Demonstration of DC Grid Protection: PROMOTioN WP9 Updates

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Demonstration of DC Grid Protection - PROMOTioN WP9 Updates

Agenda

- Introduction
- Test objects
  - MELCO IED
  - KTH IED
- Testing and Results
  - Test Setup and Modelling
  - KPIs
  - Partially and fully selective results
  - Multivendor results
- Summary

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Frederick Page (Mitsubishi Electric Company)  Habib Rahman (The National HVDC Centre)
Introduction
Ian Cowan (The National HVDC Centre)
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PROMOTioN Overview

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
Fault Currents within a DC Grid

Fault current characteristics
- No zero crossings
- High rate-of-rise
- High steady state value

Sensitive (& expensive) converters and fast controls

Options for Protection

Converter AC breakers
- As used in existing projects
- Slow (40-60 ms opening time)
- Not selective

Fault-current blocking converters
- Higher losses compared to half-bridge
- Fast (responsive within a few ms)
- Not selective

DC circuit breakers
- Operating time of 2-10 ms
- Trade-off in losses vs speed
- Allows selective fault clearing

Selective: DCCBs on every line end

Partially selective: Split DC grid in sub-grids (protection zones)

Non-selective: Temporary shut down the whole DC grid
**HVDC IED**

- Intelligent Electronic Devices (IEDs) for HVDC protection:
  - Execute algorithms
    - Fault detection and discrimination
    - Breaker failure backup protection
  - High speed requirement (e.g. <1ms)
  - Desire for robustness, security, dependability…

- State of the art HVDC IEDs
  - Advanced algorithms not yet implemented in real systems
  - Requirement for increasing confidence/TRL
  - Standalone IED likely to be required for large scale HVDC networks

- No product on the market today, but significant industrial development
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Work Package 9 Basis

The objective is to demonstrate the operation of the DC grid protection systems.

• integrate DC relays from WP 4 and DCCB models from WP6 in real-time environment
• use hardware in the loop real-time testing in RTDS
• develop DC grid benchmark models and test procedures
• primary and back-up DC Grid protection
• equipment interoperability
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Work Package 9

HIL demonstration of fault clearing strategies (real system)

AC breaker non-selective
Sym monopole configuration

Partially selective
Sym monopole configuration

Full-selective
Sym monopole configuration

HIL demonstration of Non-selective fault clearing strategies

Converter-breaker strategy
Bipole configuration

Converter-breaker strategy
Sym monopole configuration

FB converter strategy
Bipole configuration
Mitsubishi Electric IED
Dr. Frederick Page (Mitsubishi Electric Europe)
Activity Within PROMOTioN

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WP1 – Requirements for meshed offshore grids - TenneT

WP2 - Grid topology & Converters - RWTH Aachen

WP3 - WTG – Converter interaction - DTU

WP4 - HVDC Grid Protection Sytems - KU Leuven

WP5 - Test environment for HVDC CB - DNV GL

WP6 - HVDC CB performance characterisation - UniAberdeen

WP7 - Regulation & Financing - TenneT

WP8 - HVDC GIS Demonstrator - ABB

WP9 - Protection system demonstration - SHE Transmission - RWTH Aachen

WP10 - HVDC Circuit Breaker demonstration - DNV GL

WP11 - Harmonisation towards standardisation - DTU

WP12 - Deployment plan for future European offshore grid - TenneT

WP13 - Dissemination - SDW

WP14 - Project Management - DNV GL
Hardware Activity Within PROMOTioN

High-speed DC IED (relay)

Mechanical DCCB test set-up in KEMA high-power labs

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IED Testing Progress – Work Package 4

- Unit testing within WP4 in collaboration with KU Leuven’s Energy Ville laboratory
- Algorithm development by KU Leuven; implemented by Mitsubishi Electric

Installation in Energy Ville, Genk
Key Features

- Redundant architecture: duplicate systems
- Industrial-grade equipment - builds on HVDC/FACTS technology
- Speed: Multiple, high-speed DCCB trip-outputs
- Flexibility:
  - Software programmable to utilise a variety of algorithms
  - Can be used in a variety of system configurations

Example system configurations
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Key Features

- Platform to perform research
- Low-cost
- Plug & play
- Open-source hardware and software
- Save time and cost for building laboratory setup
- Easy adaptation to different purposes
IED Hardware

- Standard and established hardware: Zedboard
- Custom and flexible I/O cards
Example Substation
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Functionality

- DC line and busbar protection for meshed HVDC grids
- Algorithms: dv/dt, travelling wave, overcurrent, undervoltage, busbar
Results

- Fastest trip time: ca. 90 μs [4]
- Algorithm accuracy: <5% [5]
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**IED Connection**

1) run PC simulation of fault scenario
2) export voltage and current waveforms
3) program waveform generator to play these

1) program and control real-time simulation
2) read-out results
Test Setup and Modelling
Habib Rahman (The National HVDC Centre)
Test Setup and Modelling

- Protection Design
- System Modelling
  - Converter Modelling
  - Converter Control
  - DC Circuit Breaker (DCCB)
  - Others
- DC Grid Configuration
  - AC and DC Network Model
  - HVDC Cable Model
  - IED Configuration
- DC Grid: Overview in run-time window
- Key Challenges
### Protection System Design

#### Methodology

- **Choice of protection philosophy**
- **Definition of minimum behaviour at each converter**
- **Choice of protection system implementation**
- **Location of circuit breakers**
- **Selection of inductor rating**
- **Examination of backup protection strategy**
- **Calculation of protection IED thresholds**

#### Example 1: Partially Selective with Mechanical DCCB

- Partially selective
- DC-FRTS3 (all converters)
- Mechanical circuit breaker
- 1 circuit breaker per pole at the switching station end of cable 3
- 105 mH per pole at each circuit breaker location
- AC-side CBs -> no requirement for additional inductance
- IED thresholds calculated

#### Example 2: Fully Selective with Hybrid DCCB

- Partially selective
- DC-FRTS3 (all converters)
- Hybrid circuit breaker
- 1 circuit breaker per pole at the switching station end of cable 3
- 25 mH per pole at each circuit breaker location
- AC-side CBs -> no requirement for additional inductance
- IED thresholds calculated
System Model: Converter

Open-source converter model: developed through a research project in collaboration with the University of Strathclyde, UK.

- Converter Modelling
  - Open source Converter Model
  - Converter topology-HB MMC
  - Average HB-MMC

- Converter Control Design
  - High level Control
  - Low level control

- Real-time Implementation
  - Small-time step
  - Large-time step
  - Interface

A basic circuit diagram of an MMC

A single phase representation of an Average HB-MMC

MMC implementation in RTDS Platform

Simulation time step: 2.5µs

System level control

Converter level control

Voltage balancing and calculation

Control system

Simulation time step: 50µs

Open source converter model developed through a research project in collaboration with the University of Strathclyde, UK.
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System Model: DC Circuit Breaker

Developed by PROMOTioN WP6 in collaboration with industrial partners. To be used for WP9 demonstration:

- Partially-selective DC protections strategies
- Fully-selective DC protections strategies

- ABB Hybrid DCCB
  - A rated current of 16 kA
  - 2ms operation time

- Mitsubishi Electric Mechanical DCCB
  - A rated current of 16 kA
  - 8ms operation time

- VSC Assisted Resonant Current (VARC) DCCB
  - A rated current of 16 kA
  - ~3ms operation time

All developed DCCB models are validated against PSCAD model.

Source: PROMOTioN WP6: D6.9 & D6.2

Source: PROMOTioN WP6: D6.8

Source: PROMOTioN WP6: D6.9
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System Model: Others

- **HVDC Cable**
  - Cable parameters are representative of the CMS HVDC project
  - Travelling wave frequency-dependent phase model is used
  - Avoid the use of long interface Bergeron lines
  - Modelled in small-time step
  - More accurate representation of electrical network resulting in more representative results from IED tests

- **Simulated IED**
  - Avoid complexity when testing a large network
  - Used when physical IED number is limited

- **Other Components**
  - Converter Transformer
  - AC breaker
  - High Speed DC Switch (HSS)
  - Surge Arrestor (Type 3 Arrestor-similar arrester model in PSCAD)
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Real time Simulation Test Setup: DC Grid Configuration

- Converter and DC-side electrical elements are modelled in the small-time step (~4μs)
- AC-side circuits and converter control are modelled in the main time step (50μs)
- AC networks are modelled as a source and equivalent impedance
- Cables are modelled in the small-time step on GTFPGA units
- No communication is used for time-sensitive operations (e.g. DC protection)
- Hardware requirement for three-terminal network implementation:
  - ✓ 2x NovaCor chassis
  - ✓ 3x GTAO card
  - ✓ 5x GTFPGA Units
  - ✓ 1x GTDI card
  - ✓ 1x Global Bus Hub
  - ✓ 1x GTDO card
  - ✓ 1x IRC Switch

![Diagram of DC Grid Configuration](image-url)
Real time Simulation Test Setup: RSCAD Simulation run-time window

• Converter BLK-DBLK
• Automated repetitive scripts
• Fault Control
  ✓ Cable selection
  ✓ Fault location selection
  ✓ Fault type selection
• Transition between SW and HW IED
• PROMOTioN IED activation
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Real time Simulation Test Setup: Lessons Learnt

- Cable modelling-additional hardware requirement
- Avoiding interfaces between large time-step and small time-step
- Small time-step interface between different:
  - ✓ bridge boxes
  - ✓ GTFPGA Unit
  - ✓ MOV model
- Impedance of the interface t-line \( Z_o = \sqrt{L/C} \) has to be compensate with other network elements:
  - ✓ DCCB
  - ✓ HVDC Cable
- Simulated IED Configuration-requires hardware to interface (through GTAO and GTAI cards) between sub-step to small time-step
- Developed model structure varies depending on particular test cases:
  - ✓ multivendor
  - ✓ different DCCB topologies
  - ✓ different IED configurations
Key Performance Indicators
Geraint Chaffey (KU Leuven)
Key Performance Indicators for HVDC Protection Systems

- Protection IED indicators
  - Dependability
  - Operation time

Ability of the protection IED to **successfully detect** a fault in the protection zone
- Determined through dynamic validation testing i.e. repetitive fault testing in time domain simulation

Time from arrival of travelling wave front to instant IED sends a trip signal
Key Performance Indicators for HVDC Protection Systems

- Protection IED indicators
  - Dependability
  - Operation time

- System indicators*
  - Efficiency indicators: Fault interruption time, Active power restoration time, Reactive power restoration time, DC voltage restoration time, Transient energy imbalance.
  - Failure indicators (probability based)

*System KPIs developed by PROMOTioN WP4 partners. Fact sheet to be published in D11.2 (Q2 2020).
Key Performance Indicators for HVDC Protection Systems

• Protection IED indicators
  • Dependability
  • Operation time

• System indicators*
  • Efficiency indicators: Fault interruption time, Active power restoration time, Reactive power restoration time, DC voltage restoration time, Transient energy imbalance.
  • Failure indicators (probability based)

• DCCB KPIs

• Protection margin

*System KPIs developed by PROMOTiON WP4 partners. Fact sheet to be published in D11.2 (Q2 2020).
Evaluating Protection IED Performance: Partially Selective
Geraint Chaffey (KU Leuven)
Protection IED performance: Partially Selective Protection System

- Single vendor test cases (only PROMOTioN IED or only Mitsubishi IED)
- Partially selective case study – one IED and DCCB per pole
- Repetitive testing to evaluate functional performance and dependability:
  - Pole-to-pole faults every 5 km (on cable34)
  - Three repetitions at each fault location

Example Time Domain Result

- Voltage
- Current

Measurements at IED location
Hybrid DCCB
Mid-cable pole-to-pole fault
(MELCO under test)
Protection IED performance: Partially Selective Protection System

- Single vendor test cases on partially selective protection system:

Example Time Domain Result

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements at IED location Hybrid DCCB Mid-cable pole-to-pole fault (MELCO under test)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example results from partially selective system [6].
Evaluating Protection IED Performance: Fully Selective and Multivendor
Geraint Chaffey (KU Leuven)
Multivendor HVDC Protection

• What do we mean by multivendor interoperability?
Multivendor HVDC Protection IEDs – Test Setup

- Interoperability of IEDs from multiple vendors is one essential aspect for achieving successful fault clearing in a future multi-vendor system.

- Fully selective strategy
  - IEDs are placed at both ends of a cable
  - DCCBs are placed at the DC switching station: inductors are chosen to allow breaking current to fall within the capability of hybrid DCCBs (2 ms/16 kA)
  - ACCBs at the converter side
**Multivendor HVDC Protection IEDs – Primary Protection**

- **IED configuration:**
  - Single-vendor setup:
    - C2: MELCO IED functional units connected to IED42 and IED24
  - Multi-vendor setup:
    - C4: KTH IED: IED42, MELCO IED: IED24

- **Example results (Mitsubishi IED):**
  - Mean operating time: less than 600 $\mu$s
  - Single-vendor and multi-vendor cases:
    - Comparable operating time
    - 100% dependable along the 136 km cable
Multivendor HVDC Protection IEDs – IED Failure Backup (Dual Redundant)

- IED configuration (multi-vendor setup (C5)):
  - KTH IED as IED42a, MELCO IED as IED42b with separate measurement inputs, and independent trip outputs
  - One of the hardware IEDs is disabled to simulate a failure

- IED performance:
  - Operating time: few hundreds $\mu$s
  - 100% dependable
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Multivendor HVDC Protection IEDs – Breaker Failure Backup

- IED configuration:
  - Single-vendor setup (C3):
    - MELCO IED functional units are connected to IED$_{42}$, IED$_{41}$ and IED$_{43}$.
  - Multi-vendor setup (C6):
    - MELCO IED: IED$_{42}$
    - KTH IED: IED$_{41}$ and IED$_{43}$
    - MELCO and KTH IED: directly connected with a wire
Multivendor HVDC Protection IEDs – Breaker Failure Backup

- IED performance:
  - BF delay setting: 10.42 ms
  - Single-vendor and multi-vendor cases:
    - BF backup IED time: comparable
    - BF decision time: few hundreds $\mu$s
    - 100% dependable

![Diagram showing BF backup IED time, primary IED time, BF delay time, and BF decision time](image-url)
Use of CMS Control and Protection Replicas
Ian Cowan (The National HVDC Centre)
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Replica Setup

Real-Time Simulator

Measured Voltage and Current

Analogue signals

Firing Pulses (Digital Signal)

Replica HVDC Control

Captured Setup

Real-time Simulator Runtime Interface
• Apply network faults
• Change generation dispatch
• etc

Real Time Simulator Rack

Modelled in RTS Software

HVDC Control Replica Cubicle

Sign Processing at Interface Cubicles

VSC Station Computer

Valve Control Unit

Firing Pulses

Operator Work Station
• Start up / shut down
• Change control mode
• Change set points
• etc

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**Different Setup, Same Result?**

- Replica model used as basis
- Not immediately suitable

**Diagram:**

- Onshore HVDC Converter Station 1
- Onshore HVDC Converter Station 2
- Offshore HVDC Converter Station 3
- DC Switching Station 4
- Wind Farm
- AC Network 1
- AC Network 2
- Cable 1 (269km)
- Cable 2 (136km)
- Cable 3 (31km)
- 840 MVA
- 275 kV/380 kV
- 16%
- 1 GW
- 800 MW
- 626 MVA
- 380 kV/132 kV
- 16%
- 800 MW
- 600 MW
- 1200 MW
- 1265 MVA
- 380 kV/400 kV
- 16%
- 1200 MW
- IED 3
- ACCB 2
- ACCB 1
- SCR = med/low
- SCR = high

**Updates:**

- Moved to small time step
- Frequency dependent line used
- Another type of interoperability
- Subject to ‘normal’ system events
- Same IED performance observed
Summary

Ian Cowan (The National HVDC Centre)
• Two hardware IEDs are tested in a realistic three-terminal network for primary, IED failure backup and breaker failure backup protection. The test results demonstrate:
  • Single-vendor and multi-vendor cases: comparable performance
  • Multi-vendor HVDC grid protection system: feasible and a viable option
• Initial steps to test with CMS control and protection replicas undertaken

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Summary

PROGRESS

NEXT STEPS

• Further testing with different combinations of DCCB models and IED locations
• Extend model to 4T system
• Add in pole rebalancing to allow move to system level testing
• Further testing including the CMS control and protection replicas
• Prepare for the final demonstration
How to Protect an HVDC Grid?

• Answer is likely to be highly case specific:
  • AC system constraints
  • Choices by system operator
  • Location of system (onshore/offshore)

• But, there are numerous options
  • Each technically feasible but with different trade-offs (cost, system impact,…)

• Key components to realise DC Grid protection are ready
  • IEDs as discussed within this presentation
  • DCCBs as demonstrated at KEMA labs through PROMOTioN
    • Devices from multiple vendors tested

• Further results coming soon

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Further Reading