Network DC

SIF Beta Round 1

End of Phase Webinar

25th March 2026

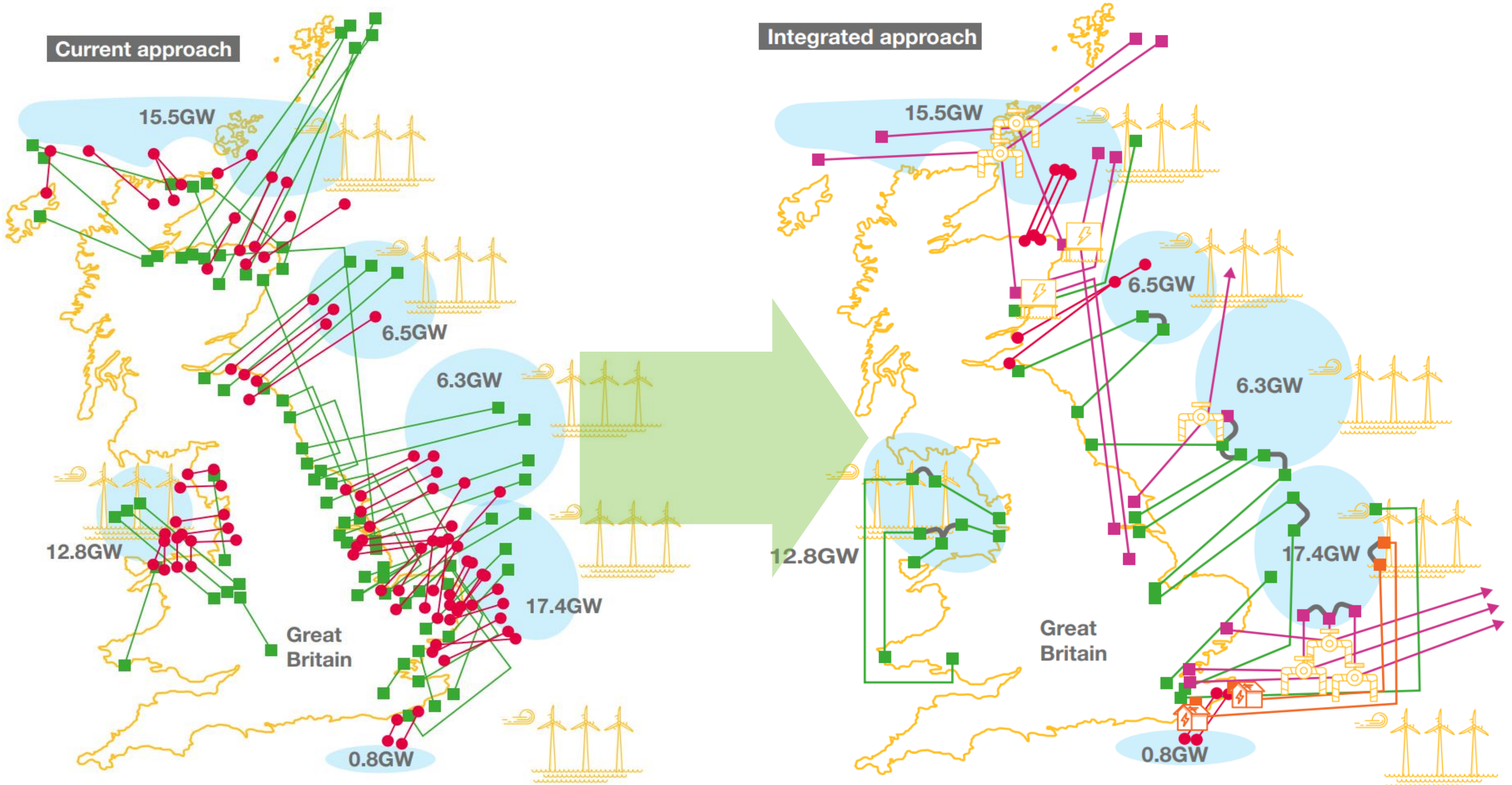
Webinar Recording

A recording of the webinar can be found on Vimeo:
https://vimeo.com/1177006717?share=copy&fl=sv&fe=ci

How can DCCBs help?

The Network DC project, funded through Ofgem’s Strategic Innovation Fund (SIF), set out to explore how Direct Current Circuit Breakers (DCCB) could support more efficient and resilient offshore high voltage direct current (HVDC) networks for Great Britain (GB).

- **Massive opportunity and challenge of offshore wind**
- **Reduce the number of transmission assets required.**
- **Reduce impact on coastal communities.**
- **Reduce cost by avoiding the need for additional infrastructure.**
- **Increases the DC networks flexibility.**
- **Uncertainty of implementing DCCBs in GB**



Source: NESO, Offshore Coordination Phase 1

Journey to Beta

Discovery

CBA identified three potential use cases.

Stakeholder map developed to address major risks.

Developed a collaborative pathway to accelerate first DCCB deployment, focusing on shared risk reduction.

Alpha

Case study identified, documented, formed the basis for a Cost-Benefit Assessment.

Desktop simulations and performance analysis.

Stakeholder interviews gathered views and experience from TSOs, offshore wind developers and academia.

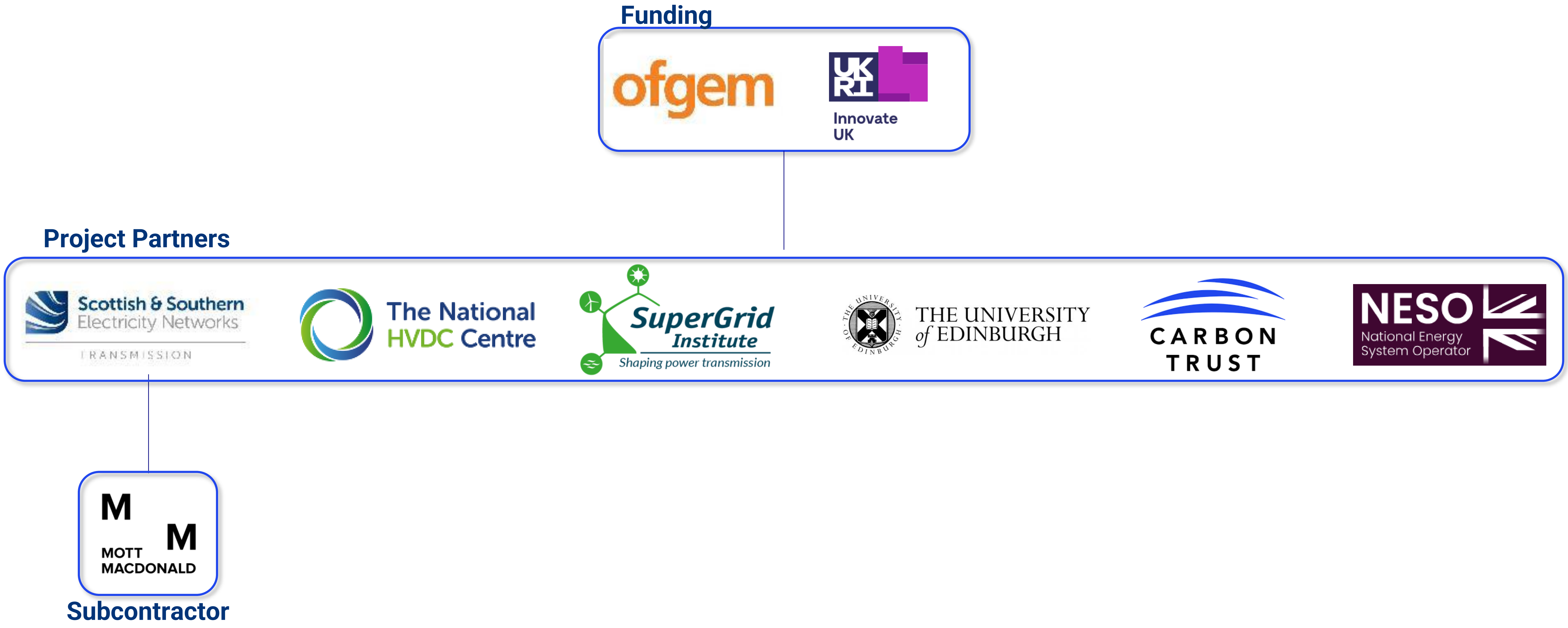
Beta

Demonstrate performance of DCCBs though detailed testing of a DCCB replica as part of GB network model.

Develop vendor agnostic specification to specify DCCBs on the GB network.

Address uncertainties highlighted in the Alpha phase.

Project Consortium



Funding

ofgem

UKRI Innovate UK

Project Partners

Scottish & Southern Electricity Networks TRANSMISSION

The National HVDC Centre

SuperGrid Institute
Shaping power transmission

THE UNIVERSITY of EDINBURGH

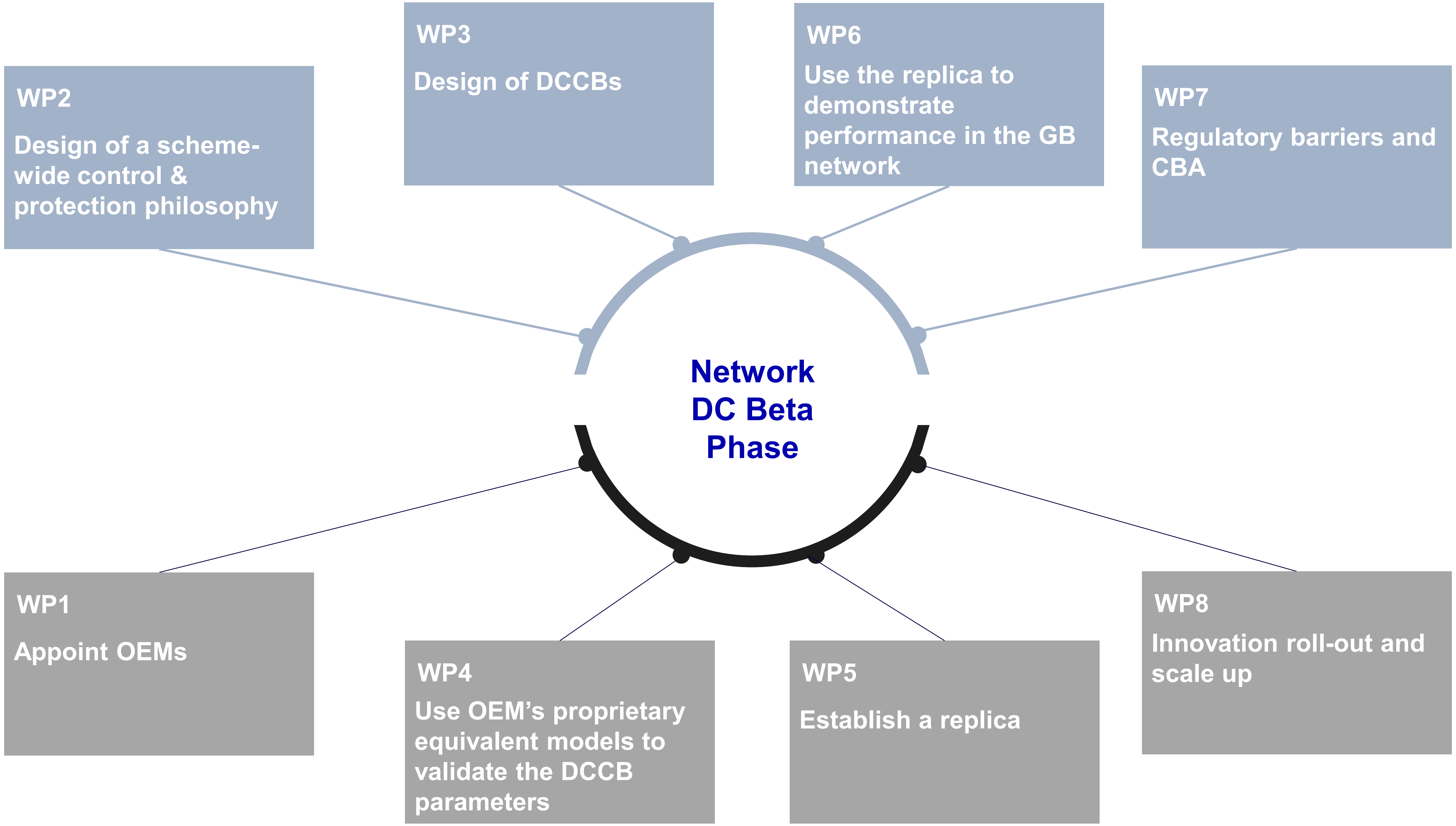
CARBON TRUST

NESO National Energy System Operator

MOTT MACDONALD

Subcontractor

Network DC Beta Phase



Network DC Beta Phase

WP1

Appoint OEMs

WP2

Design of a scheme-wide control & protection philosophy

WP3

Design of DCCBs

WP4

Use OEM's proprietary equivalent models to validate the DCCB parameters

WP5

Establish a replica

WP6

Use the replica to demonstrate performance in the GB network

WP7

Regulatory barriers and CBA

WP8

Innovation roll-out and scale up

Ben Marshall - The National HVDC Centre

WP2 – Control & Protection Philosophy

WP2 – Control & Protection Philosophy

- September 2023 to July 2025
  - Report updates in March 2026
- “WP2 Summary Report” presents key outcomes

- Analysis of a possible future GB-relevant DC grid with realistic control and protection philosophy
- Demonstrate feasibility and highlight technical challenges
- Inform the development of vendor-neutral specification for DCCBs

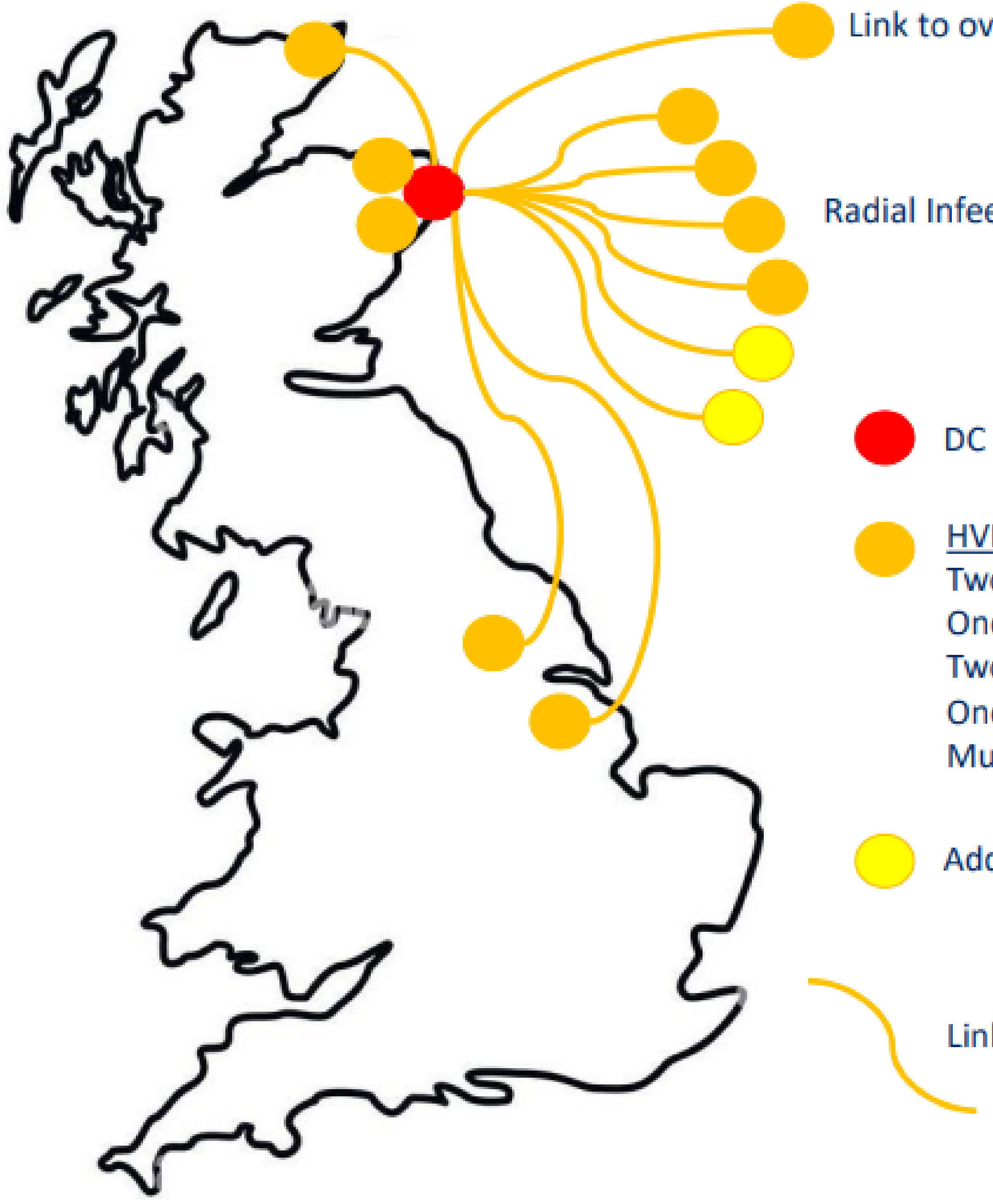
The National HVDC Centre

SuperGrid Institute
Shaping power transmission

THE UNIVERSITY of EDINBURGH

WP2 Activities

- Detailed models of 12-terminal HVDC use case
- Different simulation platforms
  - RTDS
  - EMTP-RV
  - MATLAB/Simulink
- Evaluate DCCB performance, DC reactor sizing, grounding strategies, and control approaches for a range of DC grid operating conditions and fault disturbances
- Review DCCB functional specification
- Significant external engagement
  - Public dissemination activities
  - Consultation with original equipment manufacturers (OEMs)



Link to overseas AC network

Radial Infeeds from offshore wind farms

● DC Hub at Peterhead

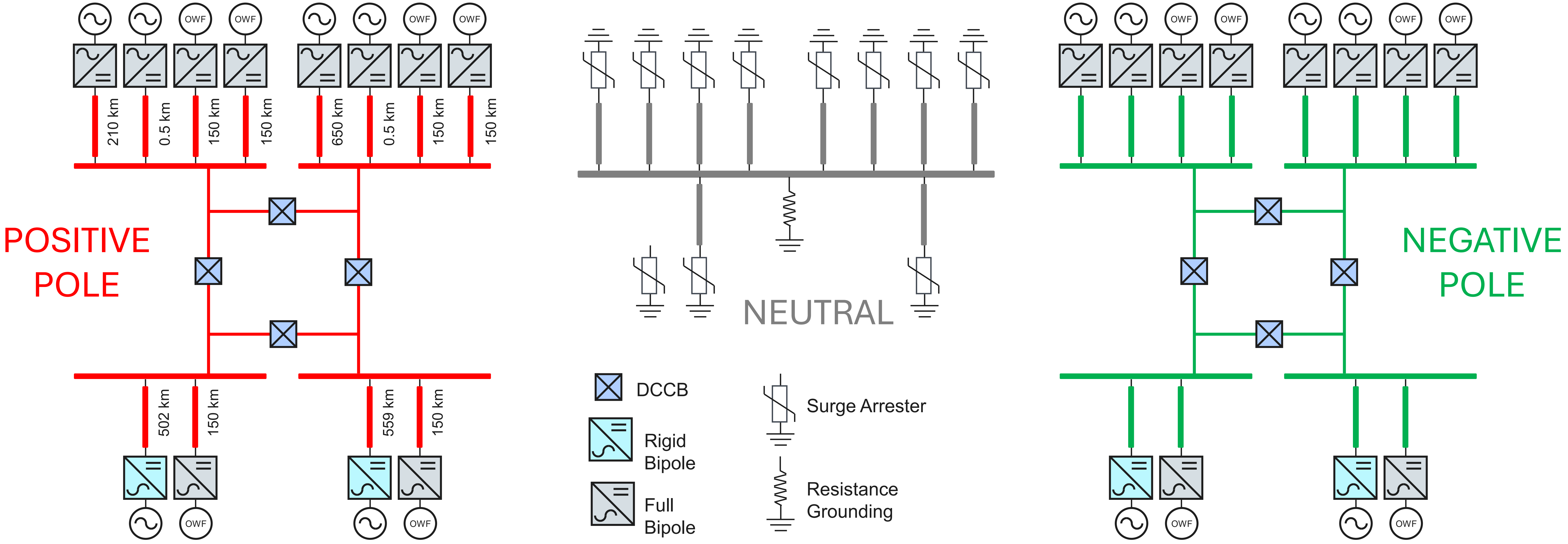
● HVDC Converter Stations
Two at Peterhead
One in the far north of Scotland (Spittal)
Two in central England
One in an another country
Multiple at offshore wind farms (or other radial infeed sources)

● Additional connections made possible by use of DCCBs

Links shown as single lines but all are BIPOLE connections

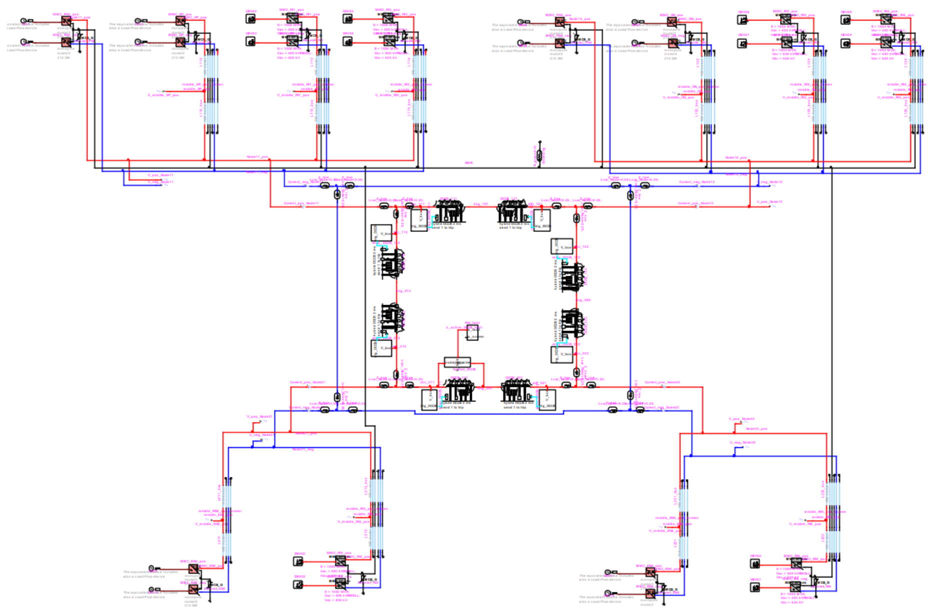
Network DC Use Case

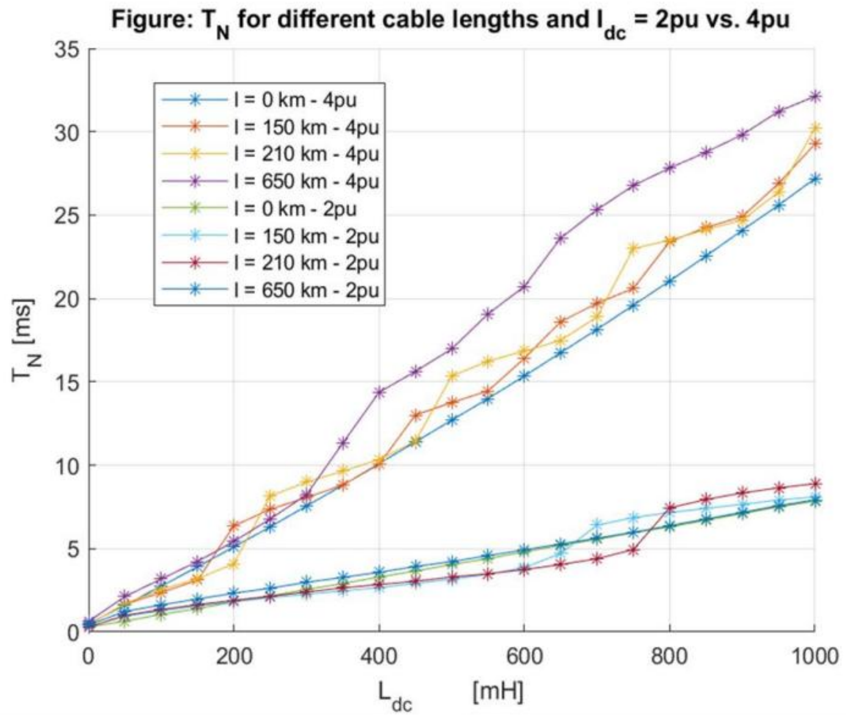
12-terminal HVDC grid with a four-node DC Switching Station (DCSS) mesh, connecting offshore wind farms and onshore converters. DC reactors (not shown) and a single-point grounding system with surge arresters.

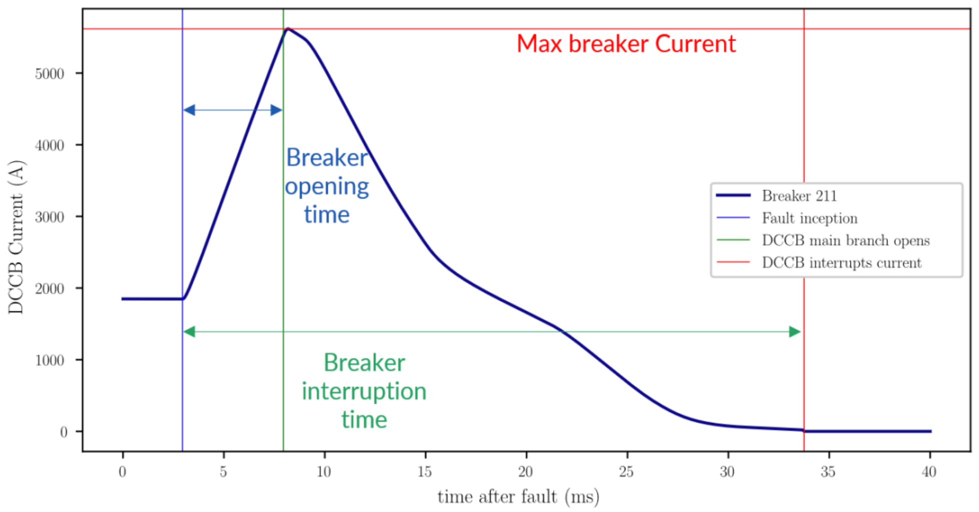


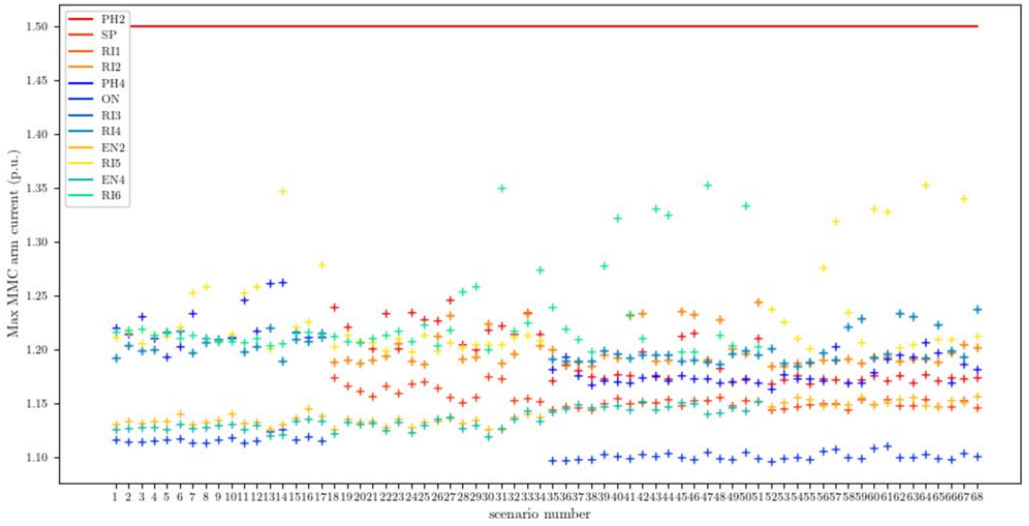
SuperGrid Institute

- EMTP-RV simulations
- Defined minimal functional and technical requirements for DCCBs and DC reactors
- Established protection strategies for fault isolation
- Optimized DC reactor sizing to balance fault current limitation and system stability
- Confirmed technical feasibility with vendor-neutral design guidance









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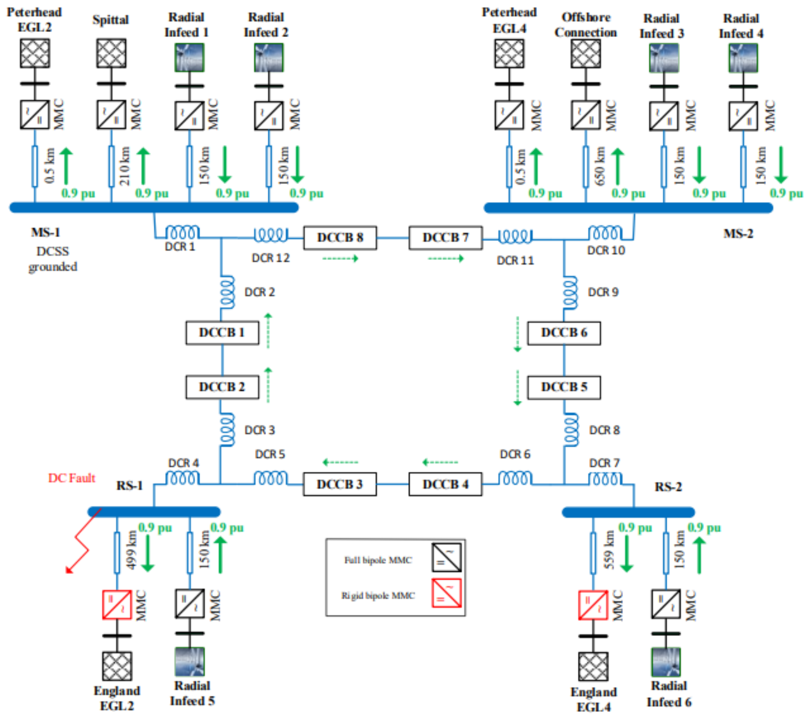
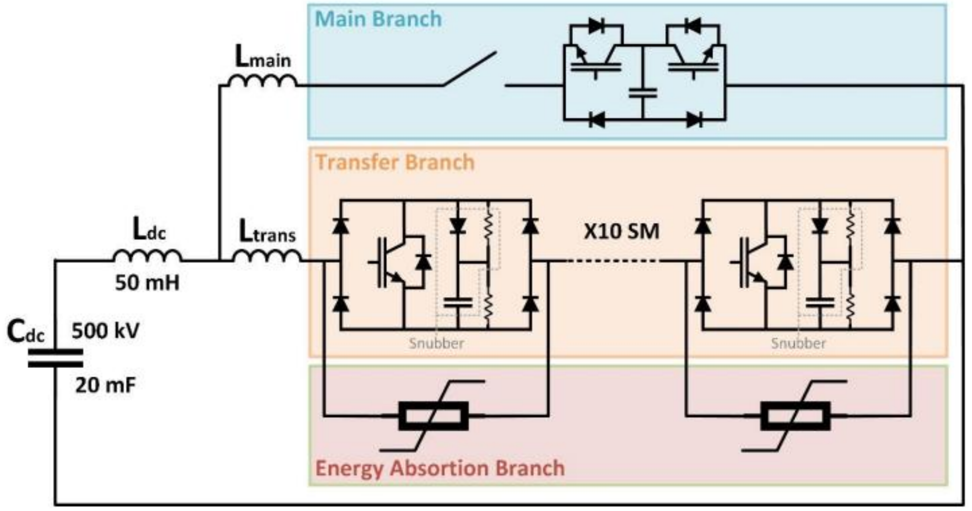
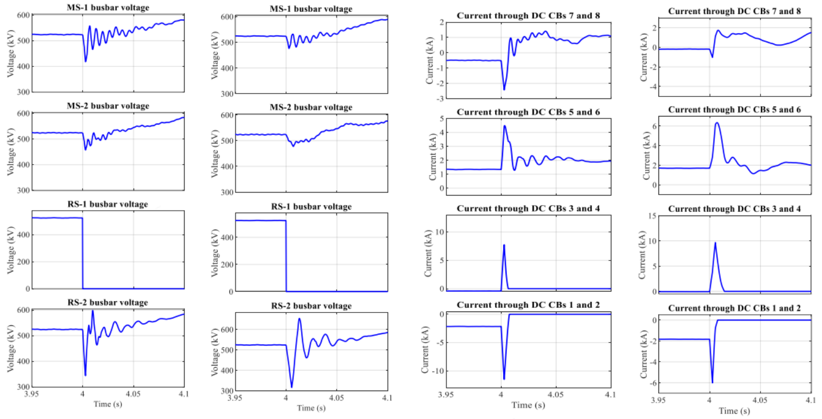
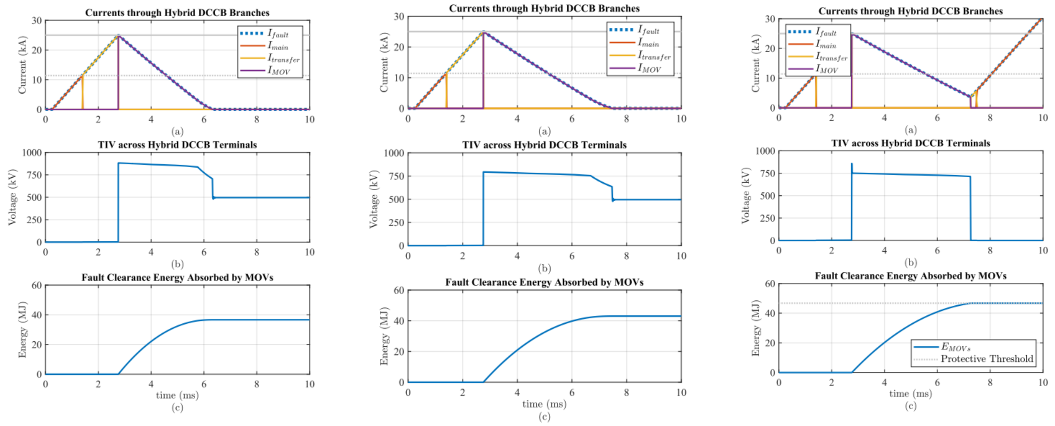
- Advanced hybrid DCCB models in MATLAB/Simulink
  - System-level simulation
  - Real-time device implementation
- Studies on HVDC hub control and protection
  - Optimal DC reactor sizing
  - Fault current interruption requirements
  - Coordinated control for fault ride-through and post-fault recovery.



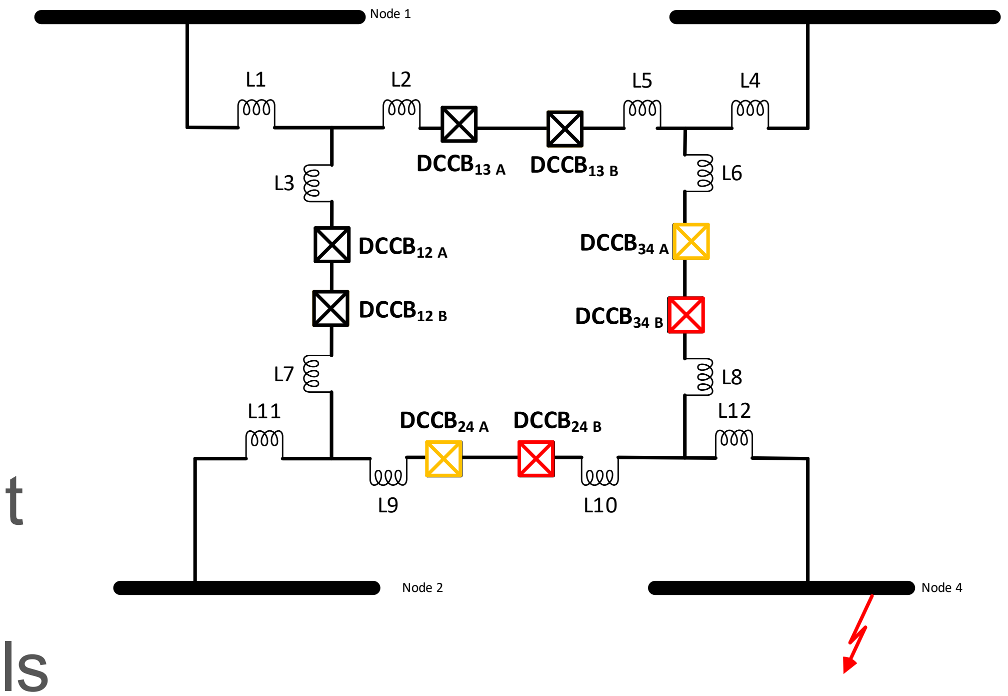


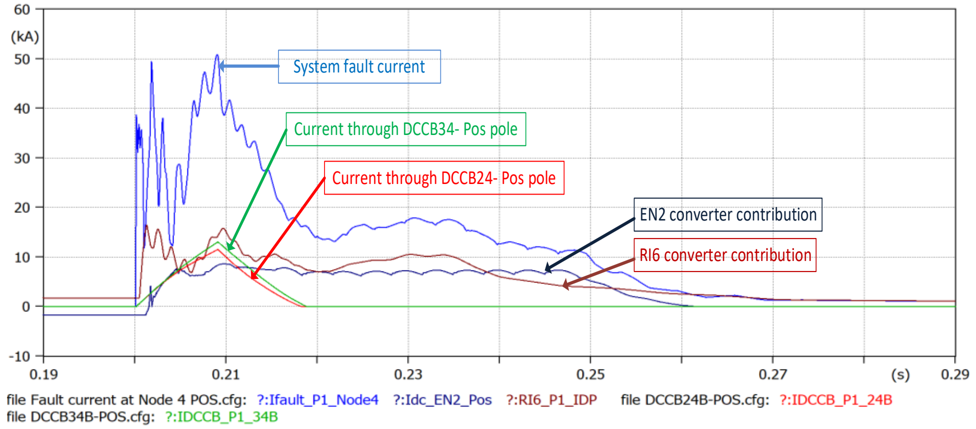


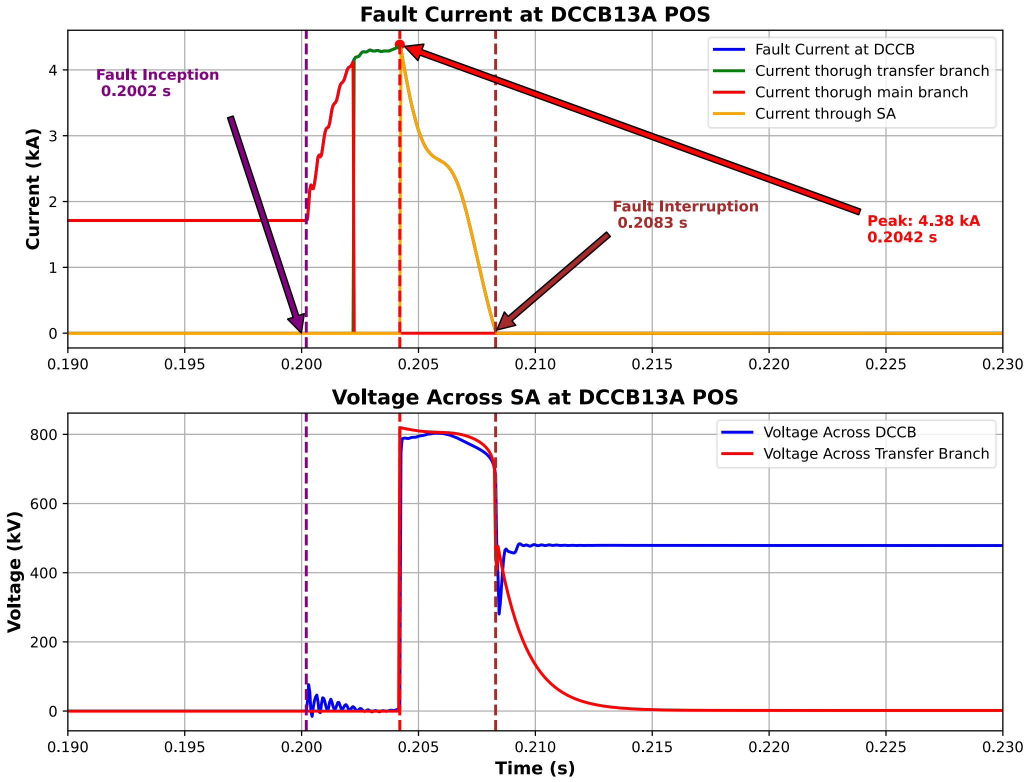


The National HVDC Centre

- Developed use case models in the RTDS platform
- Performed studies to explore DCCB and DC grid behaviour in different conditions
- Highlighted the importance of pre-fault dispatch, converter overload management, and coordinated controls for post-fault recovery
- RTDS models support future testing with hardware

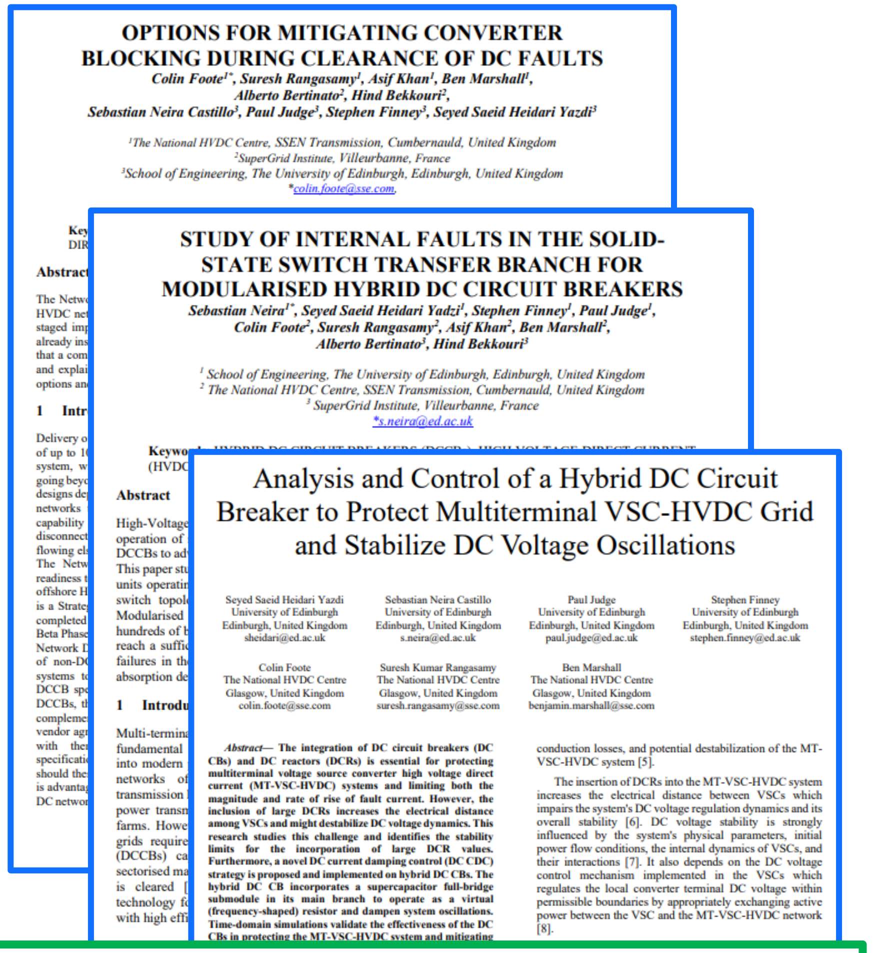






External Engagement

- **Original Equipment Manufacturers (OEMs)**
- Standards: IEC 62271 Part 313 – Working Group 64 on “DC Circuit-Breakers”
- Conference papers
    - “Options for Mitigating Converter Blocking During Clearance of DC Faults,” IET ACDC Conference 2025.
    - “Study of Internal Faults in the Solid-State Switch Transfer Branch for Modularised Hybrid DC Circuit Breakers,” IET ACDC Conference 2025.
    - “Analysis and Control of a Hybrid DC Circuit Breaker to Protect Multiterminal VSC-HVDC Grid and Stabilize DC Voltage Oscillations,” IEEE PowerTech Conference 2025.
    - “System-Level Impacts of Proactive Isolation and Failure-Mode Operation Of Hybrid DCCBs In Multi-Terminal HVDC Hubs”, IET ACDC Europe Conference 2026.
    - “Method for DC Reactor and DC Circuit Breaker Design In HVDC Grids”, IET ACDC Europe Conference 2026.
    - “Performance Study and Specification Framework for DC Circuit Breakers in Multi-terminal HVDC Networks”, CIGRE Paris Session 2026.
- Webinars
    - “Network DC – The Why and How of DC Circuit Breakers”, 25 October 2023
    - “Network DC – Innovations in DCCBs and HVDC Grid Technologies”, 20 May 2025



OPTIONS FOR MITIGATING CONVERTER BLOCKING DURING CLEARANCE OF DC FAULTS

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STUDY OF INTERNAL FAULTS IN THE SOLID-STATE SWITCH TRANSFER BRANCH FOR MODULARISED HYBRID DC CIRCUIT BREAKERS

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Analysis and Control of a Hybrid DC Circuit Breaker to Protect Multiterminal VSC-HVDC Grid and Stabilize DC Voltage Oscillations

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***Abstract*— The integration of DC circuit breakers (DC CBs) and DC reactors (DCRs) is essential for protecting multiterminal voltage source converter high voltage direct current (MT-VSC-HVDC) systems and limiting both the magnitude and rate of rise of fault current. However, the inclusion of large DCRs increases the electrical distance among VSCs and might destabilize DC voltage dynamics. This research studies this challenge and identifies the stability limits for the incorporation of large DCR values. Furthermore, a novel DC current damping control (DC CDC) strategy is proposed and implemented on hybrid DC CBs. The hybrid DC CB incorporates a supercapacitor full-bridge submodule in its main branch to operate as a virtual (frequency-shaped) resistor and dampen system oscillations. Time-domain simulations validate the effectiveness of the DC CBs in protecting the MT-VSC-HVDC system and mitigating**

conduction losses, and potential destabilization of the MT-VSC-HVDC system [5].

The insertion of DCRs into the MT-VSC-HVDC system increases the electrical distance between VSCs which impairs the system's DC voltage regulation dynamics and its overall stability [6]. DC voltage stability is strongly influenced by the system's physical parameters, initial power flow conditions, the internal dynamics of VSCs, and their interactions [7]. It also depends on the DC voltage control mechanism implemented in the VSCs which regulates the local converter terminal DC voltage within permissible boundaries by appropriately exchanging active power between the VSC and the MT-VSC-HVDC network [8].

> Technical Films > WEBINAR: Network DC – Innovations in DCCBs and HVDC Grid Technologies

WEBINAR: Network DC – Innovations in DCCBs and HVDC Grid Technologies

Webinar (20 May 2025)

Supporting materials: **Slides** and **Q&A**

In this section

- VIDEO: Aquila Project
- VIDEO: Moyle Interconnector Control System Upgrade
- VIDEO: Network DC Project
- VIDEO: Project INCENTIVE
- WEBCAST: COMPOSITE (Mar 2021)
- WEBINAR: AC Protection Solutions in a Low Strength Network (Aug 2024)
- WEBINAR: COP26 (Nov 2021)
- WEBINAR: Demonstration of DC

WP2 Key Technical Outcomes

- Development and demonstration of methodologies for assessing DC reactor placement and sizing to support fault current limitation and converter protection
- Development and testing of advanced DCCB models and control strategies to support fault ride-through and post-fault recovery
- Studies demonstrate the technical feasibility of DCCBs interrupting fault currents in realistic worst-case conditions
- No direct interface between DC grid control and DCCB is required, although wider DC grid control strategy must be appropriate to ensure acceptable post-fault performance.
- **Identification of key constraints in DCCB performance:**
  - **Sufficiently fast action of DCCB operations**
  - **Limiting the rate of rise of current through the DCCB (larger DC reactors)**
  - **Energy absorption within DCCB capabilities**
  - **Transient Interruption Voltage (TIV) within limits of other DC grid components**
  - **Enabling ride through of HVDC converters in non-faulted zones (essential for retro-fitting)**
- **Confirmation that a vendor-neutral, technically feasible DCCB specification can be developed and applied in retrofit of DCCBs in a realistic DC grid operating with a practical control and protection philosophy.**

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WP 3.6/3.7/6.5 – Advanced DCCB Modelling

WP 3.6/3.7 – Advanced DCCB Modelling

Objectives

- Develop FPGA-based real-time models of hybrid DCCB sub-modules using HDL/HLS workflows and evaluate their performance for closed-loop studies with DC network models.

Scope

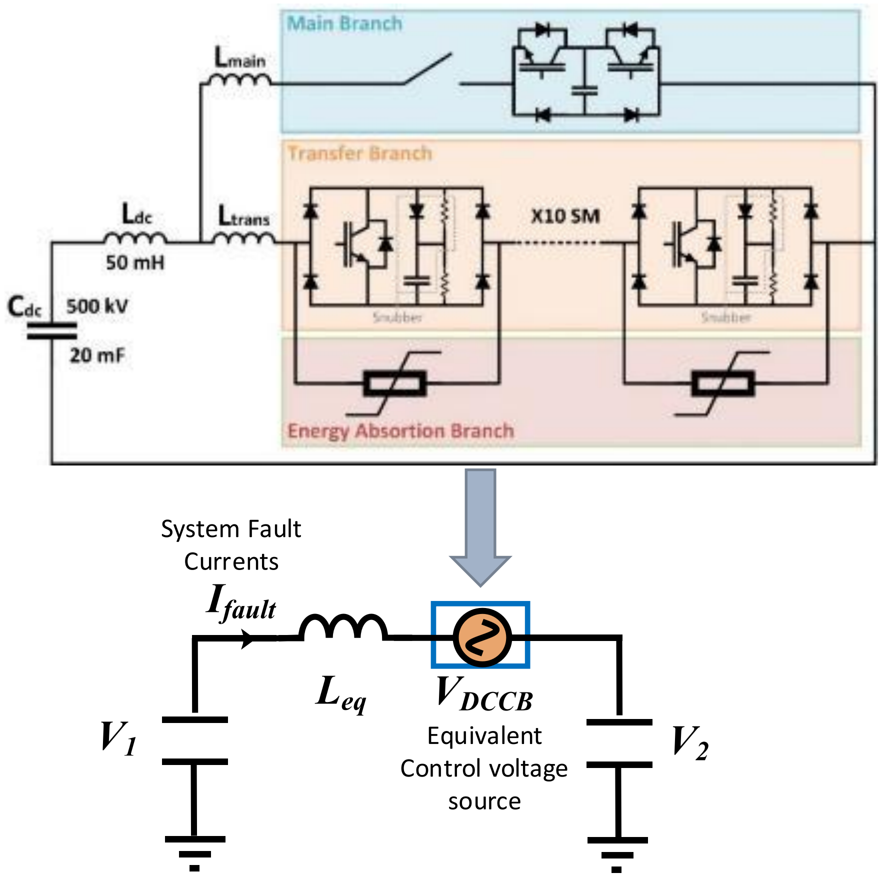
- Designed FPGA-based modelling of hybrid DCCB sub-modules and advanced functions.
- Closed-loop real-time validation of DCCB behaviour when interfaced with a represented DC network model.
- Implementation of FPGA control blocks with the advanced current limiting function and evaluate the performance with RTDS system in real-time experiment.

Mathematical DCCB Model in MATLAB/Simulink

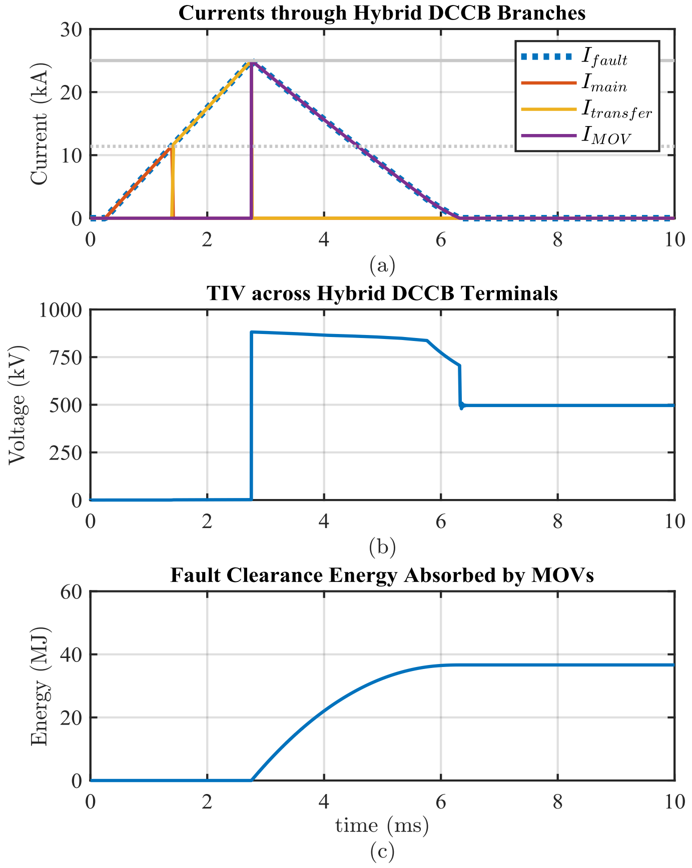
The equivalent DCCB is represented as a controlled voltage source connected between DC nodes V_1 and V_2. Its output voltage is determined by a controller that emulates the main, transfer, and energy-absorption branches of a hybrid breaker.

DCCB simulation model with three branches and electric components

DCCB simulation model with controlled voltage source



Consider DCCB as a controlled voltage source

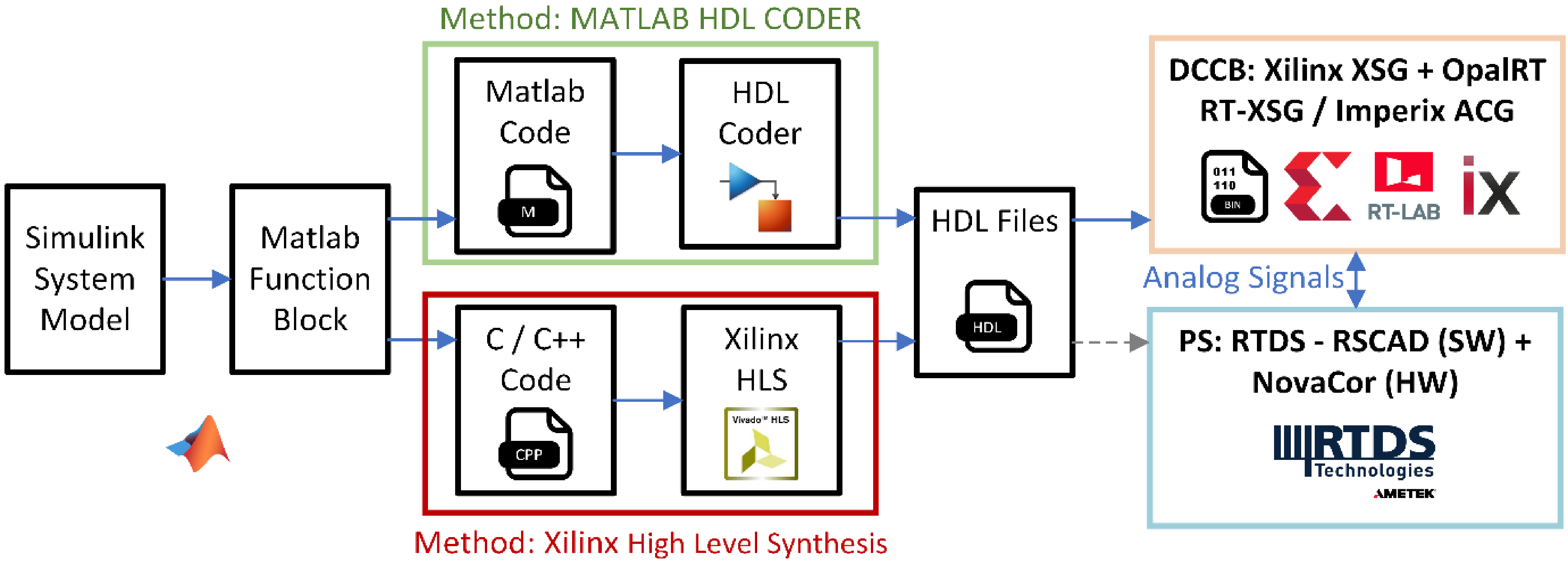


DCCB simulation waveform in WP 2

HDL Generation and FPGA Implementation Workflow

These workflows support the transition from the validated control-oriented model to a synthesizable FPGA real-time implementation.

- **MATLAB HDL Coder**
- **Xilinx Vitis High-Level Synthesis (HLS)**

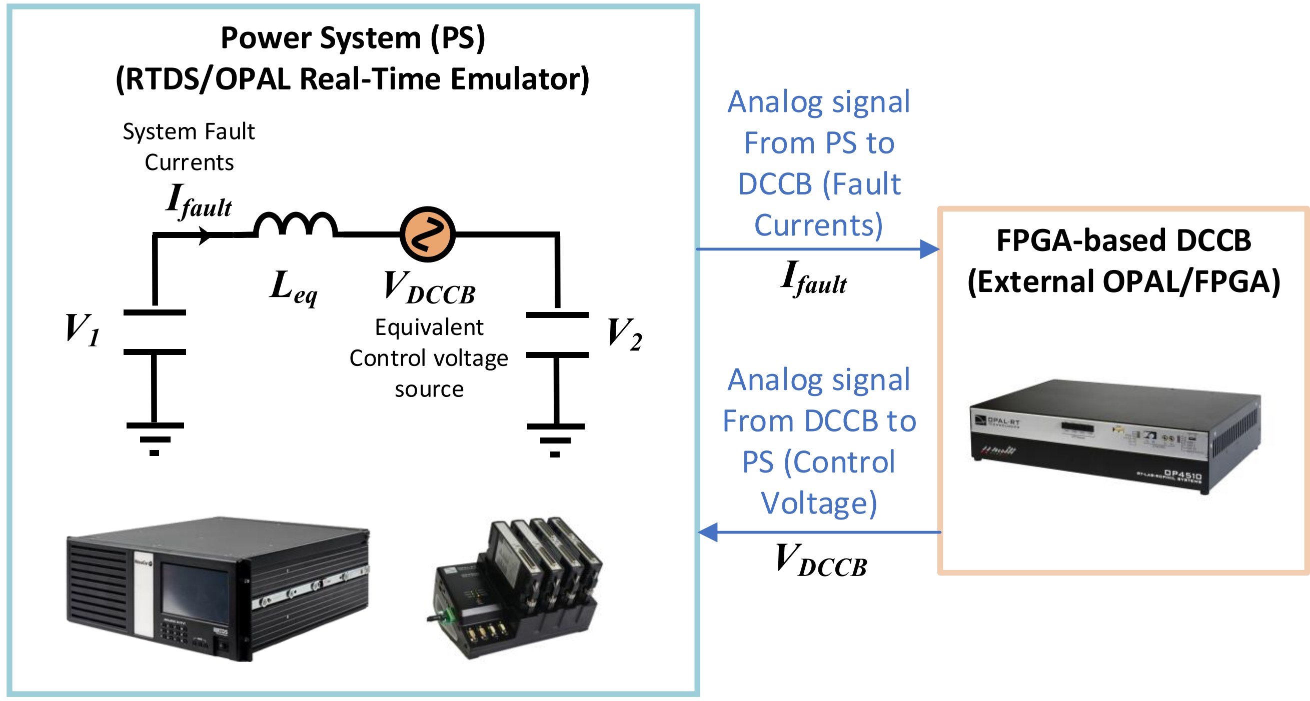


Two workflows for HDL code generation and implementation

System Integration and Real-Time Validation

The two platforms exchange interface signals for closed-loop testing and validation. A real-time FPGA DCCB model has been implemented and benchmarked against the simulation model. The Proposed model also tested with RTDS system in HVDC Centre.

Analog Signal Output Voltage Range: -10 to 10 V
Voltage Signal Gain: 100,000 (-1e6 to 1e6 V)
Current Signal Gain: 1,000 (-1e4 to 1e4 A)



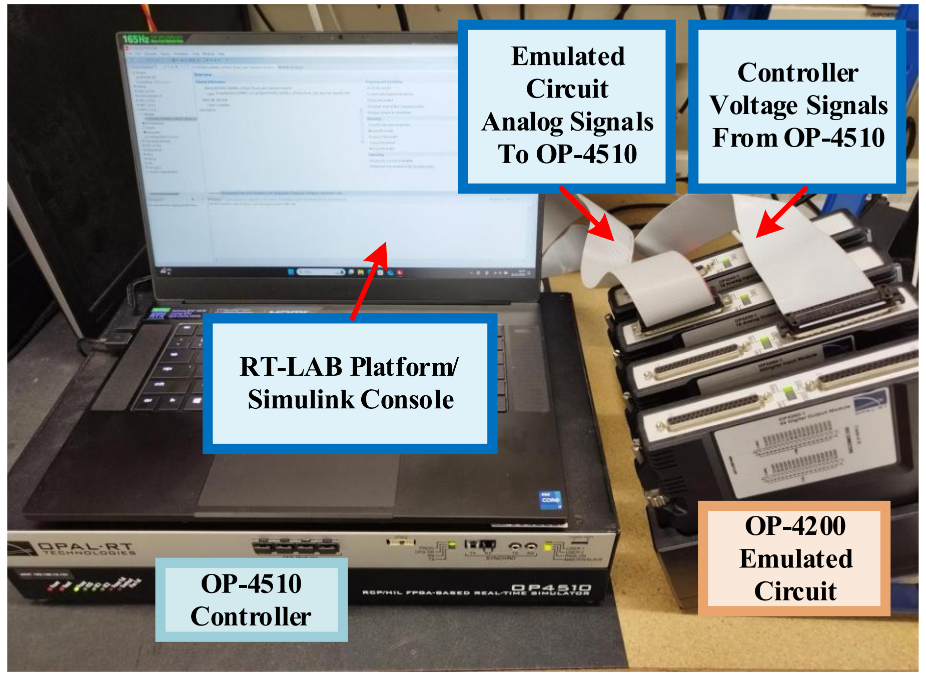
Power System (PS)
(RTDS/OPAL Real-Time Emulator)

Analog signal From PS to DCCB (Fault Currents)

FPGA-based DCCB
(External OPAL/FPGA)

Analog signal From DCCB to PS (Control Voltage)

A representative setup uses OPAL-RT platforms such as OP4510 and OP4200, together with a control workstation.



Emulated Circuit Analog Signals To OP-4510

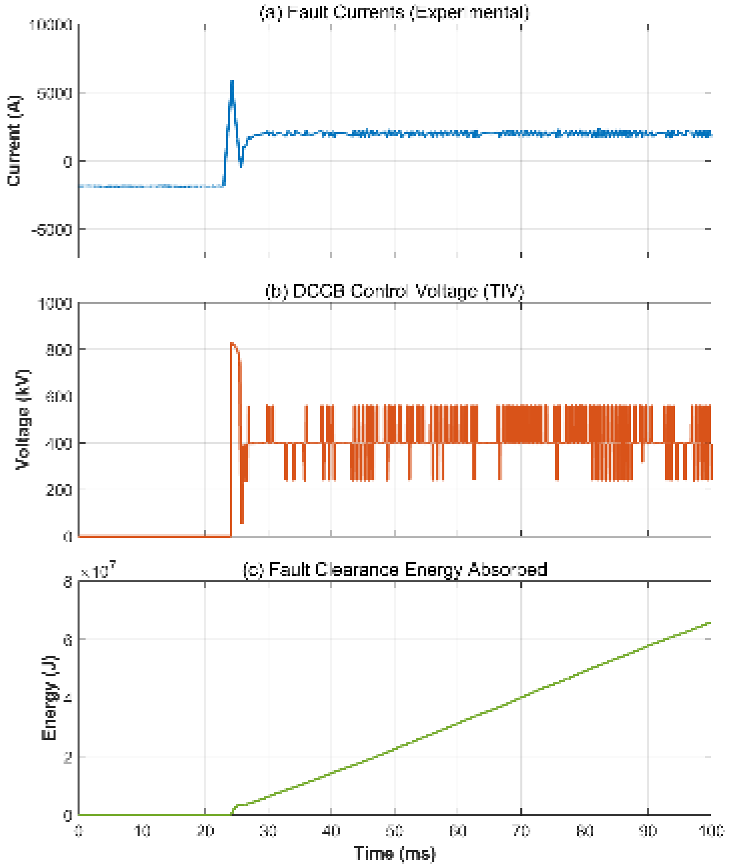
Controller Voltage Signals From OP-4510

RT-LAB Platform/ Simulink Console

OP-4200 Emulated Circuit

OP-4510 Controller

The power-system side hosts the real-time DC network model, while the DCCB side hosts the FPGA implementation of the hybrid breaker model.



DCCB experiment waveform with RTDS system

WP 6.5 – Advanced DCCB Modelling

Objectives

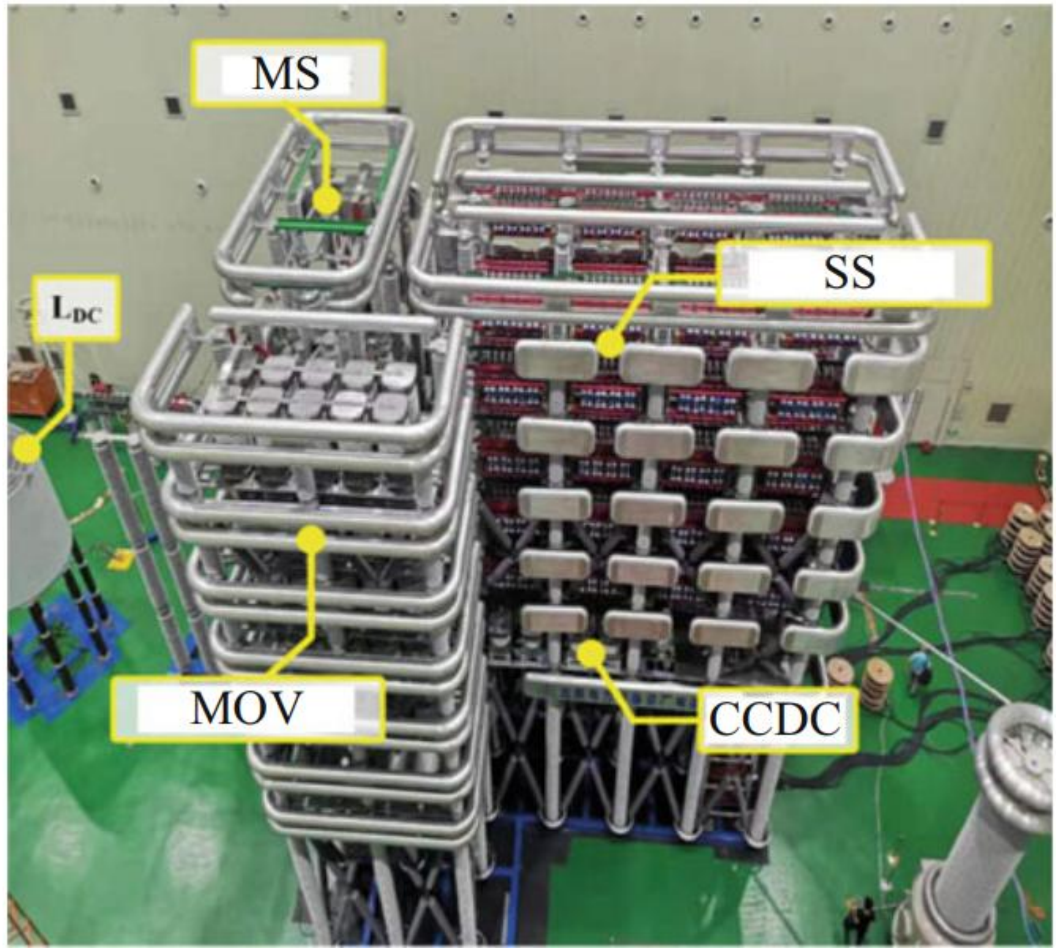
- Quantify the system-level value of advanced hybrid DCCB functions: proactive operation, fault-current limiting, and DC flow control; benchmark against alternative breaker implementations.

Scope

- System-level EMT/desktop studies with open-source breaker models.
- Three technical strands: proactive action to reduce clearance time and peak breaking current; current limiting with attention to protection interactions; DC flow control (and stabilizing) under large DC reactors with EMT assessment.

Hybrid DC circuit breakers: complexity that enables advanced functions

- Hybrid DC circuit breakers are feasible, and the industry now builds them.
- They are complex by necessity: DC has no natural current zero, so interruption requires an internal sequence.
- Architecture: main branch (low-loss), transfer branch (fast solid-state), energy absorption (surge arresters).
- High-level sequence: normal low-loss conduction → fast commutation → blocking voltage → energy absorption.
- Key message: this complexity enables advanced functions beyond "open/close", such as proactive action and fault current limiting.
- Our contribution: we have developed EMT/desktop models of advanced functionality DCCBs (including hybrid technology), and we have integrated them in system-level HVDC hub studies.



Practical Implementation of Hybrid DCCB*

***Source: Z. Yu et al, "535 kV/25 kA Hybrid Circuit Breaker Development", DOI: https://doi.org/10.1007/978-3-031-26572-3_13**

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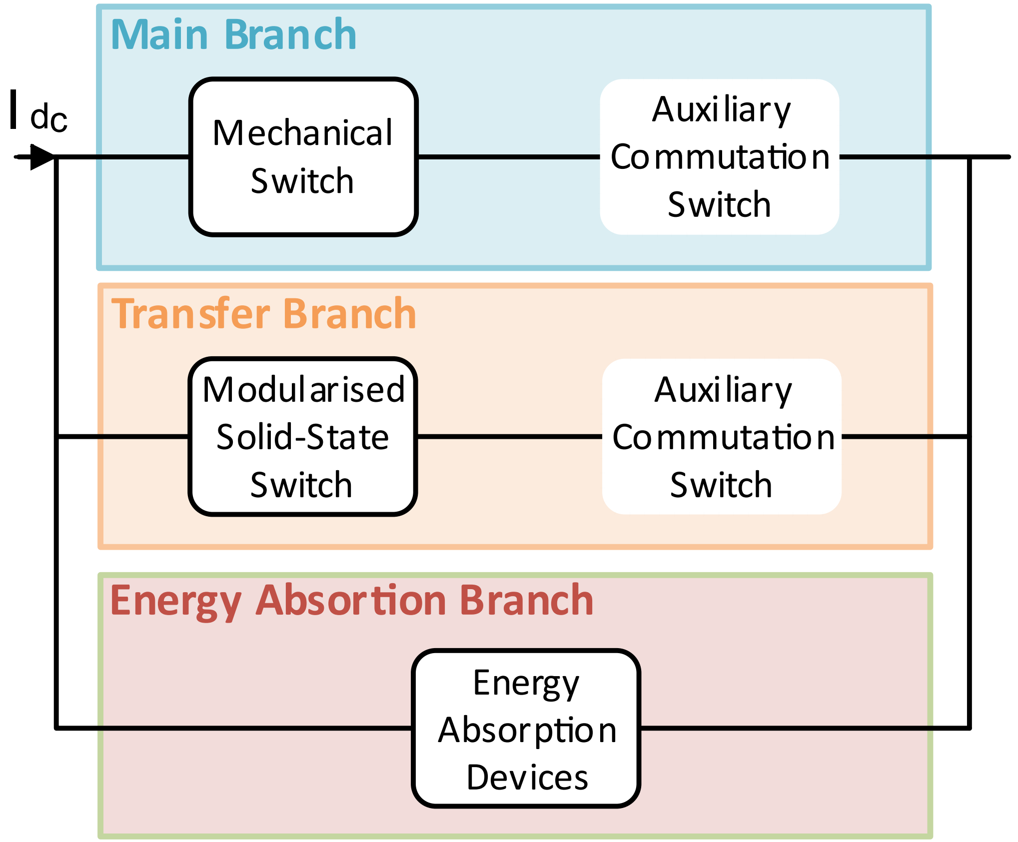

Hybrid DCCB Overall Structure

Hybrid DC circuit breakers: complexity that enables advanced functions

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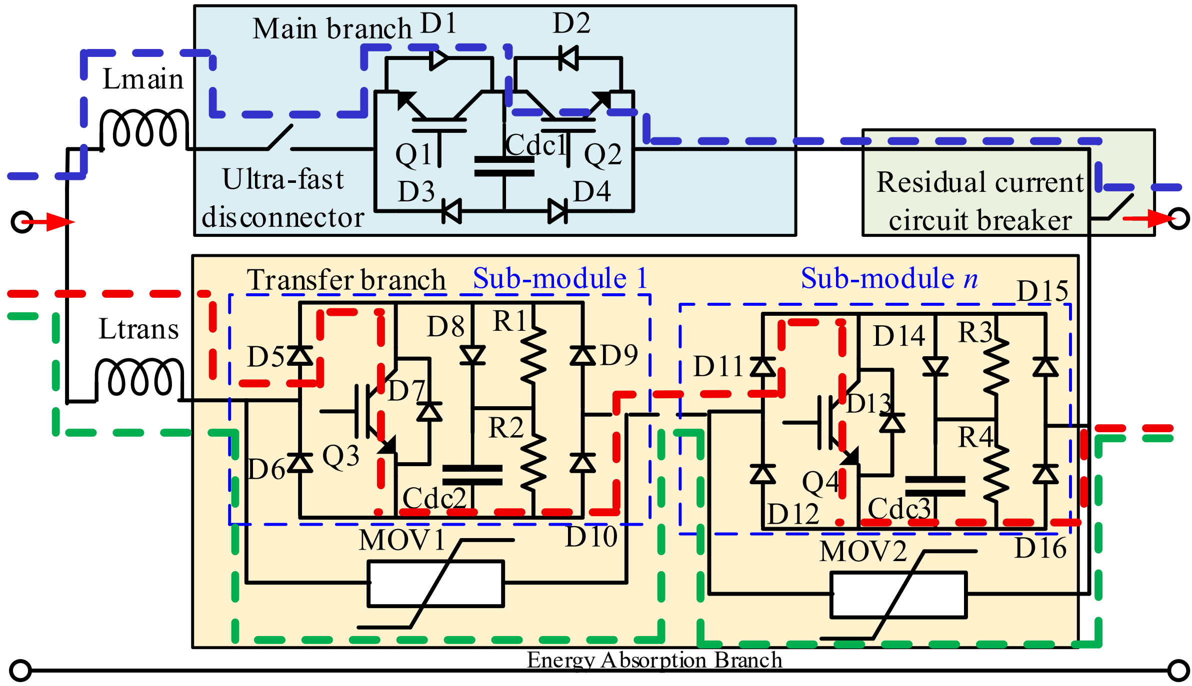
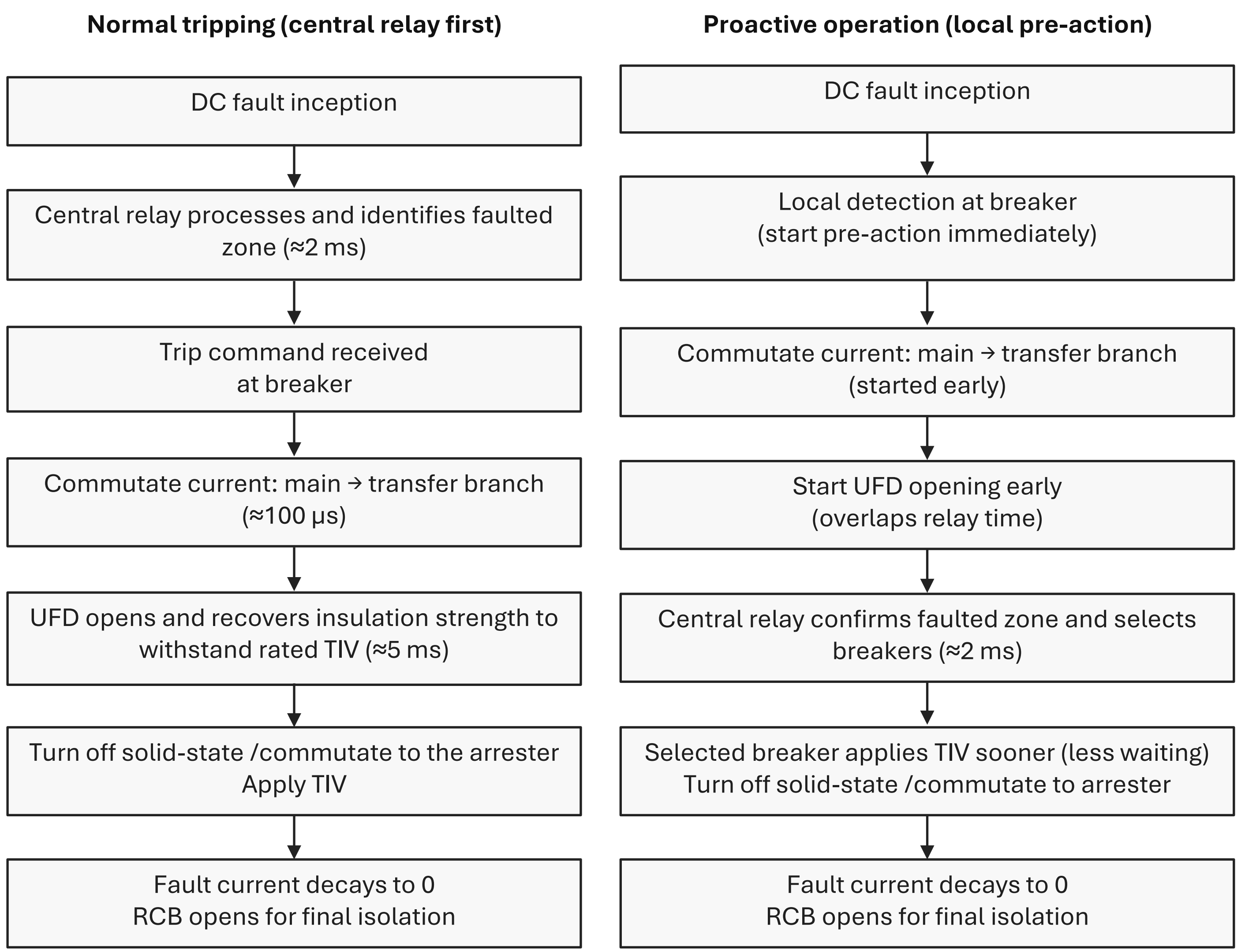


Load Commutation Switch with Diode Bridge

Proactive Operation Advanced Functionality

- Proactive isolation: the breaker starts its opening sequence as soon as local measurements indicate an incipient DC fault, and it does not wait for the central DC fault relay trip.
- What this buys: a shorter fault-neutralisation interval, with earlier TIV application once the faulted zone is confirmed.
- Practical extension: for low pre-fault currents, selected breakers can carry current in the solid-state branch continuously, which avoids the mechanical switch opening delay and accelerates interruption further.
- Illustrative outcome: In the hub study, proactive operation reduced peak current through the system breakers and reduced the early voltage dip at nearby healthy busbars.



Normal tripping (central relay first)

DC fault inception

Central relay processes and identifies faulted zone (≈2 ms)

Trip command received at breaker

Commutate current: main → transfer branch (≈100 µs)

UFD opens and recovers insulation strength to withstand rated TIV (≈5 ms)

Turn off solid-state /commutate to the arrester
Apply TIV

Fault current decays to 0
RCB opens for final isolation

Proactive operation (local pre-action)

DC fault inception

Local detection at breaker (start pre-action immediately)

Commutate current: main → transfer branch (started early)

Start UFD opening early (overlaps relay time)

Central relay confirms faulted zone and selects breakers (≈2 ms)

Selected breaker applies TIV sooner (less waiting)
Turn off solid-state /commutate to arrester

Fault current decays to 0
RCB opens for final isolation

Key difference: proactive mode removes relay time from the critical path by overlapping it with commutation and UFD opening.

Proactive Operation Advanced Functionality

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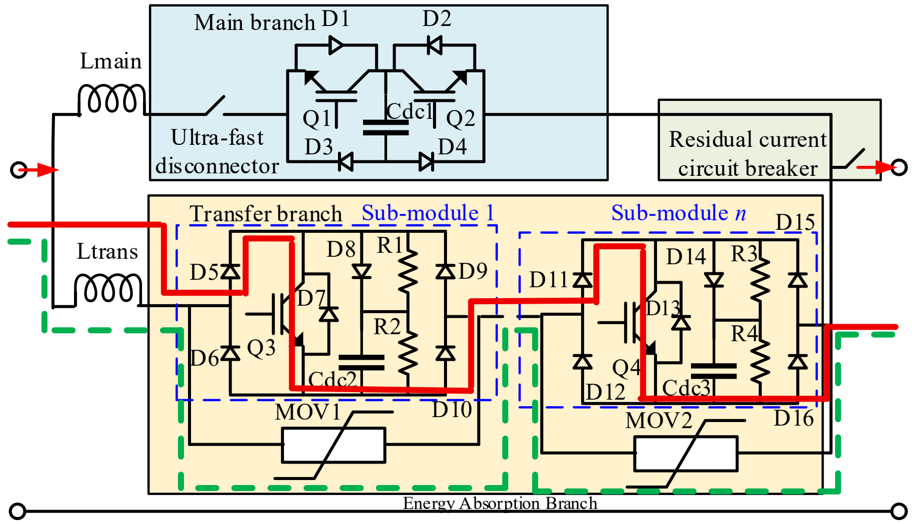

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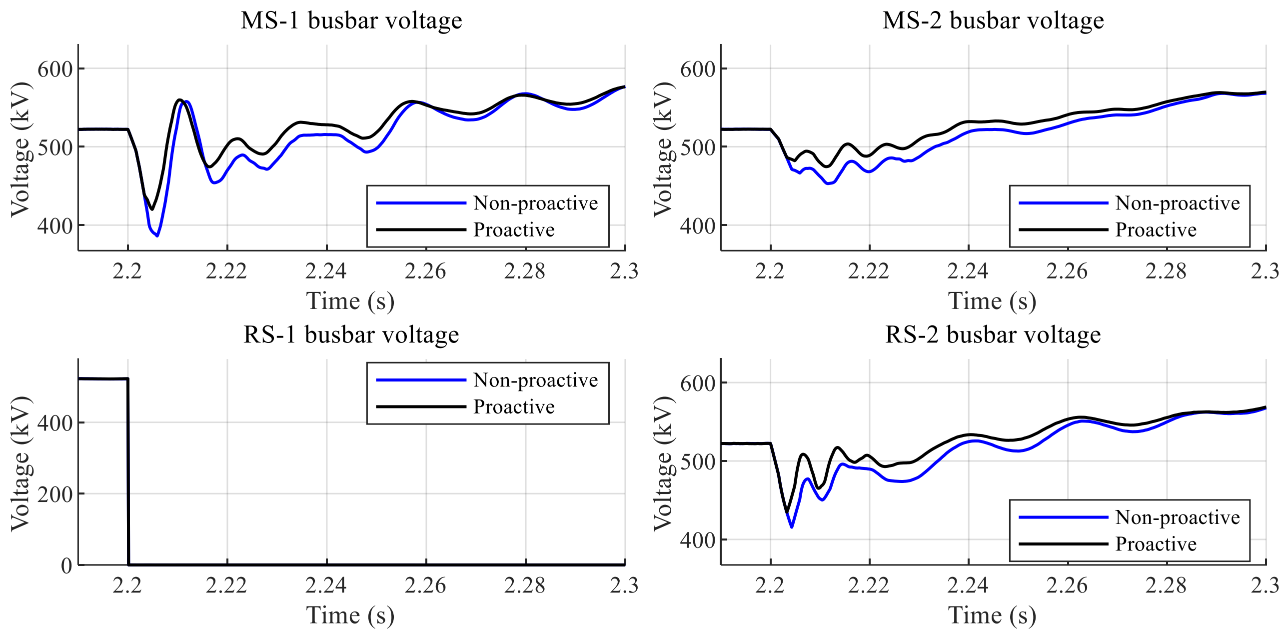
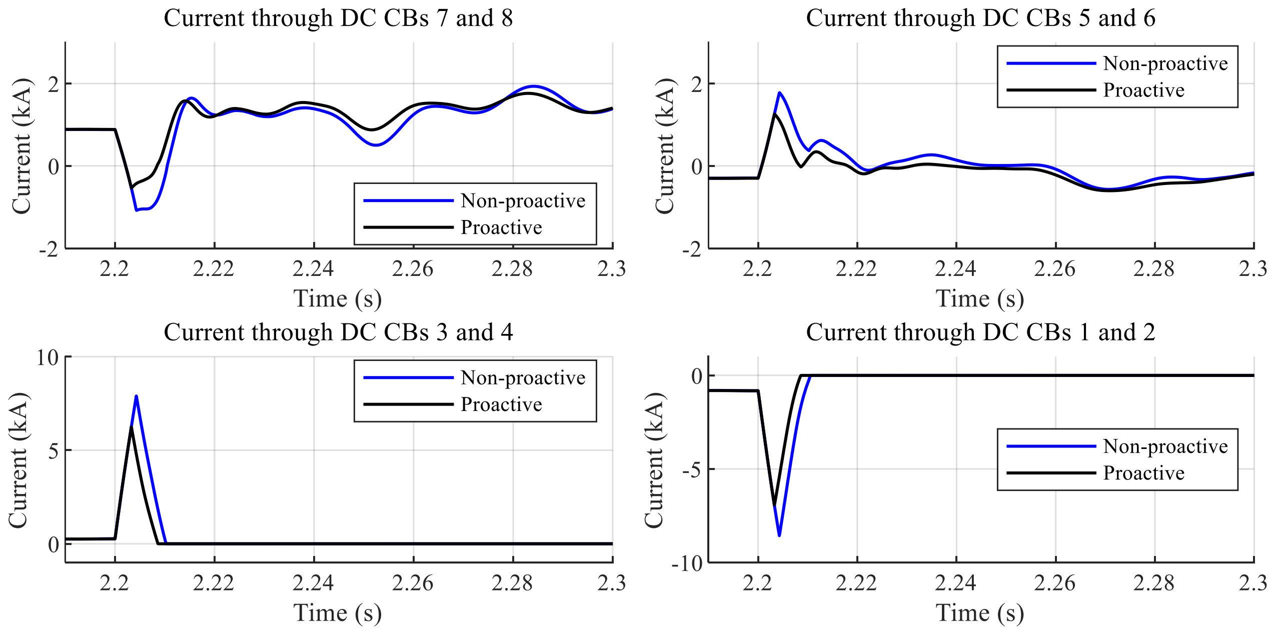
- Practical extension: for low pre-fault currents, selected breakers can carry current in the solid-state branch continuously, which avoids the mechanical switch opening delay and accelerates interruption further.
- Illustrative outcome: In the hub study, proactive operation reduced peak current through the system breakers and reduced the early voltage dip at nearby healthy busbars.



Voltages of switching station busbars



Currents through the switching station DCCBs

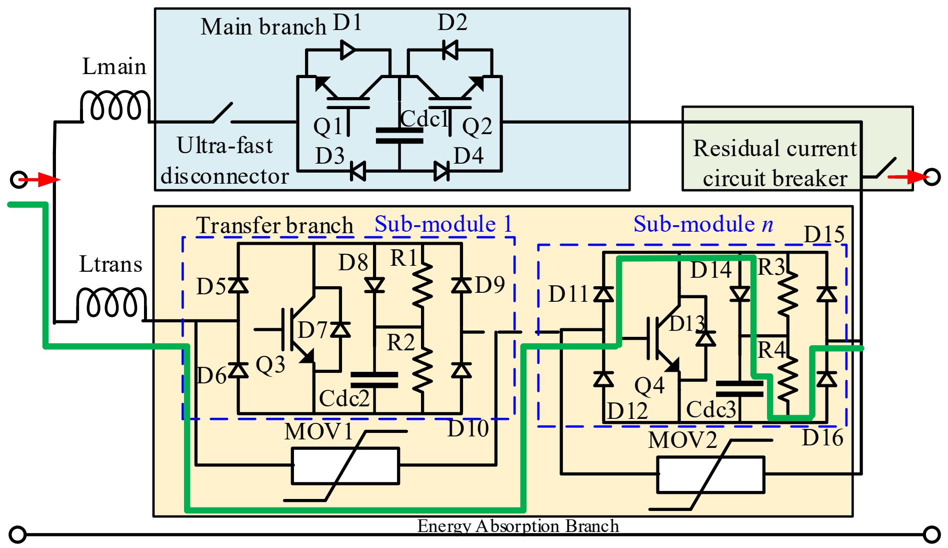
Fault Current Limiting Advanced Functionality

- Fault-current limiting, not interruption: the breaker inserts a controlled counter-voltage to restrain current rise, and it does not aim to drive current to zero at this stage.

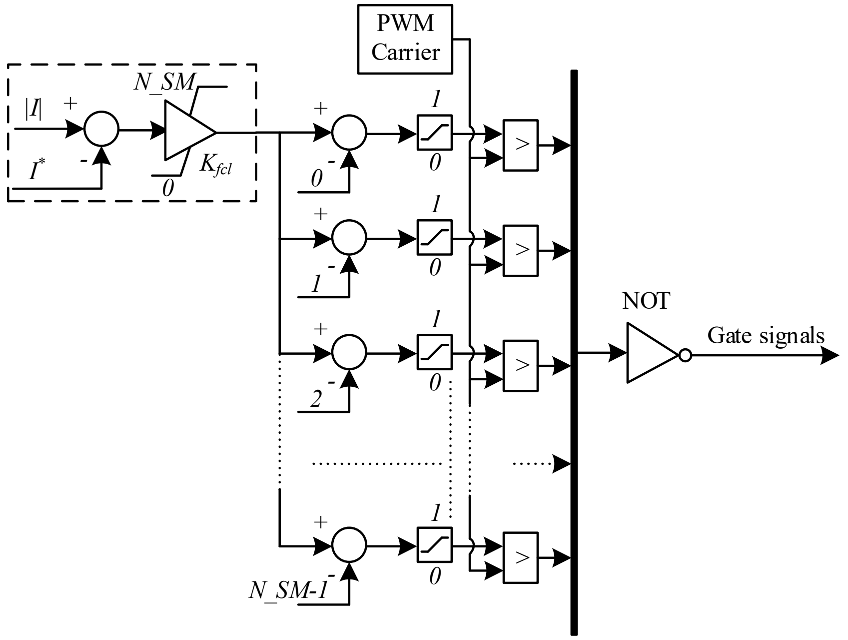
- Mechanism: the hybrid DCCB turns off only a small number of solid-state submodules, which introduces a limited TIV across the breaker terminals.

- Objective: keep fault current below a threshold while the protection system confirms the faulted section and selects breakers for full isolation.

- Illustrative outcome: In the hub study, the designated current-limiting breaker successfully reduced its own peak current, but the fault-current duty redistributed to other breakers; MS-1 and MS-2 experienced smaller voltage dips, whereas RS-2 suffered a deeper dip due to increased fault-current draw.



Circuit diagram of the hybrid DCCB operating as a fault current limiter



Implemented control scheme to realize fault current limitation with hybrid DCCBs.

Fault Current Limiting Advanced Functionality

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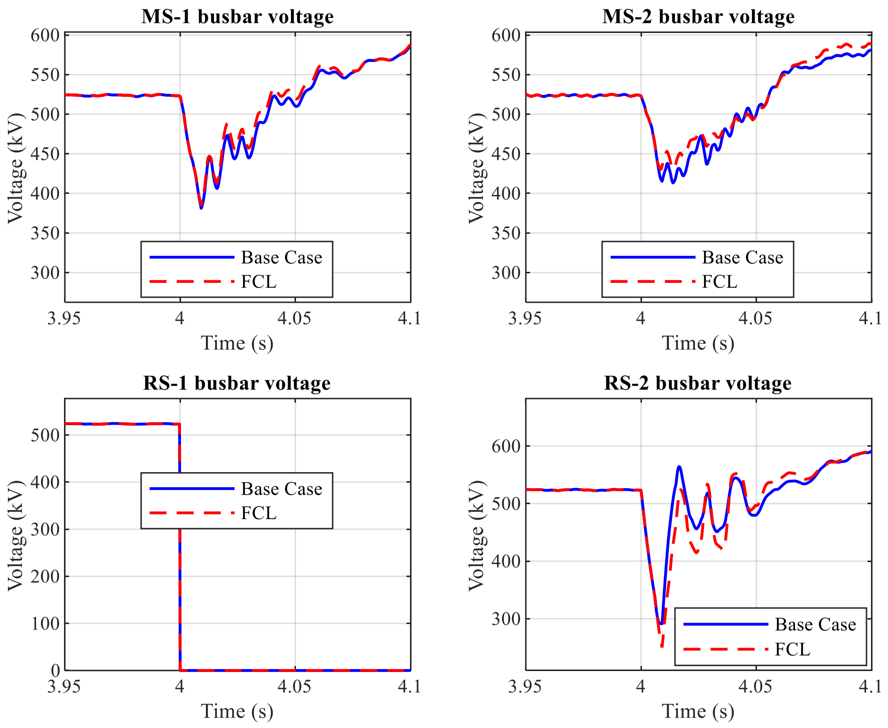
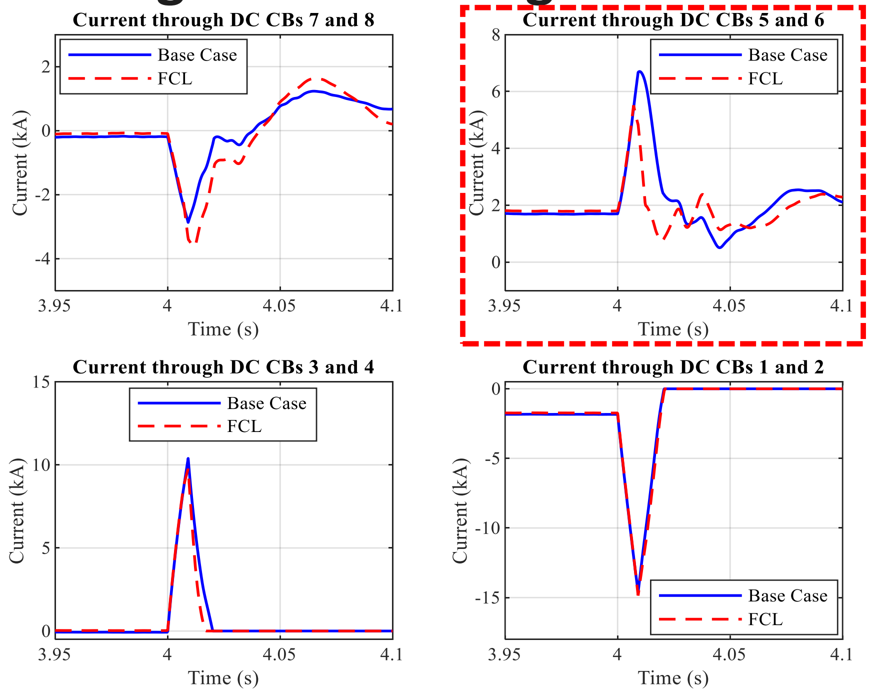


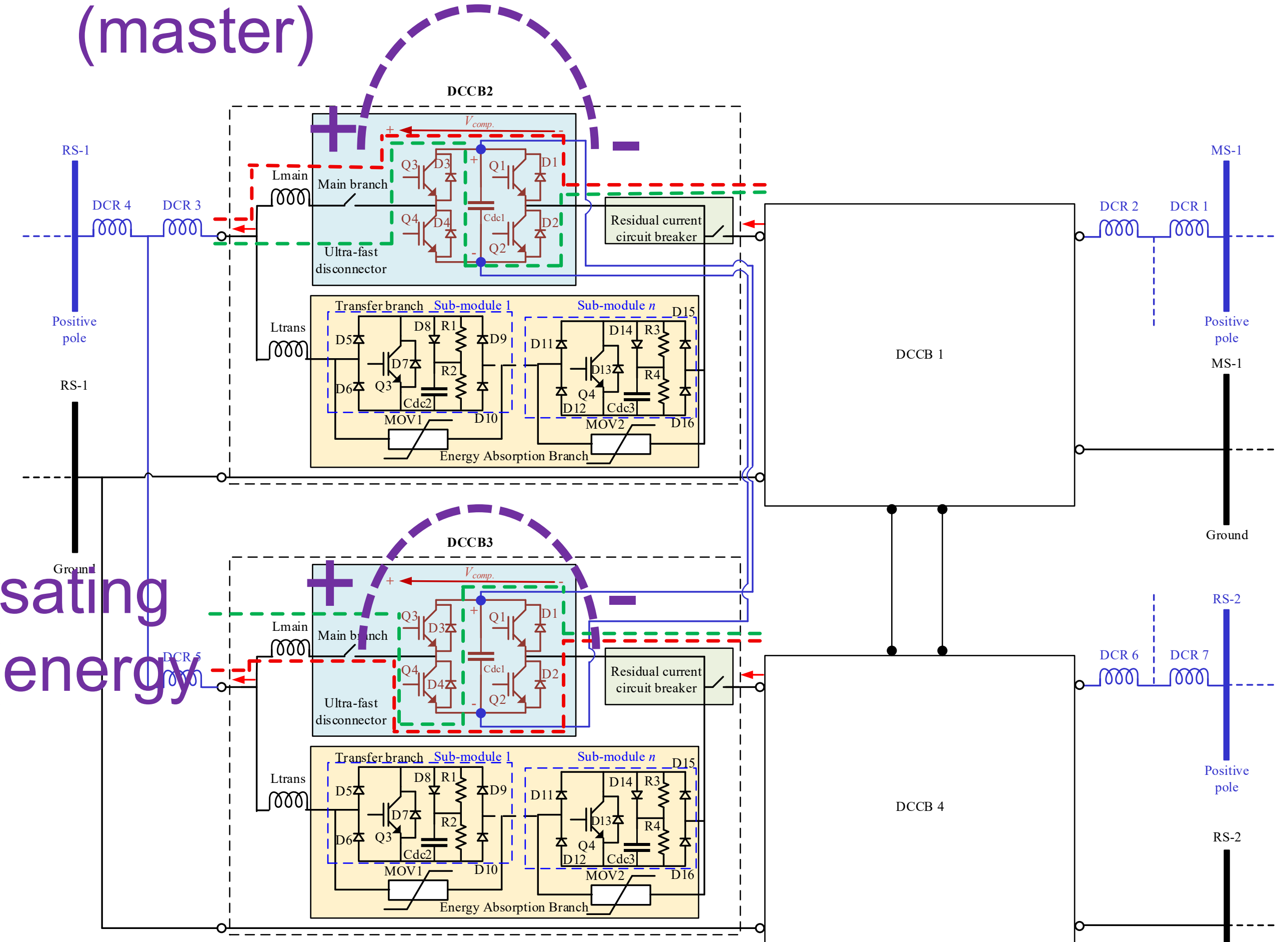
Voltages of switching station busbars



Currents through the switching station DCCBs

DC Flow Control Advanced Functionality

- **Principle**: DC flow between MTDC busbars is set by differential voltage and path resistance; series compensation can shift current by kA for only a few kV.
- **How hybrid DCCBs do it**: adjacent breakers use the load-commutation-switch capacitor as a shared energy buffer.
- **Control action**: apply ±V_comp in the master path, and the neighbour applies the complementary voltage in a slave path to keep energy balanced.
- **Implementation point**: current remains in the main branch; transfer-branch commutation is not required.
- **Stabilisation potential**: the same actuator can provide damping, with the master breaker operated as a virtual resistor under large reactors.
- **Illustrative outcome**: DCCBs 1–2 regulated to 1 kA at t = 4 s, with ~0.45 s settling; flow redistributed through DCCBs 3–8.



Compensating voltage (master)

Compensating voltage (energy balance)

Adjacent hybrid DC circuit breakers with a shared load-commutation-switch intermediate capacitor

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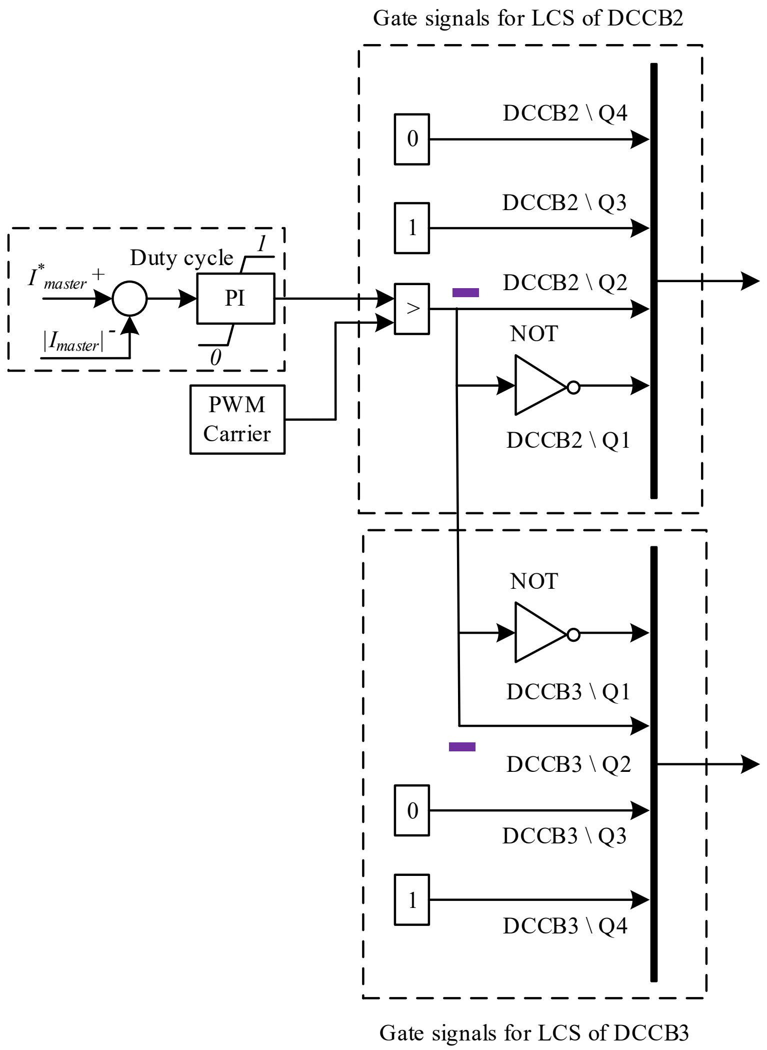

Implemented control scheme to realize current-flow capability by adjacent hybrid DCCBs

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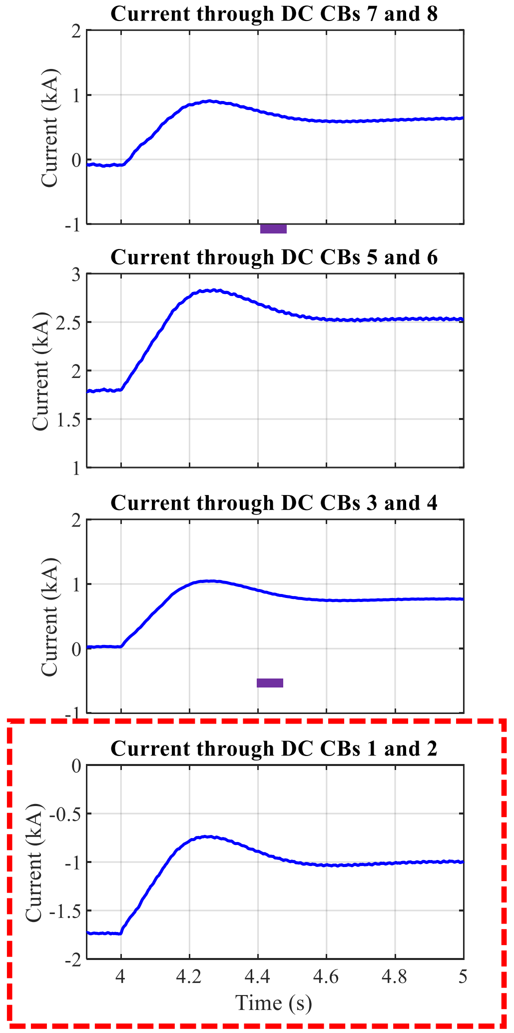


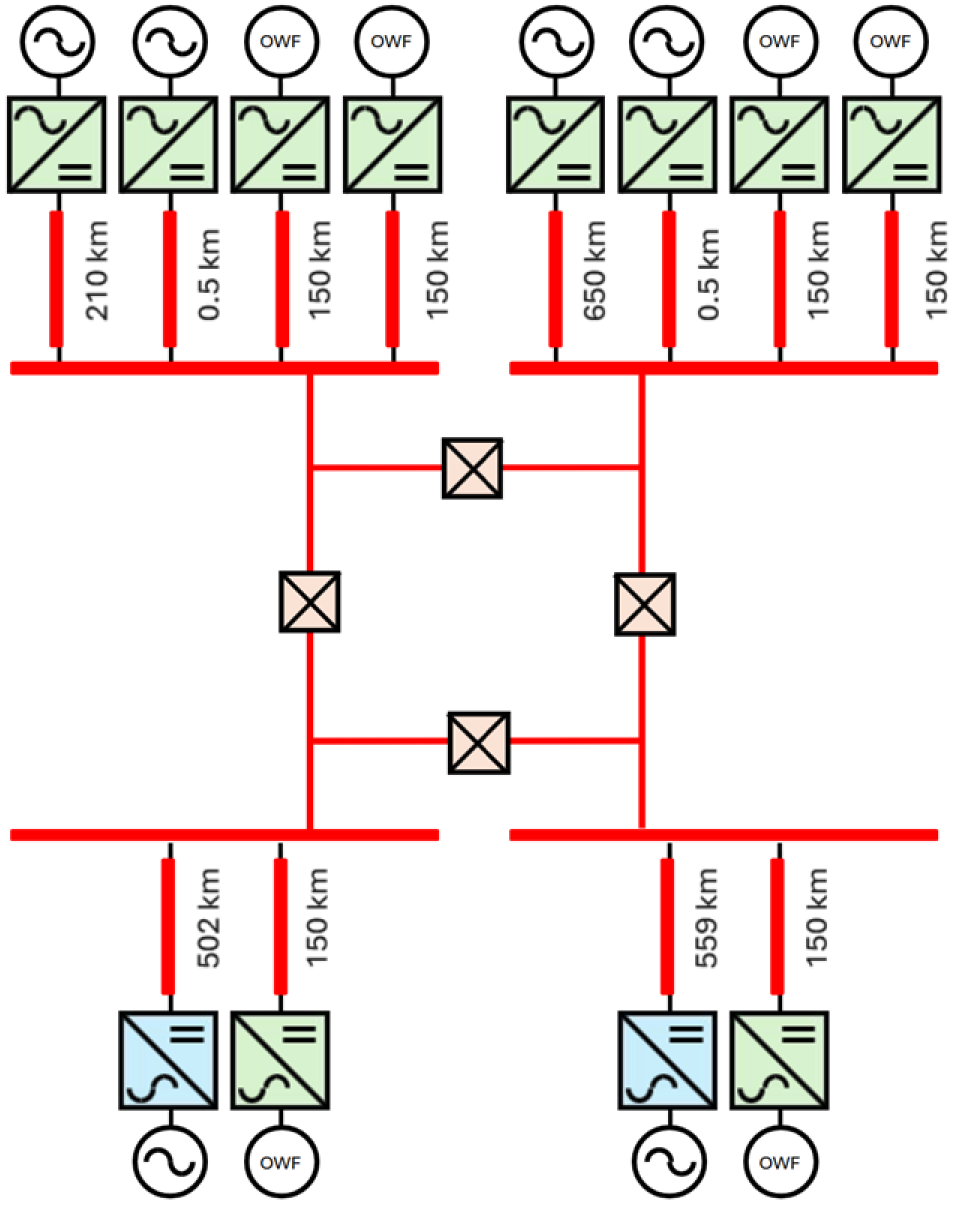
Currents through the switching station DCCBs

Chris Dent – University of Edinburgh

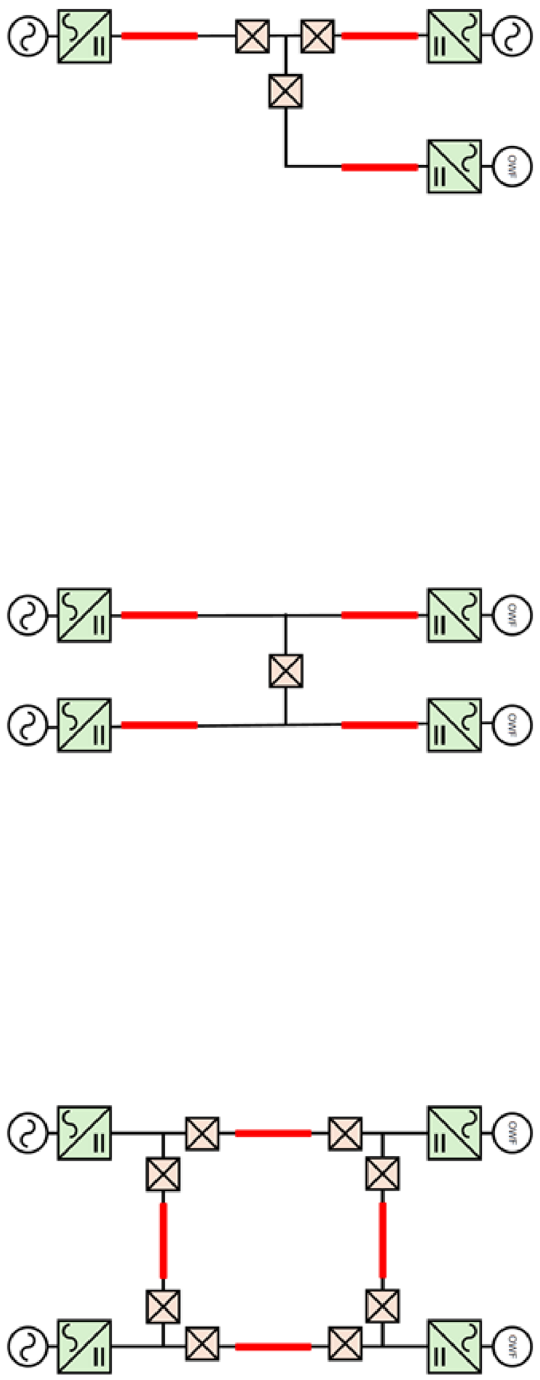
WP 3.8 – Reliability Studies

WP 3.8 – Reliability Studies

- (With Newcastle and Warwick Universities)
- New technology
  - Experience in different circumstances (Zhangbei, then Germany)
  - Previous component use: different duty cycles (Zhang et al, IEEE PE mag, https://ieeexplore.ieee.org/document/10684854)
  - Reliability inevitably uncertain in early deployment
- Framework for analysis
  - If fault not successfully isolated, consequences (loss of infeed) could be very severe
  - Very wide range of views on readiness
    - Ready for what?
    - Need agreed framework for assurance and requirements
  - Broad options: probability or redundancy analysis
  - Analogies to AC: requirements, reliability of devices, cost of devices



Reliability – the way forward



- Agreed requirements
  - Deterministic: N-x standard
    - Analogy to AC but cost/use/reliability
    - Greater confidence with multiple DCCB designs?
  - Probabilistic: rate of unsecured events
    - Need to determine acceptable rate
    - Probability provides framework for integrating issues
- Deployment over time
  - Early deployment in smaller networks
    - Assurance in real deployment
    - Programme of reliability improvement
  - CT: “Meshed networks appear “riskier” than radial ones”
  - Long term commitment required to realise full benefits

Aurelia Hibbert – Mott Macdonald

WP 7.1 – Cost Benefit Analysis

WP 7.1 – Cost Benefit Analysis

External Changes

In the US, $8m of Federal R&D funding

In Europe, ENTSO-E made the economic case for an offshore network using Direct Current Circuit Breakers(DCCBs)

Several offshore wind and HVDC projects have halted due to cost increases or political changes.

In GB, the National Energy System Operator (NESO) proposes to continue to reduce overall inertia on the GB system

Constants

The use case and comparison cases

The quantity of DCCBs required

We still do not have direct input from the Original Equipment Manufacturers (OEMs) in terms of budget pricing or reliability

Other business cases in the literature are either making similar positive arguments (ENTSO-E) or are also reliant on (and waiting for) the cost of DCCBs to become clearer (van Hertem).

WP 7.1 – Cost Benefit Analysis

What was the original business case?

The original business case demonstrated Net Present Value (NPV) savings of £361m over a 35-year asset lifetime.

We assumed that developers would benefit from sharing onshore HVDC converter capacity

What is our current best estimate of the business case?

Our updated business case demonstrates NPV savings of £834m over a 35-year asset lifetime.

What were the most significant sources of change?

Rising supply and installation costs have raised the CAPEX of HVDC infrastructure, and DCCB supply costs

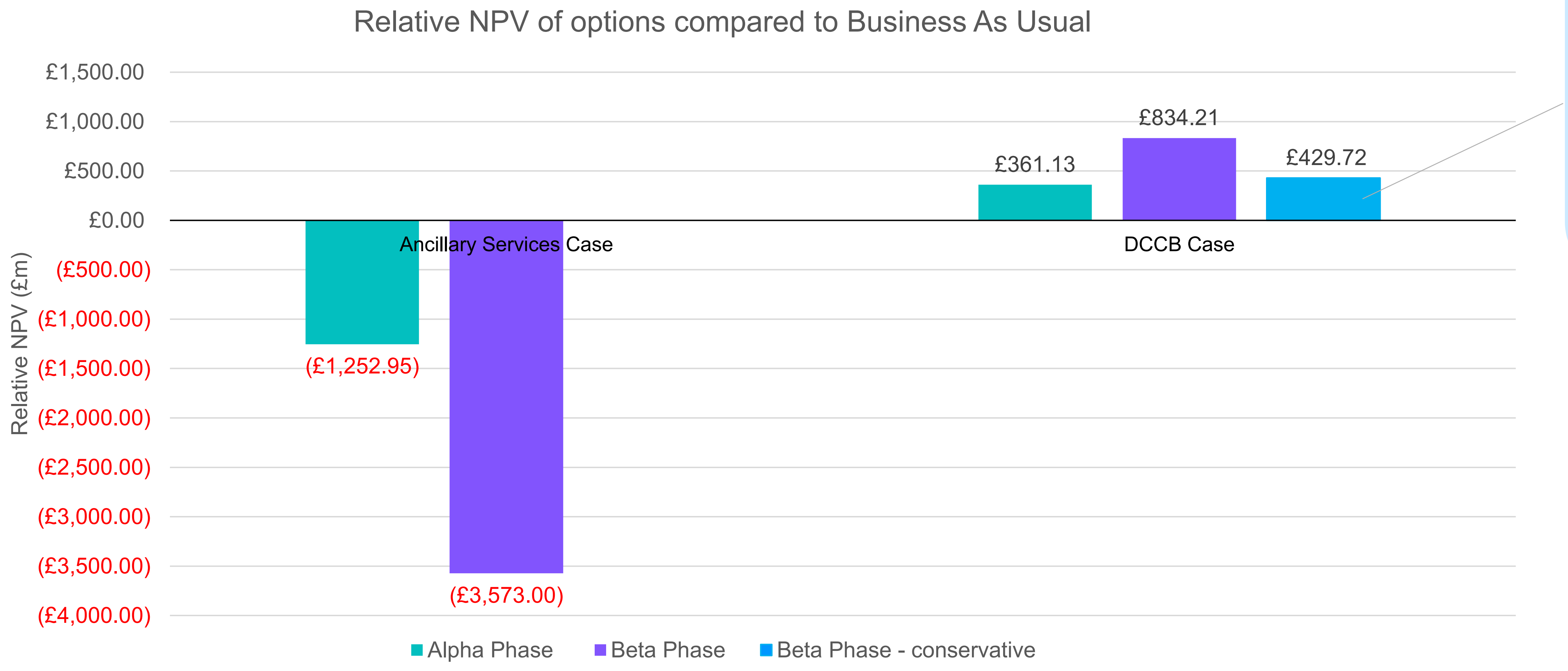
Inertia and frequency response (ancillary services) costs have more than doubled.

What are the next steps?

The next major update to the CBA would include OEM’s information on reliability and cost.

WP 7.1 – Cost Benefit Analysis

The DCCB case **appears resilient** at this stage



This bar shows the NPV in a DCCB scenario with one additional onshore converter station, testing the sensitivity of the CBA to additional converter capacity being required to manage correlation of wind sources

Karolina Zieba – Carbon Trust

WP 7.4 – Policy & Regulatory Barriers

WP7.4 – Policy & Regulatory Barriers

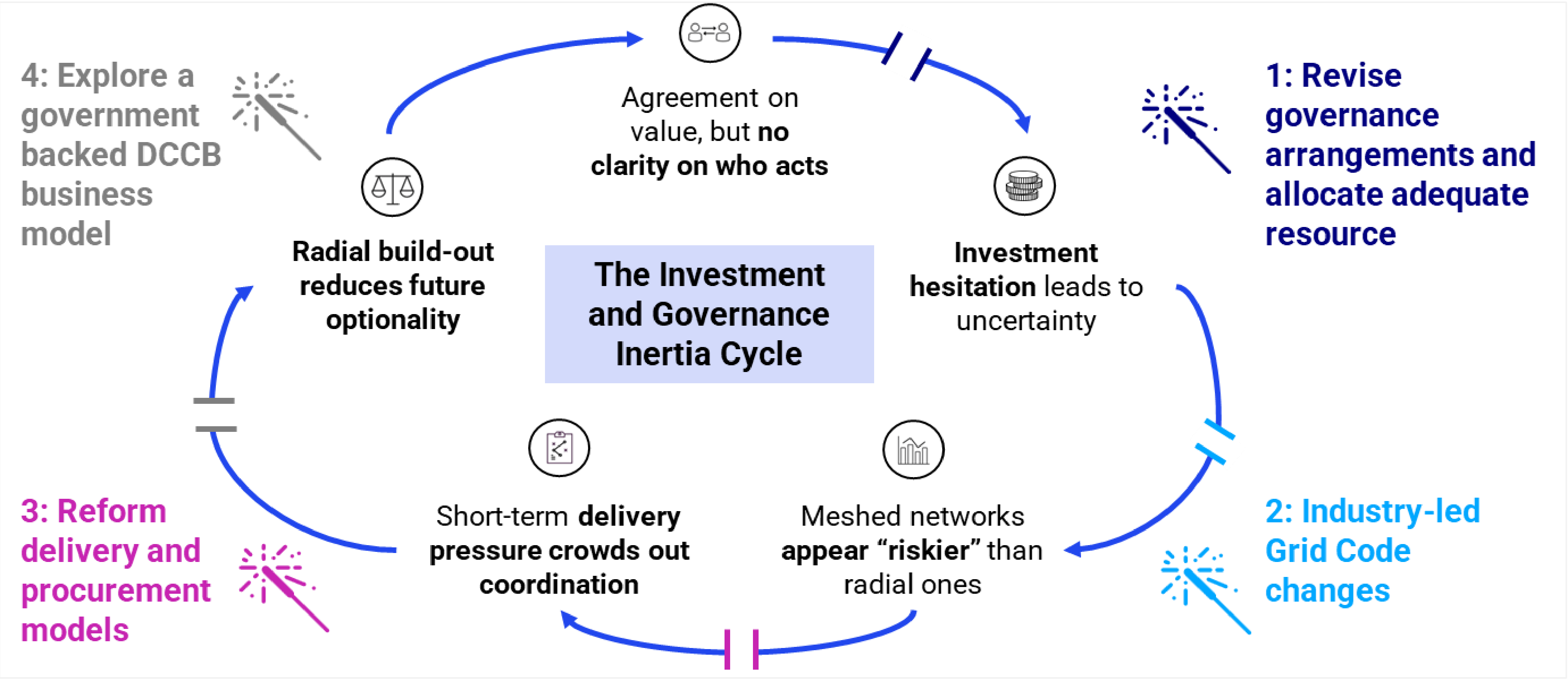
Objective To identify and assess policy, regulatory and commercial barriers to the deployment of DC circuit breakers (DCCBs) in Great Britain, and to define actions needed to enable investment and deployment in support of future HVDC meshed offshore networks.

Scope

- Refresh of Alpha-phase recommendations against the evolving GB policy and system planning landscape (incl. NESO, CSNP, CP2030)
- Stakeholder interviews and workshops across government, regulators, TOs, OFTOs, OEMs, developers and academia to test barriers, roles and responsibilities

Key learnings

- Policy intent alone is insufficient. OEMs and investors require clear governance, credible timelines and bankable delivery models
- Tension between speed and coordination risks locking in radial solutions unless meshed networks are actively enabled now
- DCCBs will not be manufactured “ahead of demand” without risk-sharing mechanisms, due to cost, long lead times and limited revenue certainty
- Near-term action is critical: decisions taken this decade determine whether DCCBs can be deployed in the mid-2030s



The Investment and Governance Inertia Cycle

Agreement on value, but **no clarity on who acts**

Investment hesitation leads to uncertainty

Meshed networks **appear “riskier”** than radial ones

Short-term **delivery pressure crowds out coordination**

Radial build-out reduces future optionality

1: Revise governance arrangements and allocate adequate resource

2: Industry-led Grid Code changes

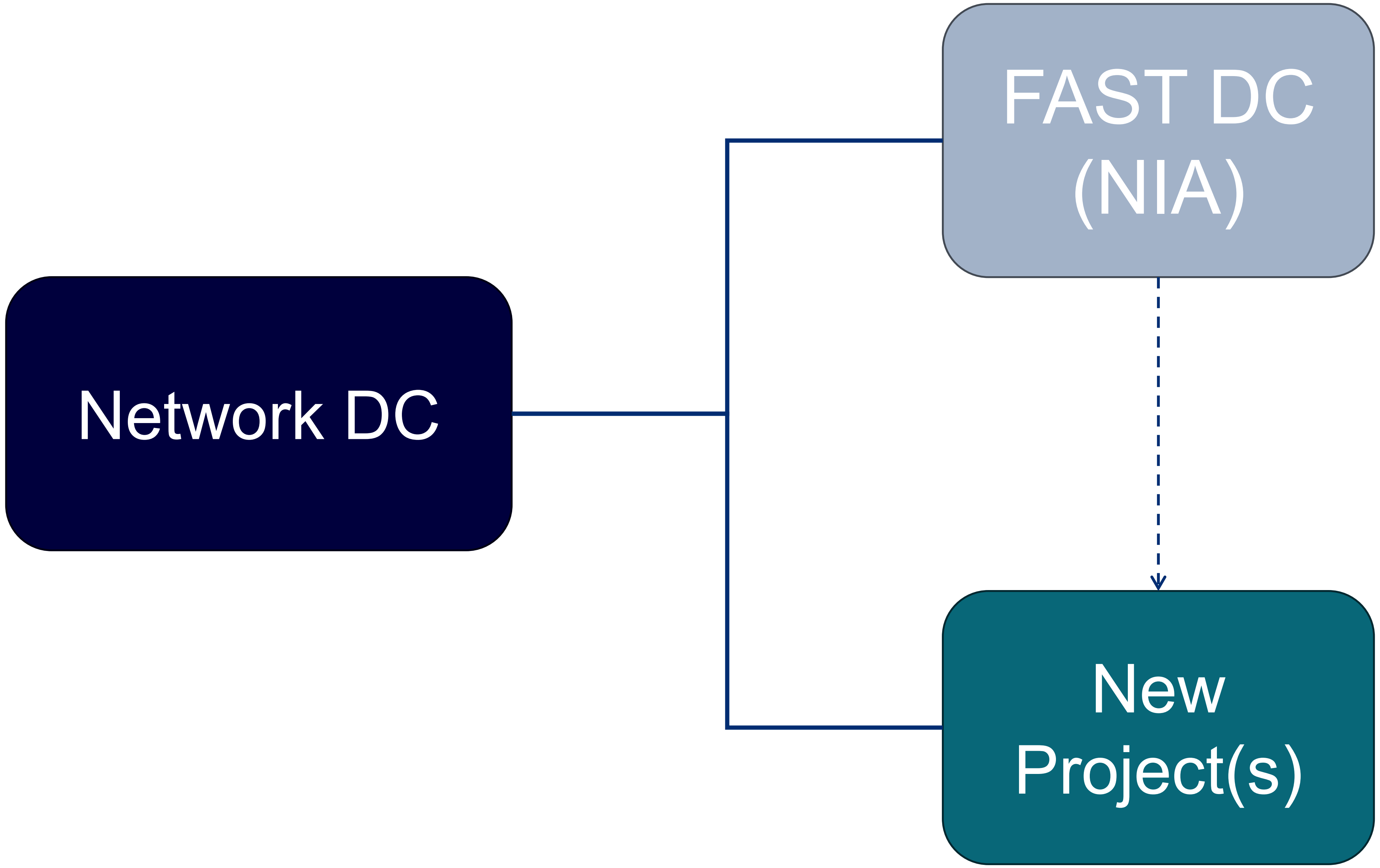
3: Reform delivery and procurement models

4: Explore a government backed DCCB business model

Adnan Mahmood – SSEN-T

Next Steps

Next Steps



Scottish & Southern Electricity Networks TRANSMISSION
The National HVDC Centre
THE UNIVERSITY of EDINBURGH

- Develop a framework for advanced studies of multi-terminal DC grids, focusing on the modelling and assessment of DCCBs with advanced functionalities to improve grid resilience and protection.
- April 2026 – March 2027

- Discussions ongoing within SSEN-T on follow-on project(s).

Get in touch

To find out more about what we are doing in Innovation, our future ambitions, the Network DC project, or to discuss your innovation ideas. Please reach out to us:-

transmissioninnovation@sse.com