Multi-Terminal HVDC
Part 1: Introduction and Energisation

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Agenda

- Overview of HVDC and Multi-Terminal Design
  - Network Topologies
  - Benefits
  - Core Component

- Energisation Methods
  - Background
  - Challenges and Mitigations
  - MMC Charging Process
  - Energisation Sequence

- Demonstration of Multi-terminal Energisation
  - Three-Terminal Energisation Sequence
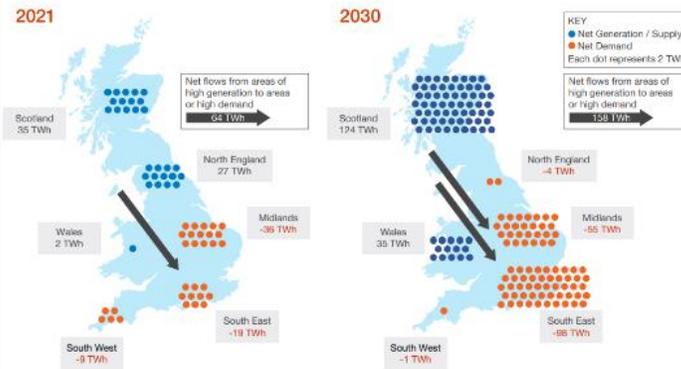 - Steady State Power Flow

- Multi-terminal Considerations

Why HVDC?

In long distance transmission, HVDC is preferred over HVAC due to lower capital costs and losses
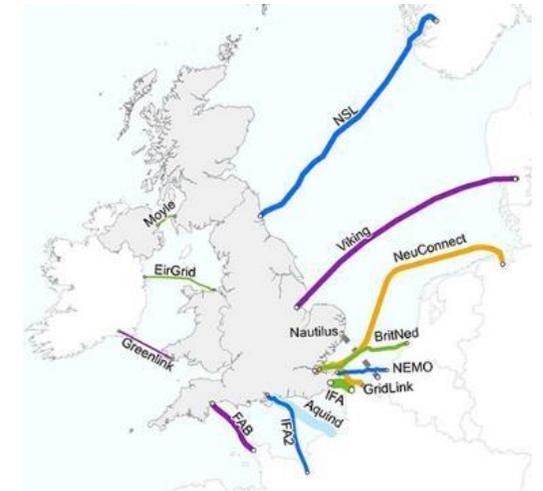
1) To connect offshore wind farms
(AC cannot be used for very long cables, over ~ 80 km)

2) Efficient long-distance power transmission with controllable power flow

### 3) To interconnect to the asynchronous networks

Types of HVDC Systems

- ## Converter technologies:
  - LCC (Line Commutated Converter) – uses thyristors, suitable for bulk power
  - VSC (Voltage Source Converter) – uses IGBTs, offer better control and black start capability
- ## System Configurations:
  - Symmetrical Monopole
  - Bipole configuration:
    - Full Bipole – Neutral with dedicated metallic return (DMR)
    - Rigid Bipole – No DMR
- ## Typical voltages: $\pm$320 kV and $\pm$ 525 kV
- ## Standard power capacity 2 GW ($\pm$ 525 kV)
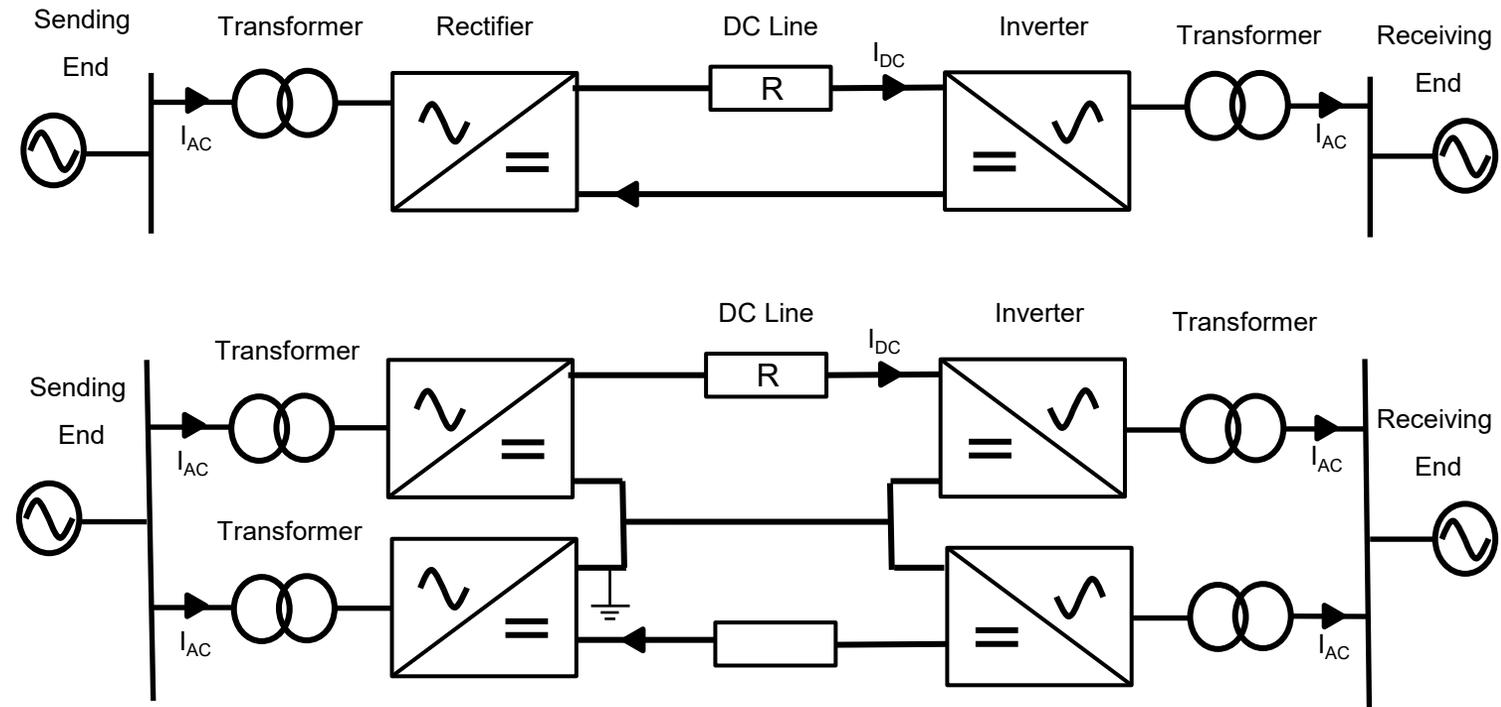
What happens as HVDC connections increase?

Multi-Terminal HVDC System

- Extension of point-to-point HVDC with 3 or more converter stations.
- All terminals share a common DC network.
- Each terminal can inject or draw power based on system needs.
- Enables integration of multiple offshore wind farms and cross-border grids.
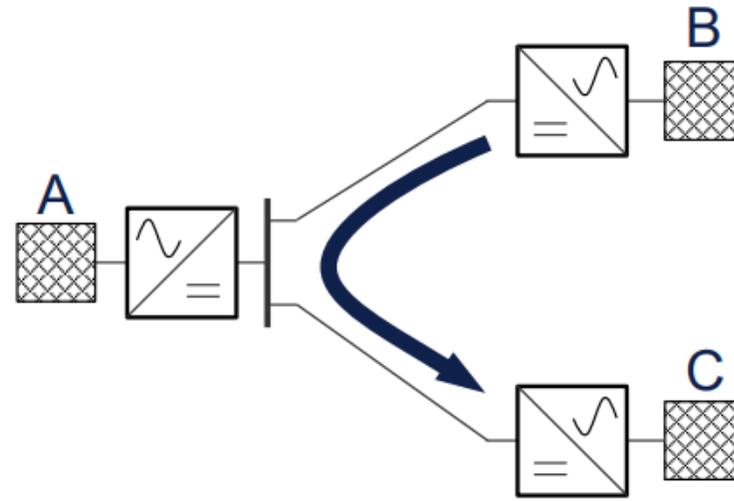- Improves flexibility, efficiency, and reliability of power systems.

Multi-terminal HVDC Grid

HVDC Network Topologies
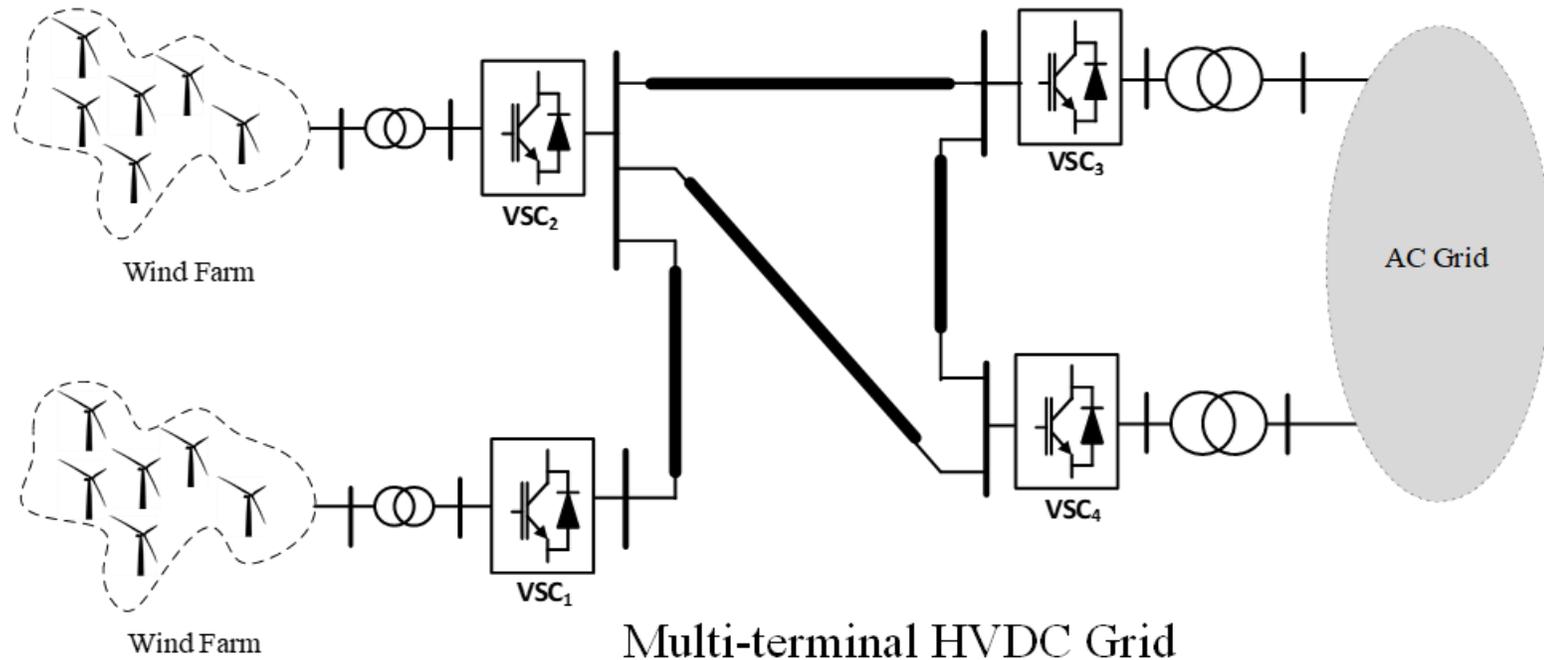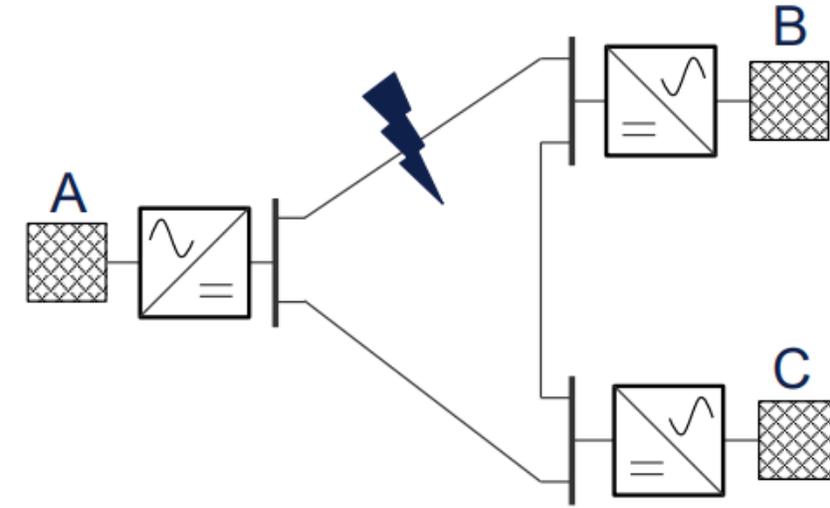
Multiple Point to Point
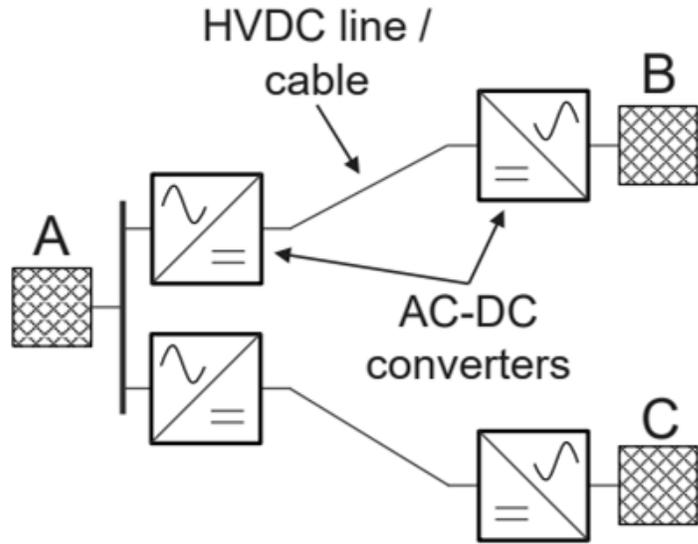
- Project specific/Single vendor
- Simple protection and control Philosophy
- Mature and widely applied
- Designed and optimised per project, not per system

Radial Multi-Terminal

- Multi-purpose
- Less converters, cost (compared to multiple point-to-point), footprint and losses
- Requires compatibility

Meshed Multi-Terminal

- Redundant paths
- Potential for Increased Availability
- Requires DC protection system

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Core Component: MMC

- **Backbone of MT-HVDC**
- **Core Concept:**
  - Series submodules synthesize multi-level voltage waveform
  - Low harmonics, minimal filtering.
- **Configurations:**
 - Half-Bridge MMC
  - Full-Bridge MMC
  - Hybrid MMC
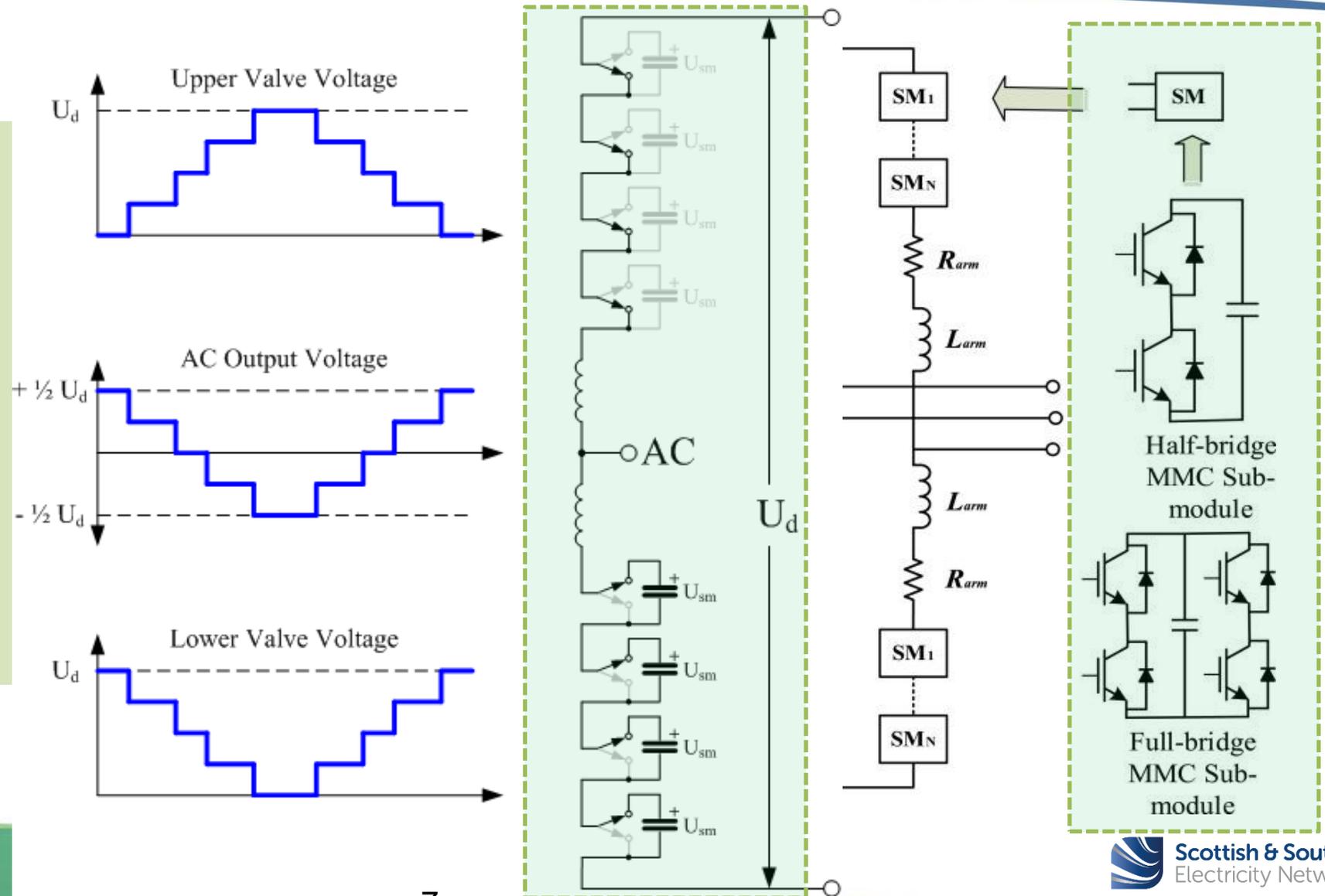
MMC-HVDC Energisation

Adam Scott

Energisation Background

- Transient phenomena in energisation driven by dynamics of reactive components

- Energising components such as transformers, cables, reactive compensation, or filters can be challenging

- Current-sensitive power electronics-based HVDC converters also demand care in energisation sequences
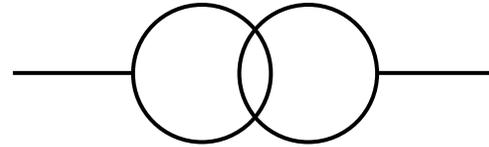
$$v_L = L \frac{di_L}{dt} = \frac{d\varphi}{dt}$$
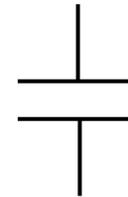
$$i_c = C \frac{dv_C}{dt} \qquad \int i_c \, dt = C v_c$$

$\therefore \uparrow \Delta v$ leads to large energisation currents

Energisation Challenges and Mitigations

Challenges

- Inrush currents
- Voltage dips
- Magnetic phenomena (saturation, residual flux)
- Power quality and harmonics
- Resonance
- Can demand high power from energising source
- Instability in low system strength scenarios

Common Mitigations

- Pre-insertion resistors (PIRs)
- Point on Wave (PoW) switching
- Soft start (controlled Vac ramp $0 \rightarrow 1pu$)
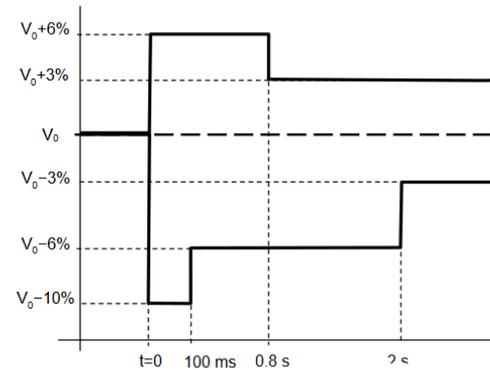
Grid Code

Figure CC.6.1.7 (2) — Voltage characteristic for infrequent events

Cat-egory	Title	Maximum number of occurrence	Limits %ΔV_{max} & %$\Delta V_{steadystate}$	Example Applicability
1	Frequent events	(see NOTE 1)	As per Figure CC.6.1.7 (1)	Any single or repetitive RVC that falls inside Figure CC.6.1.7 (1)
2	Infrequent events	4 events in 1 calendar month (see NOTE 2)	As per Figure CC.6.1.7 (2) |%$\Delta V_{steadystate}$| ≤ 3% For decrease in voltage: |%ΔV_{max}| ≤ 10% (see NOTE 3) For increase in voltage: |%ΔV_{max}| ≤ 6% (see NOTE 4)	Infrequent motor starting, transformer energisation, re-energisation (see NOTE 7)
3	Very infrequent events	1 event in 3 calendar months (see NOTE 2)	As per Figure CC.6.1.7 (3) |%$\Delta V_{steadystate}$| ≤ 3% For decrease in voltage: |%ΔV_{max}| ≤ 12% (see NOTE 5) For increase in voltage: |%ΔV_{max}| ≤ 6% (see NOTE 6)	Commissioning, maintenance & post fault switching (see NOTE 7)

CC.6.1.7/ECC.6.1.7 Voltage Fluctuations

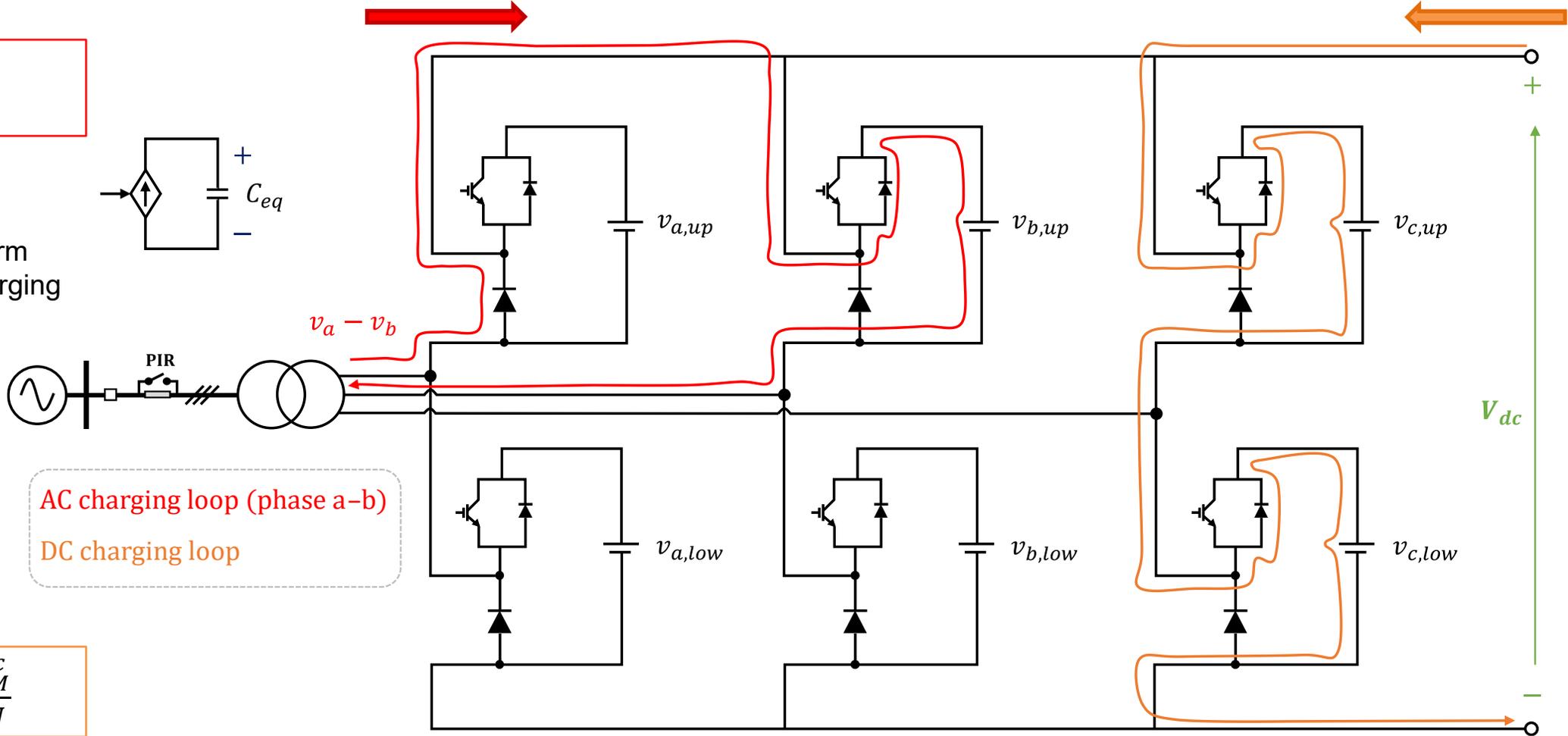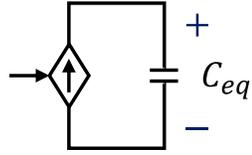$10 - 12\%$ **voltage dip permissible for 100ms**, 6% until 2s, then 3% thereafter

Multi-Terminal Use Case System
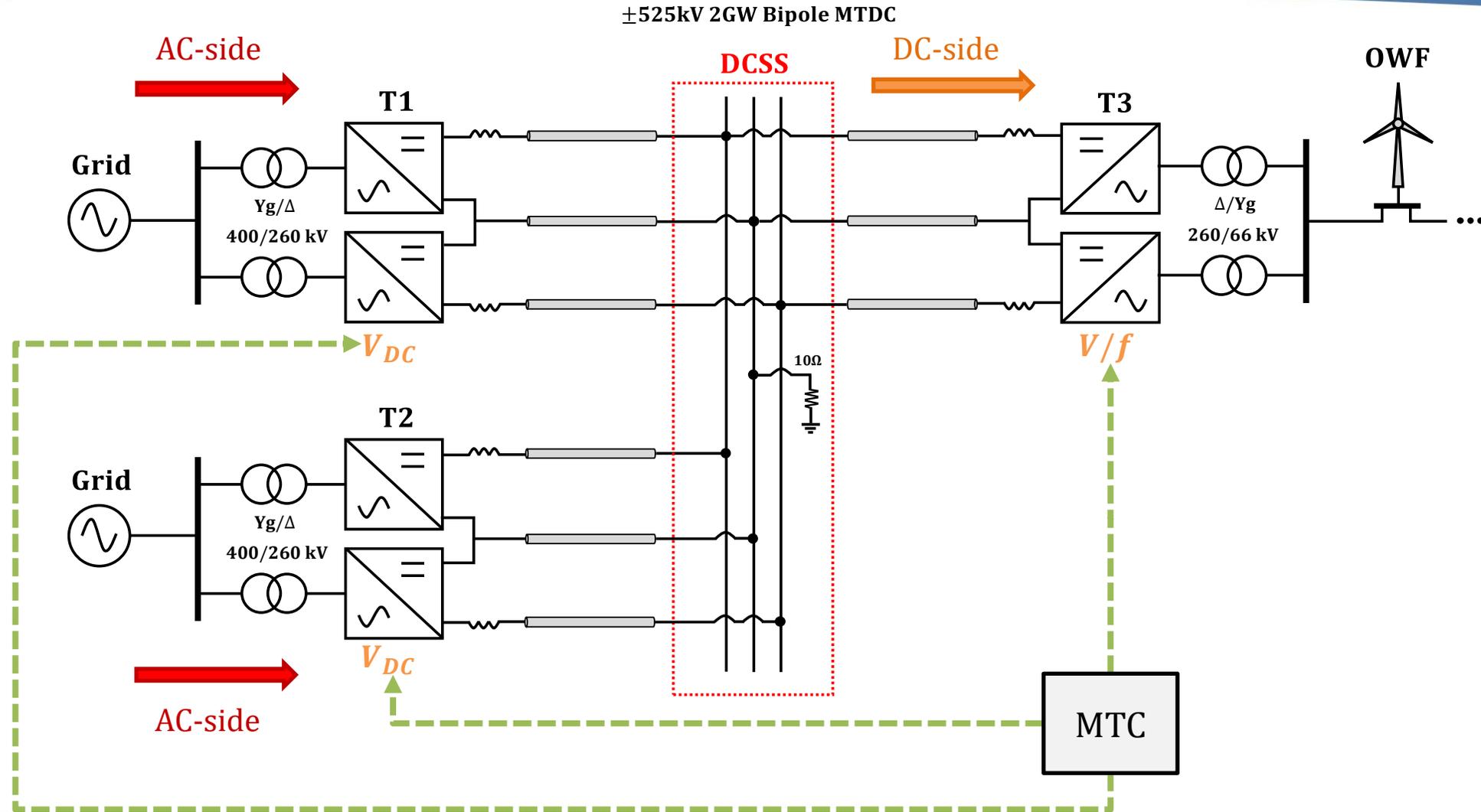
$$v_{SM}^{ac} = \frac{\sqrt{2}V_{LL}^{ac}}{N}$$

Maximum attainable arm voltage from *passive* charging

$v_a - v_b$

PIR

C_{eq}

+

−

$v_{a,up}$

$v_{b,up}$

$v_{c,up}$

$v_{a,low}$

$v_{b,low}$

$v_{c,low}$

V_{dc}

+

−

AC charging loop (phase a–b)

DC charging loop

$$v_{SM}^{dc} = \frac{V_{DC}}{2N} = \frac{v_{SM}^{ac}}{2N}$$

MMC Charging Process

- Key aim in HVDC energisation is managing the submodule charging

- The submodules undergo passive and controlled charging phases

- The controlled process should achieve two things:

  1. Avoid large step changes in voltage to mitigate inrush currents

  2. Bring the submodules up to nominal operating voltage

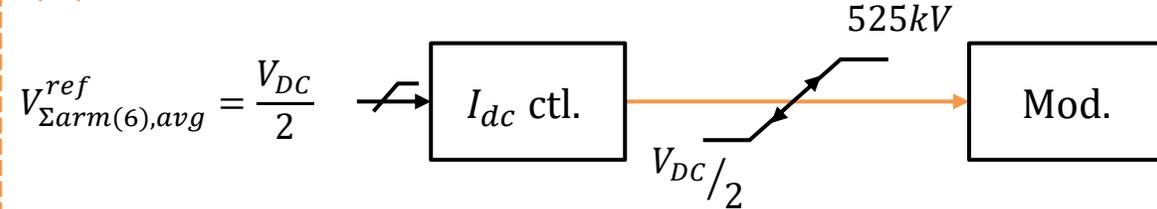| ID	Submodule Charging Process	Submodule Cell State	Applies to
1.	Uncontrolled pre-charging	Blocked	Onshore and Offshore Converter
2.	Controlled charging	Deblocked or Bypassed	Onshore and Offshore Converter
3.	Controlled operation	Deblocked	Onshore and Offshore Converter
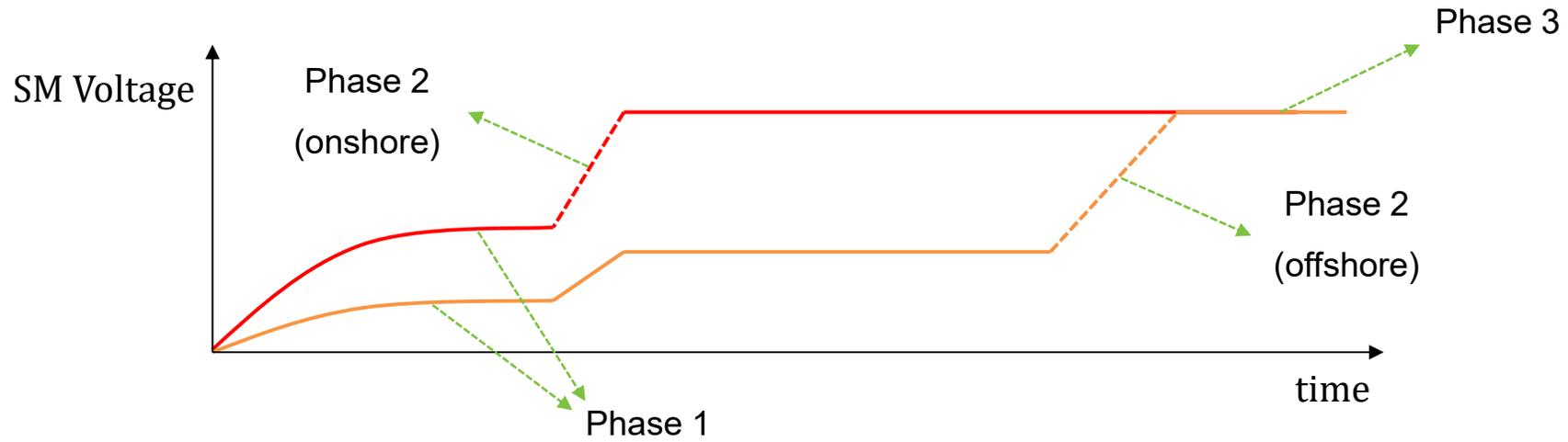
MMC/MTDC Charging Sequence and Control

Time	Event
t1	HVDC AC main breaker (MB) closed with PIR inserted
t2	PIR bypassed
t3	Onshore HVDC converter deblocks in DC voltage control mode
t4	DC voltage ramp function increases DC voltage to nominal ±525kV
t5	DCSS switch close to energise (1st V_{DC} MMC) or connect to (2nd+ V_{DC} MMCs) to DCSS
t6	DCSS switch close inserting DC-PIR to pre-charge offshore MMC and cable
t7	Offshore HVDC converter deblocks and undergoes controlled charging phase
t8	Offshore AC-MB closed
t9	Offshore HVDC converter assumes V/f control and ramps offshore AC voltage to 1pu
t10	*HVDC system energised*

Onshore MMCs (t1–t5)

Offshore MMCs (t6–t10)

(t4) Onshore MMCs

$$V_{DC,ref} = \sqrt{2}V_{LL}^{ac}$$

$525kV$

Mod.

(t6) Offshore MMCs

$$V_{\Sigma arm(6),avg}^{ref} = \frac{V_{DC}}{2}$$

I_{dc} ctl.

$V_{DC}/2$

$525kV$

Mod.

14
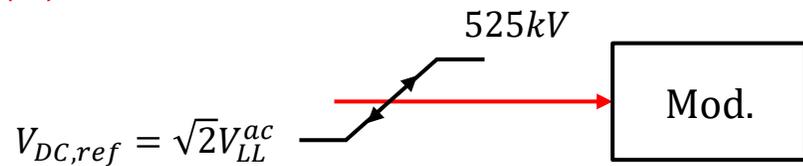
MMC Soft Energisation

Study 1: P2P bipole energisation, DCSS switches initially closed

- Onshore station V_{DC} droop control

- Offshore station V/f control

- *AC-side inrush transients managed by AC-PIR*

- *Onshore station deblocks with reduced V_{DC} and ramps to 1pu*

- *Offshore station undergoes controlled charging of submodules*

- *Offshore station assumes V/f and ramps up offshore voltage*

- ✓ Controlled energisation

- ✓ Peak P_{ac}, Q_{ac}, and I_{dc} minimised


P2P Bipole Soft Energisation
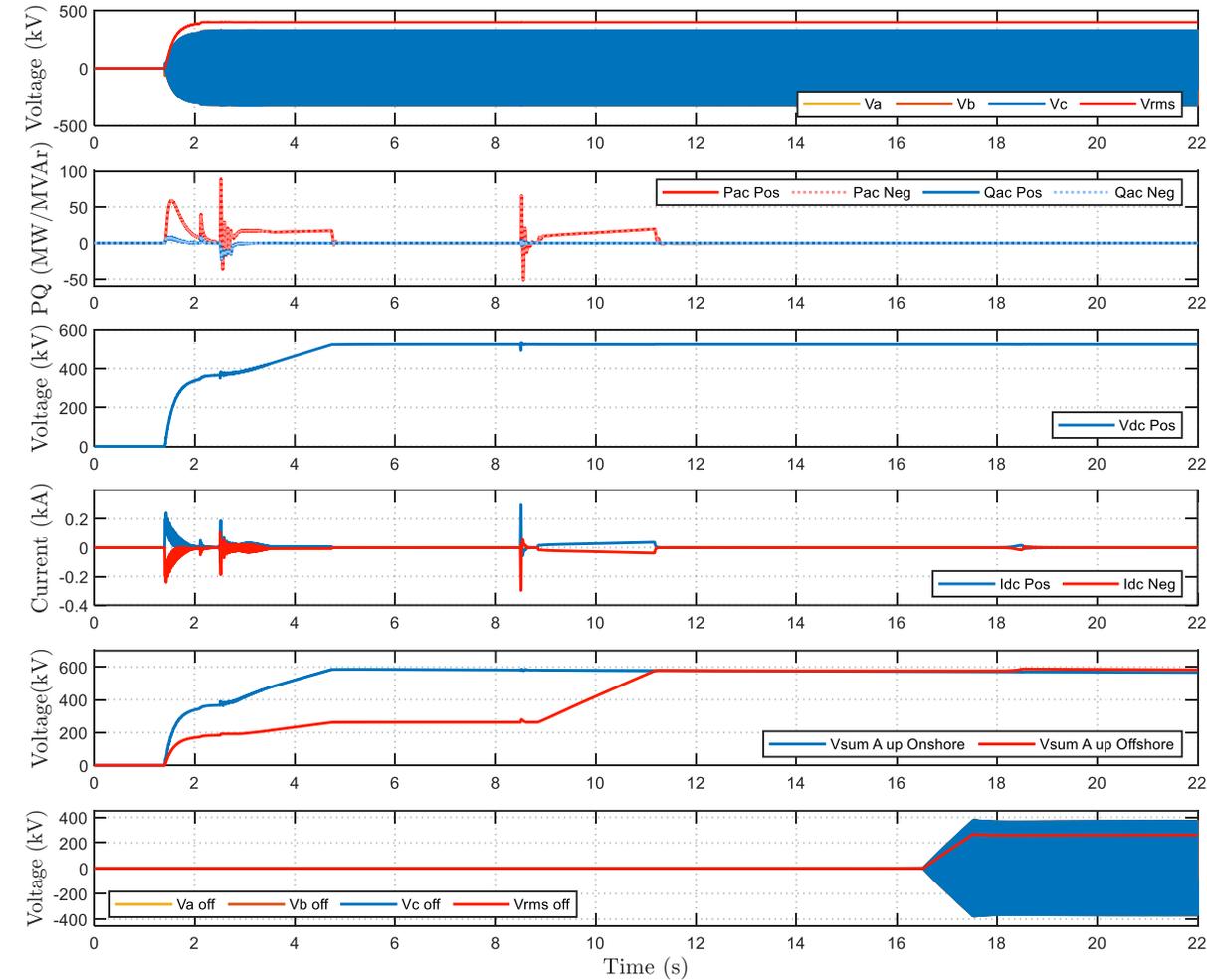
MMC Energisation without Soft Charging Functions

Study 2: DCSS switches initially closed, soft functions disabled

- *Onshore station deblocks with $V_{DC,ref} = 525kV$*

- *Offshore station deblocks without controlled charging stage*

❌ Large ΔV_{DC} inrush currents

❌ Peak $P_{ac} > 1000MW$, and $I_{dc} > 4kA$

P2P Bipole Energisation (Without Soft Functions)

Multi-Terminal Aspects: DCSS with DC-PIR
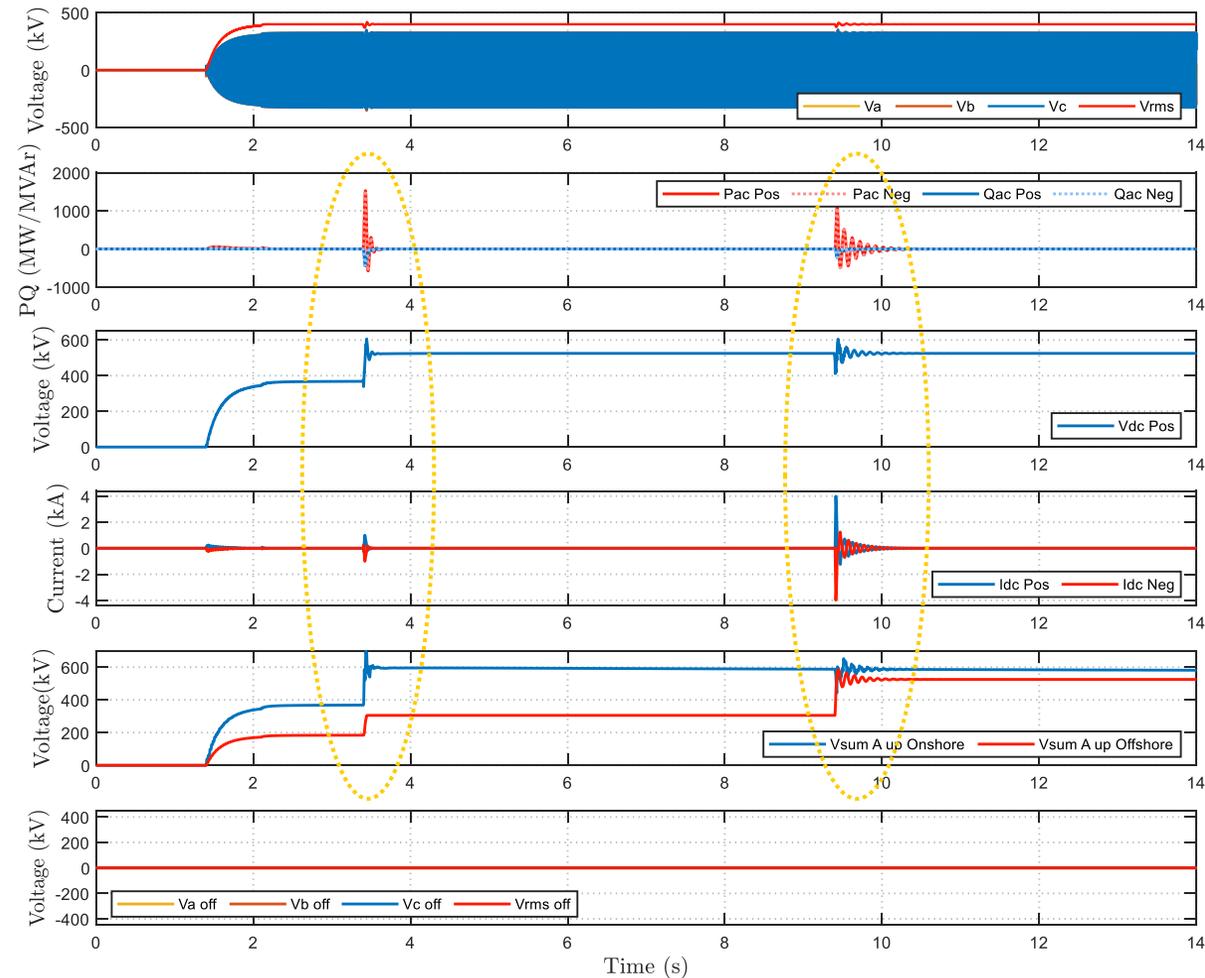
Study 3: DCSS switches initially open

- *Onshore station energises DCSS*

- *DCSS switches closes with DC-PIR inserted*

- *Offshore station deblocks and undergoes controlled charging*

✓ Controlled energisation

✓ Peak P_{ac}, Q_{ac}, and I_{dc} minimised

✓ Demonstrates DCSS-MTDC practicalities

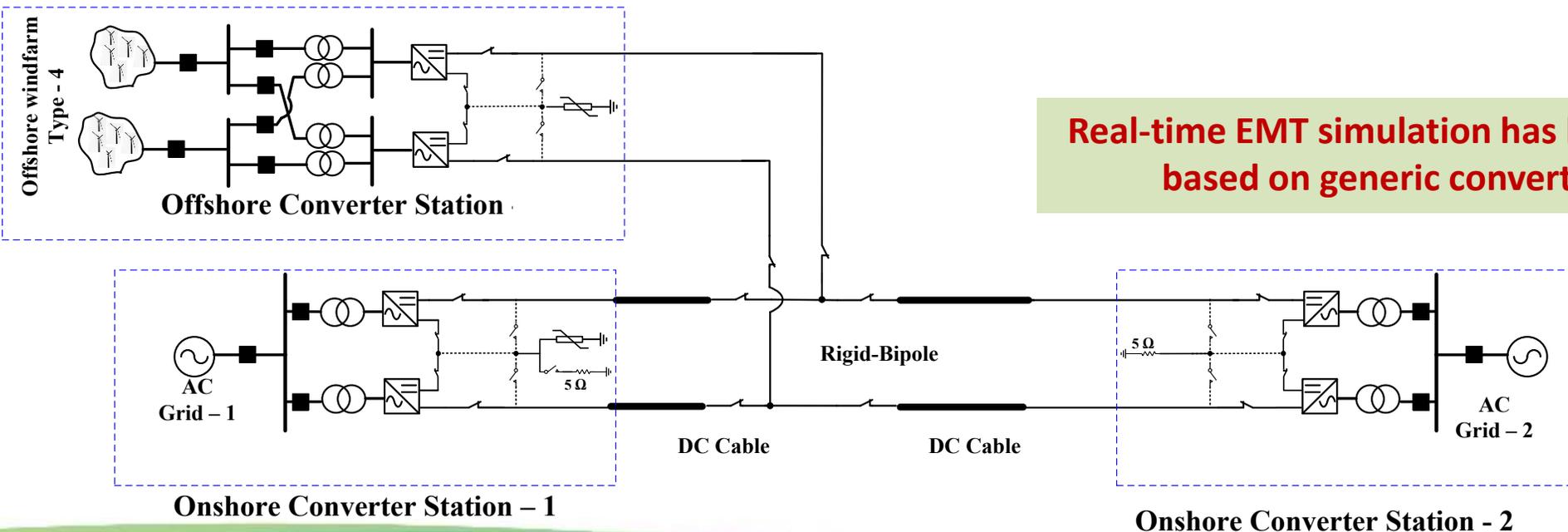P2P Bipole Soft Energisation (DCSS Switch with DC-PIR)
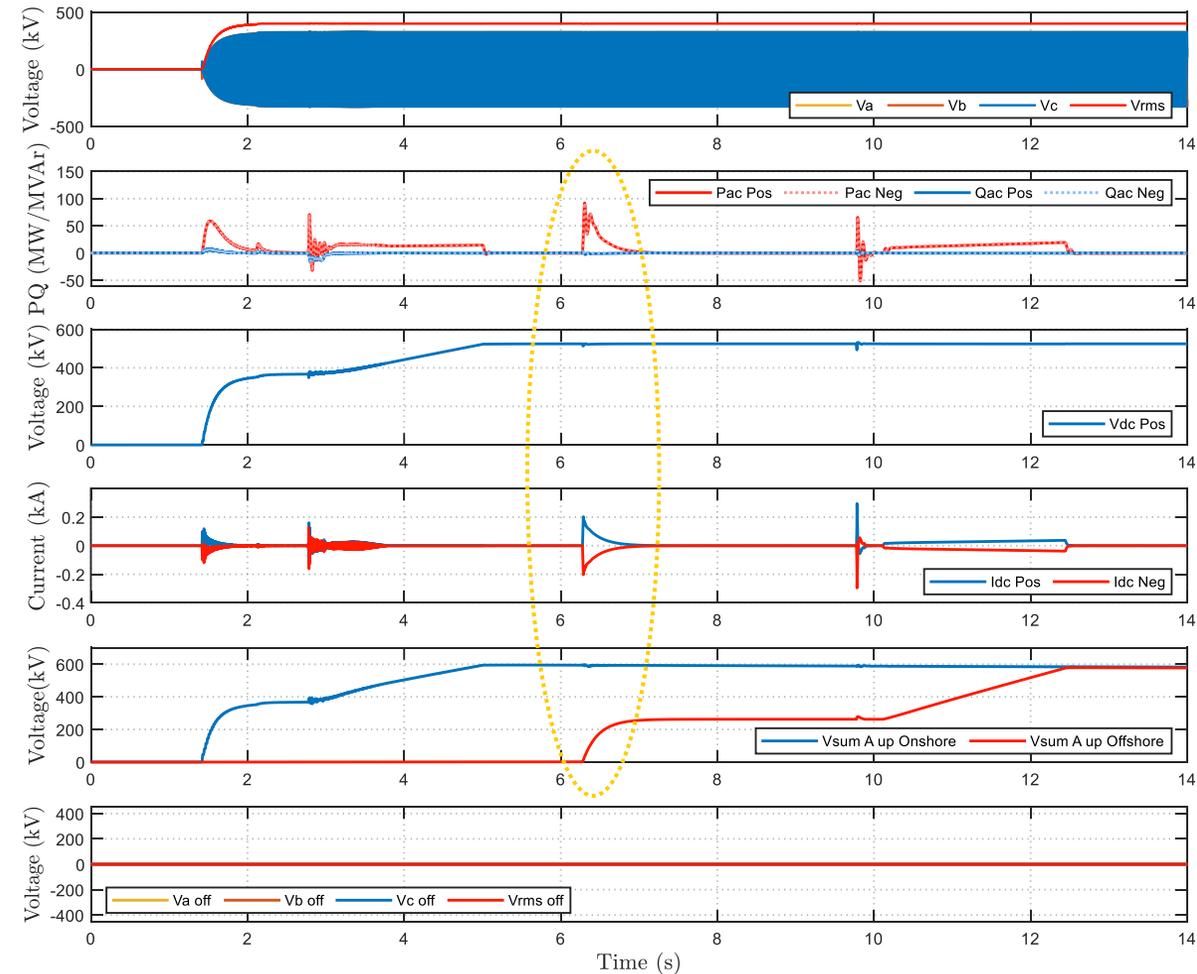
Demo with Three-Terminals

Mohamed Elgenedy

Three-Terminal System Energisation and Power Flow

System Description:

- 3T **Rigid** Bipole
- MMC technology, ± 525 kV, with power transfer capability of ± 2 GW (1 GW/pole).
- One earth reference at Station 2. Switchable earth at Station 2 for converter energisation.
- Onshore converters **GFL** and Offshore converter **V/f GFM**.
- Station 1 operates in **Active Power Control** mode, and Station 2 operates in **DC Voltage Control** mode.
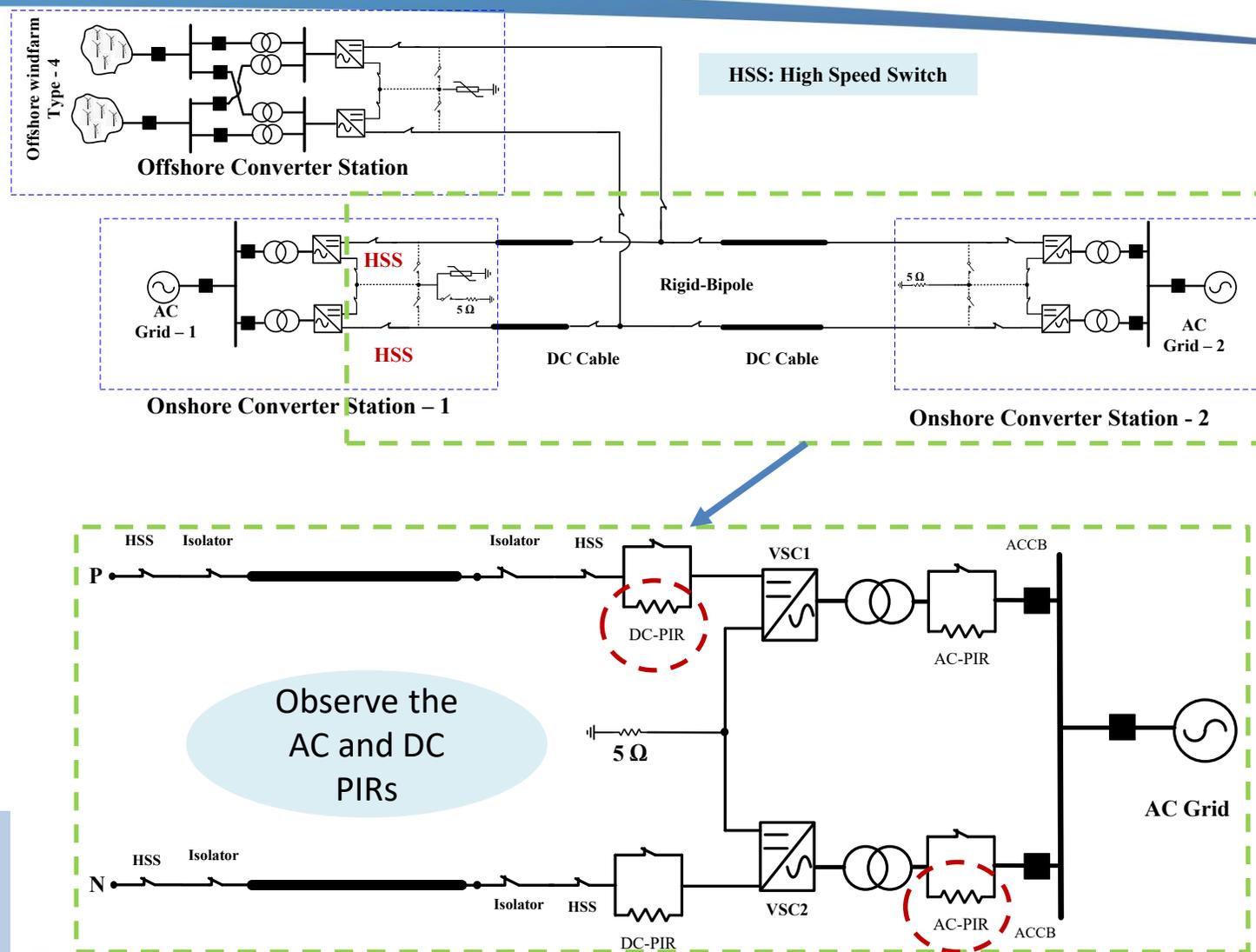

Offshore windfarm Type – 4

Offshore Converter Station

Real-time EMT simulation has been conducted based on generic converter models

AC Grid – 1

5 Ω

Rigid-Bipole

5 Ω

AC Grid – 2

DC Cable   DC Cable

Onshore Converter Station – 1

Onshore Converter Station - 2

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Three-Terminal System Energisation Sequence

A project-based example

1. Energise Station 2 from the AC side and activate DC-Voltage control
2. Energise the DC cable up to Station 1 HSS
3. Energise Station 1 from the AC side and activate DC-Voltage control
4. Ensure the DC voltage difference across the HSS is less than 3 kV
5. Close the HSS.
6. Switch the control mode on Station 1 from DC-Voltage control to Active Power Control mode.
7. Energise the offshore Station from the DC side.
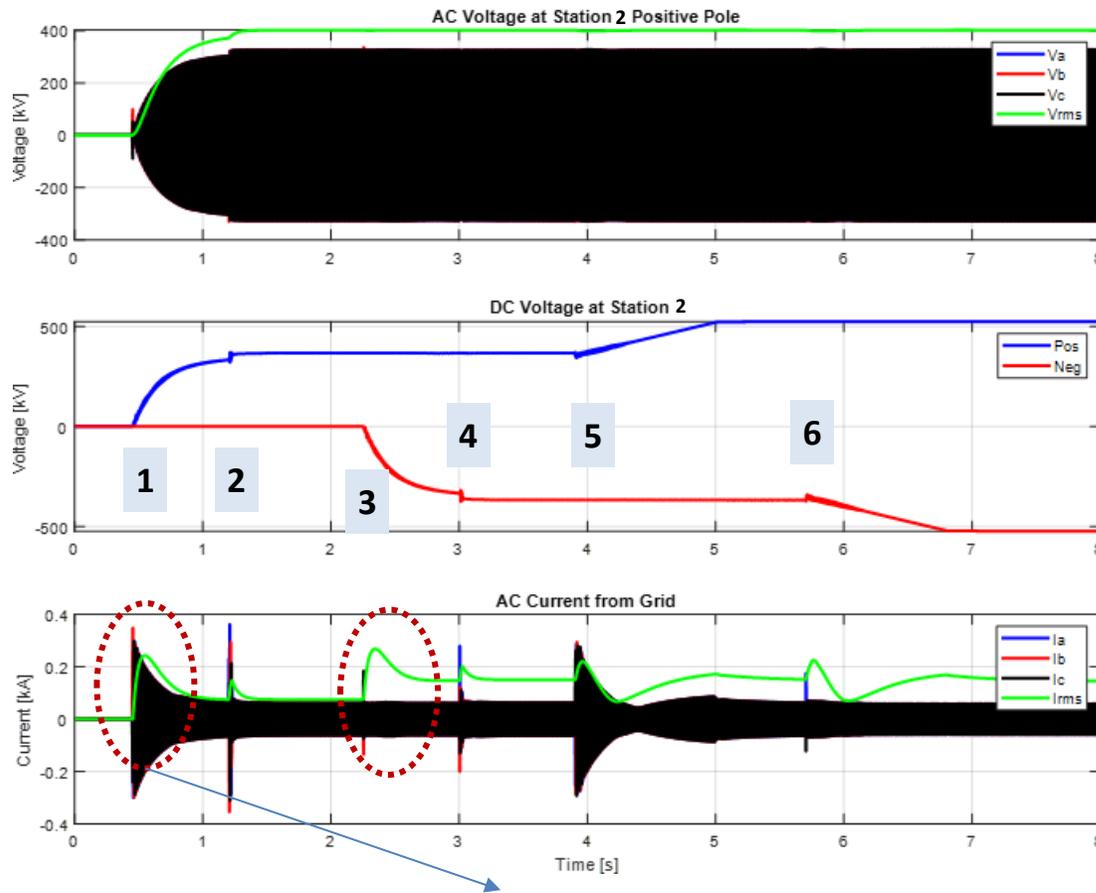8. Integrate the OWF

It is noted that there may be other effective energisation sequences using vendor-dependent approaches.

HSS: High Speed Switch

Offshore windfarm Type – 4

Offshore Converter Station

AC Grid – 1

HSS

HSS

Onshore Converter Station – 1

Rigid-Bipole

5 Ω

DC Cable

DC Cable

5 Ω

AC Grid – 2

Onshore Converter Station - 2

P

HSS   Isolator   Isolator   HSS   VSC1   ACCB

DC-PIR

AC-PIR

Observe the AC and DC PIRs

5 Ω

AC Grid

N

HSS   Isolator   Isolator   HSS   VSC2   AC-PIR   ACCB

DC-PIR

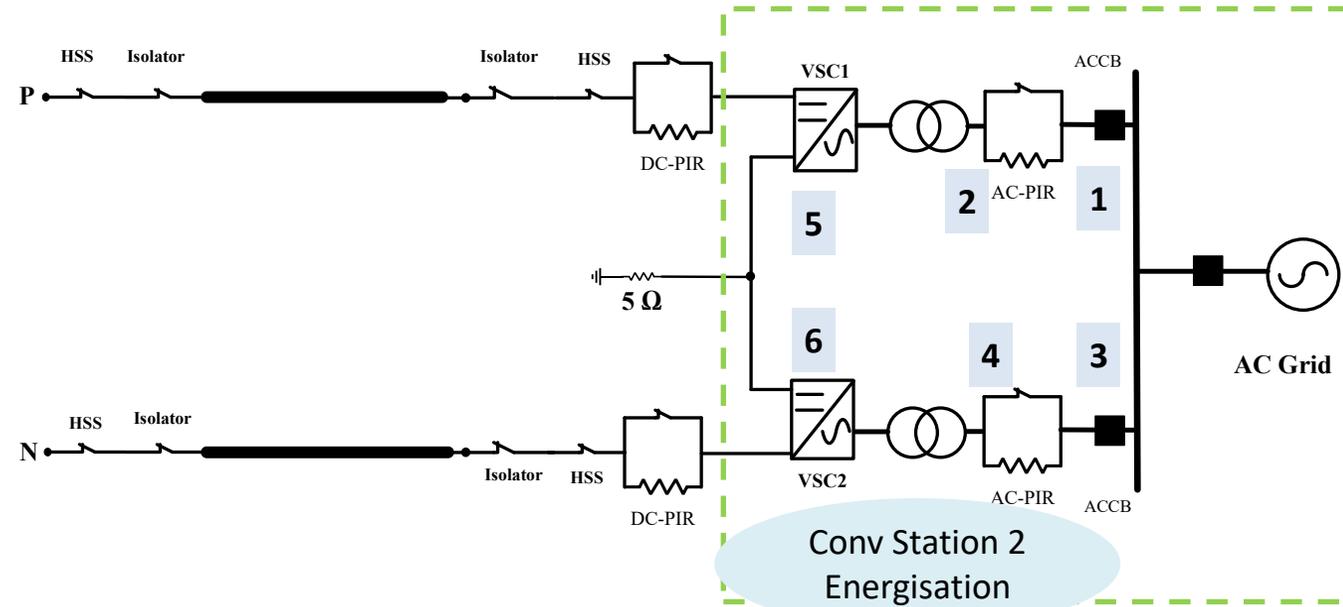# Point-to-Point Energisation

- **Energise Station 2 from the AC side and activate DC-Voltage control**

Energisation along with the onshore grid AC voltage and currents
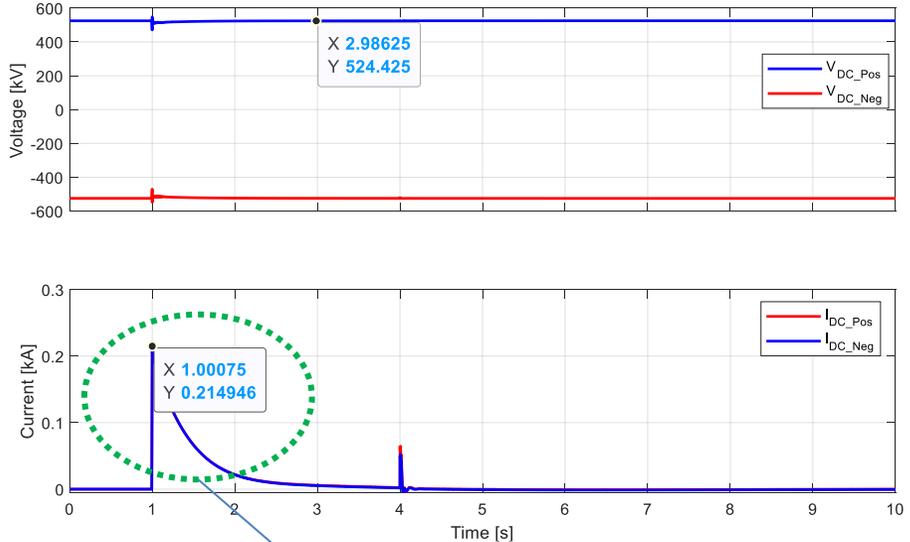

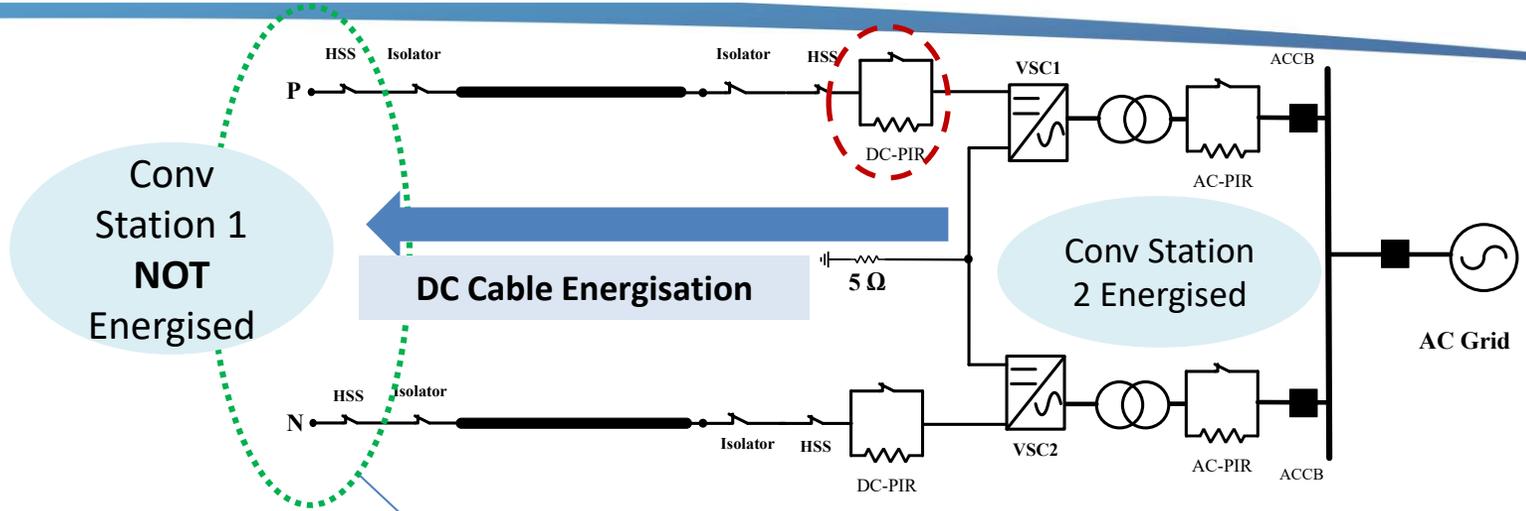| Step / Timing	Description
1 (t = 0.5 s)	Positive pole AC circuit breaker is closed
2 (t = 1.2 s)	Positive pole AC-PIR is bypassed
3 (t = 2.3 s)	Negative pole AC circuit breaker is closed
4 (t = 3 s)	Negative pole AC-PIR is bypassed
5 (t = 3.9 s)	Positive pole converter is deblocked and ramp the DC voltage to 525 kV
6 (t = 5.8 s)	Negative pole converter is deblocked and ramp the DC voltage to 525 kV

Due to AC-PIR utilisation, the maximum inrush current during this phase peak is below 0.3 kA

Conv Station 2 Energisation

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Point-to-Point Energisation

- **Energise the DC cable up to Station 1 HSS**

Terminal DC voltage and current

X 2.98625
Y 524.425

Legend: V_{DC_Pos}, V_{DC_Neg}

X 1.00075
Y 0.214946

Legend: I_{DC_Pos}, I_{DC_Neg}

Due to DC-PIR utilisation, the maximum DC current is 0.214 kA, whereas the cable is rated for 2 kA.

Conv Station 1 **NOT** Energised

DC Cable Energisation

5 Ω

Conv Station 2 Energised

AC Grid

Voltage difference across the HSS

X 4.97695
Y -524.914

Legend: V Diff pos

X 5.0077
Y 524.938

Legend: V Diff neg

Point-to-Point Energisation

- **Energise Station 1 from the AC side and activate DC-Voltage control**
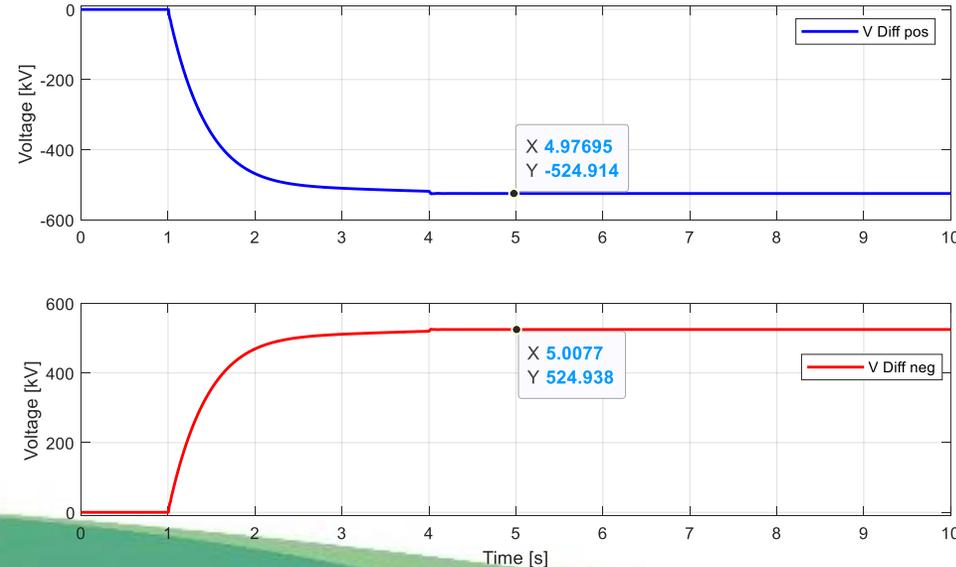
- **Ensure the DC voltage difference across the HSS is less than 3 kV**
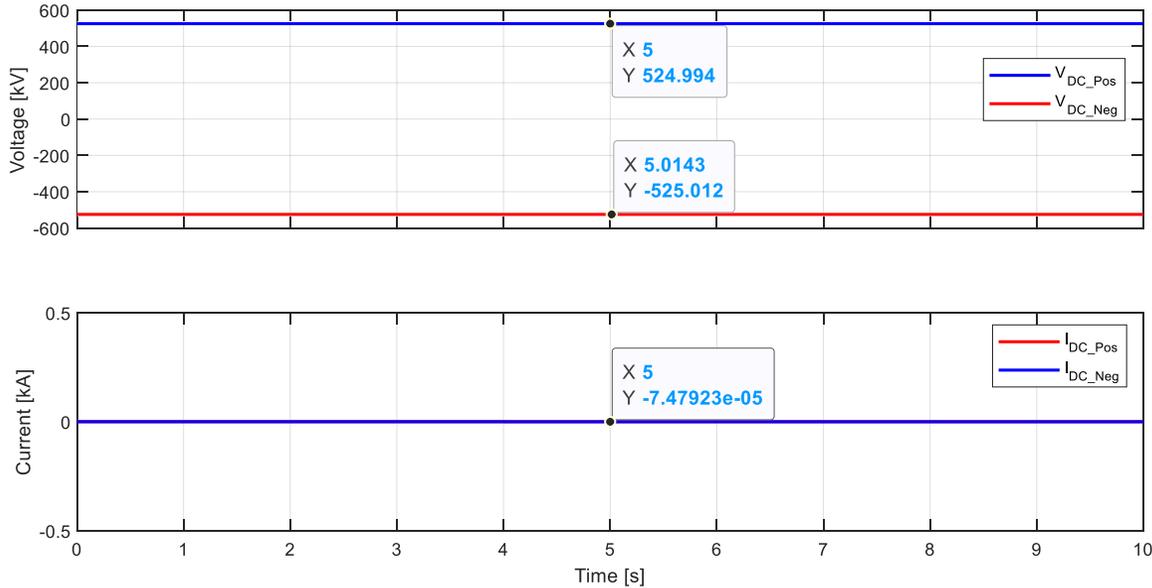
- **Close the HSS.**

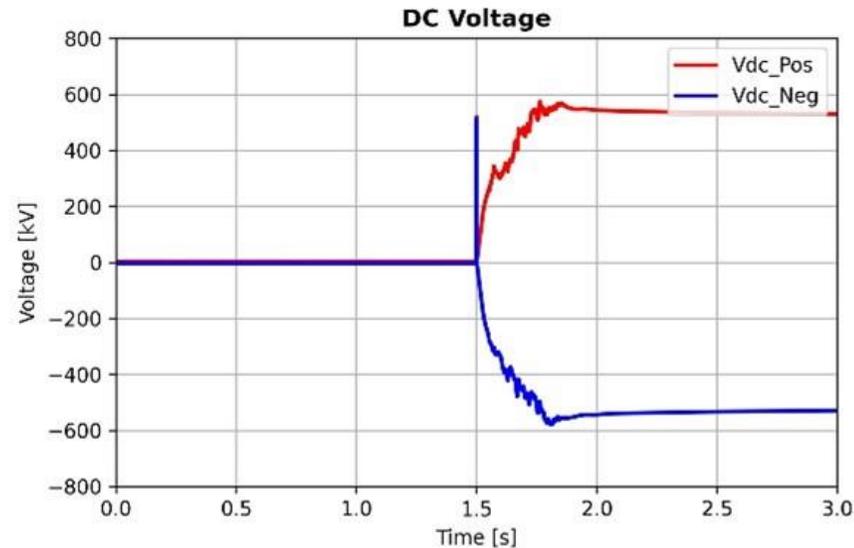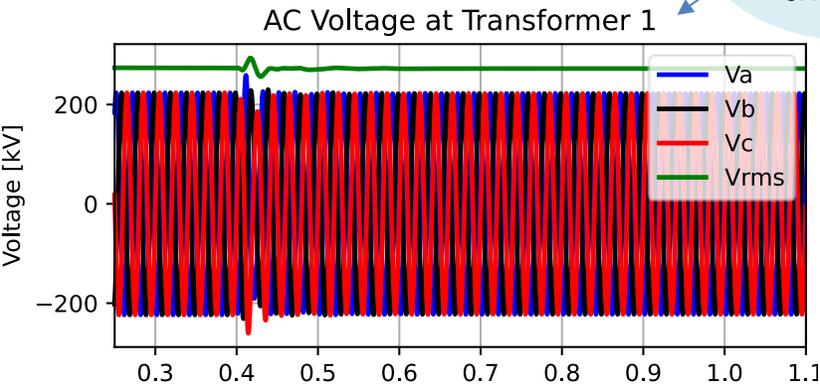

Conv station 1 steady state DC voltage and currents
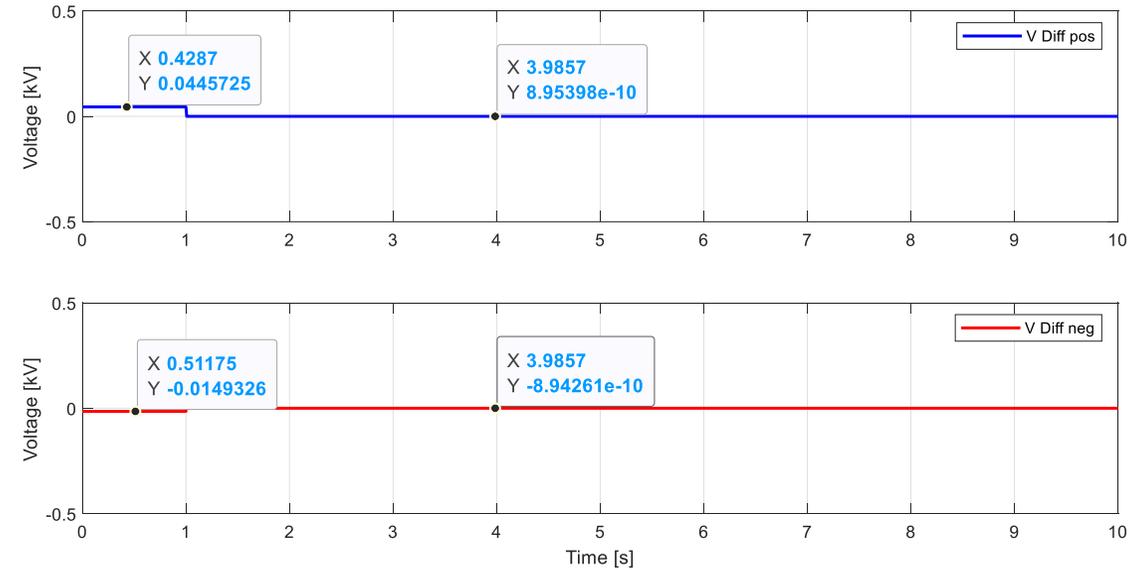
HSS voltage difference (pre/post-closing)

OWF Integration

- Once the HVDC link is stabilised, the HSS switches at the OWF sides are closed.
- The OWF HVDC GFM converter will set the Voltage and Frequency
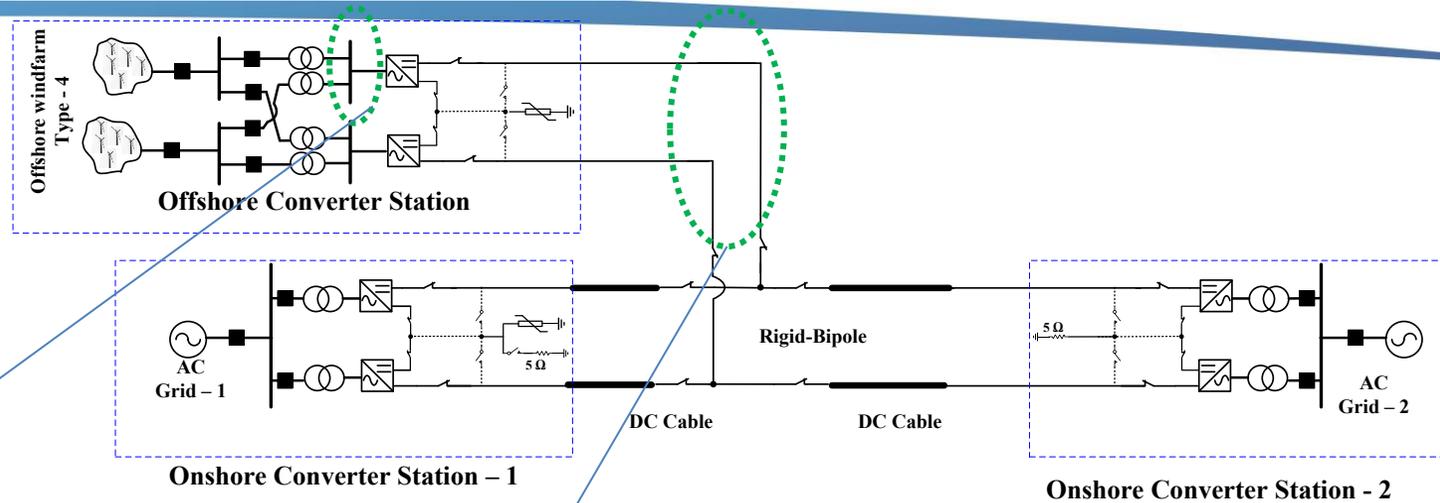
Setting the *V* and *f* for the OWF

Offshore Converter Station

Onshore Converter Station – 1

Onshore Converter Station - 2
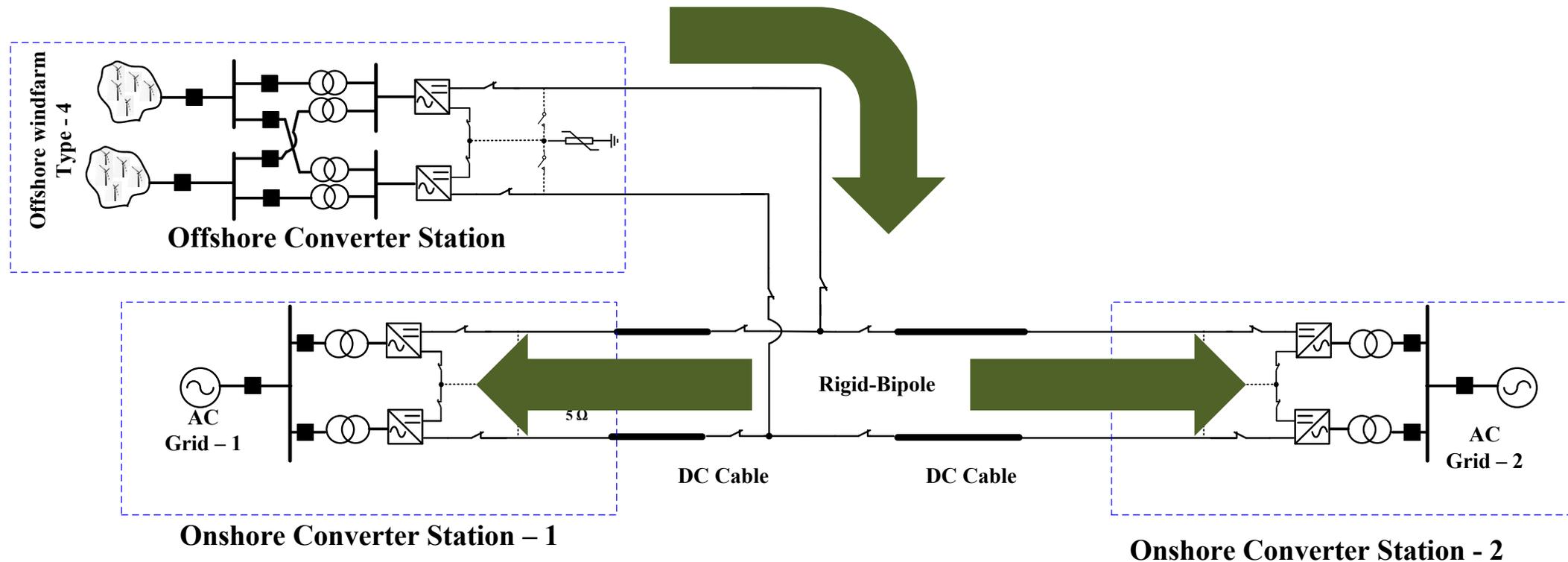
AC Voltage at Transformer 1

N.B. No DC-PIR implemented offshore

Three-Terminal Power Transfer

Demonstration of controlled OWF power flow from the OWF to Grid-1 and Grid-2

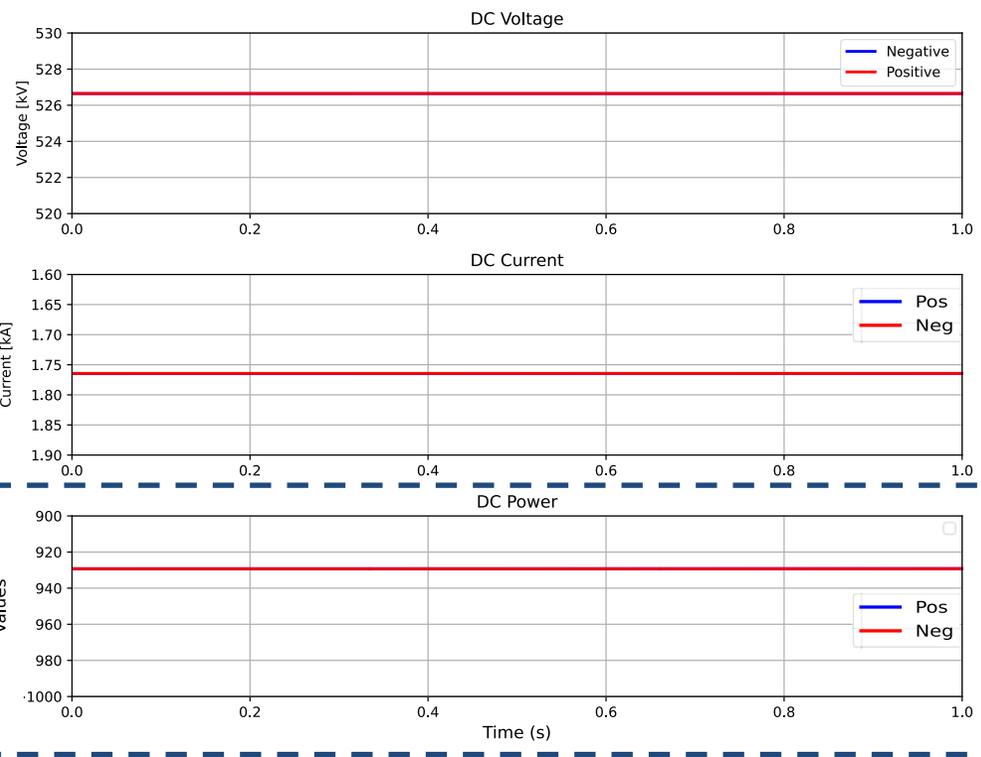**Case 1:** Grids 1 and 2 share the OWF's exported power.

Case 2: Grid 2 imports the total OWF power.

Offshore windfarm Type – 4

Offshore Converter Station

AC Grid – 1

Onshore Converter Station – 1

5 Ω

DC Cable

Rigid-Bipole

DC Cable

Onshore Converter Station - 2
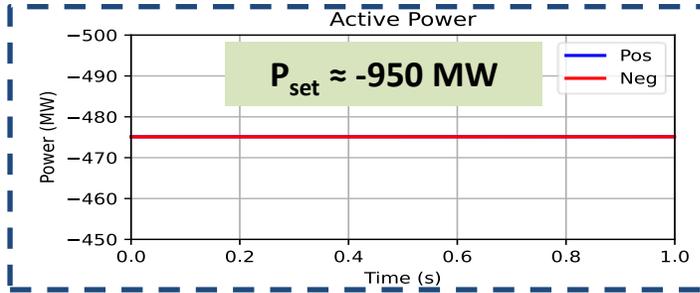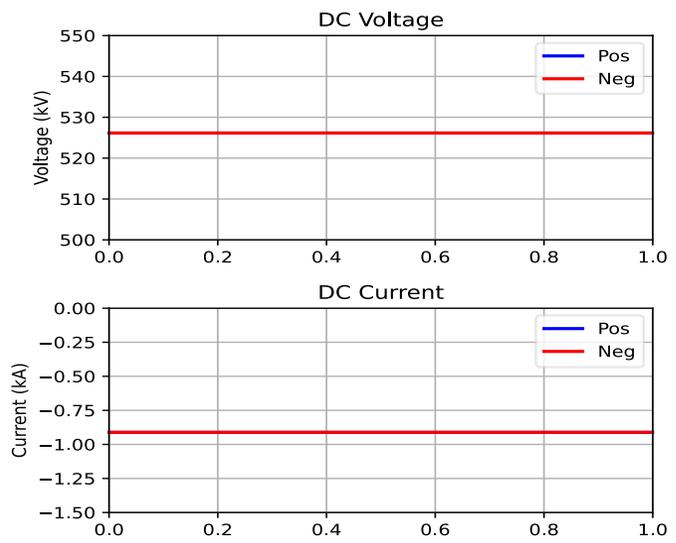
AC Grid – 2

Three-Terminal Power Transfer

Case 1: Grids 1 and 2 share the OWF's exported power.

OWF HVDC Converter

Conv station 1: Active Power Control

Conv station 2: DC Voltage Control

$P_{set} \approx$ -950 MW

OWFs Exported $P_{Ex\_tot} \approx$ 1850 MW

Onshore Imported $P_{Im\_tot} \approx$ -1820MW

Three-Terminal Power Transfer
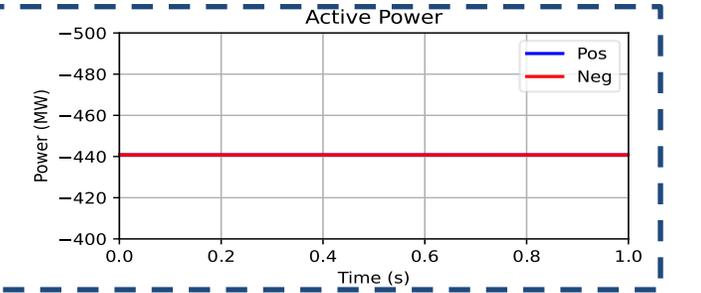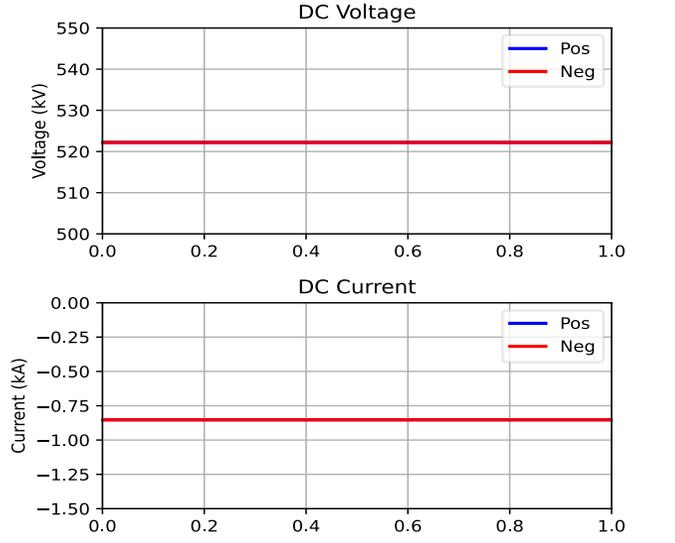
Case 2: Grid 2 imports the total OWF power.

OWF HVDC Converter
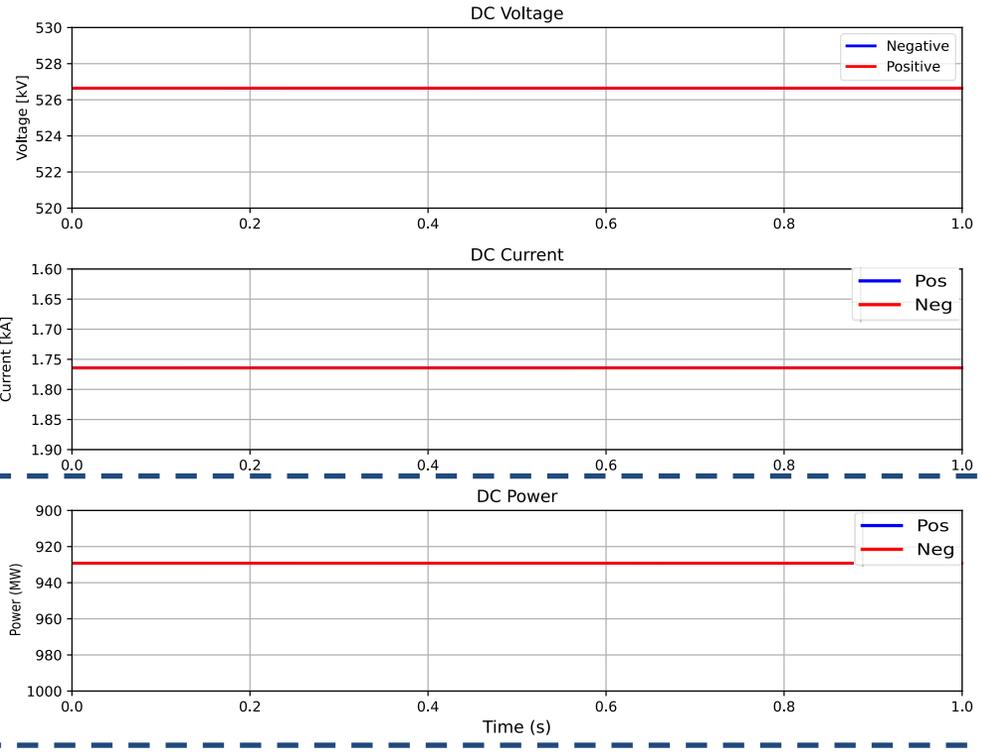
Conv station 1: Active Power Control

Conv station 2: DC Voltage Control

$P_{set} \approx 0\ MW$

OWFs Exported $P_{Ex\_tot} \approx 1850\ MW$
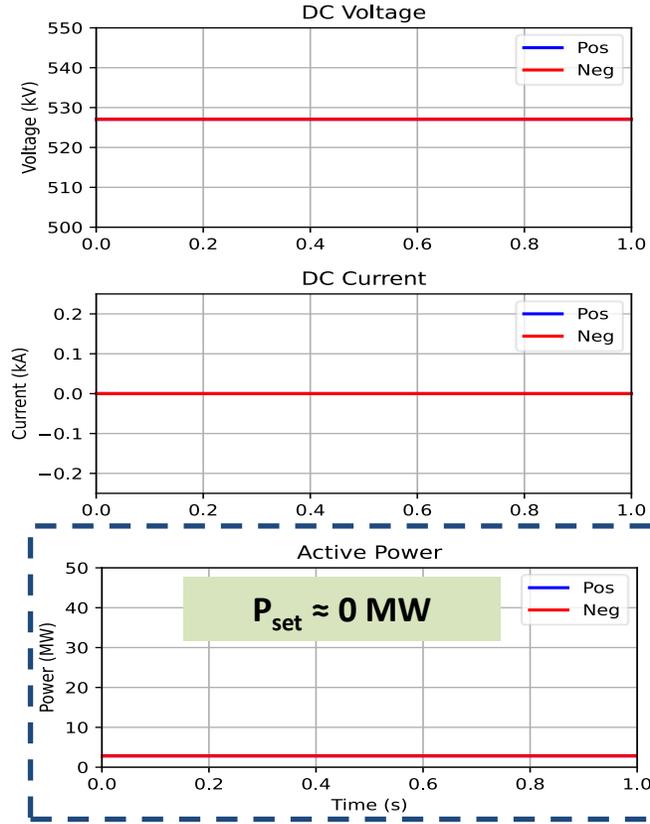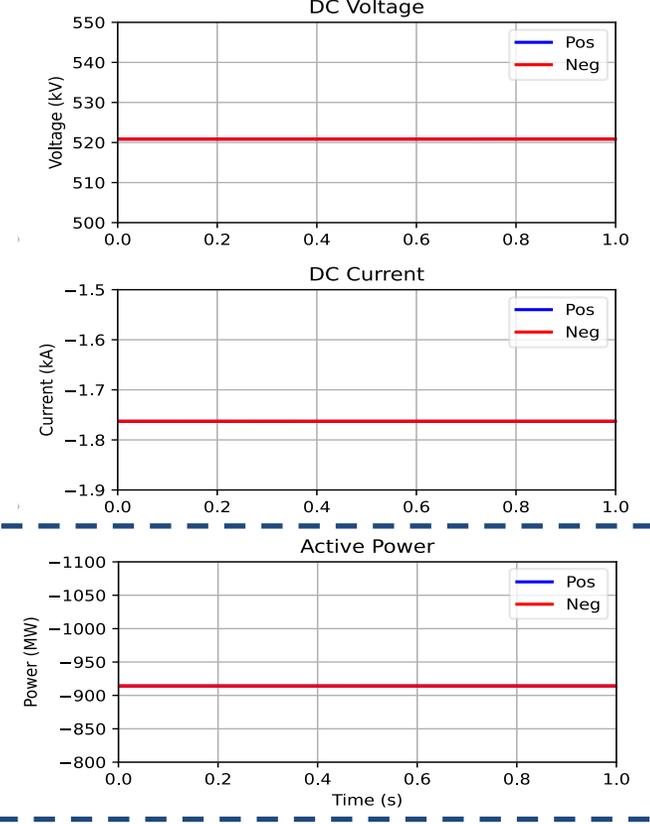
Onshore Imported $P_{Im\_tot} \approx -1820MW$

Multi-terminal Considerations

Asif Khan

$s - mins$ $ms - s$ $\mu s - ms$

Pole Control

Pole Control

Pole Control

Pole Control

Pole Control

Power Dispatch

TO defined and vendor delivered

Multi-terminal Coordination Control

Inner and Outer Control Loops with | Lower level cell balancing control algorithms

Internal protection functions

Vendor Supplied Black Box

Comm Channel

Power Line
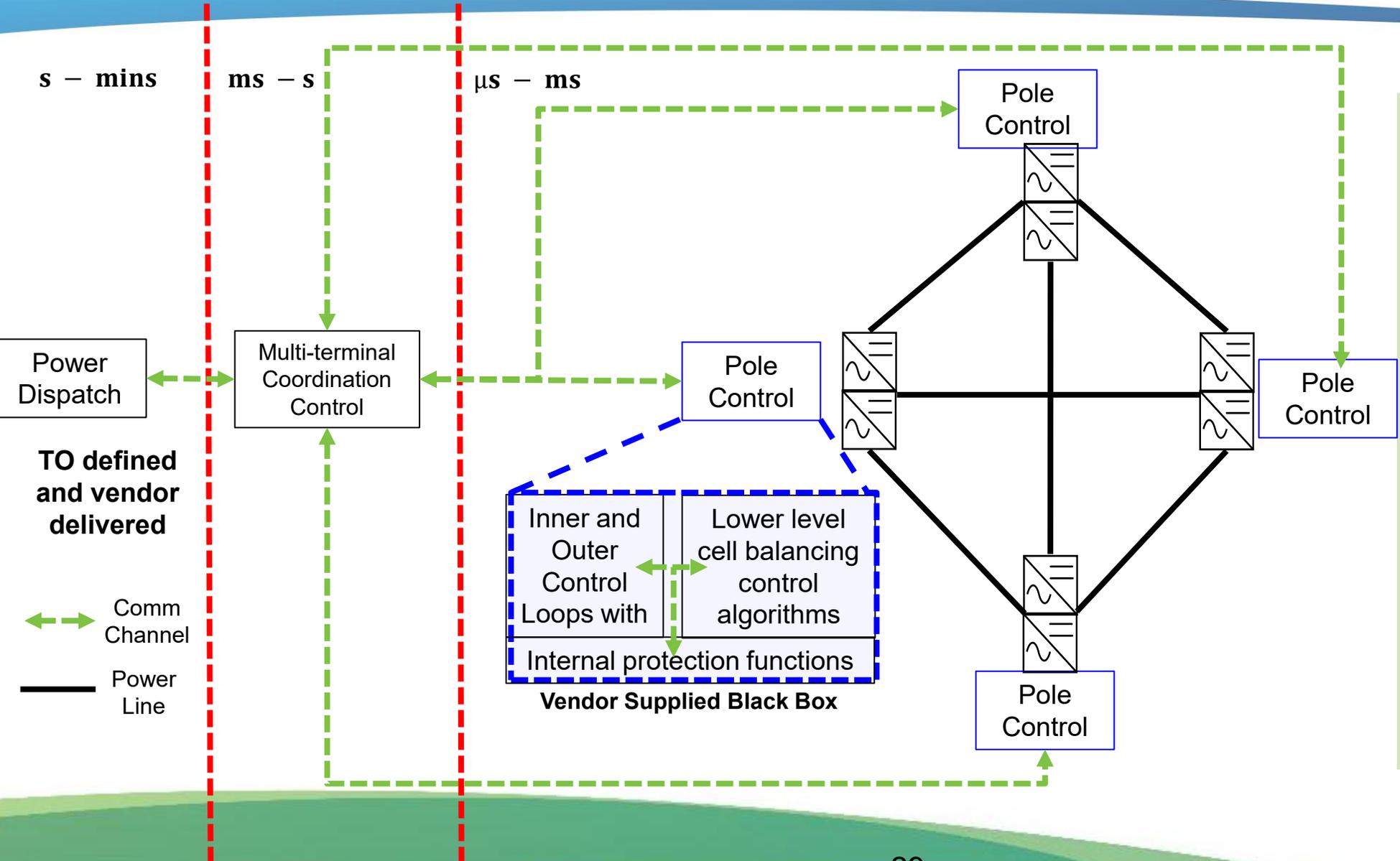
- Complex control coordination and communication.
- Interoperability between different vendors.
- Limited standardisation of MT-HVDC network.

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# Challenges (ii): MT-HVDC Protection

- **DC fault behaviour**
  - Different than AC
  - Fast rise of DC current
  - No zero-crossing
- **Fast protection**
- **DC Circuit Breaker (DCCB)**
  - Maturity
  - Expensive

- Regulatory and economic uncertainties for cross-border systems (MPI Pilot Projects)
- Other operation challenges and feasibility studies (modelling and simulation)

Generic Structure of DCCB:

VARC (VSC-assisted Resonant Current)

Hybrid

Mechanical

Key Takeaways
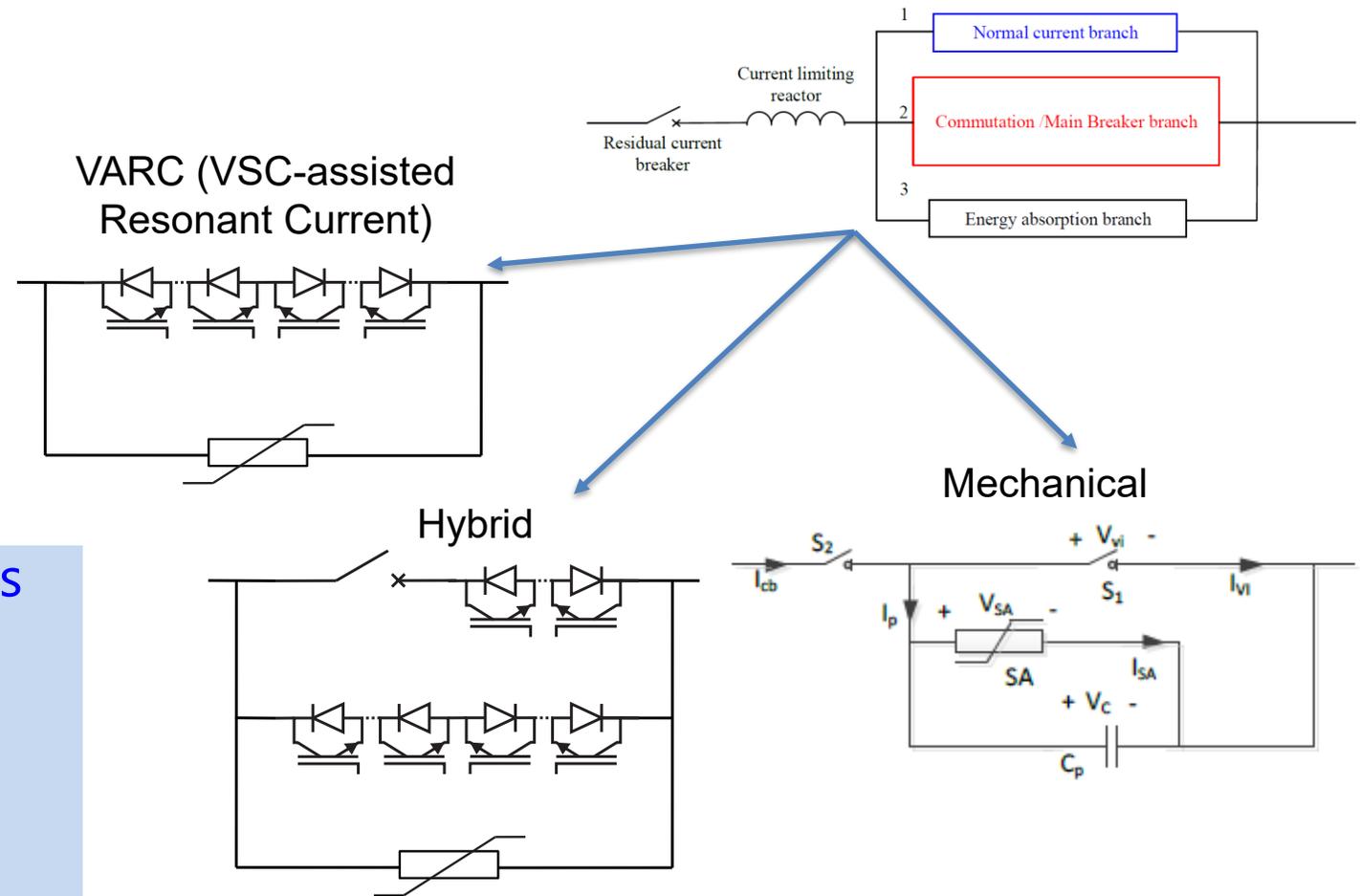
- Multi-terminal HVDC systems are key enablers for future flexible, reliable, and renewable-rich energy networks.

- Coordinated control and energisation strategies are essential

- Technical considerations: protection, interoperability, and system integration

- Addressed across a range of projects

- Q&A

Upcoming Webinars

Network DC: End of Phase Webinar (Show and Tell)

Join us for a 'show and tell' dissemination session on our Strategic Innovation Fund (SIF) Beta project, Network DC. The session will explore what the project has learned in addressing the Round 1 Whole Systems Innovation challenge

Registration

Multi-Terminal HVDC Part 2: Transient Operation and System Dynamics for Multi-Terminal HVDC

Building on the fundamentals introduced in Part 1, this session will focus on the transient operation and system dynamics of multi-terminal HVDC networks under faulted conditions.

HVDC Centre | Upcoming Events

LinkedIn | The National HVDC Centre

Thanks for listening.

Any questions, please?

Please visit **www.hvdccentre.com** or email **info@hvdccentre.com**

The National HVDC Centre

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