- 2.0 Introduction, Adam Scott
- 2.1 Hitachi Energy , Dr. Biljana Stojkovska
- 2.2 GE, Li Zou
- 2.3 Mitsubishi Electric , Dr. Frederick Page
- 2.4 SuperGrid Institute, Alberto Bertinato
- Q&A
- Closeout

Session 2

Introduction

10th June 2026

Session 2

“Technology Developments”:

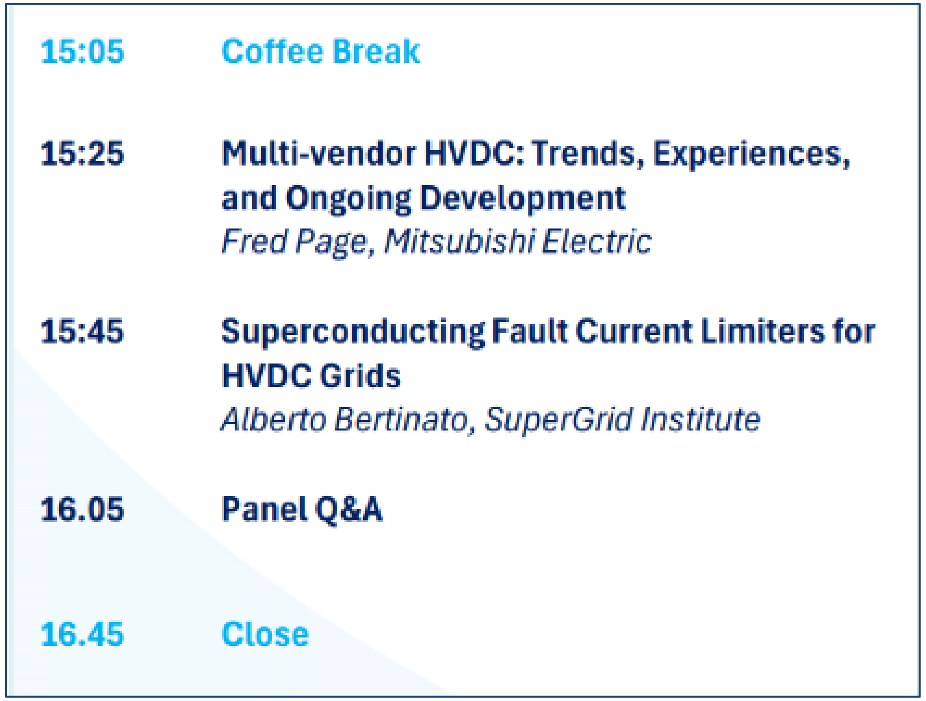
How should HVDC product design change in response to strategic needs?

- Regulatory aspects of interoperability
- AC system services
- Multi-terminal C&P
- AC/DC system dynamics
- DC system protection

Session 2 Agenda

Afternoon Session

Session 2	**"Technology Developments": How should HVDC product design change in response to strategic needs?**
14:15	**Introduction** *Adam Scott, The National HVDC Centre*
14:25	**Regulatory and Policy Aspects of the Meshed DC Grid** *Biljana Stojkovska, Hitachi Energy*
14:45	**Control & Protection Developments to Facilitate Future Multi-Terminal HVDC systems** *Li Zou, GE Vernova*
15:05	**Coffee Break**



15:05	**Coffee Break**
15:25	**Multi-vendor HVDC: Trends, Experiences, and Ongoing Development** *Fred Page, Mitsubishi Electric*
15:45	**Superconducting Fault Current Limiters for HVDC Grids** *Alberto Bertinato, SuperGrid Institute*
16.05	**Panel Q&A**
16.45	**Close**

Event Dinner
10th June 2026
Westerwood Hotel – The Conservatory
Starting at 18:30

HITACHI

Hitachi Energy

Regulatory and Policy Aspects of the meshed DC Grid

Dr. Biljana Stojkovska, Hitachi Energy

2026 HVDC Centre Operators Forum, 10 - 11 June 2026

Overview of MTMV DC Grid Deployment Challenges

Technical Benefits of HVDC

HVDC technology reduces losses, controls power flow, and is ideal for subsea and underground power transmission.

Regulatory and Legal Uncertainties

Lack of explicit regulatory and legal frameworks creates uncertainties slowing DC grid development.

Policy and Planning Challenges

Policy-level issues with network planning and procurement impact coordinated DC grid deployment.

Commercial and Investment Barriers

Commercial and investment challenges hinder large-scale MTMV DC grid deployment despite technical readiness.

Current Status of DC Grid Development

Feasibility of Multi-Terminal Grids

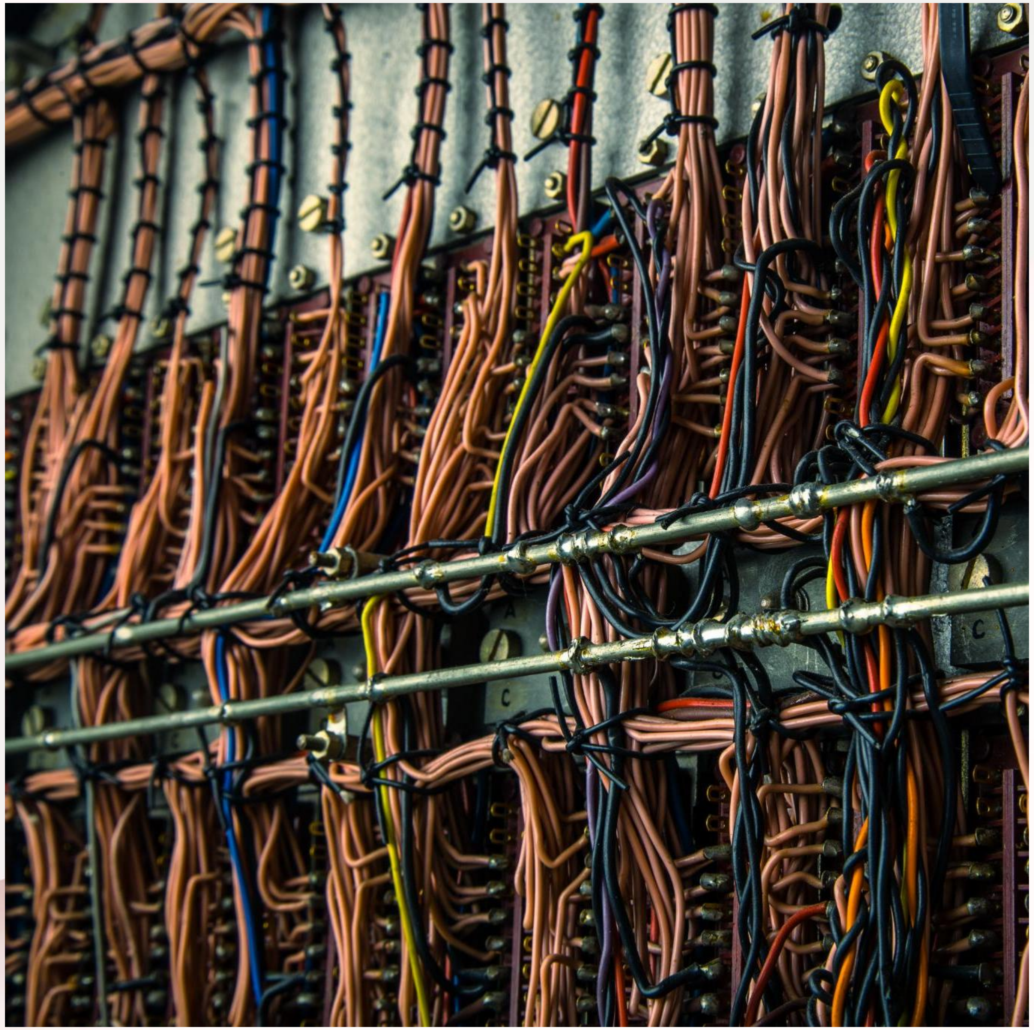
Demonstration projects confirm multi-terminal grids are technically feasible, enabling broader deployment potential.

Challenges Beyond Engineering

Non-technical challenges (integration, roles, regulation) remain underexplored, slowing MTMV deployment

Institutional and Policy Gaps

Lack of regulatory clarity, limited regional alignment, and a national-focused debate weaken investment signals—highlighting the need to go from national to regional debate, planning for space-intensive HVDC MTMV systems and unlock large-scale deployment



7

Regulatory Gaps and Grid Code Limitations

Lack of DC-specific Regulations

Current electricity regulations are based on AC systems and do not fully address the unique characteristics of DC grids.

Risk of Over-Regulation

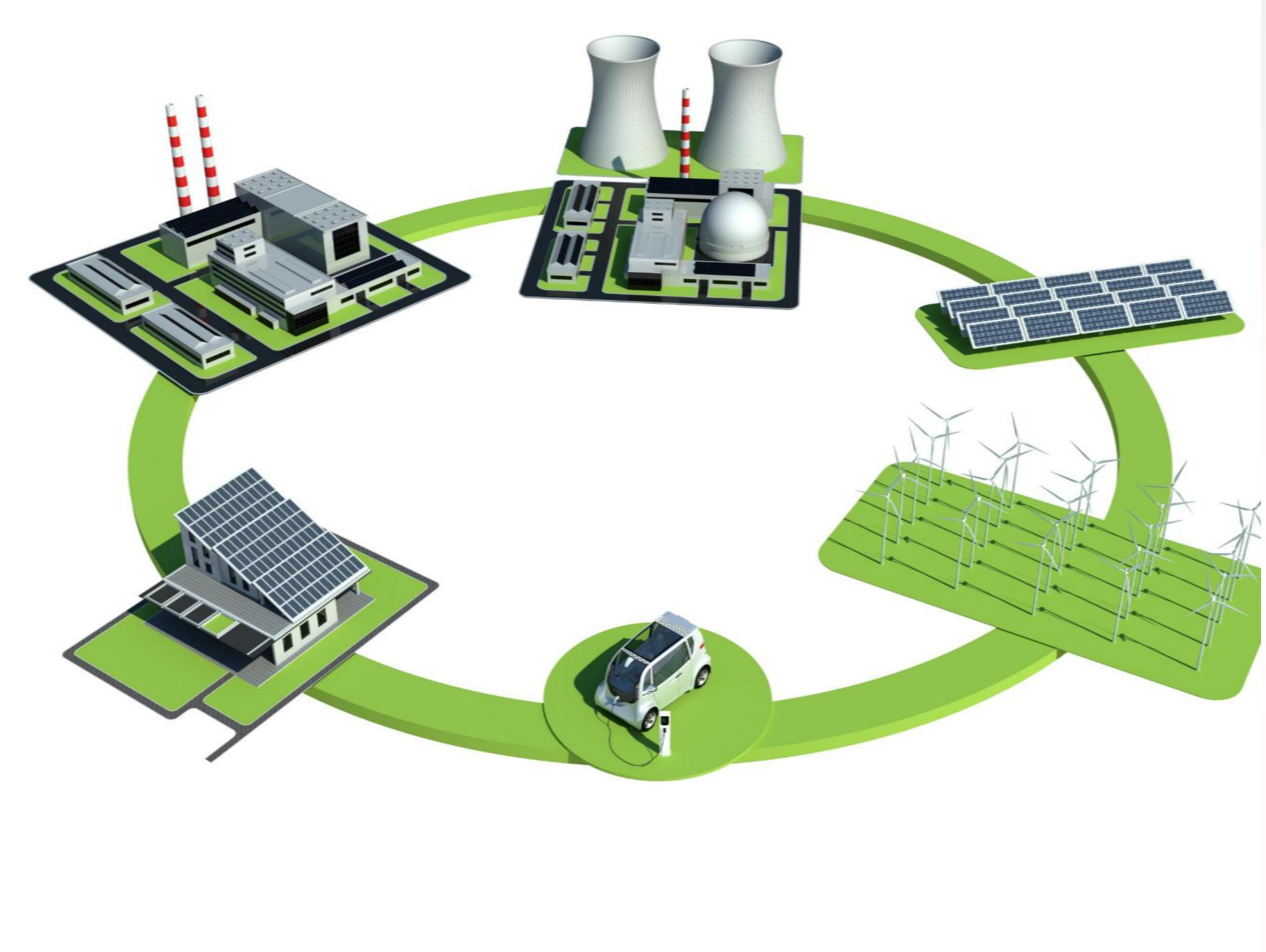
Premature detailed DC regulations could inhibit innovation and exclude emerging technologies in DC grid development.

Balanced Regulatory Approach

A stepwise and collaborative regulatory process focusing on simplified performance requirements is recommended.

Importance of Pilot Projects

Pilot projects help learn and build robust regulations suitable for future onshore and offshore DC grid applications.



Unclear System Vision and Institutional Responsibilities

Policy Uncertainty Challenges

Policy uncertainty creates significant regulatory and commercial barriers for DC grid deployment and integration with offshore renewables.

Unclear Roles and Responsibilities

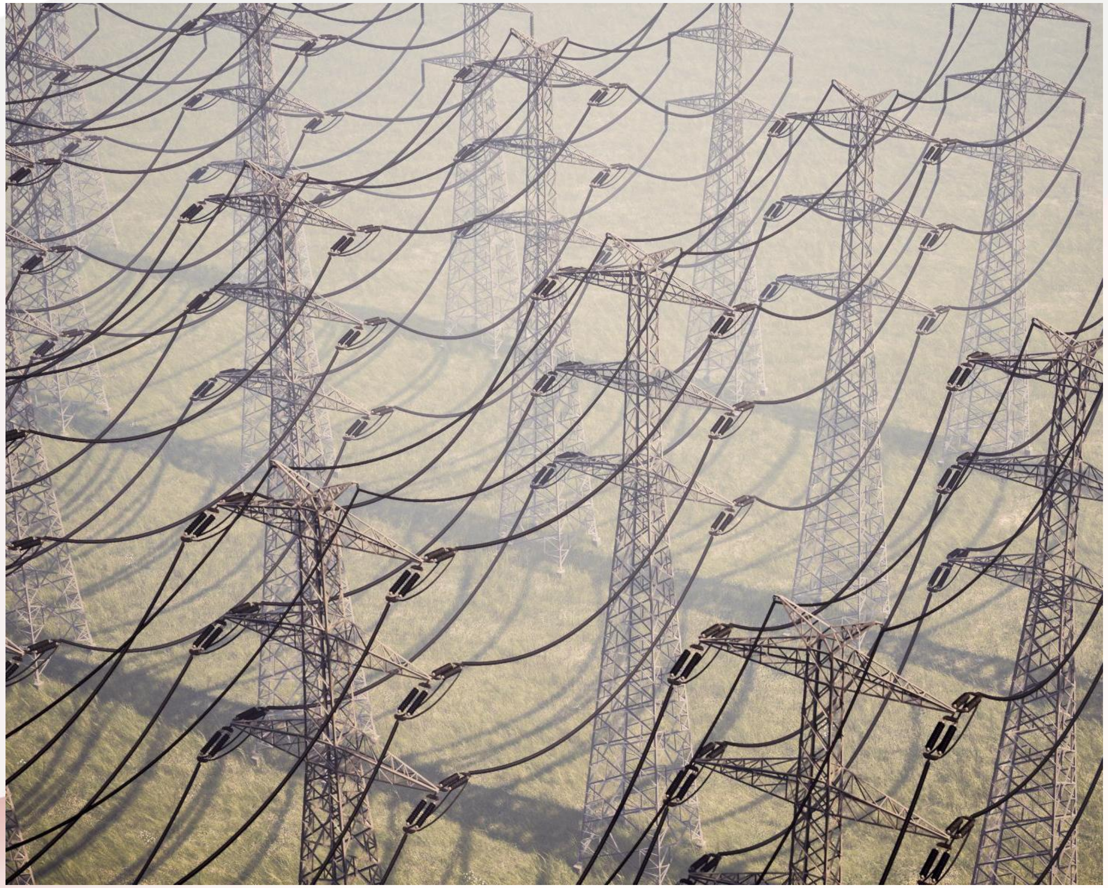
Uncertainty exists around TSOs' operational roles and institutional responsibilities for developing and managing DC grids.

Alternative Delivery Models

Exploration of centralized versus distributed ownership models is needed to address complexity and investment in MTMV DC grids.

Need for New Institutional Vehicles

Joint ventures and system integrators may be required to complement existing grid planning and operational frameworks.



Investment Risks and Governance Challenges

High Investment Risk

MTMV DC grids require large upfront capital and long asset lifetimes, increasing financial exposure for investors.

Unclear Governance Structures

Governance lacks clear roles and decision processes, complicating coordination among TSOs and vendors.

Revenue Model Uncertainty

Undefined revenue models and monetisation of system-wide benefits create unpredictability for investors.

Multi-vendor Interoperability Issues

Multiple vendors complicate liability, interoperability, and risk sharing, increasing investor reluctance.

Actions Across Policy, Regulation, and Commercial Domains

Policy Reforms for Investment

Explore reforms in delivery and procurement to support investment decisions and clarify system integrator roles.

Regulatory Code Revisions

Industry bodies should collaborate on grid code revisions to set standards and enable stepwise regulatory approaches.

Commercial Governance and Risk Sharing

Improve governance, assess gaps, and develop risk sharing mechanisms to de-risk investments and align stakeholders.

GE VERNOVA

CONTROL AND PROTECTION DEVELOPMENTS TO FACILITATE FUTURE MULTI-TERMINAL HVDC SYSTEMS

Li Zou

10 June 2026

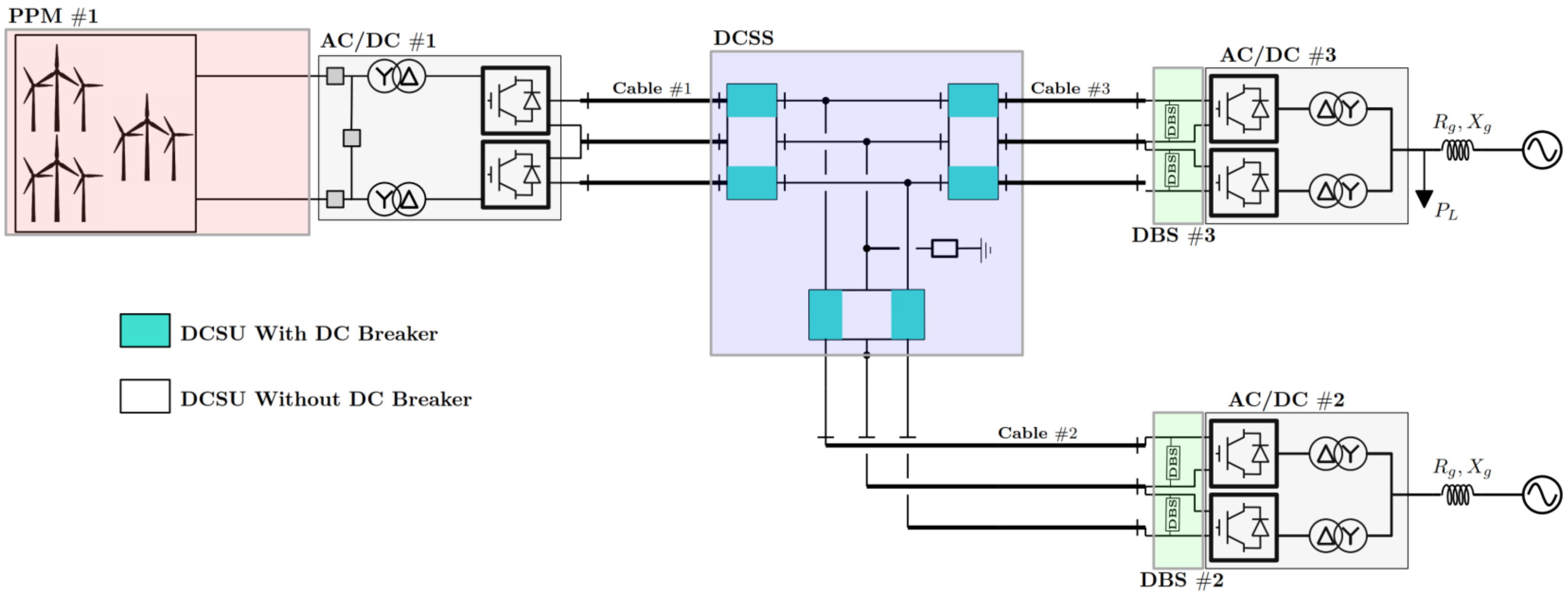
Synchronous Grid Forming Controllers in Multi-terminal HVDC Systems

Introduction

Increase Of Offshore Renewable Integration

Increase of HVDC and Multi-Terminal DC systems

- Increase of power electronic interface devices
  - challenges on power system stability – inertia reduction, limited overcurrent capability, risk of interactions ….



CIGRE Canada 2025, Paper 10634, “Synchronous Grid Forming control Interoperability in MTDC Systems”

Control Strategies

- A **Grid-Following converter:** In this control concept the converter synchronizes its output with the AC grid voltage and frequency. It behaves as a current source that tracks the grid angle and magnitude to inject or absorb active and reactive power.

Mature.

- TF-77: AC fault response options for VSC HVDC converters (**From CIGRE Science & Engineering, Volume No. 15, October 2019)**

TF-77 - AC fault response options for VSC HVDC converters

1. Introduction

KEYWORDS

- A **Grid-Forming converter** is one that can regulate both instantaneous AC frequency and AC voltage. Such a converter is also able to provide reactive current equal to the steady-state rated current during AC faults.

Mature.

- A **Synchronous Grid-Forming converter** is a Grid-Forming converter that is also able to operate in parallel with other AC frequency regulating equipment and converters.

Emerging.
Main focus for today.

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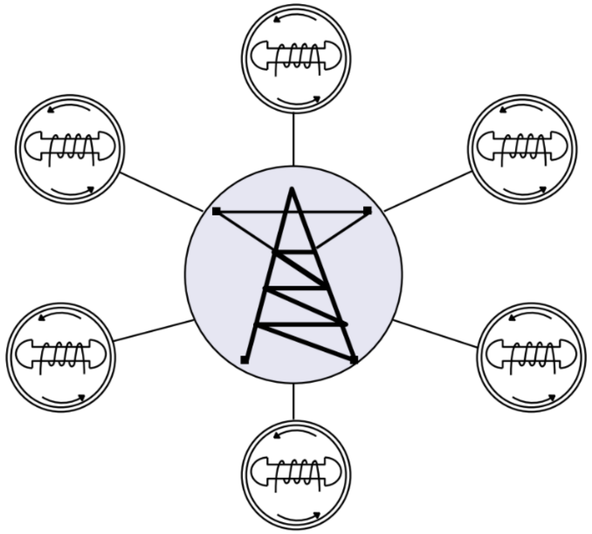
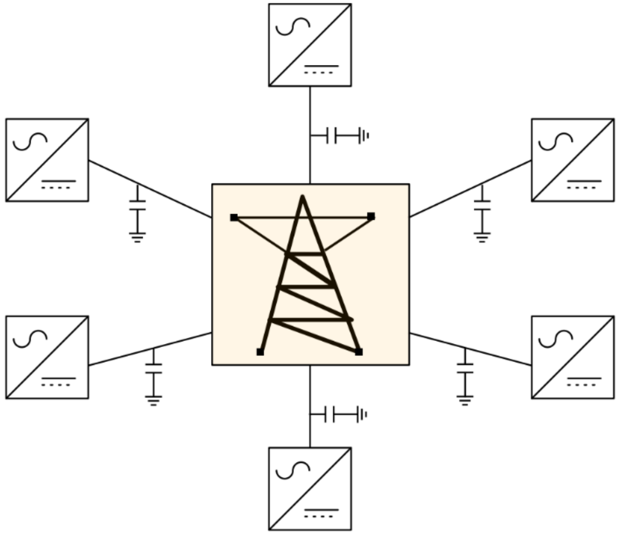
SGFM Implications

AC System



$$E_k = \frac{1}{2}J\omega^2, H \sim 5s$$

DC System



$$E_c = \frac{1}{2}Cv_{dc}^2, H \sim 40ms$$

- AC side has ***inertia thanks to the SGs***. SGFM in the AC system context often neglect the source of energy ***assuming an infinite DC system buffer***.

- DC System in practice has very limited stored energy resulting in ***fast dynamics compared to the AC system*** !

- As the HVDC is a transmission system, the DC voltage stability should be a priority if no energy is available to support the AC system, which results in some ***restricted functionalities of the SGFM, mainly the inertia emulation***.

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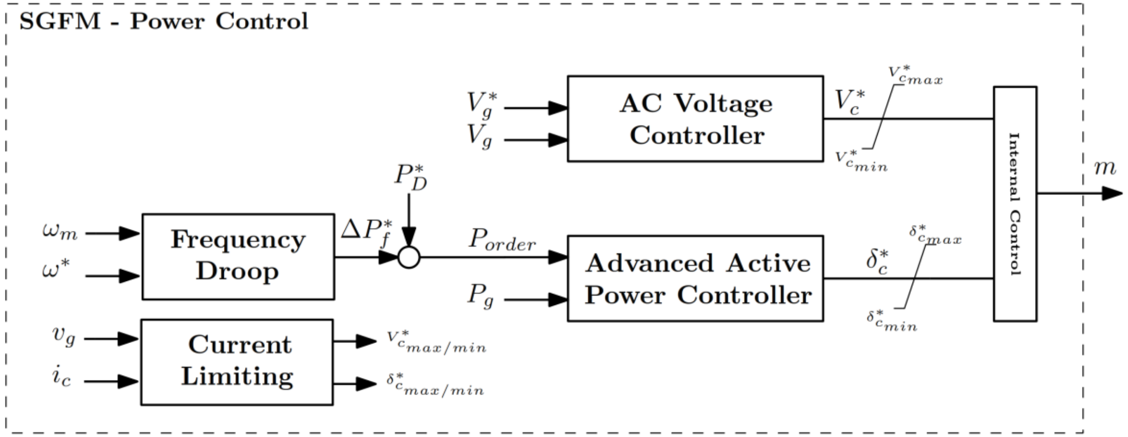
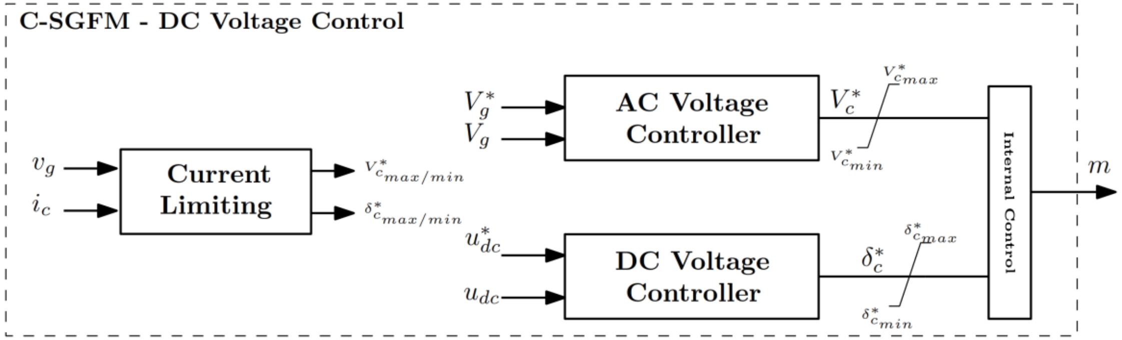
SGFM and C-SGFM local controllers



SGFM is defining the functional behaviour of a converter unit as a controlled voltage source behind an impedance that needs to deliver the following services to the power system:

- Self-Synchronization Capability
- Phase Jump Active Power
- Inertia Active Power
- Inherent Reactive Power Injection



Since the DC system has no natural inertia such as the AC system. **In this sense, the internal phasor angle variation should be fast enough to avoid significant DC voltage deviations**.

- Self-synchronization Capability
- ***Limited*** Phase Jump Active Power
- ***Limited*** Inertia Active Power
- Inherent Reactive Power Injection
- *No standalone capability*

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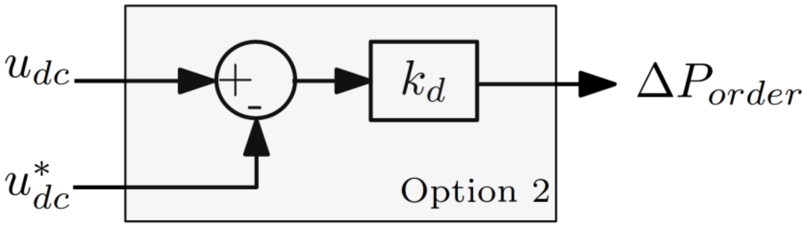
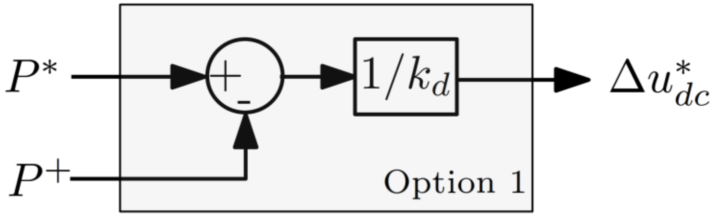
Primary DC voltage control



Associated with SGFM



Associated with C-SGFM

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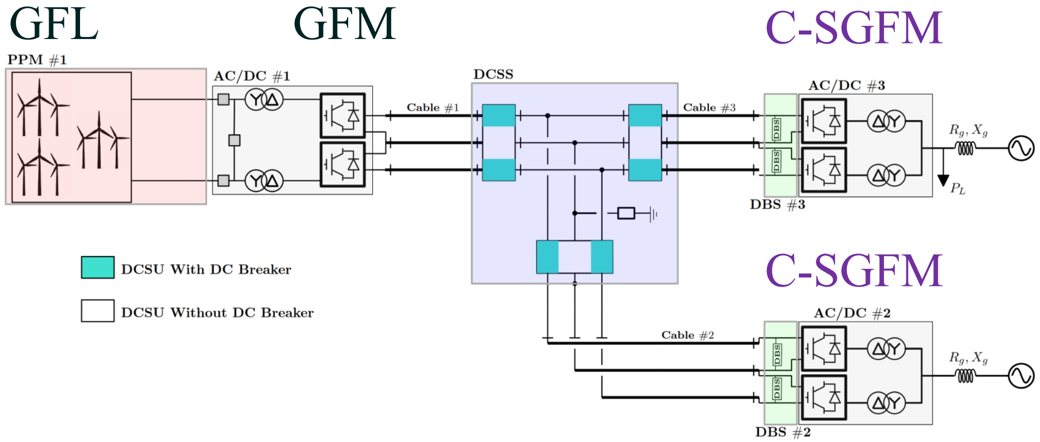
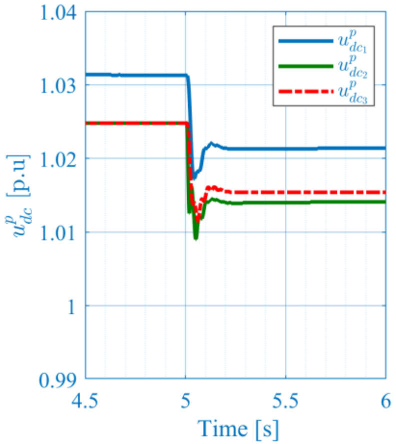
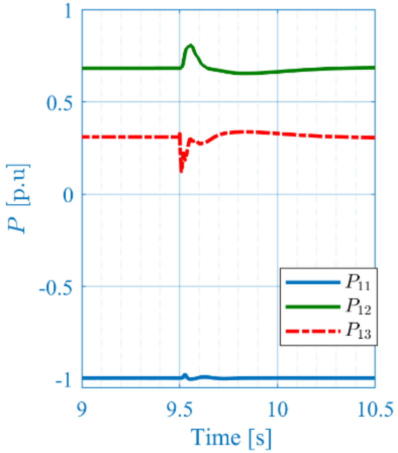
Use Cases



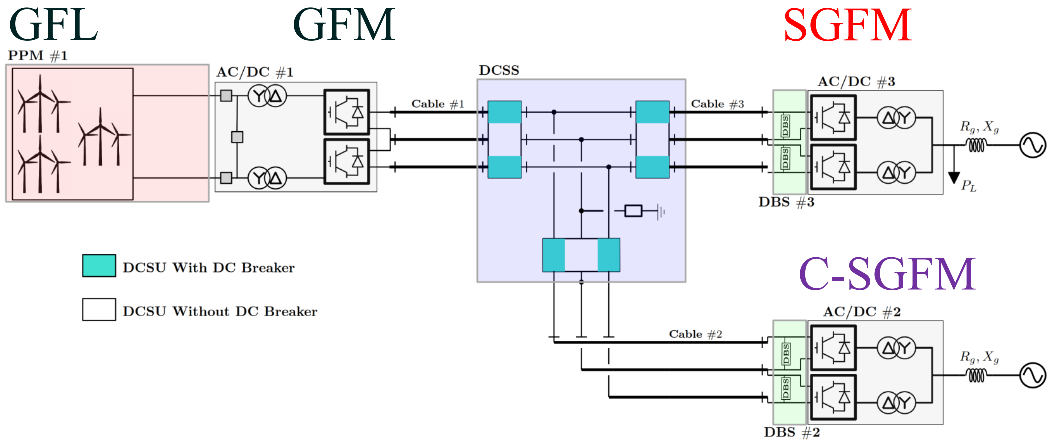


DC Voltage change

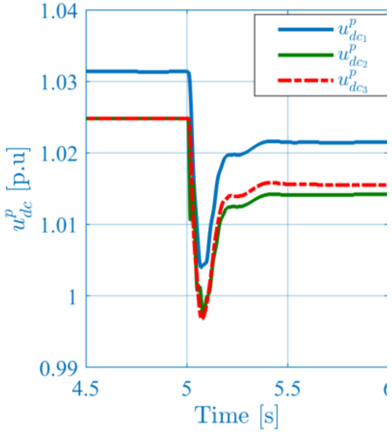


Phase Jump

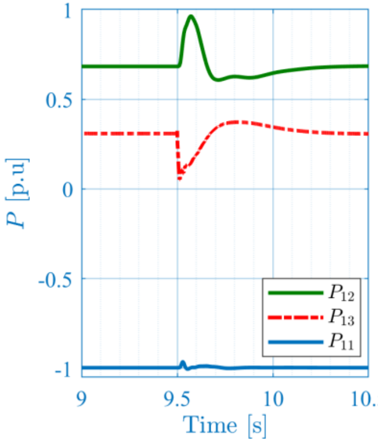
- Better DC Voltage Controllability in transient and in steady state
- Limited energy exchange



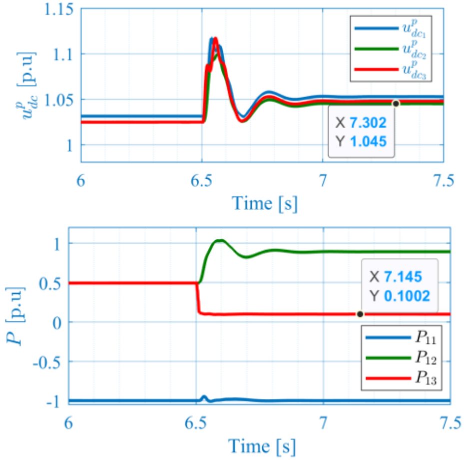
DC Voltage change



Phase Jump



Islanding

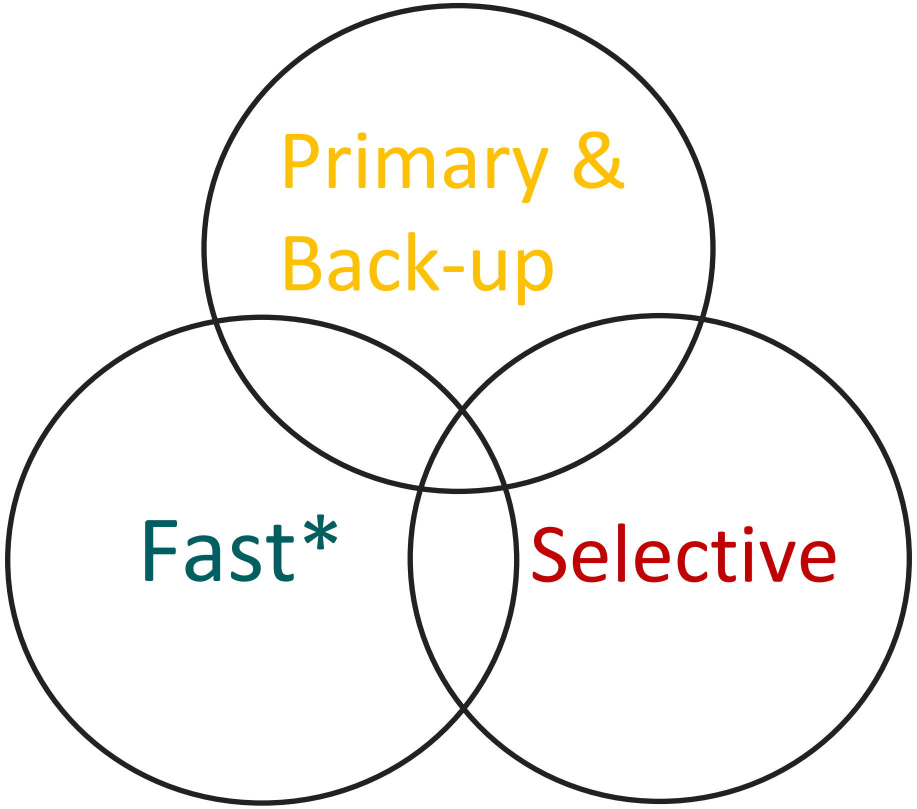


- C-SGFM station plays the role of the DC slack bus and SGFM station only support the DC voltage in quasi-static and steady state
- Possibility to support the SGFM station AC side
- Possible for SGFM station to operate in Islanding

CIGRE Canada 2025, Paper 10634, “Synchronous Grid Forming control Interoperability in MTDC Systems”

Multi-terminal Protection Strategy utilising a DC Circuit Breaker

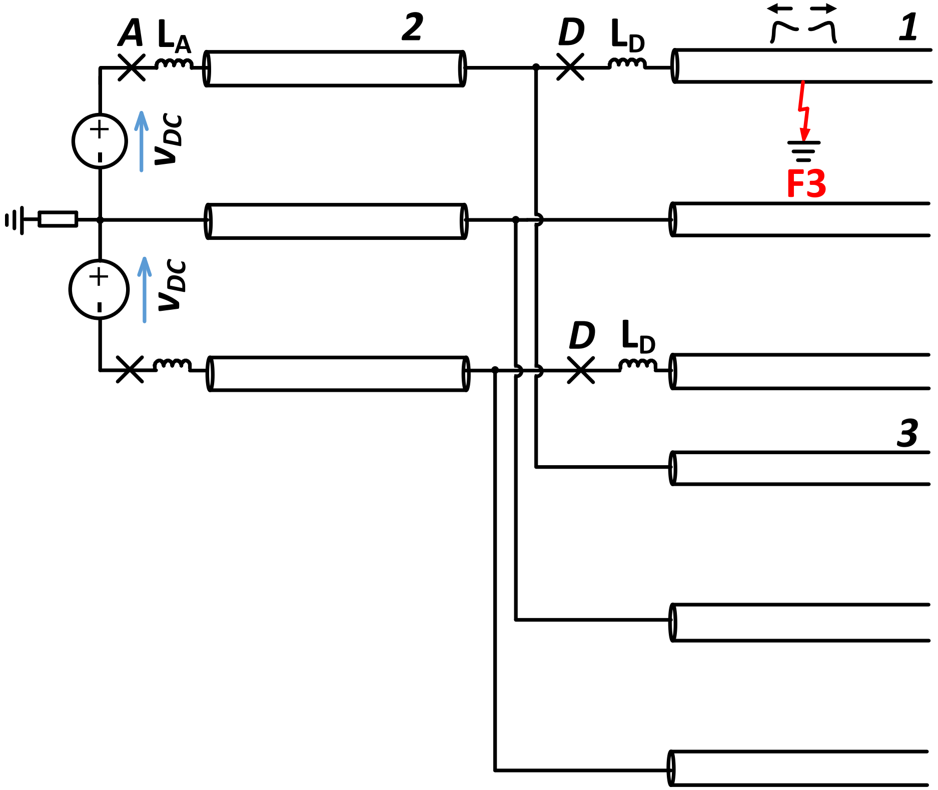
System Requirements for the Protection of MTDC



Primary & Back-up

Fast*

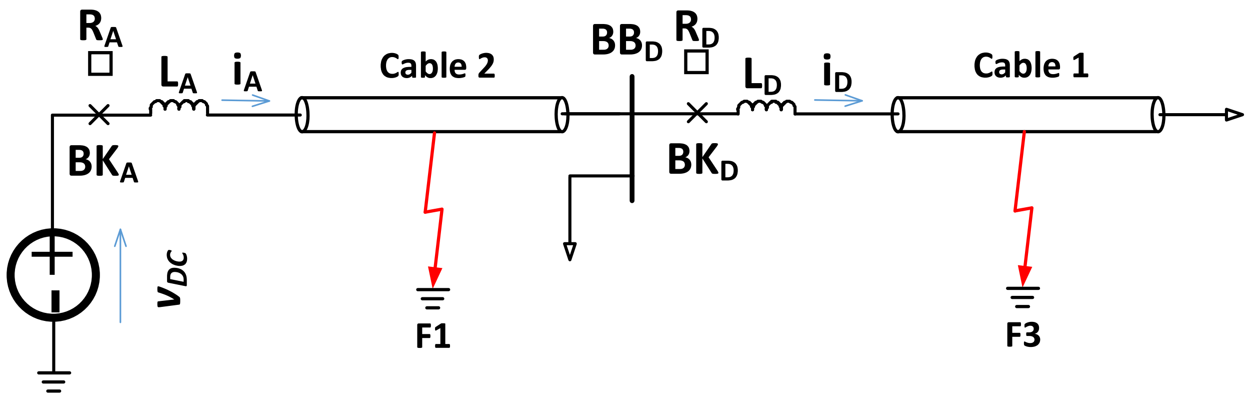
Selective

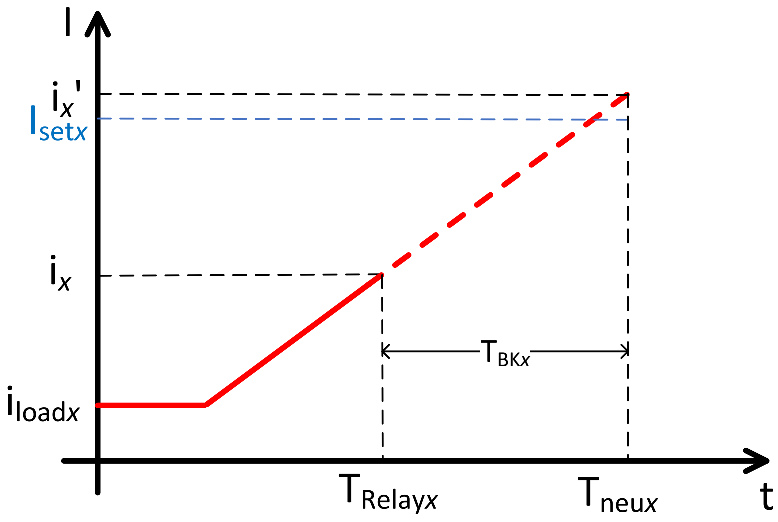


* Must be fast so that critical current limits of AC/DC converters and DC breakers are not exceeded.

IET ACDC 2025, “A Fully Selective Protection Strategy Without Telecommunications for Multi-Terminal HVDC Systems”

An Autonomous Selective Protection Concept



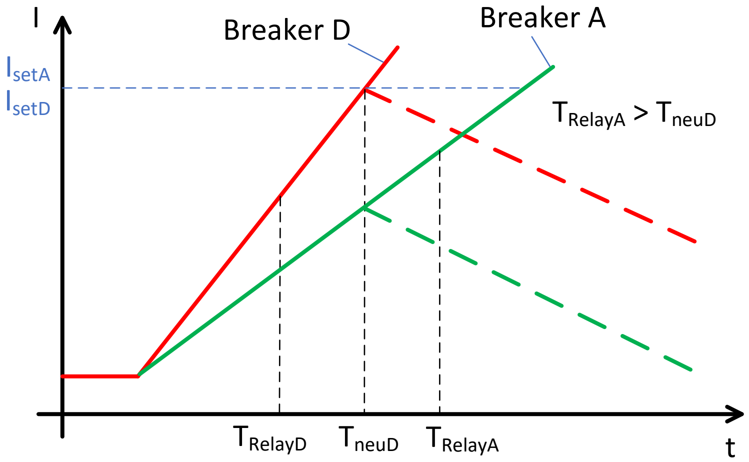


$$i_x' = |i_x + k_{i_x} \cdot T_{BK_x}| > I_{set_x}$$

, where i_x' is the prospective DC current that would flow when the DC CB neutralizes the fault, as calculated from the measured DC current, i_x, the measured rate of change of DC current, k_{i_x}, and the maximum DC CB operating time, T_{BK_x}.

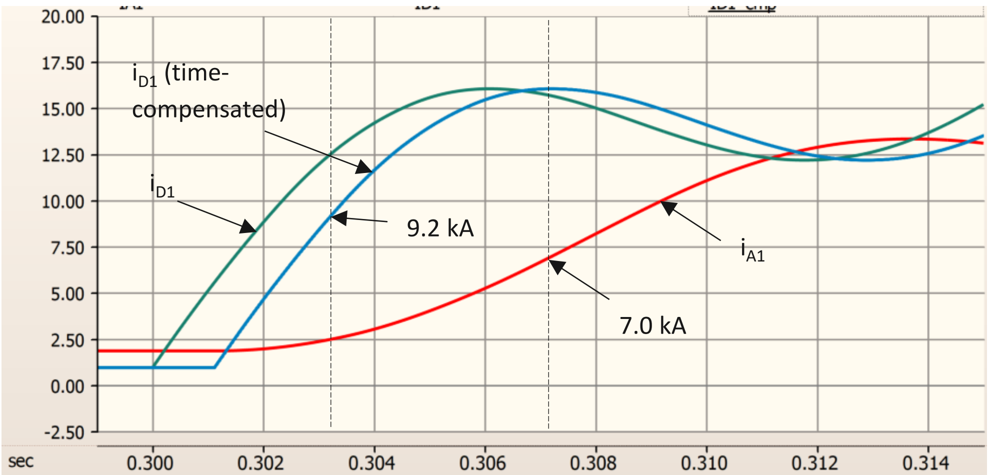
The relays operate when the prospective DC current exceeds their relay setting, I_{set_x}.

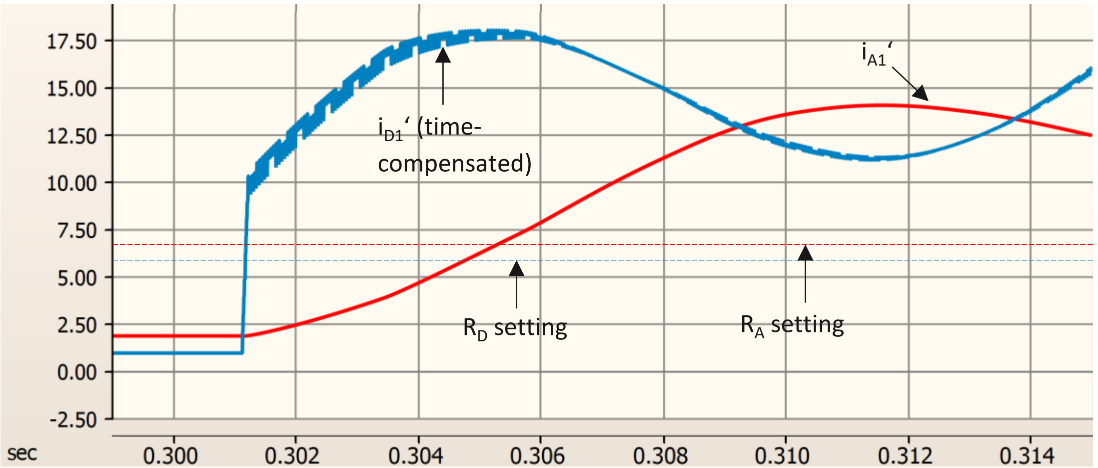
$$x = A\ or\ D.$$

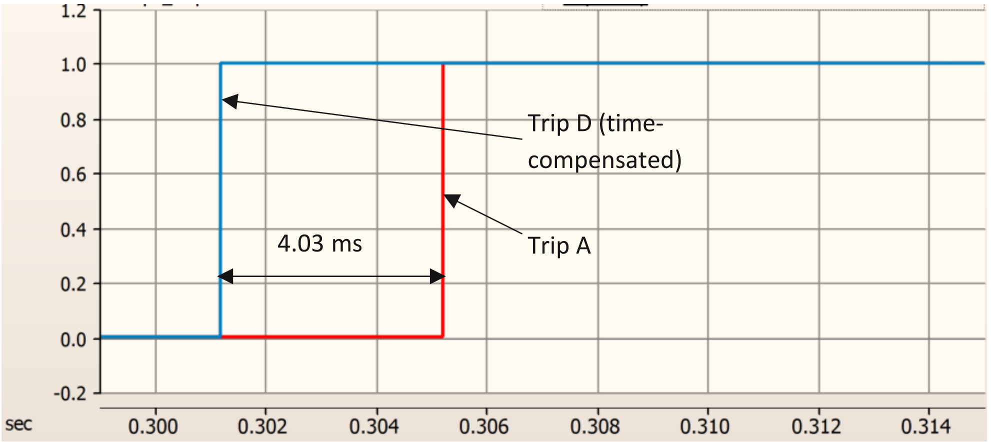


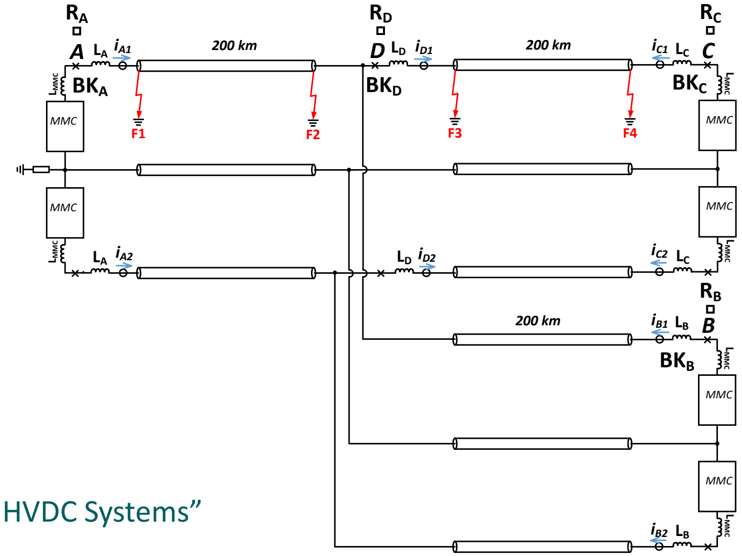
IET ACDC 2025, “A Fully Selective Protection Strategy Without Telecommunications for Multi-Terminal HVDC Systems”

Case 1 – all cables 200 km long and T_{BK} = 2 ms, F3 Open-loop Results





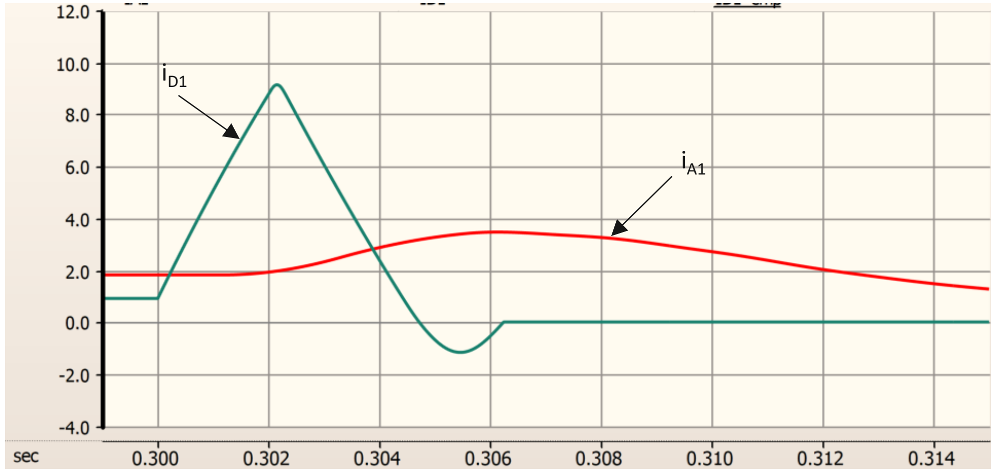


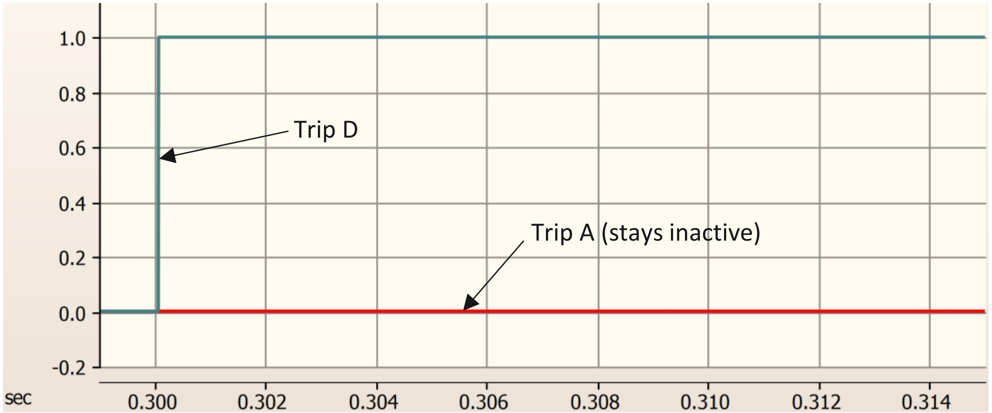


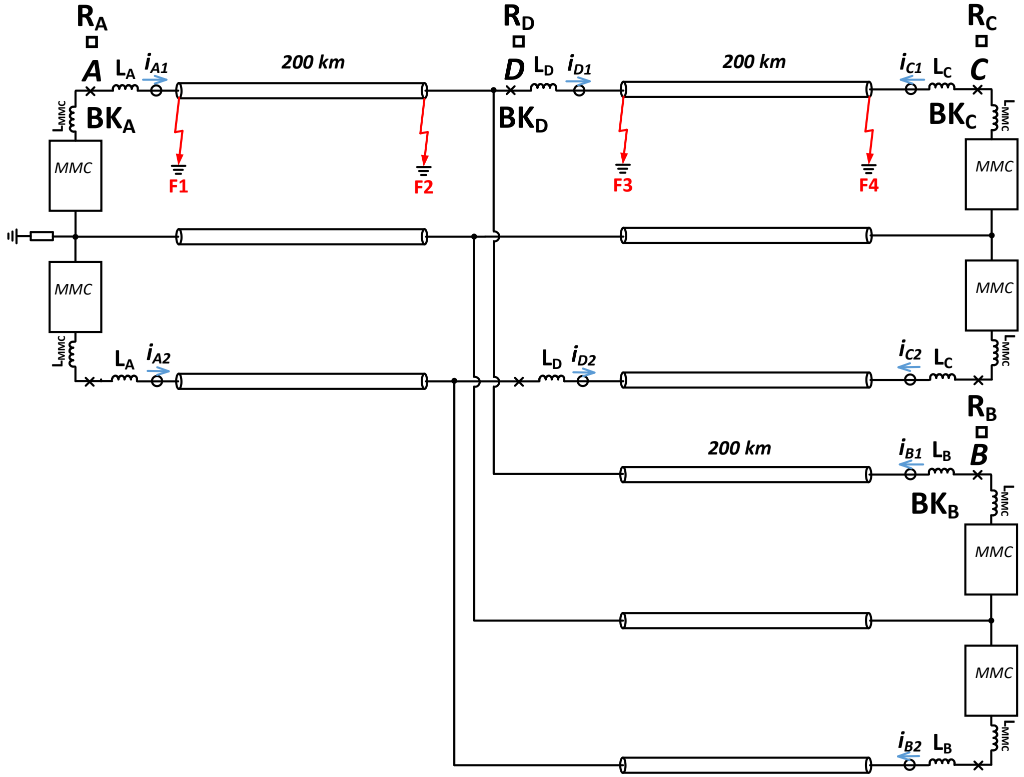
IET ACDC 2025, “A Fully Selective Protection Strategy Without Telecommunications for Multi-Terminal HVDC Systems”

Case 1 – all cables 200 km long and T_{BK} = 2 ms, F3

Closed-loop Results (neutralisation by primary protection)

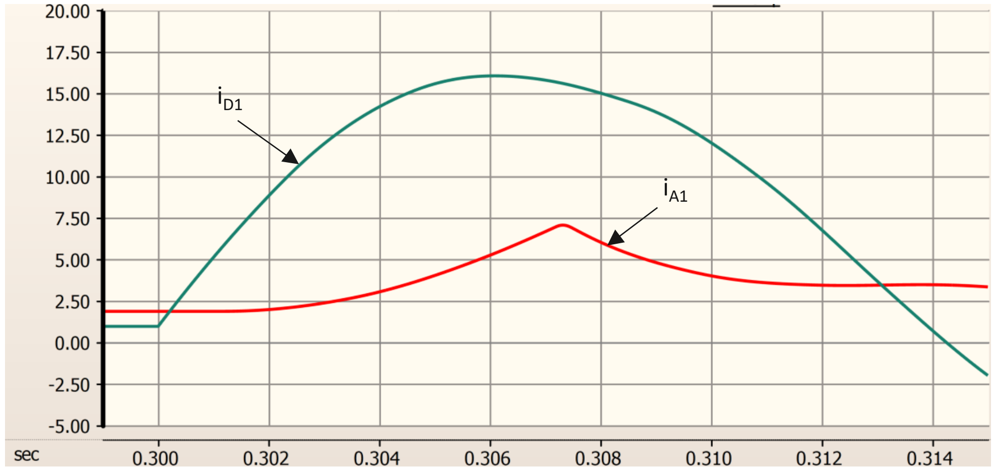


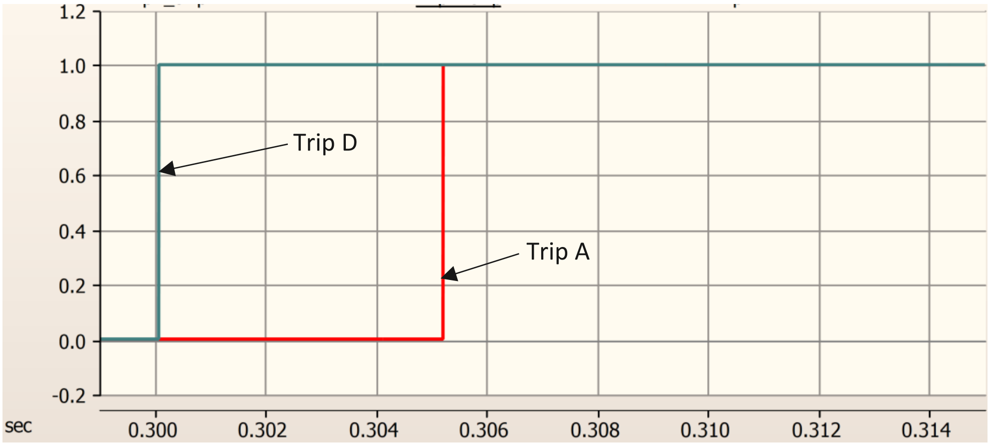


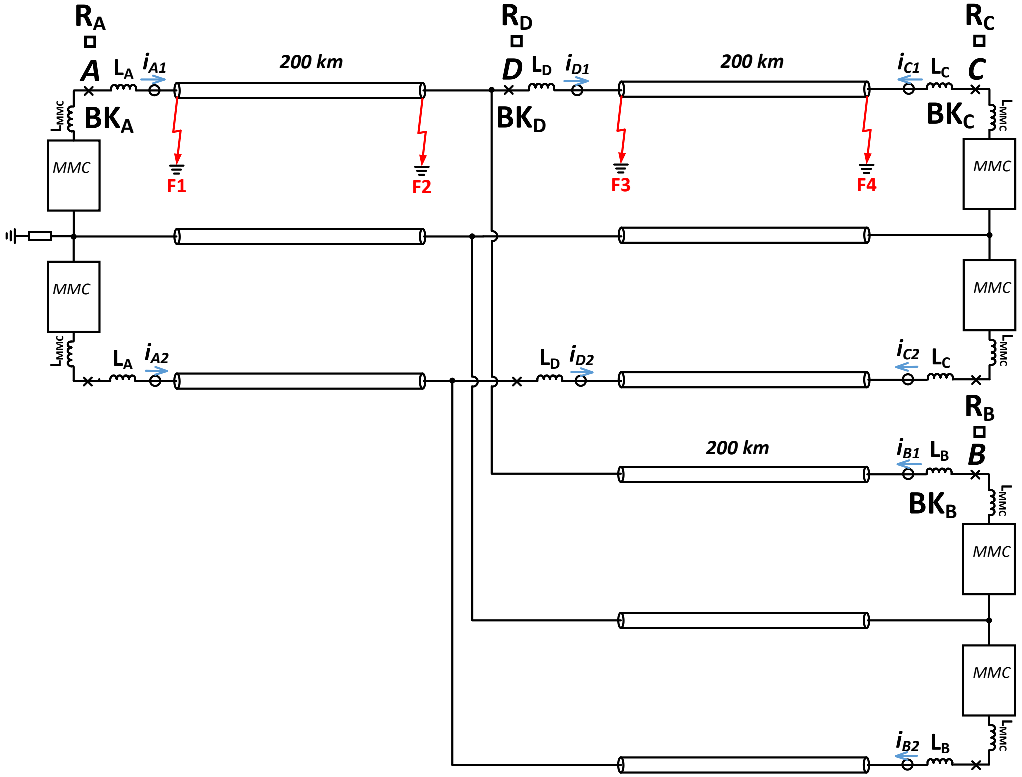


IET ACDC 2025, "A Fully Selective Protection Strategy Without Telecommunications for Multi-Terminal HVDC Systems"

Case 1 – all cables 200 km long and T_{BK} = 2 ms, F3
Closed-loop Results (neutralisation by back-up protection)







IET ACDC 2025, "A Fully Selective Protection Strategy Without Telecommunications for Multi-Terminal HVDC Systems"

Conclusions

- SGFM and C-SGFM control strategies are two core features for future MTDC systems, and their application needs to be taken into account in the overall system design (AC/DC systems).

- Primary and Back-up protection can be achieved in a multi-terminal HVDC system without the use of telecommunication

GE VERNOVA

MITSUBISHI ELECTRIC
Changes for the Better

Introduction
Mitsubishi Electric

Multi-vendor HVDC:
Trends, Experiences, and Ongoing Development

Dr. Frederick Page, HVDC Operators Forum, Cumbernauld, 2026

Experience & Collaboration

MITSUBISHI ELECTRIC
Changes for the Better

Collaboration

NEDO New Energy and Industrial Technology Development Organization

RIGHT Project

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

InterOPERA
Enabling multi-vendor HVDC grids

The National HVDC Centre

Aquila Project

Innovation Partnership Project

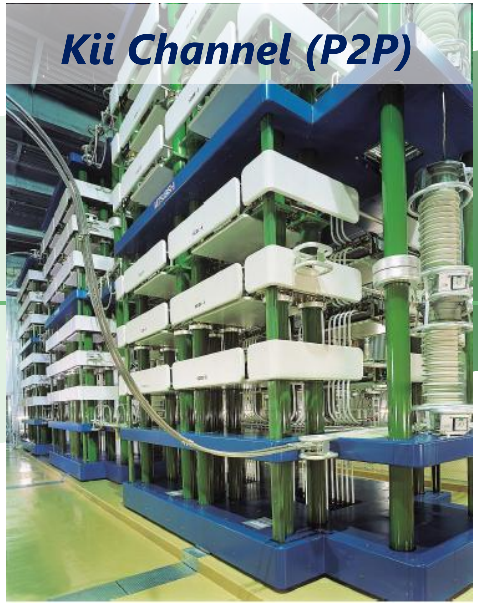
50hertz amprion TenneT TRANSNET BW

2000 — 2005 — 2010 — 2015 — 2020 — 2025

Field Experience

Shin-shinano

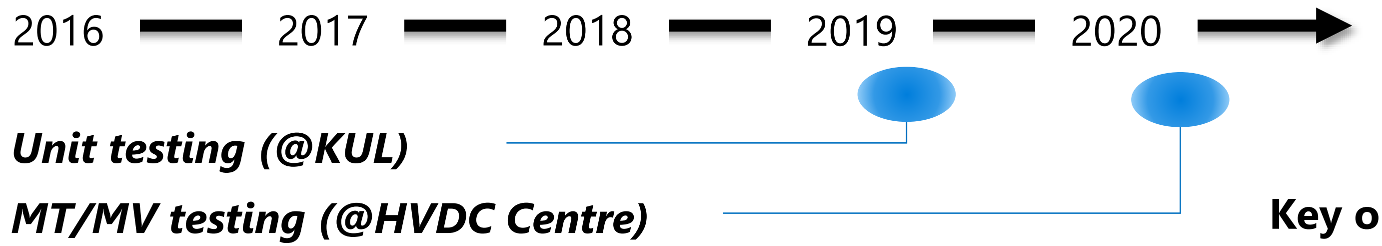
3-terminal, B2B



Kii Channel (P2P)

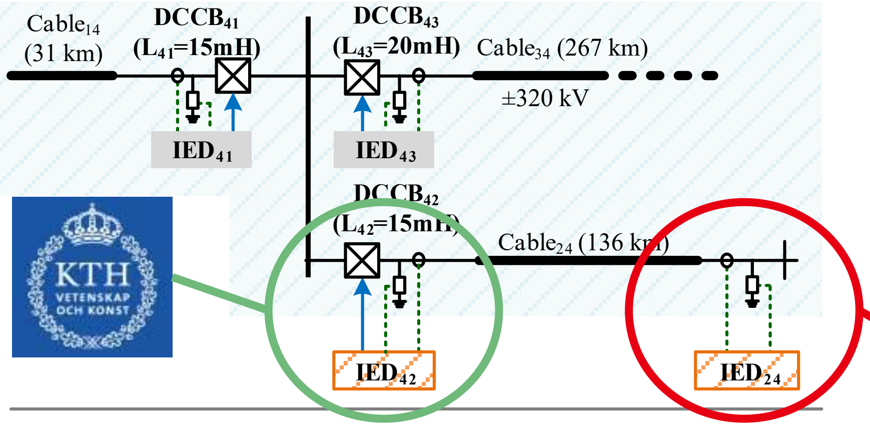
Kii Channel P2P
(C&P renewal)

Collaboration Case Study: PROMOTioN



Unit testing (@KUL)

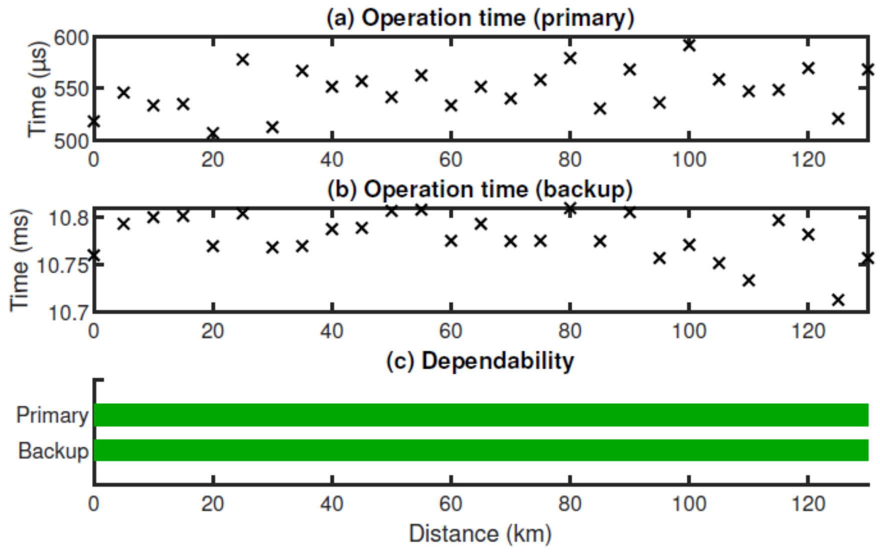
MT/MV testing (@HVDC Centre)



Key outcomes

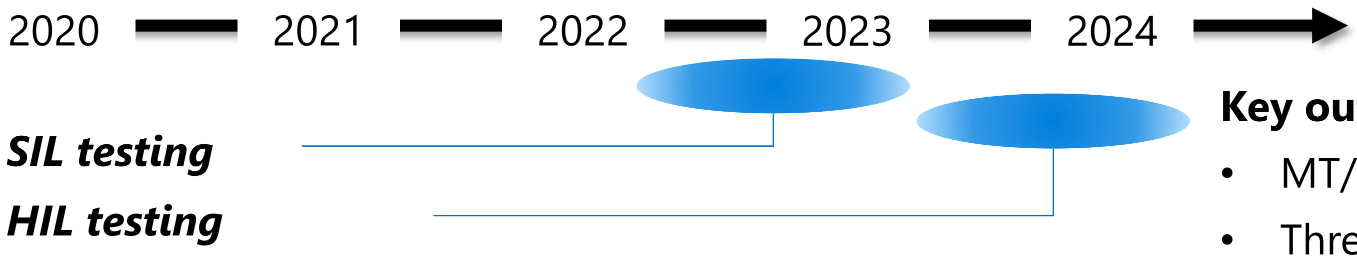
- Real-time demonstration of DC protection relay
- MV/MT environment

Converter C&P	DC Relay	DCCB	Success?
Replica	Mitsubishi Electric	VARC	☑
Replica	Mitsubishi Electric	Hybrid	☑
Replica	Mitsubishi Electric	Active current injection	☑
Replica	KTH	VARC	☑
Replica	KTH	Hybrid	☑
Replica	KTH	Active Current Injection	☑



G. Chaffey et al., "Demonstration of Multi-vendor Protection Systems for Multiterminal VSC-HVDC Networks," IEEE PowerTech, Madrid, 2021.

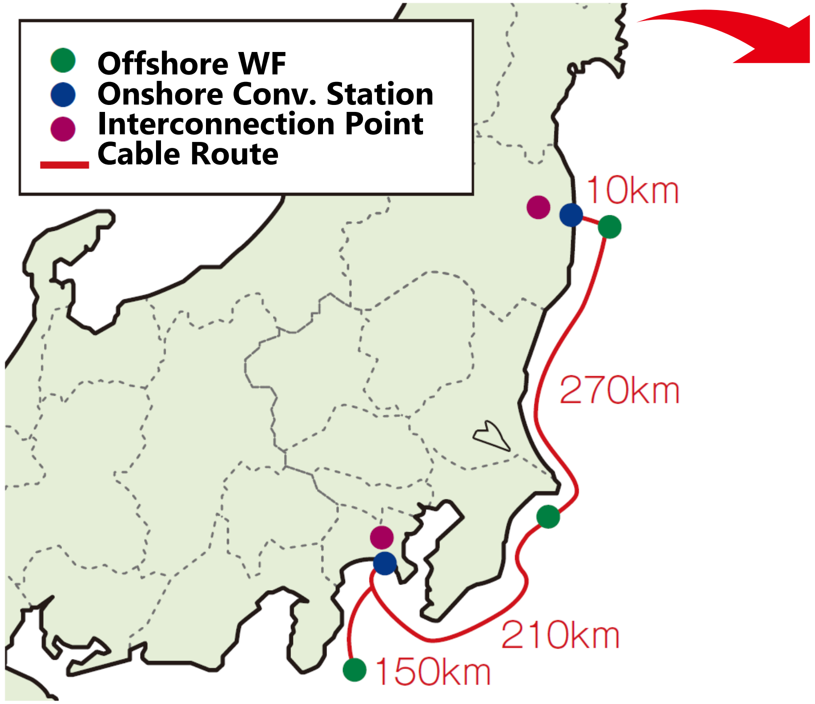
Collaboration Case Study : NEDO RIGHT PROJECT



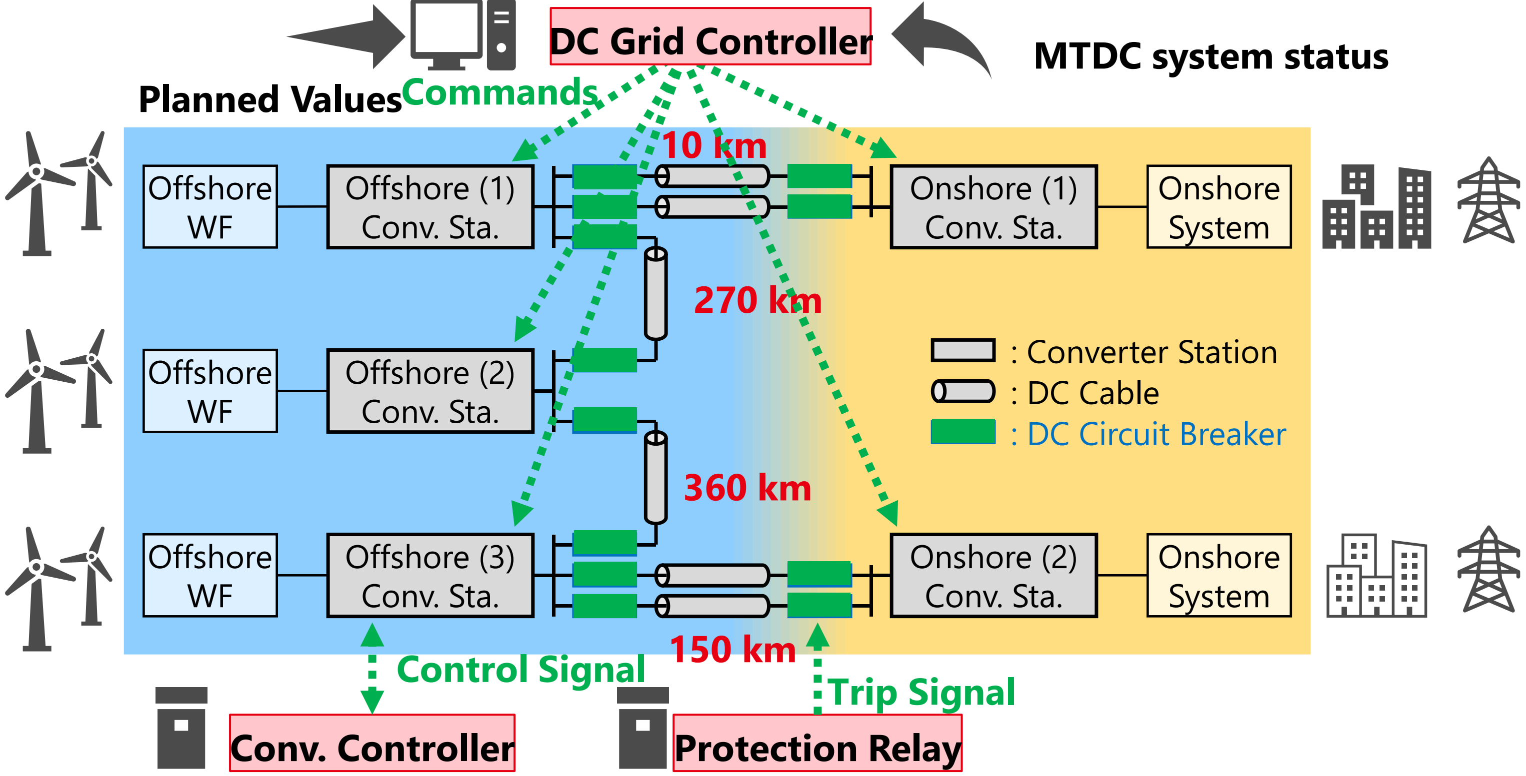
Key outcomes

- MT/MV real-time C&P demonstration
- Three converter vendors.
- Converter control, dc line protection relay, dc grid controller

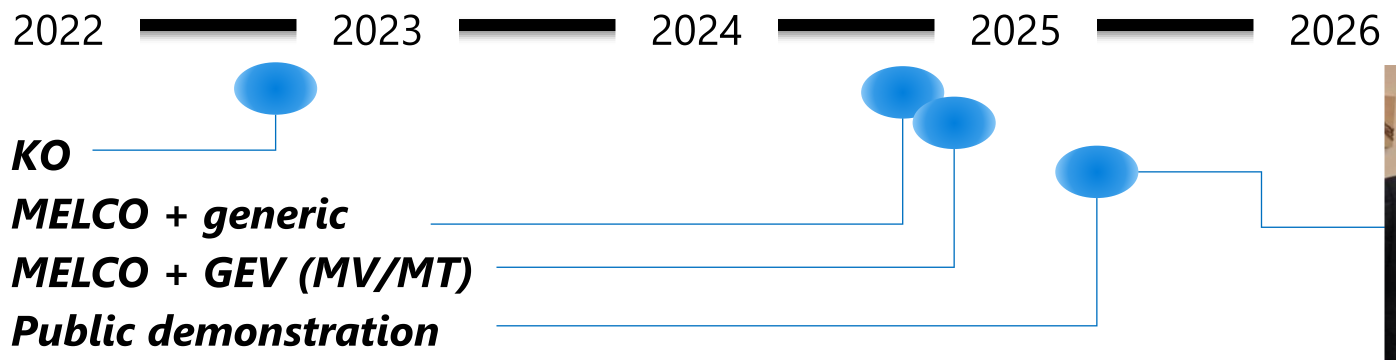
C&P MT/MV real-time verification



NEDO, "NEDO's 40-year History, Transmission route assumed in the Next Generation Offshore HVDC System Research and Development Project," March 2021, https://www.nedo.go.jp/content/100928863.pdf (in Japanese)



Collaboration Case Study : Aquila

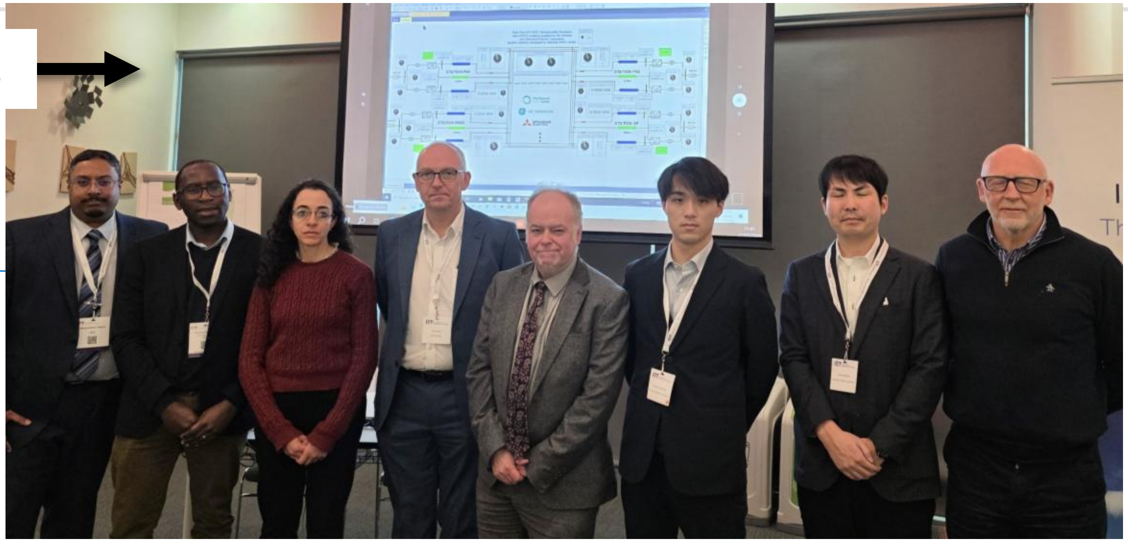


KO

MELCO + generic

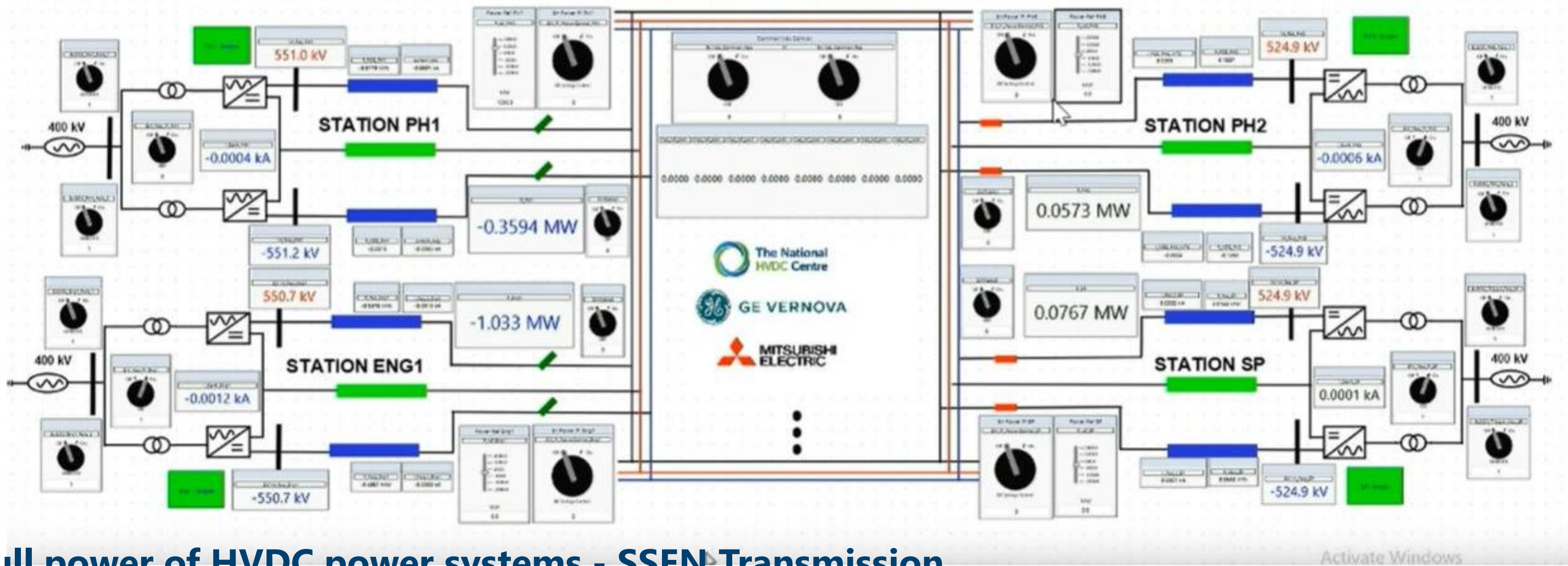
MELCO + GEV (MV/MT)

Public demonstration



The National HVDC Centre

Aquila Project



[World-first technology to unlock full power of HVDC power systems - SSEN Transmission]

Collaboration Case Study : Interopera

2023 2024 2025 2026

DCSS control unit delivered

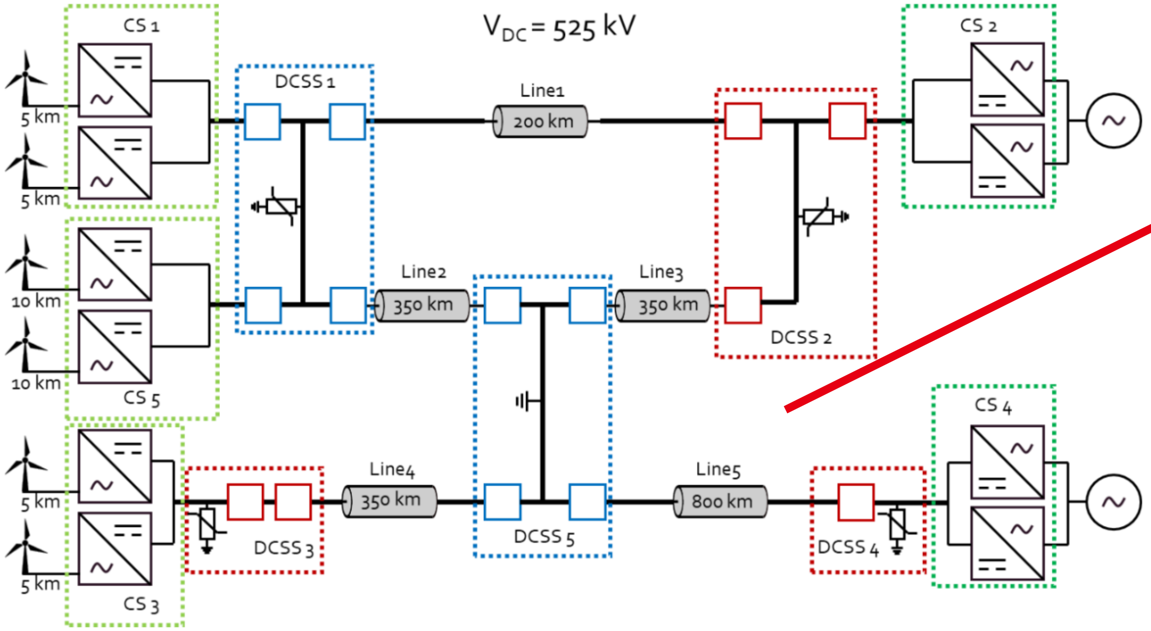
DC protection relay unit delivered

Status

- Installation and dry-runs successful

Next steps

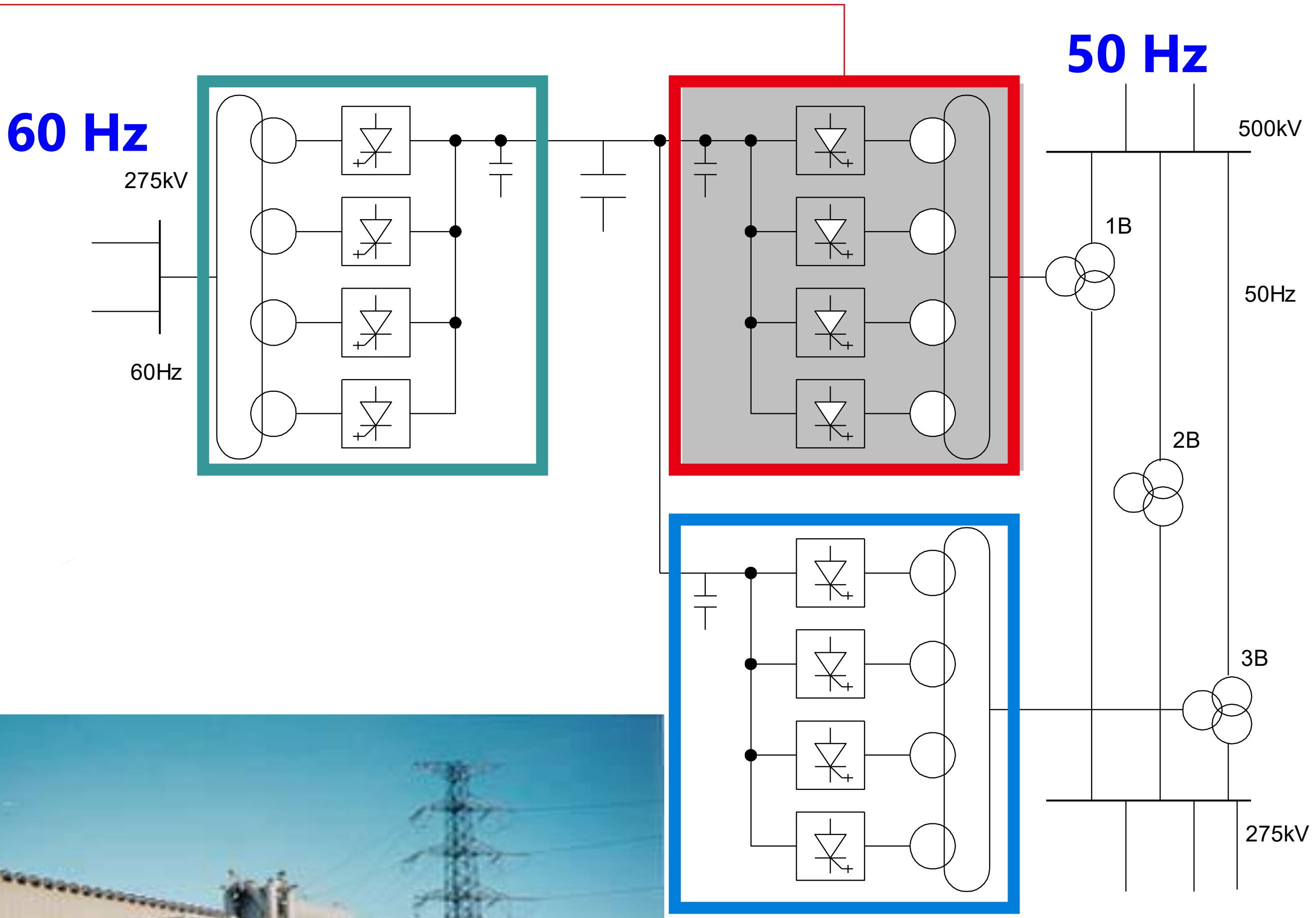
- Real-time verification demonstration

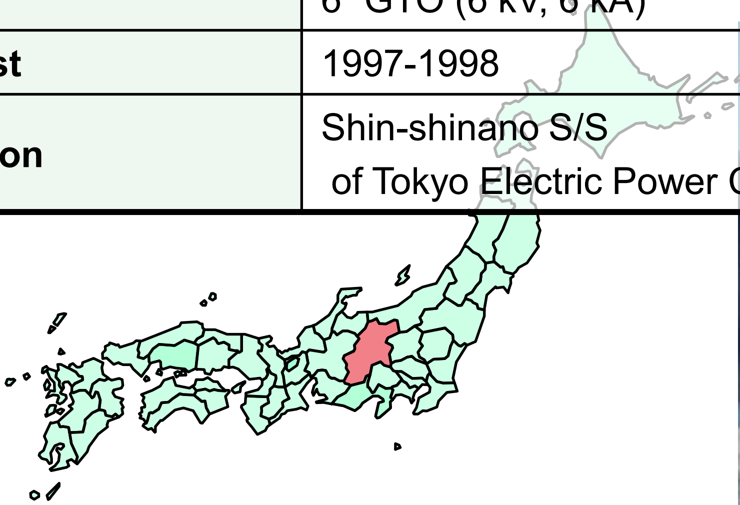


DCSS: Blue: with DCCB; Red: disconnectors.

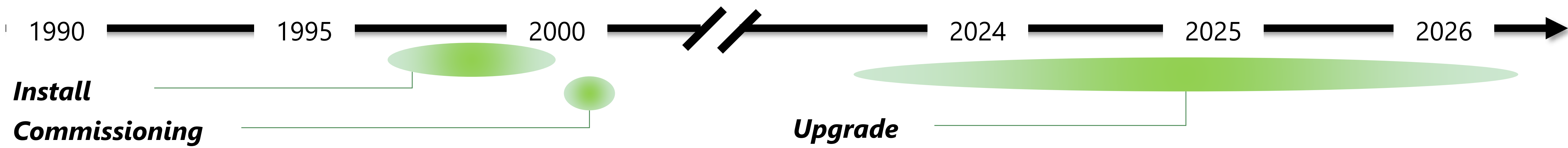
Field Experience Case study: Shin-shinano

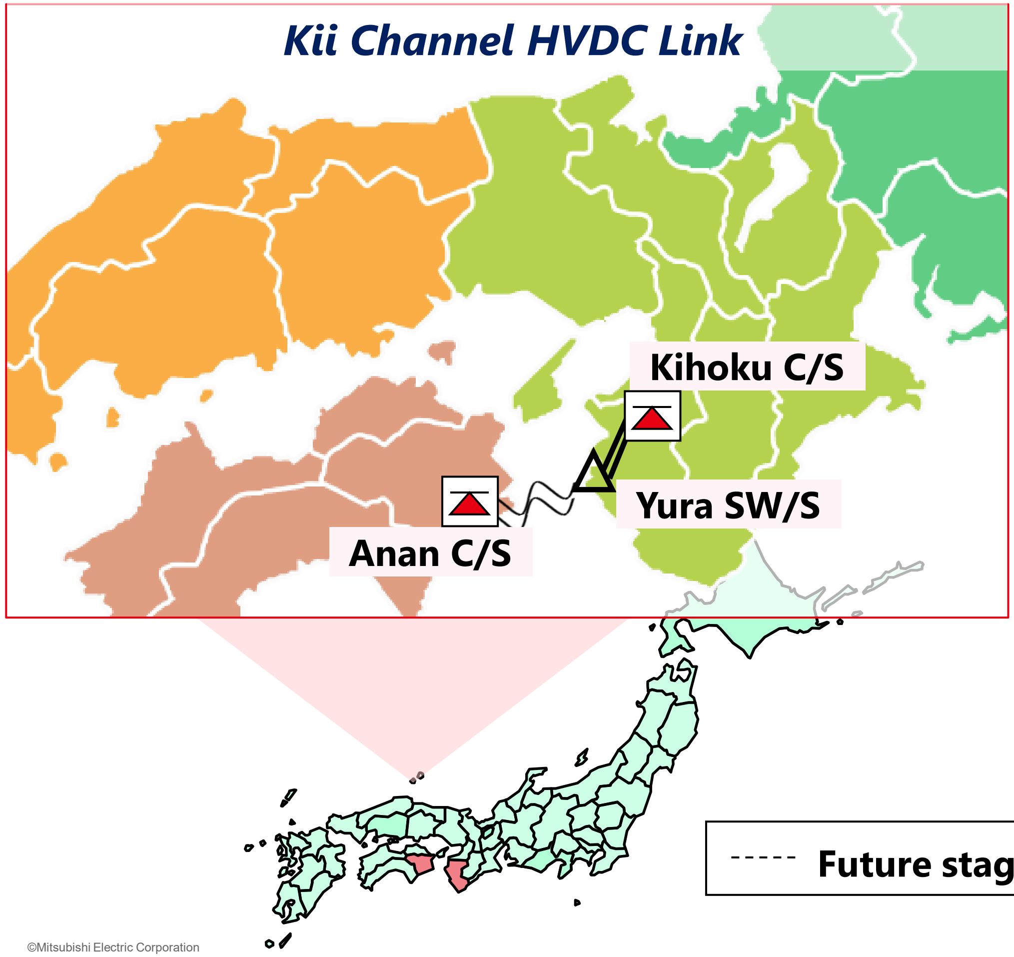
Rated Capacity	53.0 MVA (37.5 MW,37.5 MVAr)
System Voltage	66kV (500 kV / 275 kV / 66 kV Tr)
Output Voltage, Current	4,620 V, 1,710 A
DC voltage	10.6kV
Switching frequency	9 pulse PWM
Converter	Voltage source converter (4 multiple-stage)
Device	6” GTO (6 kV, 6 kA)
Field Test	1997-1998
Substation	Shin-shinano S/S of Tokyo Electric Power Co.

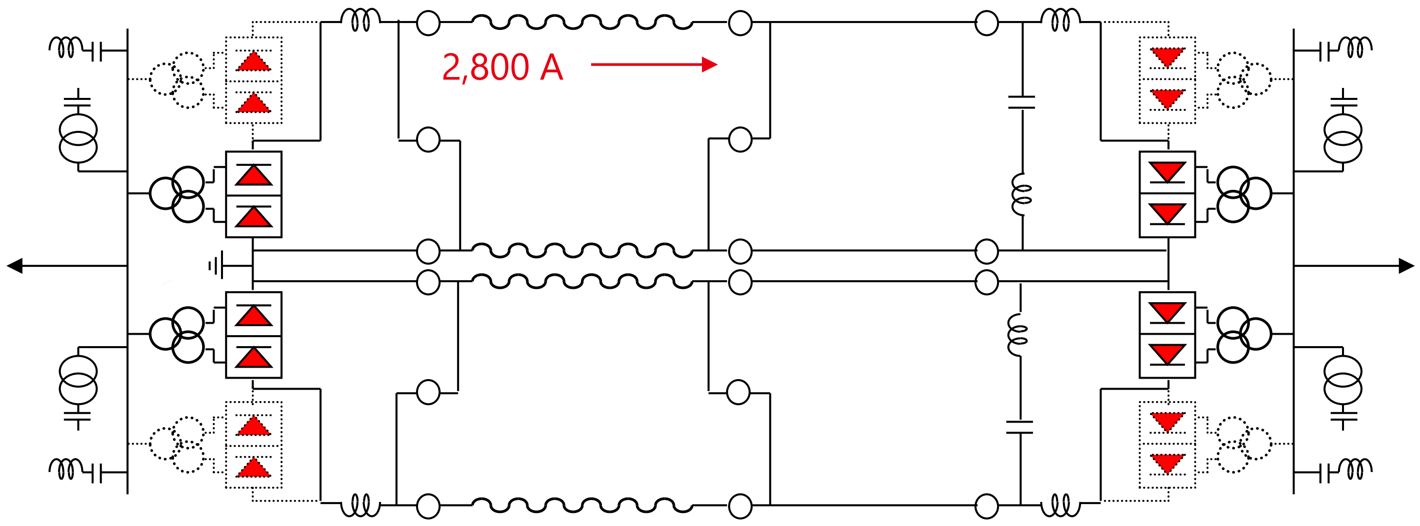




Field Experience Case study: Kii Channel (system overview)



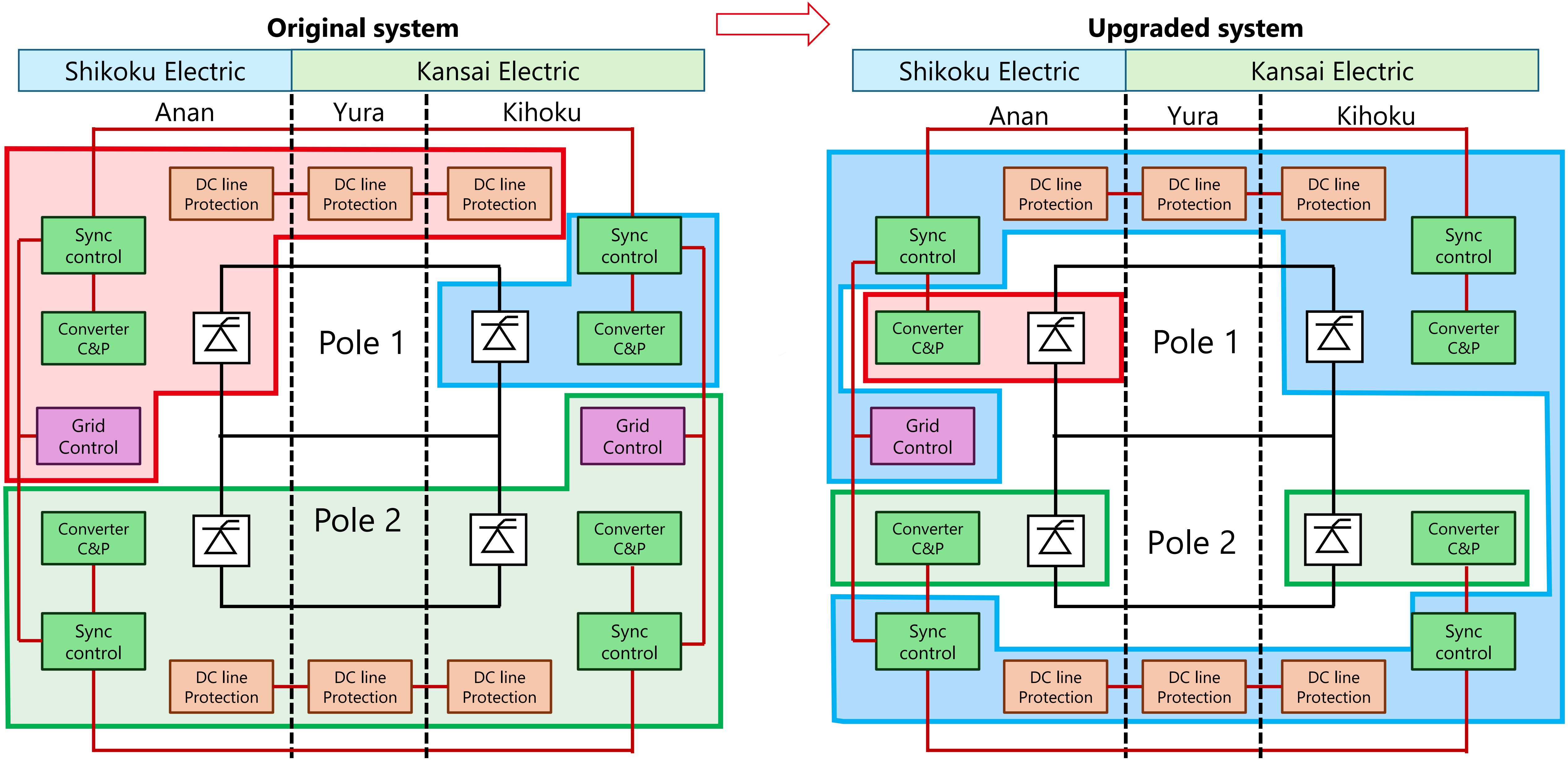




----- Future stage

Converter Station	Kansai T & D, Shikoku T & D and J-POWER TN
DC OHL	Kansai T &D,
Submarine Cables	Kansai T &D and J-POWER TN
Ratings	1400 MW (2800 MW design), 250 kV (500 kV design)

Case study: Kii Channel (C&P system)



Lessons learnt

Opportunities for multi-vendor

- Not reliant on single vendor:
  - Removing common mode failures,
  - Increasing competition
  - Can reduce delivery time for large-scale delivery

Challenges for multi-vendor

- It is difficult for vendors to collaborate closely – and a 3rd party is needed
- VSC control is more complex and heavily controlled by proprietary designs/IP compared to LCC
- DC-side is common for all converters - C&P should have response that is pre-determined (not freely designed by the vendor as in single-vendor)

Key take-aways

- Owners need to take system design responsibility
- Early development of specifications, particularly for interfaces is critical
- System designer (owner) should be responsible for determining response and performance of the system in both normal operation and during failures, particularly for the DC-side.

Reference material

1. *S. Tominaga, et al., "Research and Development of a Multi-Purpose and Multi-Terminal High Voltage Direct Current Transmission System Construction of HIL Test System for Symmetrical Monopole Multi-Terminal DC Transmission System," 2024 Annual Meeting IEE of Japan.*
2. *G. Chaffey et al., "Demonstration of Multi-vendor Protection Systems for Multiterminal VSC-HVDC Networks," IEEE PowerTech, Madrid, 2021.*
3. *Ryosuke Itotani, et al, "Kii Channel HVDC Control and Protection System Replacement Project", Cigre International Symposium 2025, Canada*
4. *NEDO, "NEDO's 40-year History, Transmission route assumed in the Next Generation Offshore HVDC System Research and Development Project," March 2021, https://www.nedo.go.jp/content/100928863.pdf (in Japanese)*
5. *B. Marshall, P. Hofbauer, D. Chen, C. Barker, K. Yamamoto, and J. Hernandez, "Practical delivery of multi-vendor, multi-terminal HVDC systems; the Project Aquila experience," presented at CIGRE 2025 International Symposium, Palais des Congrès de Montréal, Québec, Canada, Sept. 29–Oct. 3, 2025. Session: B4 DC Systems and Power Electronics, PS1 System Enhancement, Markets and Regulation.*

MITSUBISHI
ELECTRIC

Superconducting Fault Current Limiters for HVDC Grids

HVDC Operators' Forum 2026

Alberto Bertinato – SuperGrid Institute

10/06/2026

Agenda

- SPRINT Project Overview
- RSFCL Technology and Protection Concepts
- Impact of RSFCL on HVDC System Performance
- Techno-Economic Assessment
- Conclusions and Perspectives

SPRINT Project Overview

SPRINT project

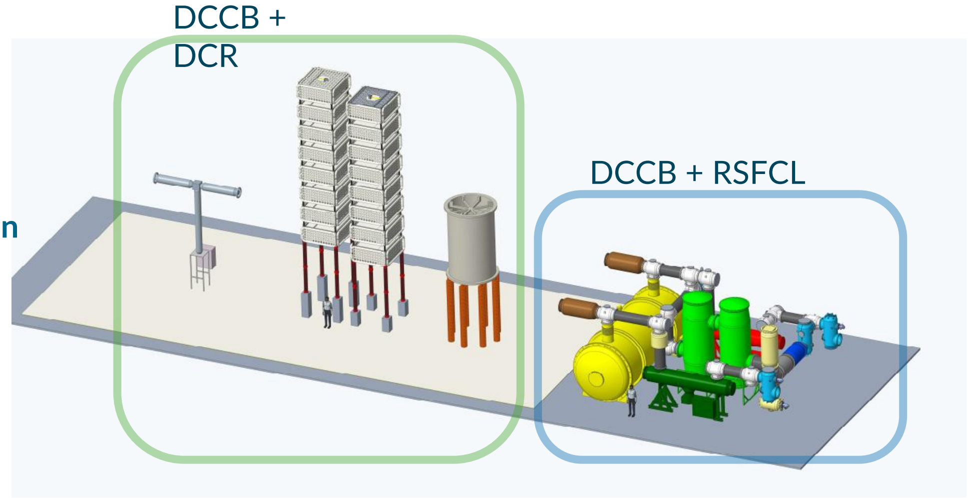
Superconducting fault current limiters **P**otential to limit **R**eactor **I**mplementation within DC **N**etwork **T**opologies

Scottish & Southern Electricity Networks TRANSMISSION
The National HVDC Centre
SuperGrid Institute

- Ofgem Strategic innovation Fund
- Discovery phase : January to Mai 2026

- Problem
  - HVDC networks must rapidly isolate and clear faults to prevent equipment damage and outages
  - The current approach relies on large DCR (DC reactors)
  - Expensive and large footprint
  - Requires larger or additional offshore platforms
  - DCRs are not only a protection solution — they impact the entire system design, cost, and operation

- Solution
  - SPRINT introduces Resistive DC Superconducting Fault Current Limiters (RSFCLs):
  - Only activates during faults
  - Smaller footprint and few units required
  - Flexible installation reduces offshore platform costs



The Discovery Phase will demonstrate technology benefits of RSFCL on real HVDC networks

SPRINT project

Superconducting fault current limiters **P**otential to limit **R**eactor **I**mplementation within DC **N**etwork **T**opologies

Structure of the project

WP1
Project management
Dissemination

WP2
Literature review
TRL evaluations

WP3
System implementation
EMT simulation
RSFCL and DCCB design

WP4
RSFCL cost model
CAPEX evaluation

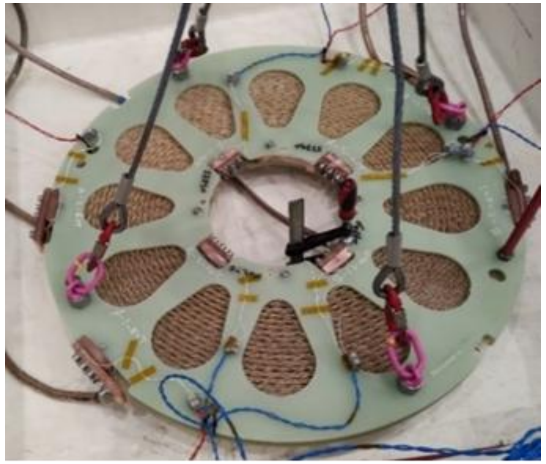
Deliverables

- **RSFCL cost model**
- **Final Report**
- **RSFCL model for EMTP simulations (DLL)**

RSFCL Technology and Protection Concepts

What is a Resistive Superconductive Fault Current Limiter ?

- Basic property of High Temperature Superconductive material
  - **A passive, no loss material if T<Tc, J<Jc and B< Bc**
  - **Use of "High Temperature" SC material: YBCO operating with Liquid Nitrogen at ~-200 °C**
  - **Tape winding into pancake, assembly of pancakes to match the voltage**



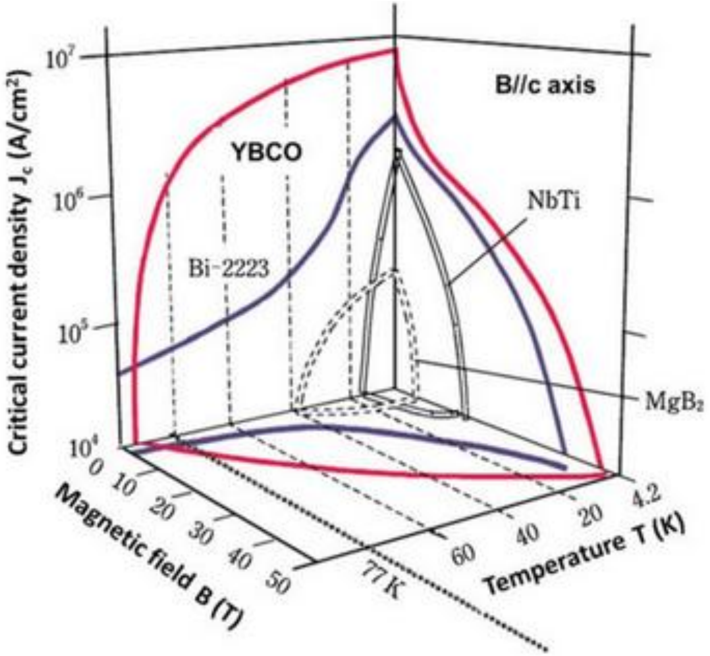


Figure 1. 3D diagrams of T_c, B_{c2} and J_c of various superconductors (including NbTi, MgB_2, YBCO and Bi-2223)[26] © 2017 Springer International Publishing AG

⑥ **Insulation / Lamination (Polyimide)**
Electrical insulation between conductors.

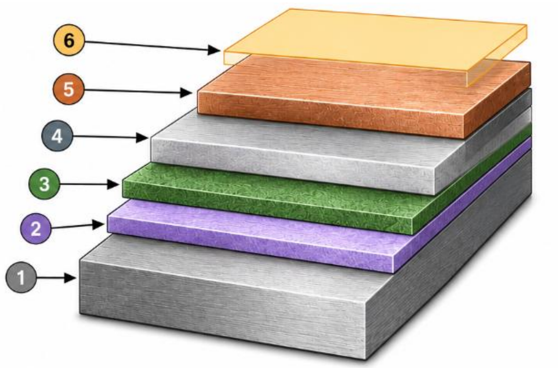
⑤ **Stabilizer / Shunt Layer**
Thermal stability and resistance in fault.

④ **Silver (Ag) Contact Layer**
Protection and good electrical contact.

③ **Superconducting Layer (REBCO/YBCO)**
Carries current with zero resistance.

② **Buffer Layers (MgO, etc.)**
Electrical insulation and crystal texture.

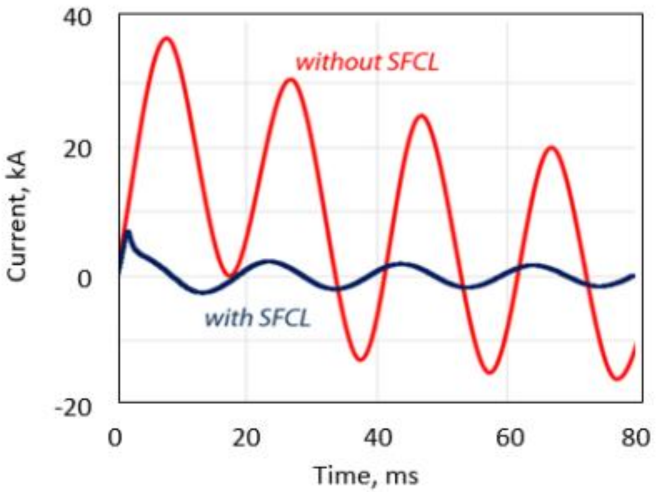
① **Substrate (Hastelloy® C276 / Ni alloy)**
Mechanical and thermal support.

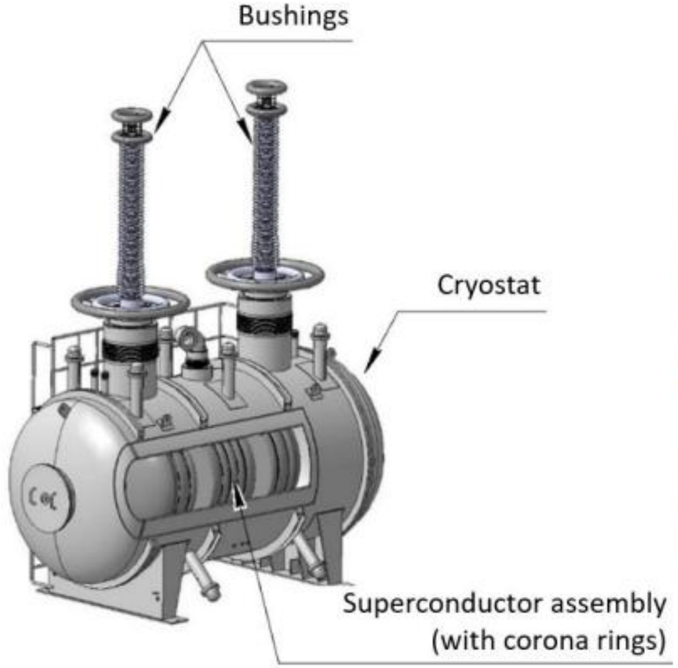


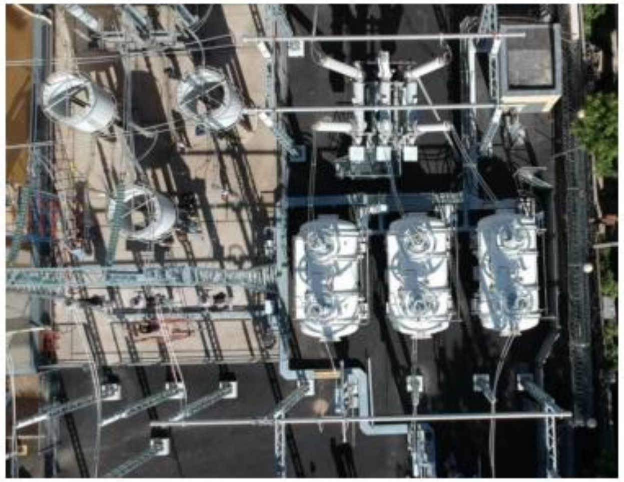
RSFCL application in HVAC grid

Mnevniki substation (Moscow)

- 2019 World-first 220 kV – 1.2 kA RSFCL installed in a 220/20 kV substation
- RSFCL aim: mitigate high fault current levels (above 50 kA) caused by rapid power consumption growth





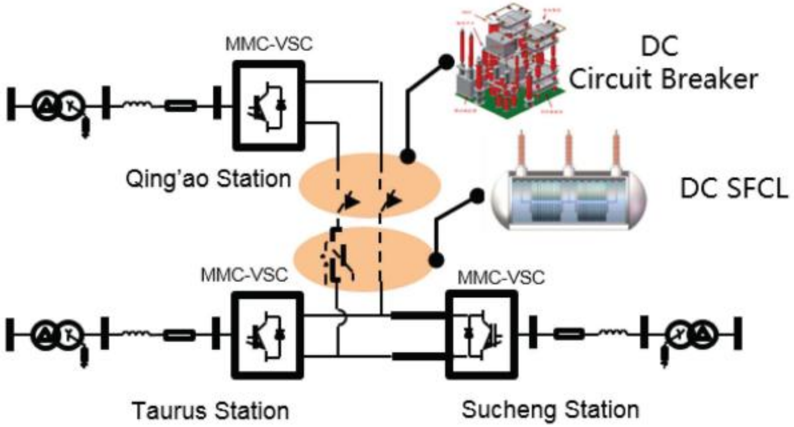


M. Moyzykh et al., "**First Russian 220 kV Superconducting Fault Current Limiter (SFCL) For Application in City Grid**," *IEEE Transactions on Applied Superconductivity*

RSFCL application in HVDC grid

Nan’ao Project (China)

- 2020 World-first application of RSFCL technology in an MTDC grid (Symmetric monopole ±160 kV)
- RSFCL aim: to expand the grid into a 4-terminal MTDC configuration to limit short-circuit current (prospective current exceeding 16 kA, while the original DCCB design was rated for 9 kA).
- RSFCL Ratings :
  - **160-kV/1-kA, Ic =1,5 kA, YBCO based, LN 77K (8 Ω within 10 m during pole-to-pole fault)**

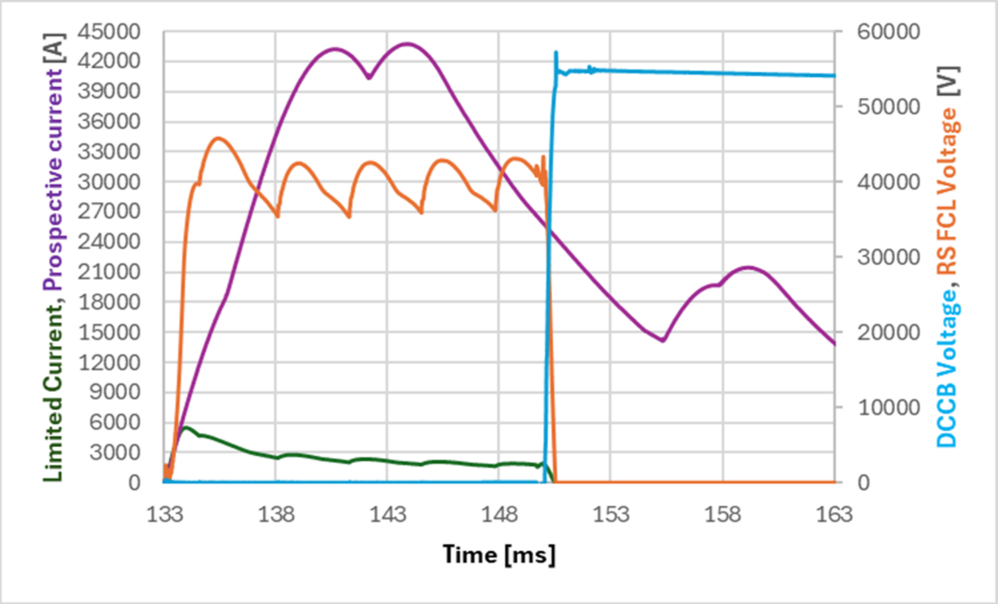


P. Guo, "**Study of 160 kV/1 kA R-SFCL Design and Application in Nanao MMC–MTDC Project**," *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 4, June 2022
M. Song, "**Design and Tests of a 160-kV/1-kA DC Superconducting Fault Current Limiter**," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 6, Sep. 2021

DC limitation tests with DC CB mechanical Breaker
Medium voltage demonstration tests

Demonstration tests at SuperGrid Institute (France)

- 50 kVDC tests
- RSFCL with 2 tapes in parallel
- Limitation of current from 43 kAp down to 5,5 kAp
- Interrupted current 2,5 kA

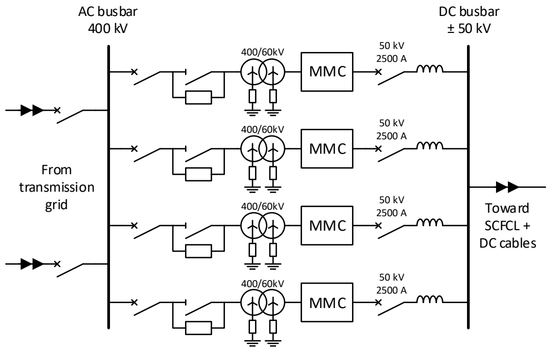


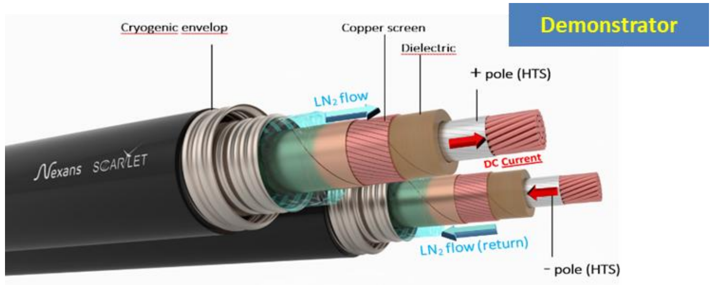
European Project

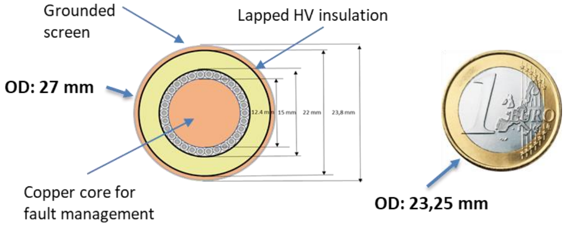
Superconducting CAbles foR sustainable Energy Transition

SCARLET

- H2020 demonstrator project
- Motivation: allow transfer of GW level of power in MVDC ≤ 100 kVDC
  - > **Reduced footprint and environmental impact**
  - > **For offshore wind: offshore conversion station could be suppressed**
- 2 types of SC cable demonstrators in 2027
  - > **LN2 cooled HTS YBCO cable**
    - ◦ Onshore / offshore solution
  - > **Electricity and chemical energy transfer: MgB2 SC cable cooled by transferred LH2**
    - ◦ Mostly foreseen for industrial applications: ports, steel smelters, …
- 1 RSFCL demonstrator
  - > **RSFCL is a solution to have an optimal protection of the SC cable combined with fast DC breaker**
  - > **10000 ADC module demonstration in 2026**







TRL analysis

RSFCL	TRL	Projects / demonstrations
HTS tapes	8-9	Nan’ao ±160 kV and Mnevniki 220 kV substation
Superconducting anti-inductive coil	8-9	Gochang 154 kV at KEPCO
Cryostat	8-9	Mnevniki 220 kV substation
Cryocooler	8-9	Mnevniki 220 kV substation
Liquid nitrogen liquefier	8-9	
Cryogenic Bushing	6-7	Nan’ao ±160 kV DC

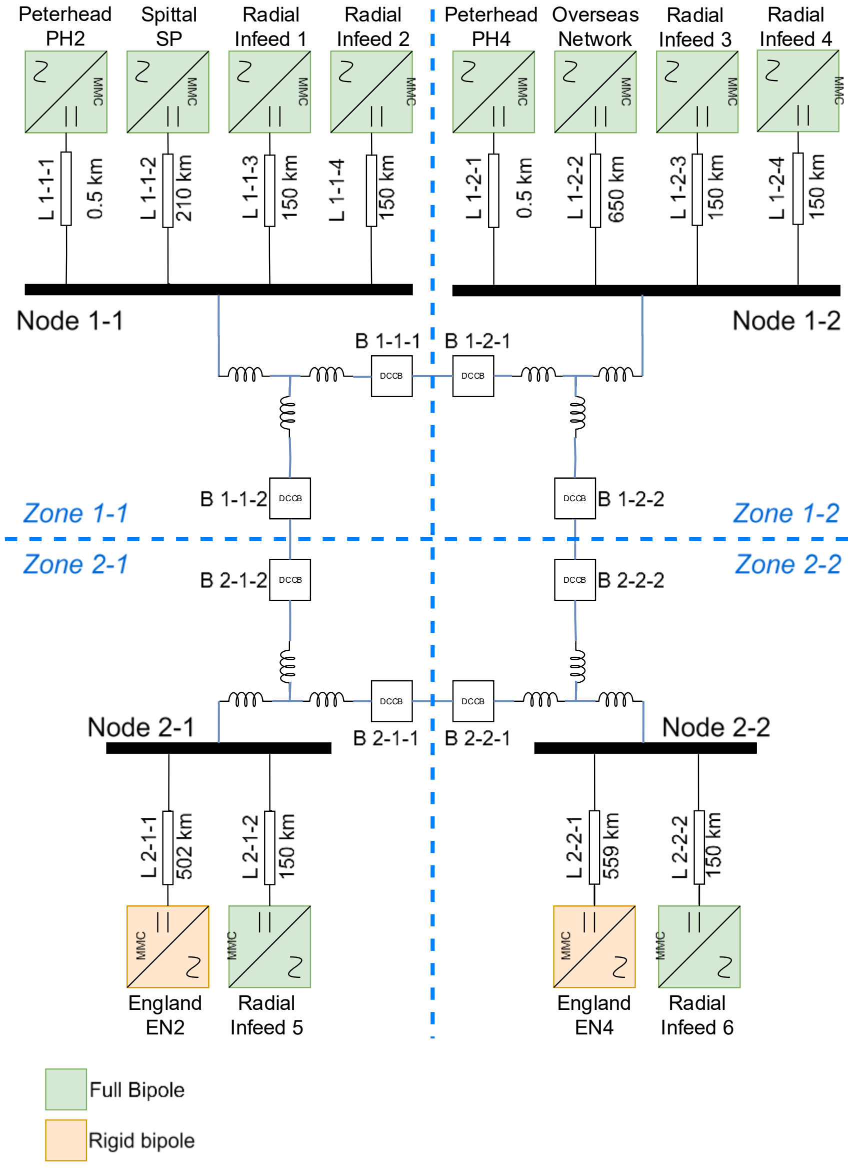
RSFCL components are mature, but system integration at HVDC level remains the key challenge (TRL 3-4)

Impact of RSFCL on HVDC System Performance

SPRINT use case

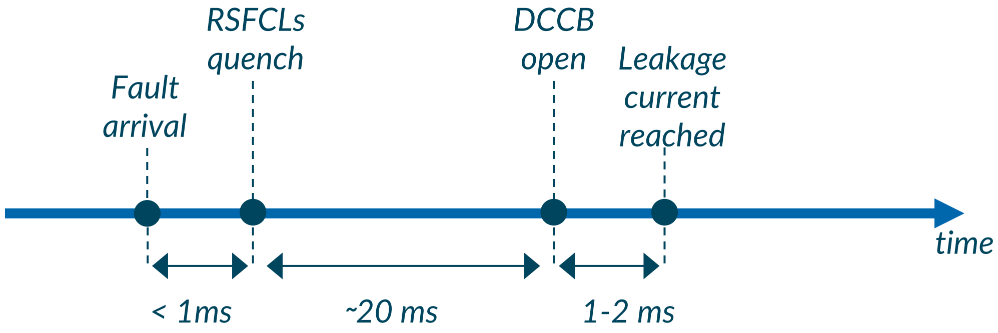
- Multi-terminal HVDC grid (based on Network DC project)
  - **12 terminals distributed in 4 nodes**
  - **Bipolar 525 kV and 1 GW per pole**
  - **Maximum LoI of 1,8 GW**
- DC switching station with ring configuration
  - **DC circuit breaker to divide the network in 4 different fault separation zones**
  - **DCCBs are doubled to avoid reliability issues**
  - **DC reactors are placed in series to the DCCBs and on the path to each node**
- The topology is designed to isolate faults and prevent convert blocking in the healthy zones

Where should RSFCLs be installed to maximize protection performance in HVDC grids?



SPRINT use case

- Retained option
  - **Placement of RSFCL within the ring between the two DCCBs**
  - **Without DCR**
- Protection sequence
  - **In case of a fault on a zone only the adjacent RSFCLs will quench**
  - **Subsequently, the DCCBs of the faulty zone will clear the fault**



Fault arrival

RSFCLs quench

DCCB open

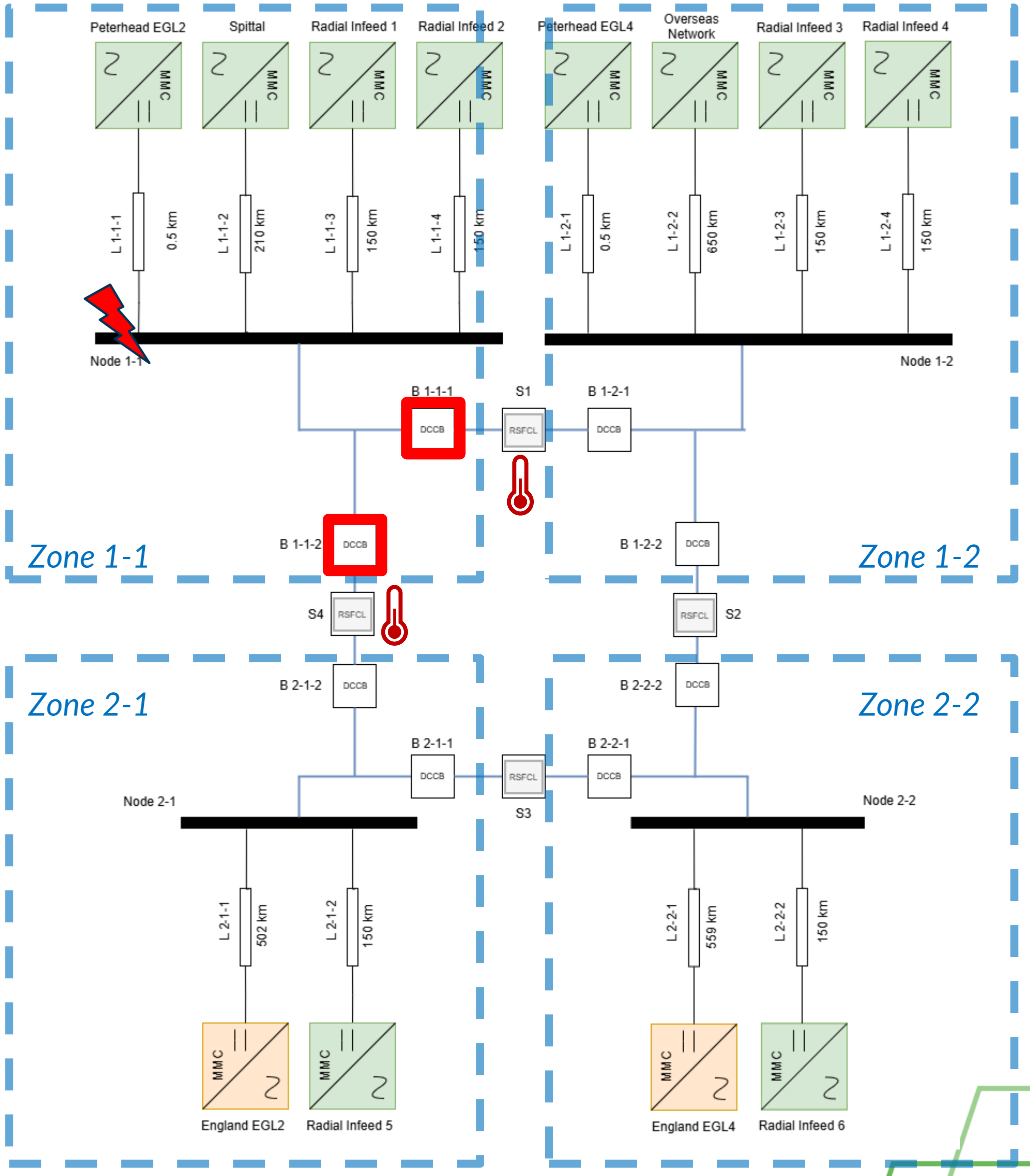
Leakage current reached

time

< 1ms

~20 ms

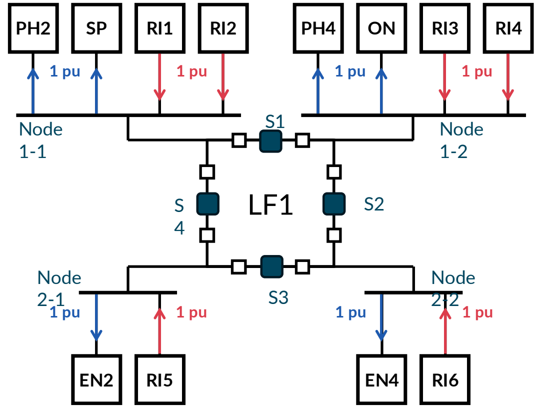
1-2 ms



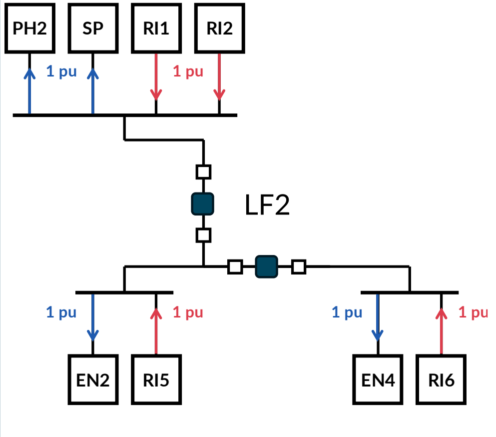
SPRINT use case

- EMT simulations
  - > **Different load flow and configurations**
  - > **Several faults type and locations**
    - ◦ PtG Line faults
    - ◦ PtG Line faults with DC breaker failure
    - ◦ PtG Active faults on DC breaker
    - ◦ PtG Busbar faults
    - ◦ PtG Busbar faults with DC breaker failure
  - > **Total of ~200 fault scenarios**

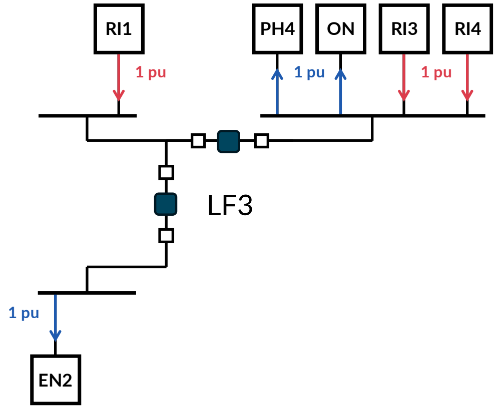
Comprehensive load flow analysis is essential → some load flows require RSFCL design optimization to ensure no MMC blocking on healthy zones



LF1 normal operation



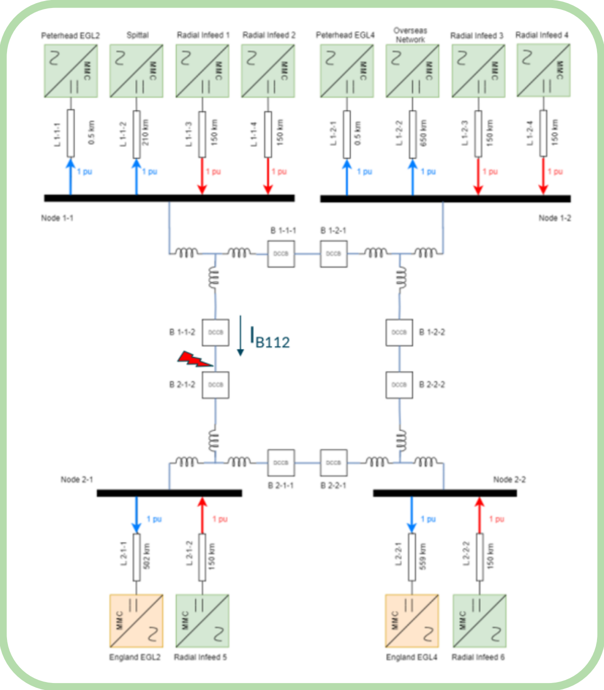
LF2 disconnecting a node

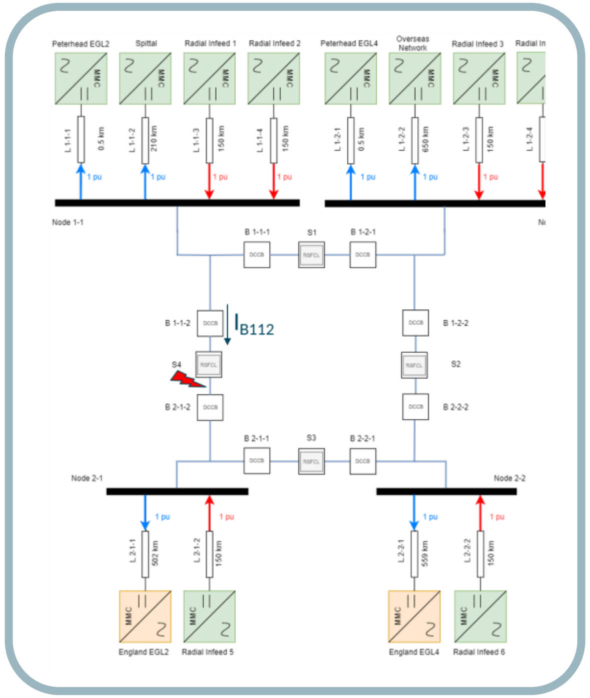


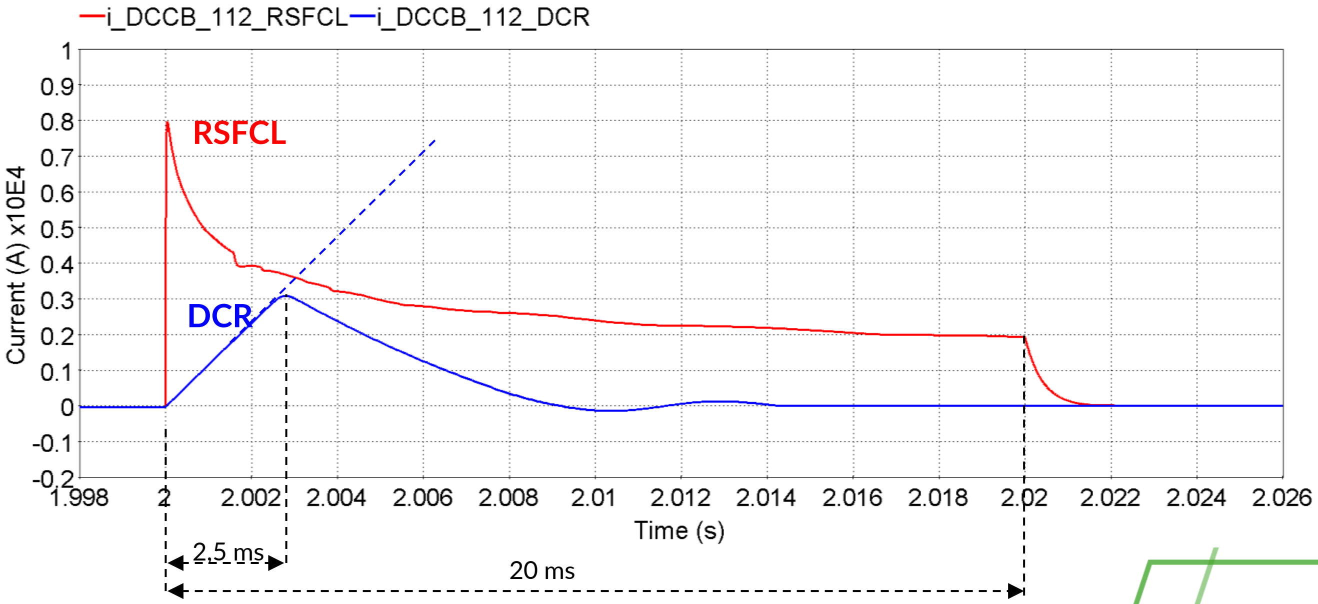
LF3 worst stress on converters

SPRINT use case

- EMT comparison of RSFCL vs DCR based protection
- RSFCL based protection
  - > High di/dt due to cable discharge (no DCR)
  - > Very fast action of RSFCL
  - > Current decrease rapidly within 5 ms
- DCR based protection
  - > DCR= 250 mH each one
  - > DCR sizing is dictated by MMC blocking avoidance
    - → large inductance
    - → slow current dynamics (low di/dt)
    - → **requires ultra-fast DCCB operation**







SPRINT use case

- Proposed design

Component	RSFCL based protection	DCR based protection
DCCB breaking current	2-3 kA	~ 10 kA
DCCB operating time	20 ms	2,5 ms
DCCB energy	< 1 MJ	37 MJ
FCL	In = 2 kA – 50% overload Critical current : 3,6 kA	250 mH
Number of FCL	4	12
FCL losses @ 2kA	16 kW	3 MW

Techno-Economic Assessment

Techno-Economic Assessment

- **CAPEX cost models**
  - > **RSFCL cost model →** based on public KIT report “380 kV Superconducting Fault Current Limiter Feasibility Study”
  - > **DCCB and DCR cost models →** based on PROMOTioN developed cost models

- **CAPEX estimation**

	RSFCL-based Protection	DCR-based Protection
DCCB cost (M£)	5 M£ (mechanical DCCB)	10,7 M£ (hybrid DCCB)
RSFCL / DCR cost (M£)	5 – 7,6 M£	0,85 M£
Number of DCCB units per pole	8	8
Number of FCL units per pole	4	12
Total CAPEX (M£/pole)	**60 – 70 M£**	**110 M£ (+ 35-45%)**

Lower number of FCL units offsets RSFCL unit cost

RSFCL Enables Significant CAPEX Reduction (~35–45%)

Conclusions and Perspectives

Conclusions

- **Key Findings**
  - **RSFCL-based protection is a promising alternative to conventional DCR-based solutions for MTDC grids**
  - **Effective fault current limitation**
    - No external tripping required
    - Reduced DCCB stress and interruption requirements
  - **Robust selectivity** → Selective quenching under various fault scenarios
  - **Techno-economic benefits**
    - CAPEX reduction
    - Decrease of network losses

- **Identified Challenges**
  - **Occurrence of undesired MMC blocking events in certain scenarios**
    - < 5 ms after fault arrival → Improve RSFCL design (e.g. higher resistance)
    - > 10 ms after fault arrival → Adapt converter control strategy

RSFCL enables fast and efficient fault limitation, with strong techno-economic benefits, but requires careful coordination with converter dynamics

Perspectives and Future Work

- **Protection & Control**
  - > EMT validation of selectivity
    - ◦ Avoid MMC blocking by means of advanced controls
    - ◦ Ensure selective RSFCL quenching
  - > Development of advanced protection algorithms and identification of HIL framework
  - > Impact of overhead lines on protection behavior and RSFCL design

- **Technology Development**
  - > RSFCL optimization and testing
  - > DCCB designs optimized for coordination with RSFCLs

- **Reliability & Economics**
  - > Reliability assessment of RSFCLs
  - > Extended TEA including reliability metrics and power flow profiles

- **System Integration & Outlook**
  - > Impact on HVDC codes and standards
  - > Identification of broader SFCL applications beyond HVDC grids

SuperGrid Institute

Thank you

Panel Q&A

***Biljana Stojkovska**, Hitachi Energy*

***Li Zou**, GE Vernova*

***Frederick Page**, Mitsubishi Electric*

***Alberto Bertinato**, SuperGrid Institute*

***Diptargha Chakravorty**, Siemens Energy*

End of Day 1

Event Dinner
10th June 2026
Westerwood Hotel – The Conservatory
Starting at 18:30