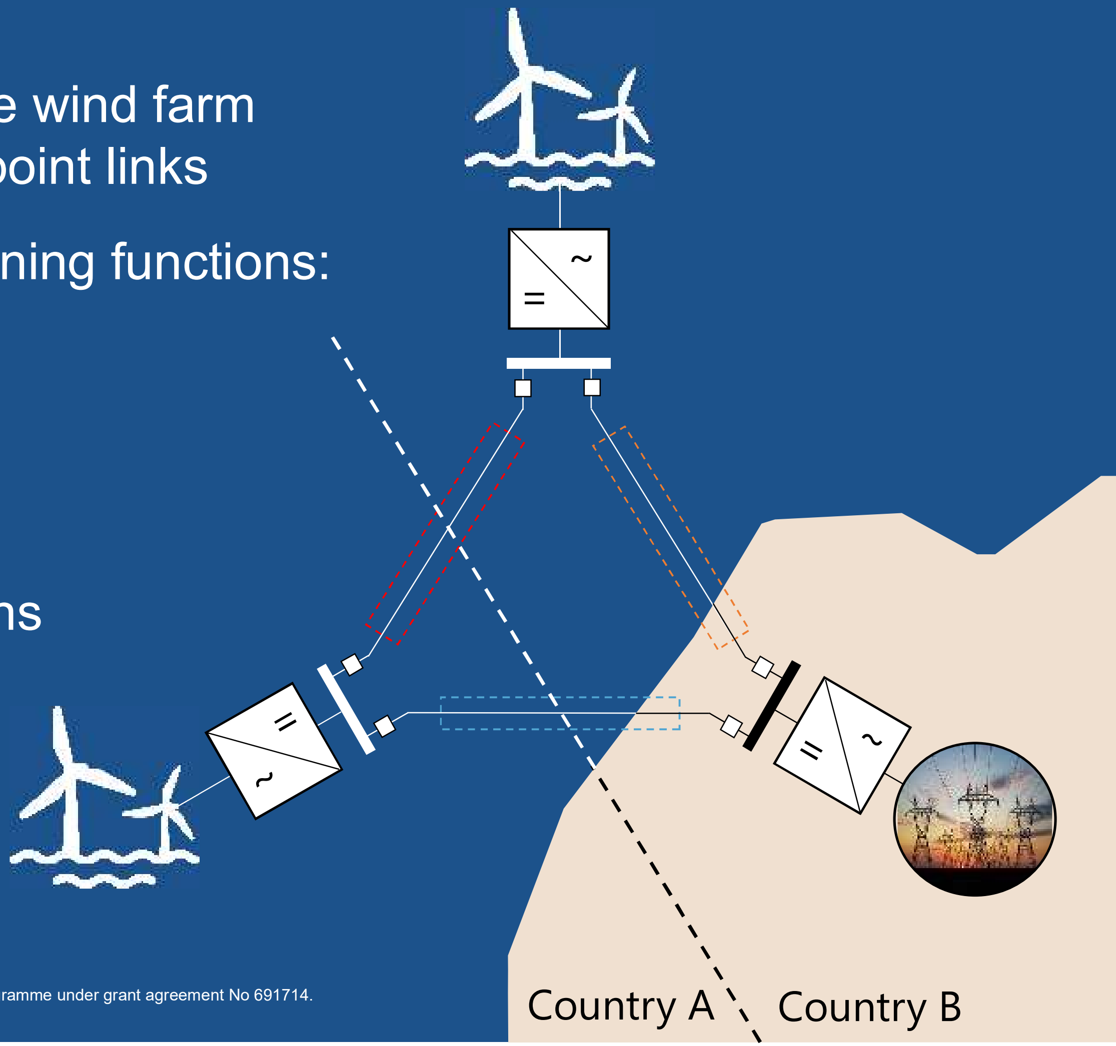
Why do we need meshed HVDC grids?

- Existing HVDC interconnectors and offshore wind farm export connections are all dedicated point-point links
- Improve availability and utilisation by combining functions:
  - Offshore wind export
  - Interconnection
  - AC grids reinforcements
- Connect on the DC side
- Benefits compared to point-point connections
  - Better utilisation
  - Better availability
  - Lower CAPEX
  - Lower OPEX



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PROMOTioN Context

Outlook: Real progress is coming but requires action now

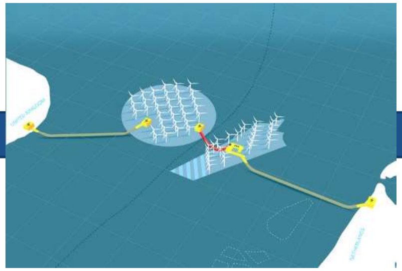
2027

Standardized 2 GW 525 kV
platform concept (TenneT)

2030

Danish energy islands
(Energinet)

2030?

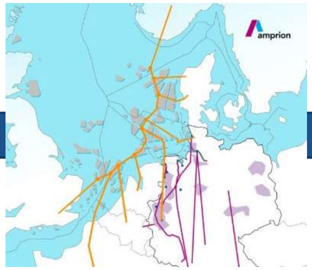


WindConnector
(MoU TenneT & Vattenfall)

2040?

North Sea Wind Power Hub
(TenneT & Energinet)

2050?



Eurobar concept
(Amprion)

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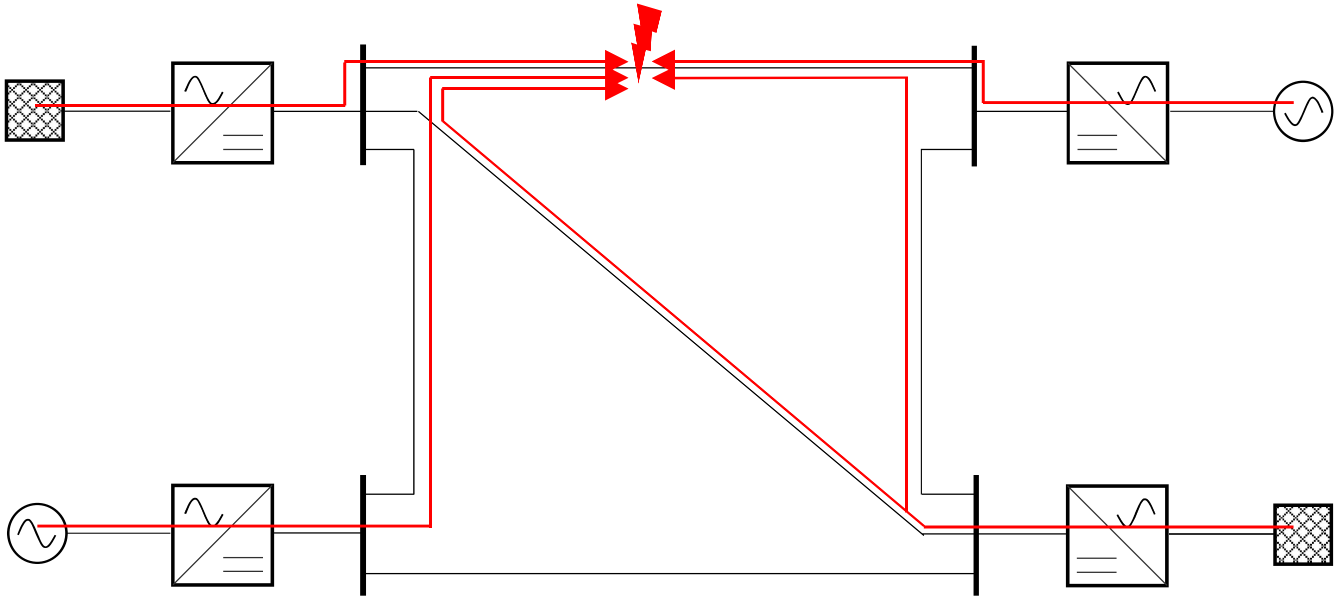
Application

HVDC system fault response



- Faults will happen
- Voltage collapses on the faulty pole
- Depending on converter type and configuration a fault current flows

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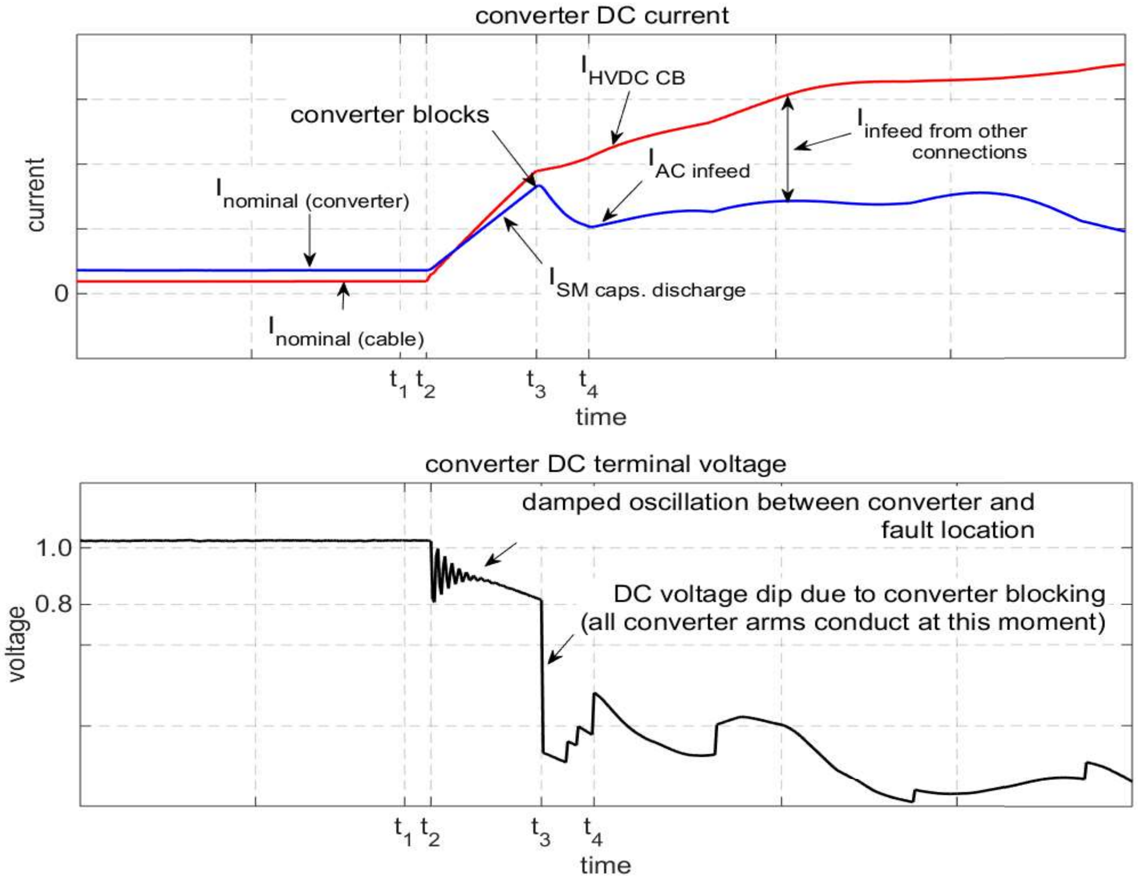
HVDC system fault response



- Fault current contributions by:
    - Discharging capacitances of neighboring cables
    - Discharging capacitances half bridge converters
    - **AC grid infeed**
- Converter blocking reduces current & energy stress
- Series reactors delay converter blocking but increase energy stress
- Fault current contributions can be modelled with passive equivalent sources

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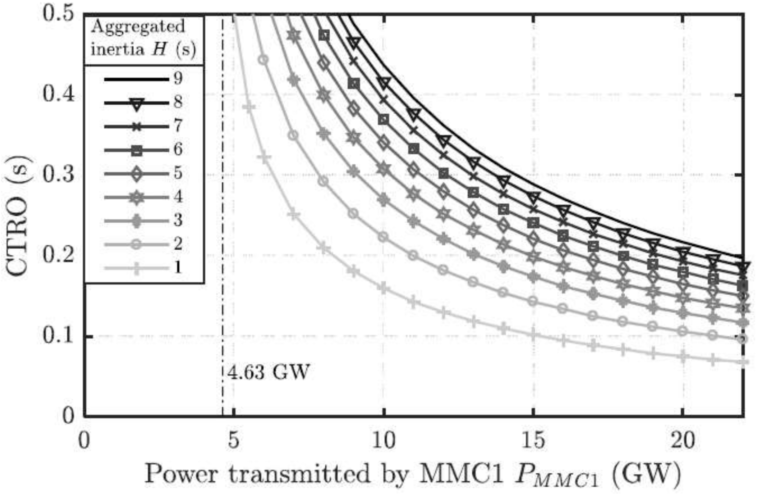
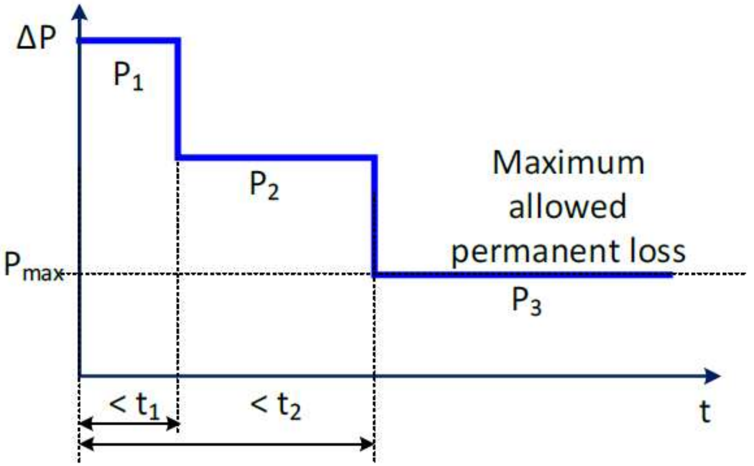
Impact on connected AC grids

- AC grids are affected by faults in connected DC grid
- In case non-fault blocking converters in asymmetric or bipole configuration are used, the **DC fault is seen as a three phase fault by the AC grid**
  - Local voltage sags at converter terminals
- During the DC fault, **no real power can be transported** through the part of the DC grid in which the voltage collapsed
- Depending on the amount of power capacity lost and the duration of the interruption, the **frequency & phase angle stability of the AC grid could be affected**
- Protection system needs to ensure the **maximum loss of infeed** does not exceed the (permanent or temporary) reference incident capacity in the connected AC grids





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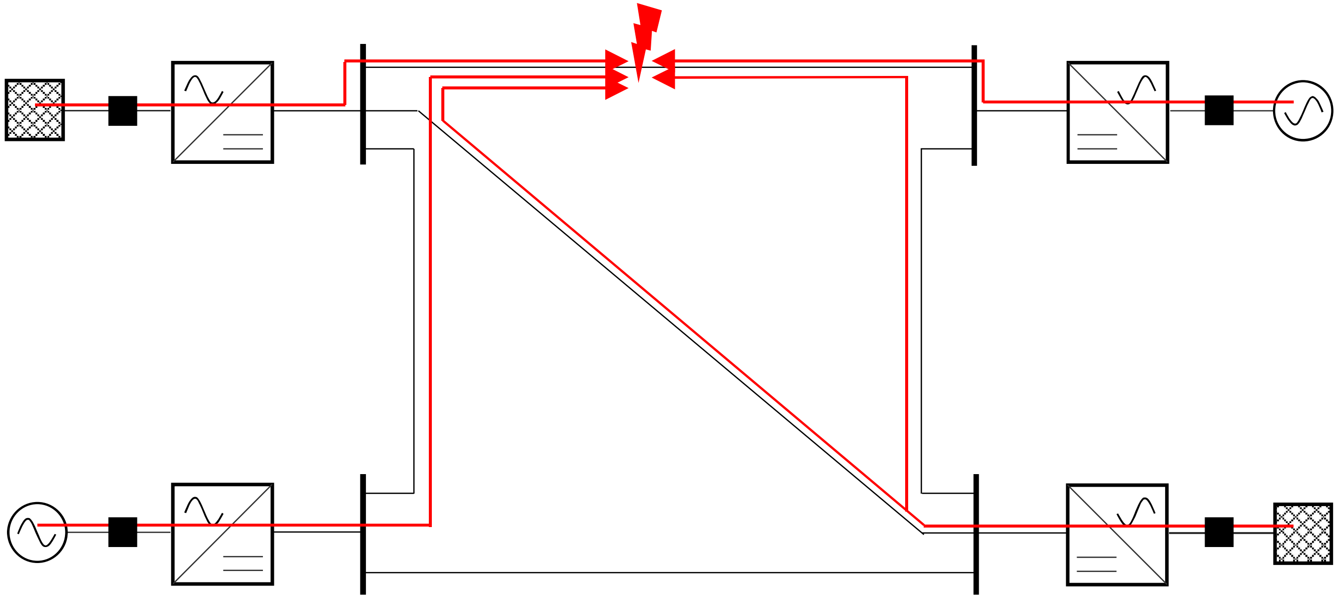
HVDC Circuit Breaker Application

AC breaker fault clearing strategy



- Current approach: place AC circuit breakers next to each converter
- Open all converter circuit breakers
- Converters trip, grid de-energises → long interruption

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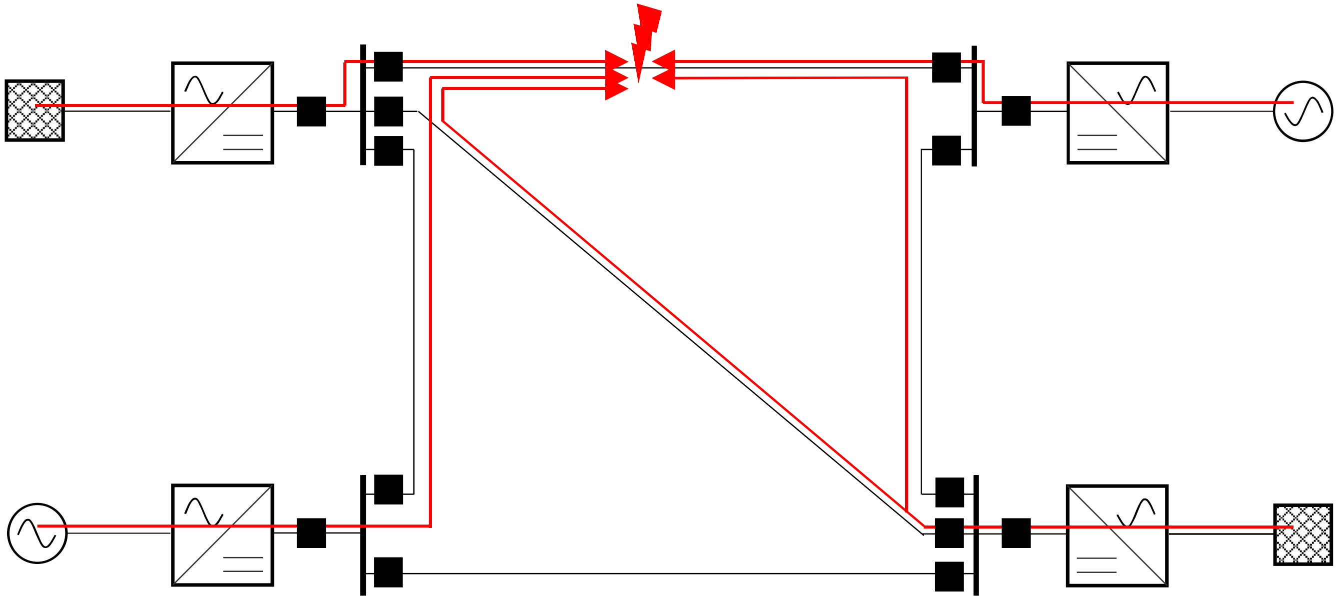
HVDC Circuit Breaker Application

Fully Selective Fault Clearing Strategy



- Place DC circuit breakers at each line end and converter
- Open circuit breakers closest to fault
- Continue operation

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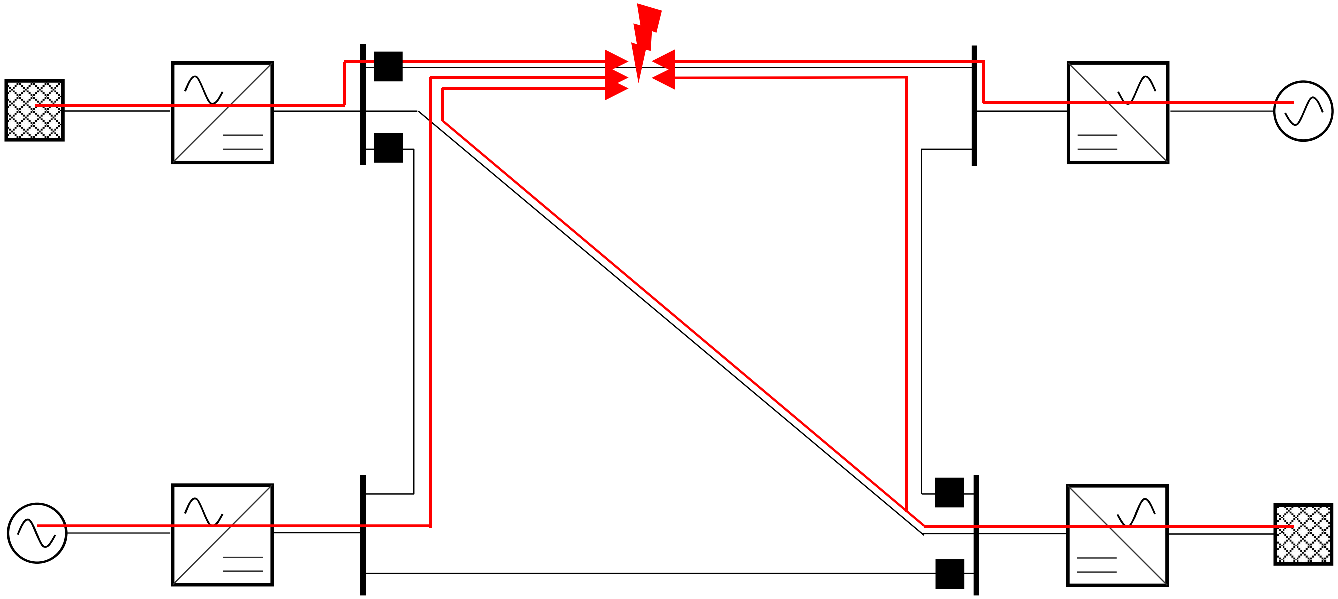
Partially Selective Fault Clearing Strategy



- Only install DC circuit breakers at strategic locations
- Split grid
- Continue reduced adequacy operation

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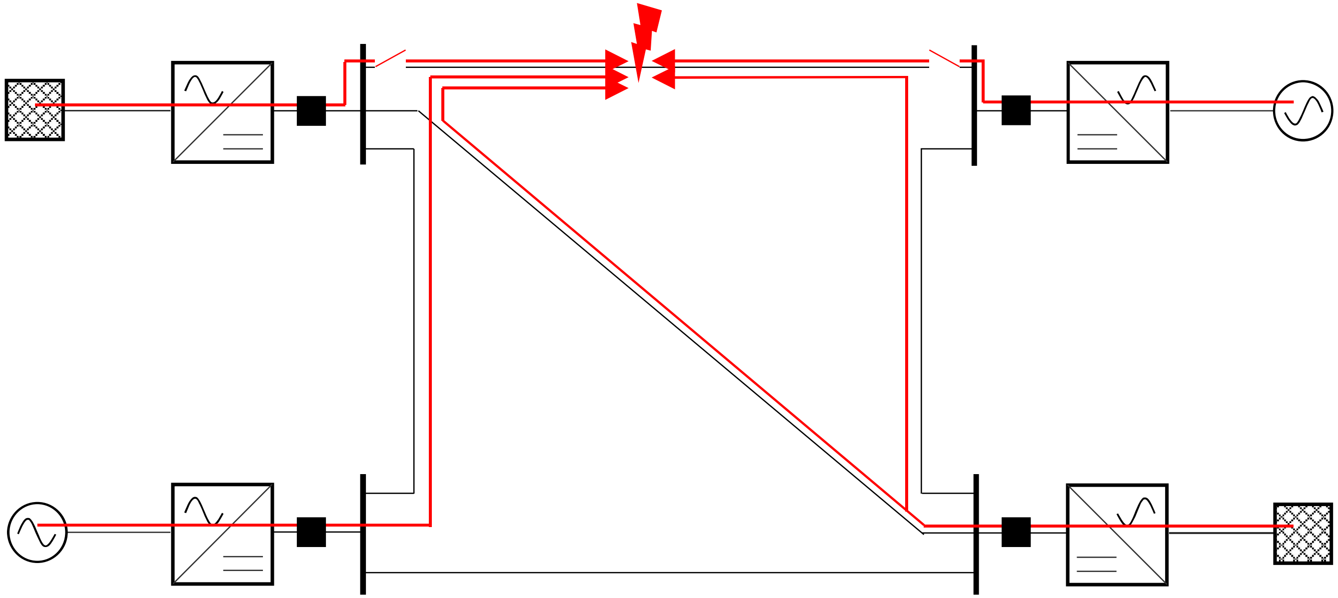
HVDC Circuit Breaker Application

Non-Selective Fault Clearing Strategy



- Only install DC converter breakers and ultra-fast line disconnectors
- Open all breakers (or converters) to suppress fault current
- Open disconnectors at faulty cable ends
- Re-energise grid and continue operation

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Fault Clearing Strategies

- What is the impact on the AC grid(s) in case the HVDC grid fails?
  - What is an acceptable magnitude and duration of loss-of-infeed to the AC grid?
  - Should protection system clear faults before converters block?
  - What does system restoration of the healthy HVDC grid look like?
- What type of converters and/or number and location of HVDC circuit breakers?
- What is the back-up protection?
- How much does it cost to buy (CAPEX) and how much does it cost to run (OPEX)?

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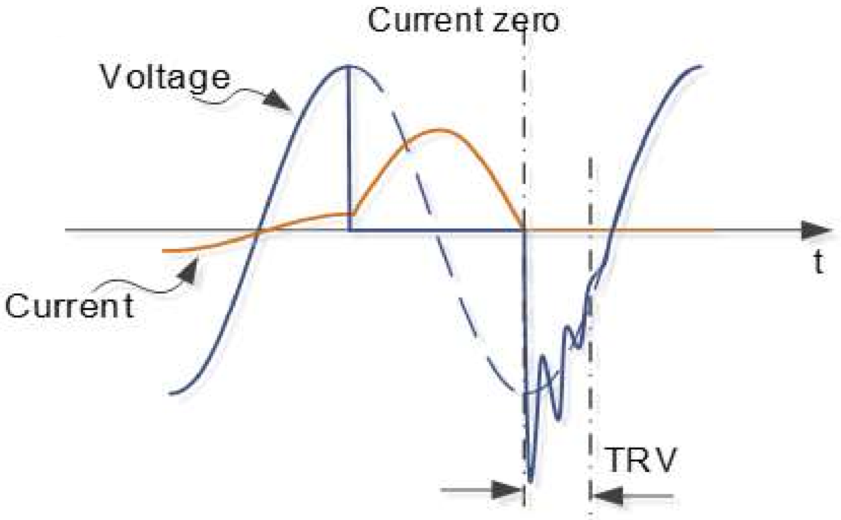
Principles

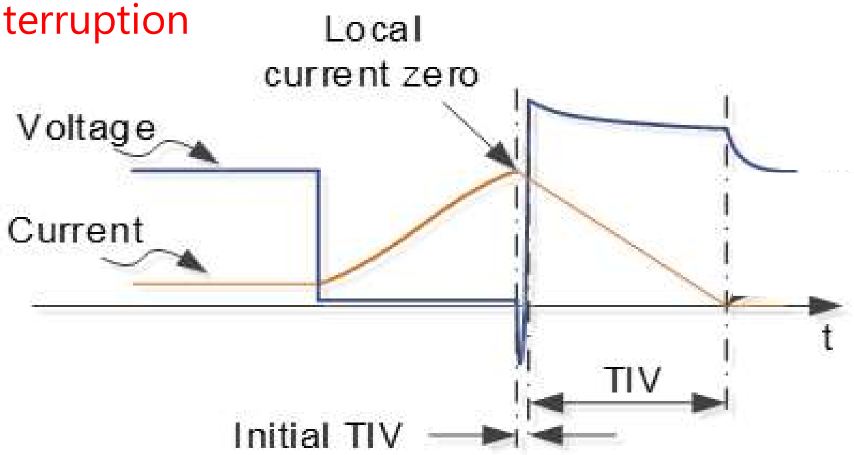
Principles of current interruption

AC interruption



- Circuit breaker passive
- System imposes current
- System imposes TRV
- Test synthetically

DC interruption



- Circuit breaker active
- CB determines current
- CB determines TRV
- Needs MW to test

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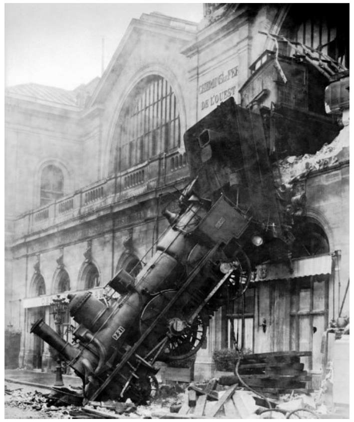
Principles of current interruption



15 kA in 100 km line = 11 MJ
= 30 ton train at 100 km/h

AC interruption:
Capture the swinging mass in its outer position (current zero).
Zero kinetic energy

DC interruption:
Oppose the motion of a linearly moving mass (counter voltage)

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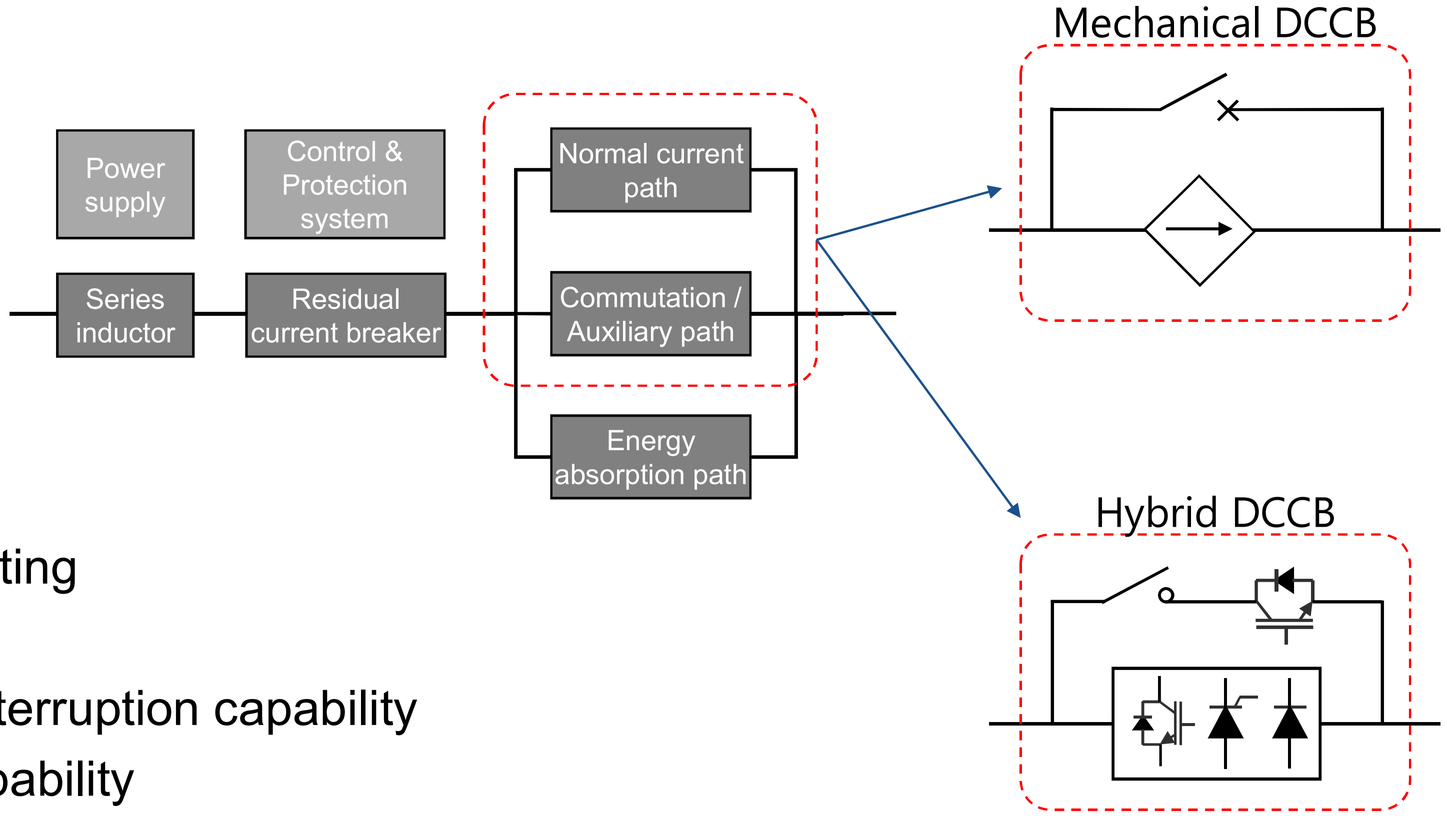
Generic Structure



- Nominal current rating
- Current interruption rating
- Speed of interruption
- Uni- or bidirectional interruption capability
- Energy absorption capability
- Transient interruption voltage
- Isolation

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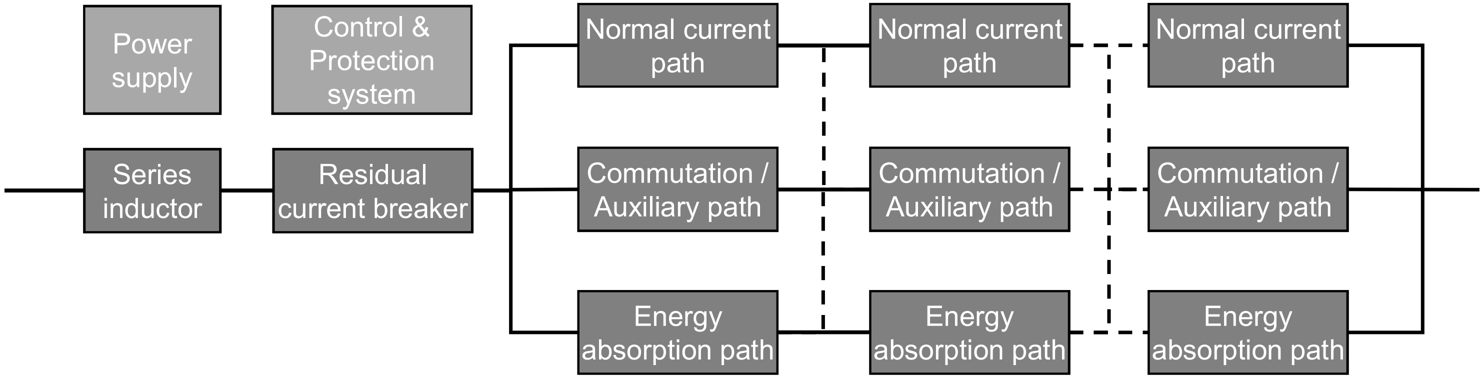
Modularity



- Modular construction to achieve full-pole voltage rating
  - Number and voltage rating of modules
  - Common (full-pole) components
  - Voltage distribution across modules
- Special features:
  - Reclosing, soft-closing / soft-opening
  - Fault current limiting
- How does choice of module rating impact reliability, size, weight & cost?
- Is redundancy required?

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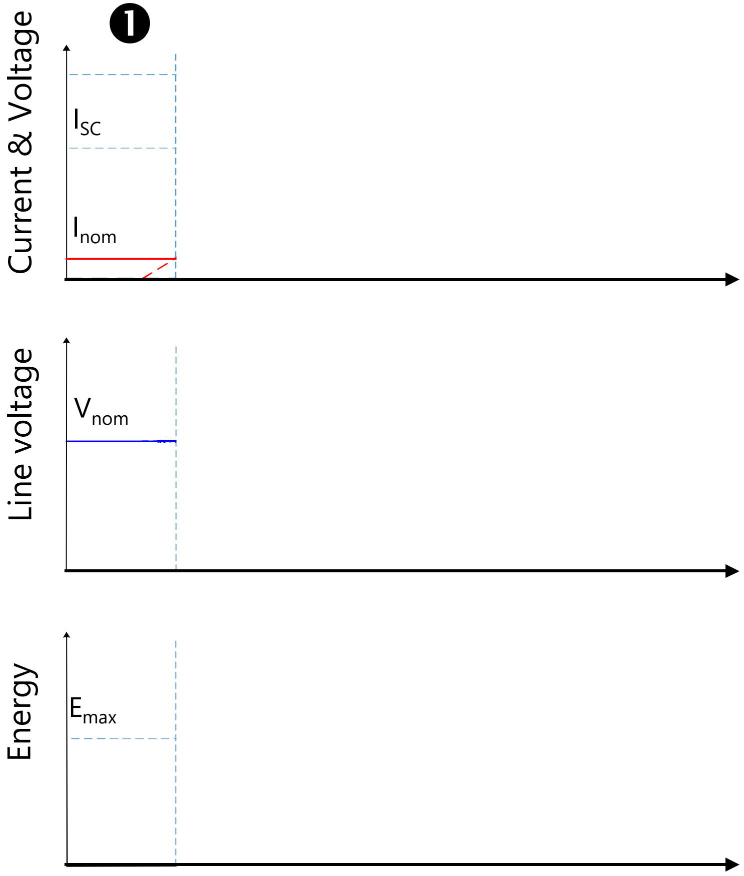
Typical operating waveforms

❶ Normal closed position
  - Dielectric stress on support structure
  - Nominal current heating

❷ Fault current commutation
  - Commutate rising fault current
  - Bidirectional, different duties

❸ Fault current suppression
  - Absorb energy
  - Withstand Transient Interruption Voltage

❹ Normal open position
  - Dielectric stress across terminals and on support structure



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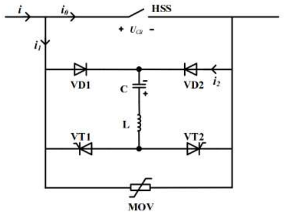
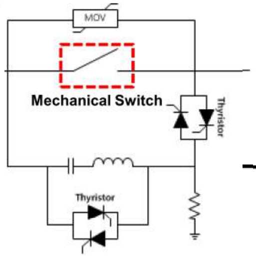
HVDC **Circuit Breaker** Principles

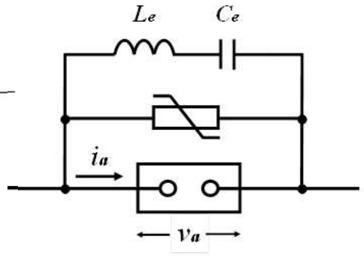
Topologies

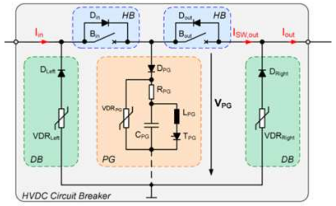
Mechanical HVDC circuit breakers

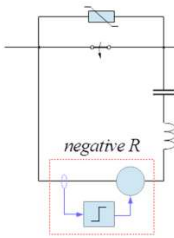
- Mechanical circuit breakers
  - Active current injection
  - Passive resonance
  - Active resonance

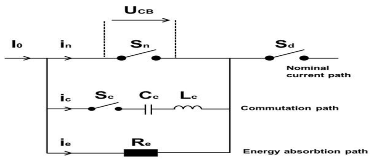






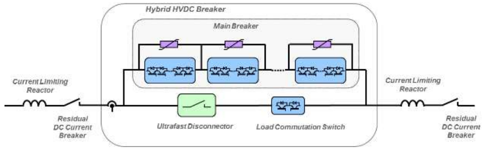


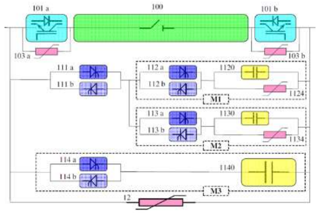


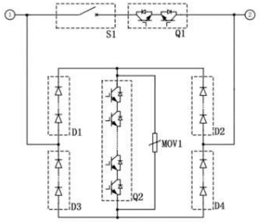


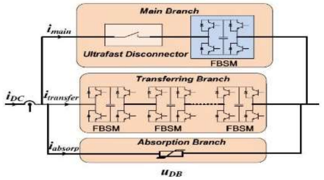
Hybrid HVDC circuit breakers

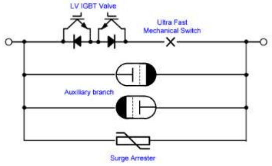
- Hybrid circuit breakers
  - Thyristor based
  - IGBT based
  - Gas discharge tube based











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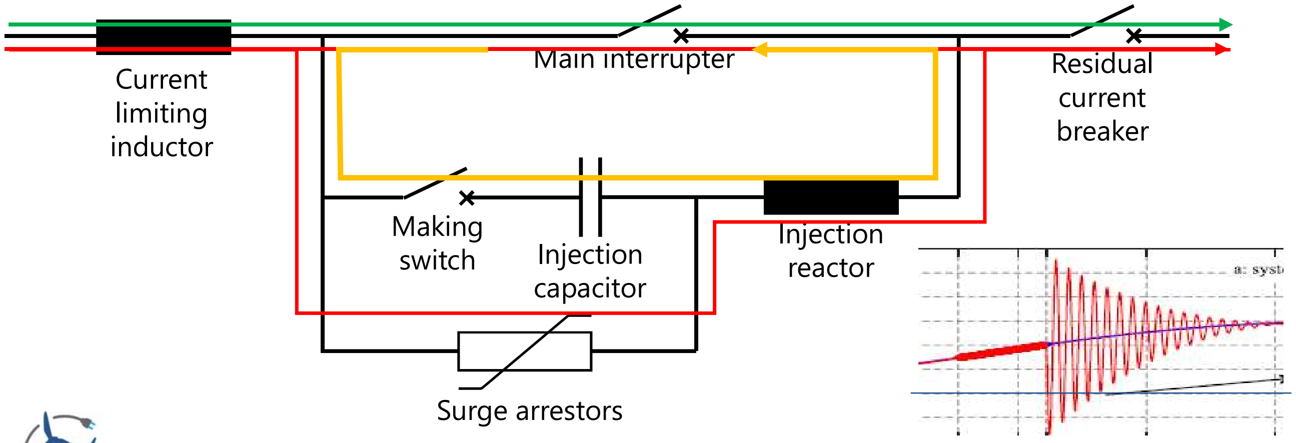
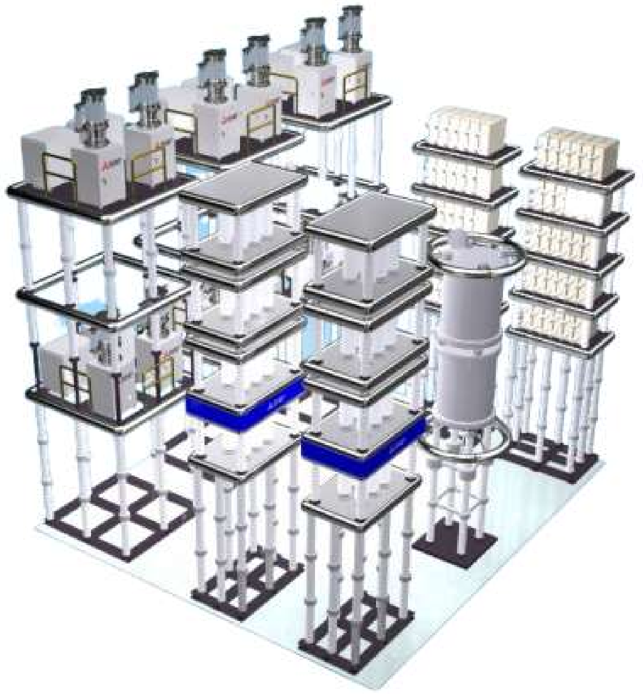
Mechanical HVDC circuit breaker with active current injection

MITSUBISHI ELECTRIC

- Local current zero created by discharging capacitor through main interrupter in opposite direction
  - Decaying resonance → finite number of current zeros
  - Needs capacitor charging equipment
- When interrupter is open, fault current commutated into surge arrestor by charging injection capacitor
- Fault current suppressed by surge arrestor



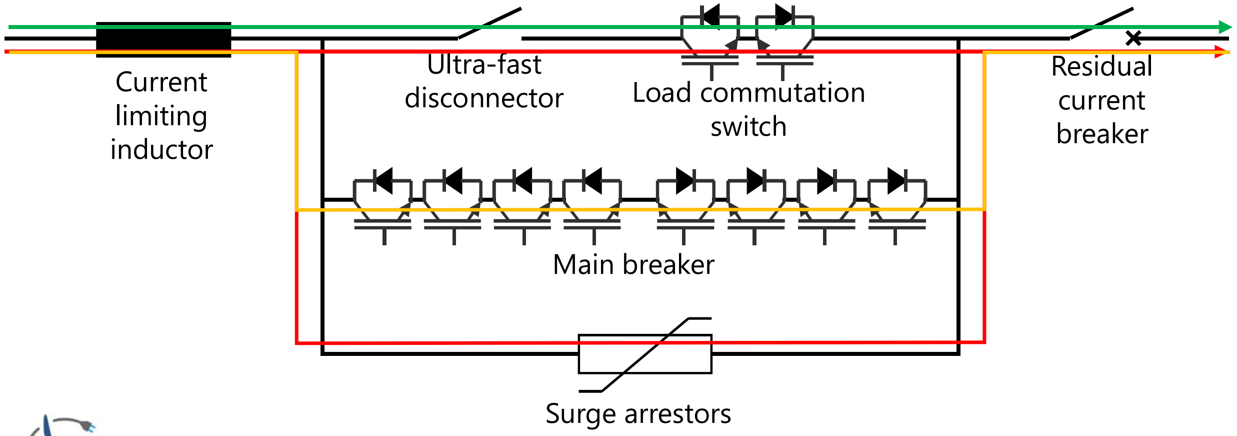


Artist impression of 525 kV rated mechanical HVDC circuit breaker with active current injection

Hybrid HVDC circuit breaker

HITACHI ABB

- Local current zero created for disconnector to open by opening load commutation switch and commutating fault current into main breaker
- When disconnector fully open, current commuted into surge arrestor by main breaker
- Fault current suppressed by surge arrestor



Artist impression of 350 kV rated hybrid HVDC circuit breaker

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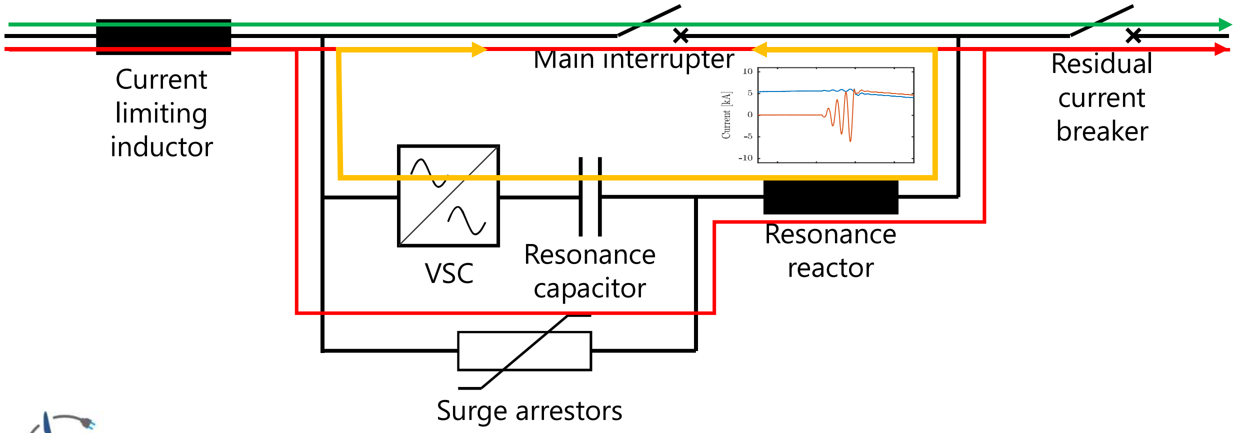
Mechanical HVDC circuit breaker with VSC assisted resonance current (VARC)

SCiBreak
Enabling the Supergrid

- Local current zero created by exciting resonance current through main interrupter
  - Growing resonance
  - Needs VSC power supply equipment
- When interrupter is open, fault current commutated into surge arrestor by charging injection capacitor
- Fault current suppressed by surge arrestor



Artist impression of 320 kV rated mechanical HVDC circuit breaker with VSC assisted resonance current

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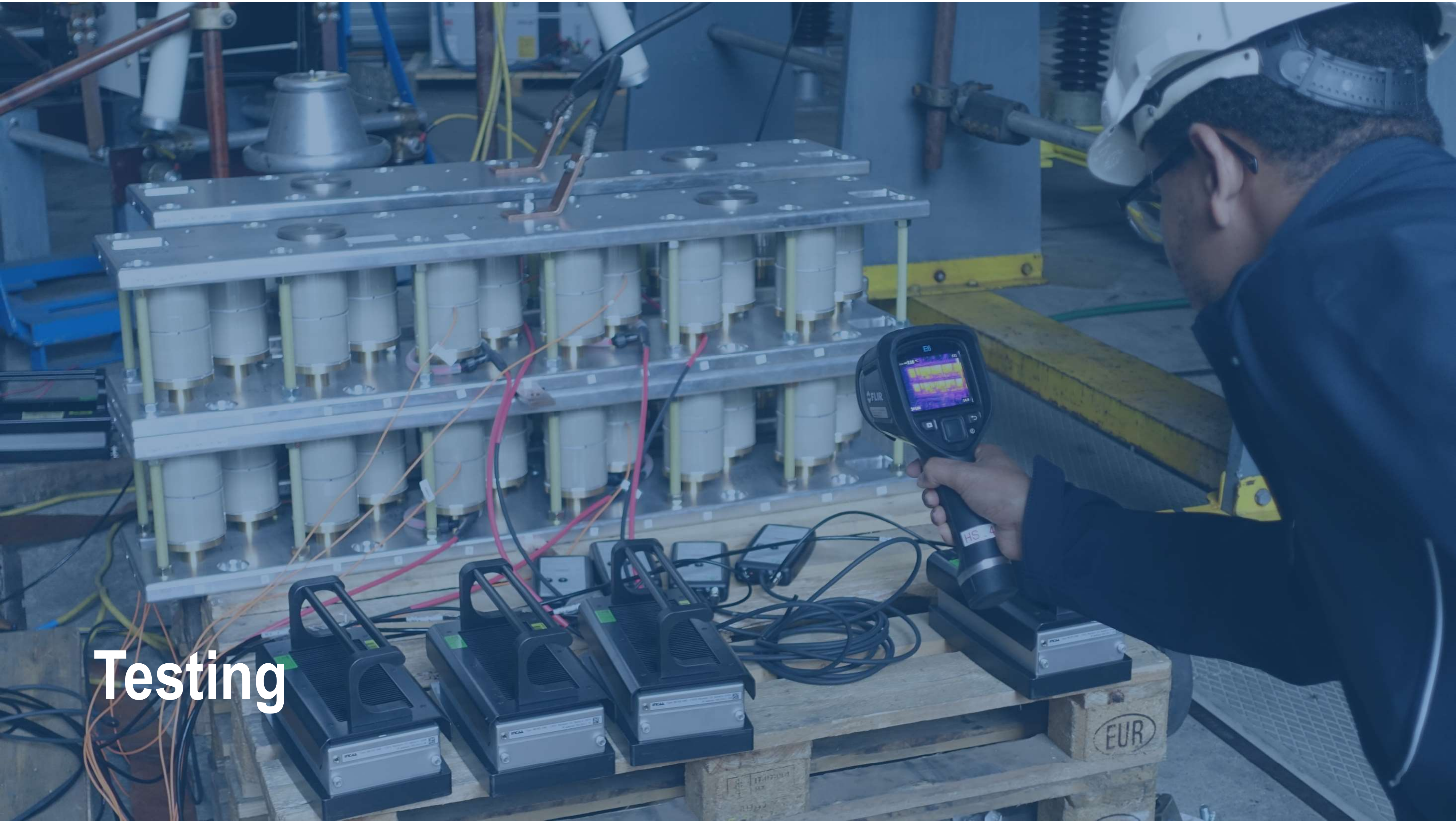

Testing

HVDC Circuit Breaker Testing

Test requirements

- Dielectric testing
  - Between terminals / Support structure
  - DC withstand / impulse / EMI
- Operational testing
  - Loss / resistance measurement
  - Temperature rise
  - Current withstand

Standard test circuits

- Current interruption testing
  - Breaking current
  - Operation time
  - Energy absorption
  - Transient interruption voltage withstand
- Special
  - Re-closing Current limiting / Soft closing
  - Endurance

Non-standard test circuits

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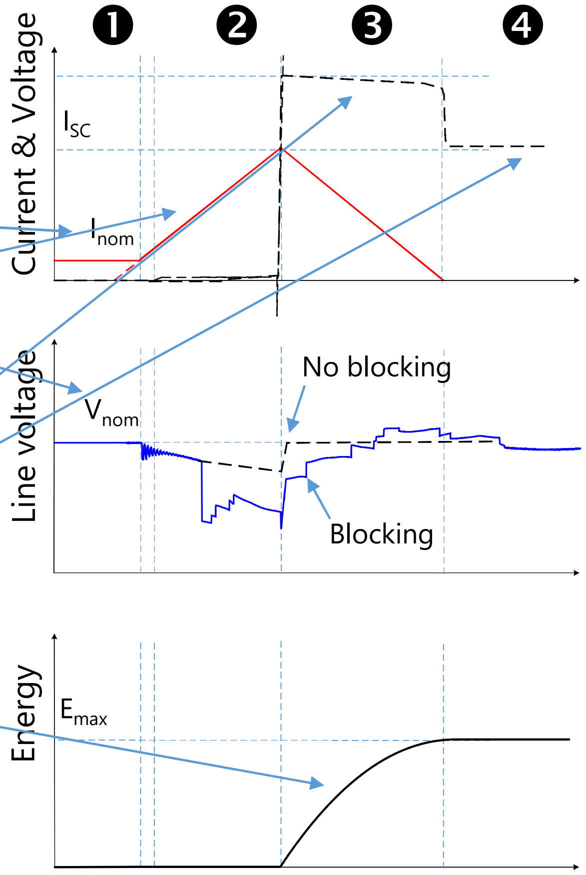
HVDC Circuit Breaker Testing

Current Interruption Test Requirements

- ❶ Normal operation
  - Apply heating – Pre-condition
  - Supply power to auxiliary systems
- ❷ Current commutation time
  - Supply range of di/dt
  - Bidirectional, different duties
- ❸ Fault current suppression time
  - Withstand Transient Interruption Voltage
  - Supply sufficient energy
- ❹ Post suppression
  - Apply DC voltage stress
- ❺ Protect test-circuit & test object



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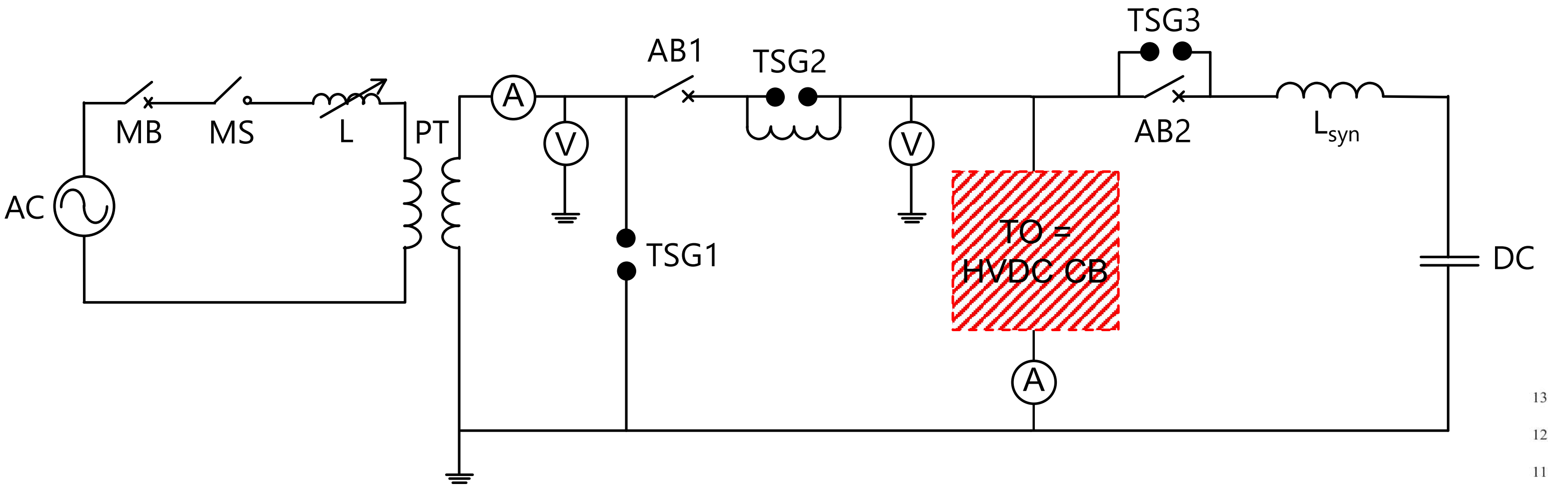
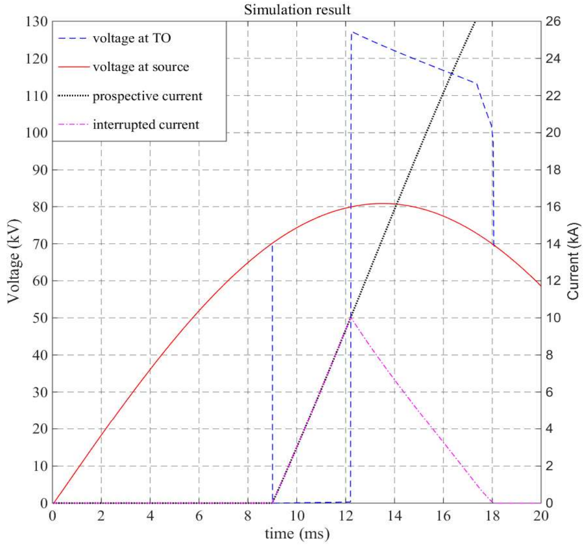
AC short-circuit generator based test circuit



- Create current and energy stresses
- Isolate test object from the short-circuit generator
- Protect HVDC CB from over-current if it fails to clear
- Inject DC voltage stress after current suppression
- Mimic effect of load current and delay operation of fast breakers
- Take measurements



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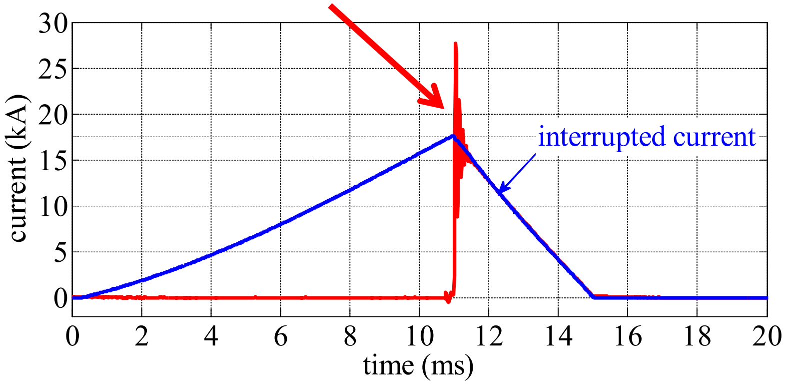
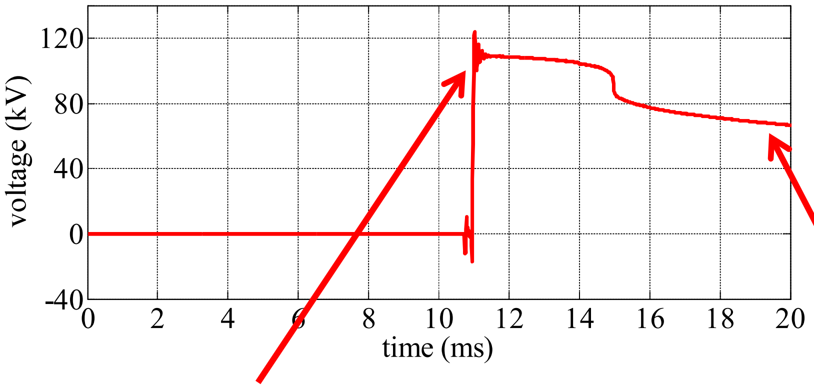
HVDC Circuit Breaker Testing

16 kA interruption (positive) + dielectric stress

current through MOSA

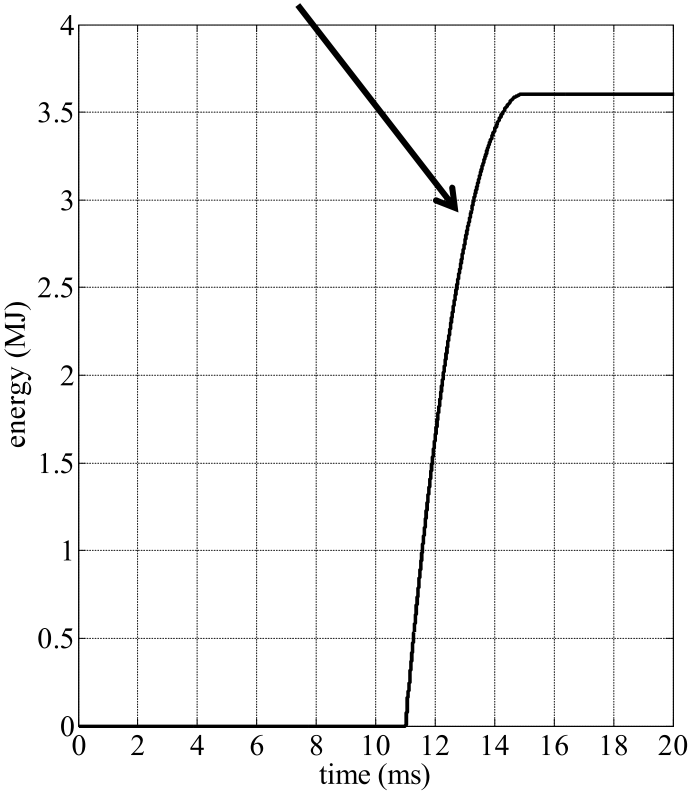




Counter voltage generated by HVDC CB

Dielectric stress

Energy absorbed by HVDC CB



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Demonstration

Full power technology demonstrations

MITSUBISHI ELECTRIC

- Mechanical DCCB with active current injection
- 200 kV
- 16 kA
- 7 ms
- 4 MJ

HITACHI ABB

- Hybrid HVDC circuit breaker
- 350 kV
- 20 kA
- 3 ms
- 10 MJ

SCiBreak
Enabling the Supergrid

- Voltage assisted resonance converter mechanical breaker
- 80 kV
- 12 kA
- 2 ms
- 2 MJ

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HVDC Circuit Breaker Demonstration

Assessing technology maturity

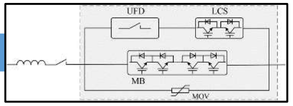
0 Idea
1 Basic principles observed
2 Technology concept formulated
3 Experimental proof of concept
4 Technology validated in lab
5 Technology validated in industrial environment
6 Technology demonstrated in industrial environment
7 System prototype demonstration in operational environment
8 System complete and qualified
9 Actual system proven & competitive manufacturing

Hardware implementation

- Conceptual requirements
- Analytical fault current/transient analysis: materials/components
- CB models design & modelling – component & system level
- Application specific simulation - normal & fault conditions
- Installing CB test circuit hardware
- prototyping CB hardware
- CB hardware demonstration & stressing
- Installed and commissioned on site

Qualification method

- Analytical fault analysis
- Benchmark by PSCAD network model
- CB modelling – materials: eg. surge arrestors
- PSCAD analysis
- Real-time simulator RTDS / OPAL
- Test circuit hardware installation
- full-scale unit tests
- full-scale tests on prototype
- Operation



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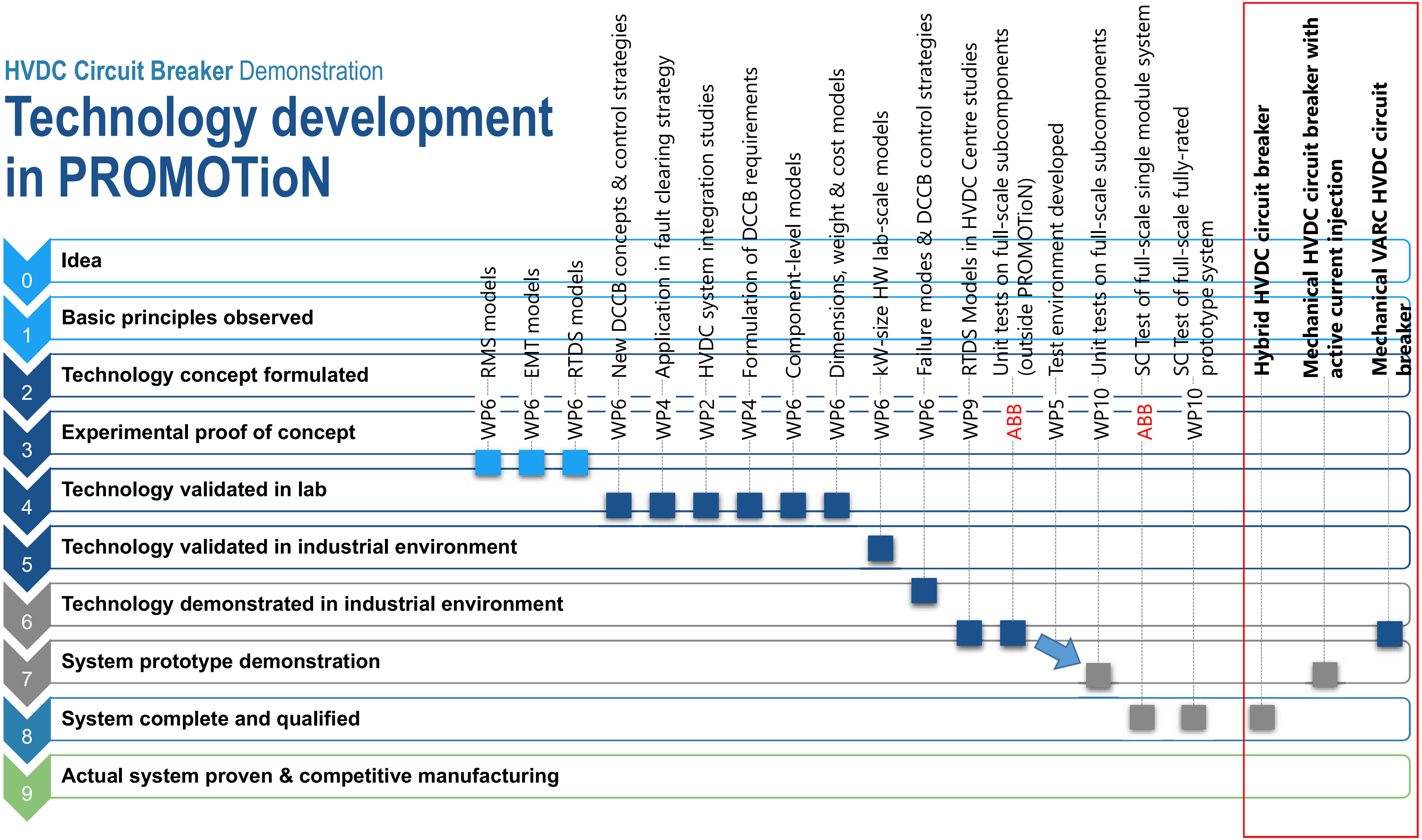
HVDC Circuit Breaker Demonstration

Technology development in PROMOTioN



0 Idea

1 Basic principles observed

2 Technology concept formulated

3 Experimental proof of concept

4 Technology validated in lab

5 Technology validated in industrial environment

6 Technology demonstrated in industrial environment

7 System prototype demonstration

8 System complete and qualified

9 Actual system proven & competitive manufacturing

WP6 RMS models

WP6 EMT models

WP6 RTDS models

WP6 New DCCB concepts & control strategies

WP4 Application in fault clearing strategy

WP2 HVDC system integration studies

WP4 Formulation of DCCB requirements

WP6 Component-level models

WP6 Dimensions, weight & cost models

WP6 kW-size HW lab-scale models

WP6 Failure modes & DCCB control strategies

WP9 RTDS Models in HVDC Centre studies

ABB Unit tests on full-scale subcomponents (outside PROMOTioN)

WP5 Test environment developed

WP10 Unit tests on full-scale subcomponents

ABB SC Test of full-scale single module system

WP10 SC Test of full-scale fully-rated prototype system

Hybrid HVDC circuit breaker

Mechanical HVDC circuit breaker with active current injection

Mechanical VARC HVDC circuit breaker

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HVDC Circuit Breaker Demonstration

Experience in Asia

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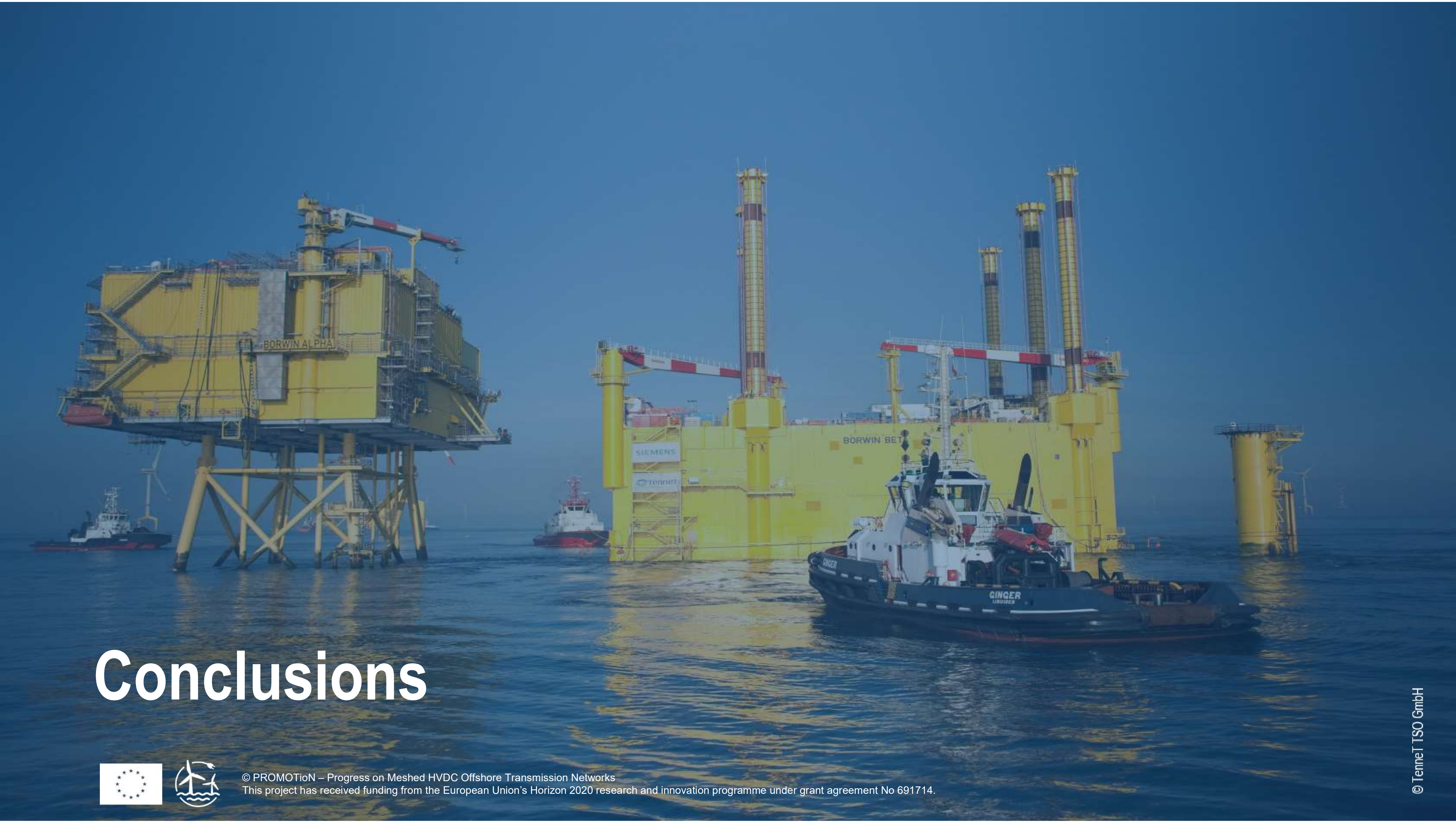

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Conclusions

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Conclusions

- A complete test environment for HVDC circuit breakers capable of providing full-stress as in service is readily available.
- Test-requirements are available for (fault) current interruption, agreed among the partner-manufacturers and applied in the demonstration test campaigns.
- Three technologies of industrial HVDC circuit breakers up to 350 kV system voltage interrupting 20 kA of fault current have been publicly demonstrated in the high-power laboratory.
- First time independent verification of the complete fault current interruption process in a lab-simulated full-power HVDC grid environment.
- Technology Readiness Level of all test-objects raised to level 7 (‘system complete and qualified’).
- Fault elimination is no longer a technical hurdle for HVDC grid development.

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PROGRESS ON MESHED HVDC
OFFSHORE TRANSMISSION
NETWORKS

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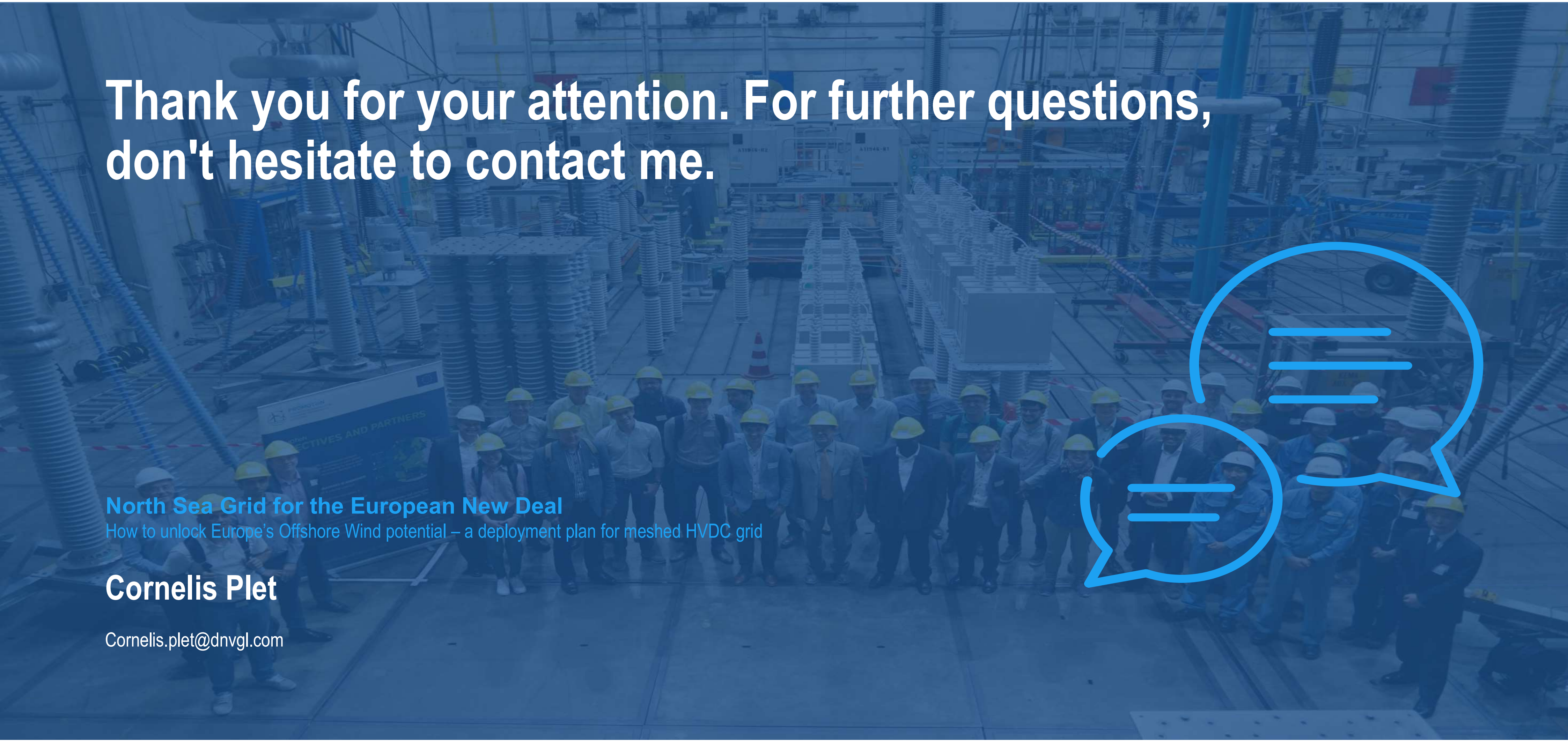

Thank you for your attention. For further questions, don't hesitate to contact me.

North Sea Grid for the European New Deal

How to unlock Europe's Offshore Wind potential – a deployment plan for meshed HVDC grid

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