Practical Use of Real Time Simulation for De-risking HVDC Integration

16th & 24th April 2020

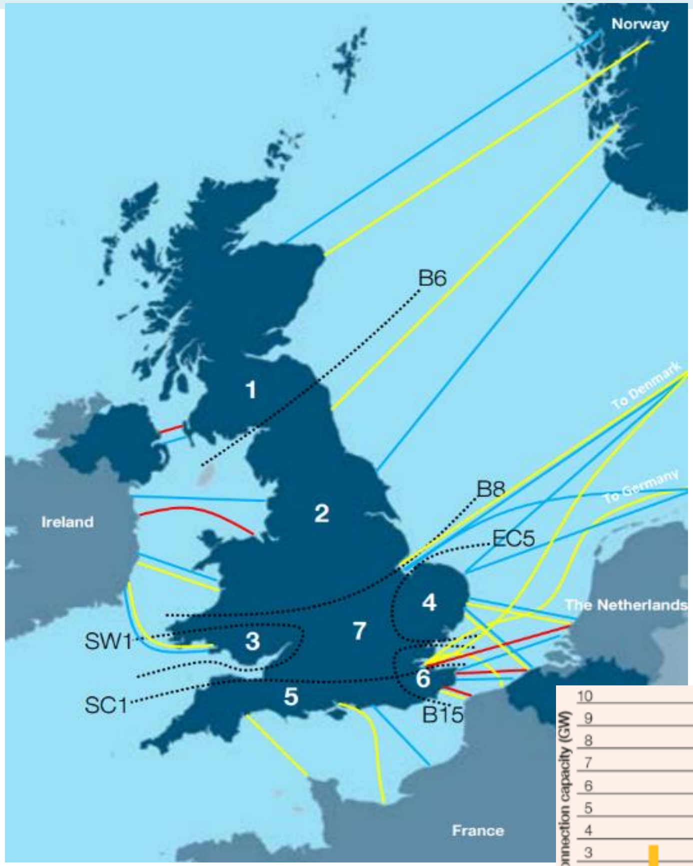
Joint Webcast

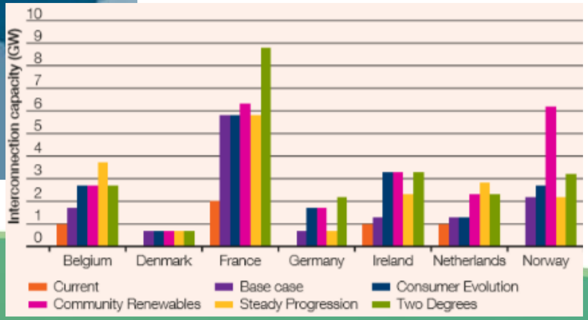
The National HVDC Centre.
&
RTDS Technologies ®.

HVDC in GB: ESO & OWIC Perspective

The National HVDC Centre

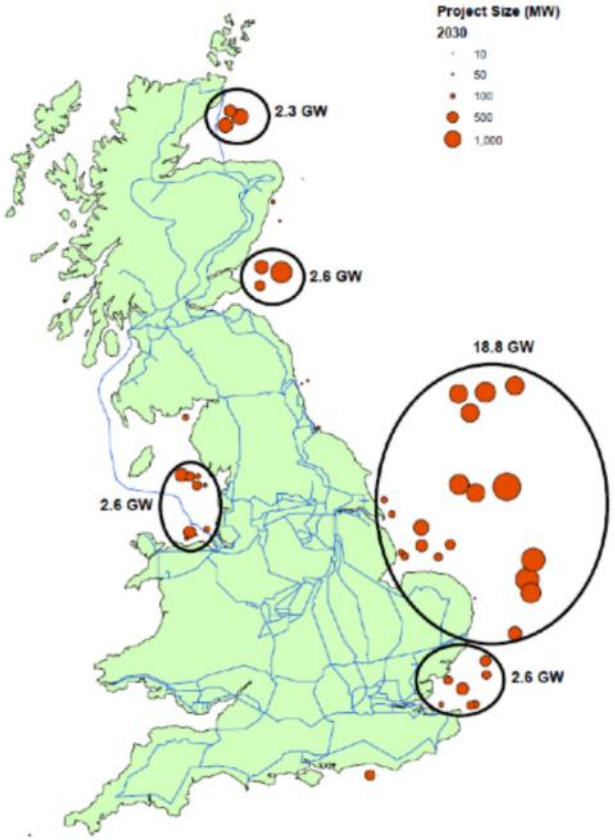
- The Electricity System Operator (ESO) is planning for significant expansion of GB HVDC interconnectors (18-23GW by 2032).





Ref: https://www.nationalgrideso.com/publications/network-options-assessment-noa

- The Offshore Wind Industry Council (OWIC) is planning for significant expansion of HVDC connected Offshore Wind (at least 30GW by 2030).



Ref: https://www.owic.org.uk/documents

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HVDC Project Life Cycle & Simulation Tools

The National HVDC Centre

- Transmission Owners, Consultants
- Bidders (Manufactures)
- RMS and EMT
- Technical Specification
- Qualification Stages

- Manufactures
- Control Design
- Protection Design
- Dynamic Performance
- Protection Coordination

- Manufactures, TO, SO
- Commissioning Tests
- Converter Performance
- System Performance
- Compliance

- Manufactures, TO, SO
- New functions
- Software upgrade
- Replica

Feasibility and options → Planning & Development → Tender / Bid → Base Design → Detailed Design → Factory system test / Factory Acceptance test → Commissioning → Operational support → Upgrade → Refurbishment

- Transmission Owners (TO), System Operators (SO) or Developers
- RMS domain Studies.
- Widely used tool in UK is DIGSILENT and PSSE.

- Transmission Owners
- Manufactures
- RMS and EMT
- Transient Stability Studies
- TOV, TRV
- Equipment design

- Manufactures
- Control and Protection implementation verification
- Dynamic Performance with Real Control System
- Protection Coordination with Real Control system

- Manufactures, TO, SO
- Investigation of incidents
- Faults, failures
- Replica, Site, offline studies

- Manufactures, TO, SO
- Control and Protection Replacement
- Valve Replacement etc
- Replica and FST, FAT

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HVDC Project Life Cycle & Simulation Tools– CM Example

The National HVDC Centre

Feasibility and options → Planning & Development → Tender / Bid → Base Design → Detailed Design → Factory system test / Factory Acceptance test → Commissioning → Operational support → Upgrade → Refurbishment

Past | Present | Future

Supplier: ABB

- RMS and EMT Qualification Stages

RTDS Technologies

- Control and Protection implementation verification
- Dynamic Performance with Real Control System
- Protection Coordination with Real Control system

PSCAD

- Control Design & Protection Design
- Dynamic Performance
- Protection Coordination

RTDS Technologies

- Commissioning Tests
- Converter Performance
- System Performance
- Compliance

PSCAD, RTDS Technologies

- New functions
- Software upgrade

RTDS Technologies

- Investigation of incidents, faults & failures

PSCAD, PSS®E

- Control and Protection Replacement
- Valve Replacement etc
- Replica and FST, FAT

Owner: SHE Transmission

- RMS domain Studies to assess requirements

PSS®E

PSS®E, PSCAD

- RMS and EMT Technical Specification

The National HVDC Centre, PSCAD, PSS®E, RTDS Technologies

- Enhanced FST
- Commissioning run through
- In-service verification & modification tracking
- Control room training

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The RTDS Environment and its Value

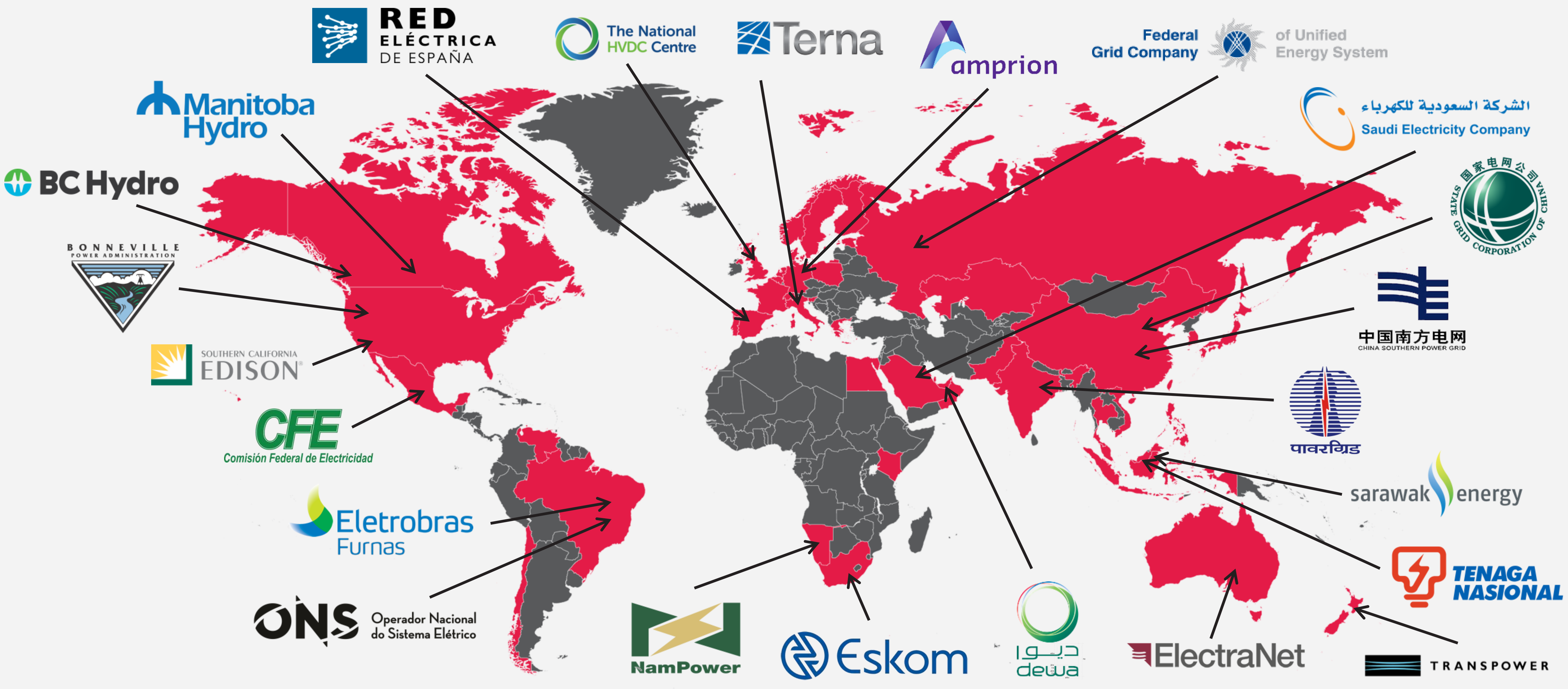
RTDS TECHNOLOGIES - THE COMPANY

- Based in Winnipeg, Canada
- ~75 employees
- World pioneer of real-time simulation and exclusive supplier of the RTDS Simulator
- Representatives in over 50 countries
- Hardware and software development, model development, customer support, sales and marketing, finance, product assembly and testing all under one roof

HISTORY OF REAL-TIME SIMULATION

- **1986**
  RTDS development project begins
- **1989**
  World's 1st real-time digital HVDC simulation
- **1993**
  1st commercial installation
- **1994**
  RTDS Technologies Inc. created

WORLDWIDE USER BASE



WORLDWIDE USER BASE

SIEMENS

GE

ABB

SEL SCHWEITZER ENGINEERING LABORATORIES

NREL NATIONAL RENEWABLE ENERGY LABORATORY

UNSW THE UNIVERSITY OF NEW SOUTH WALES

FLORIDA STATE UNIVERSITY 1851

TU Delft

MANCHESTER 1824 The University of Manchester

APPLICATION AREAS

Distribution

- Microgrid testing.
- Renewables/DERs.
- Distribution automation.
- Inverter testing.

Smart Grid

- Wide Area P&C testing.
- PMU studies.
- Cyber security.

Power Electronics

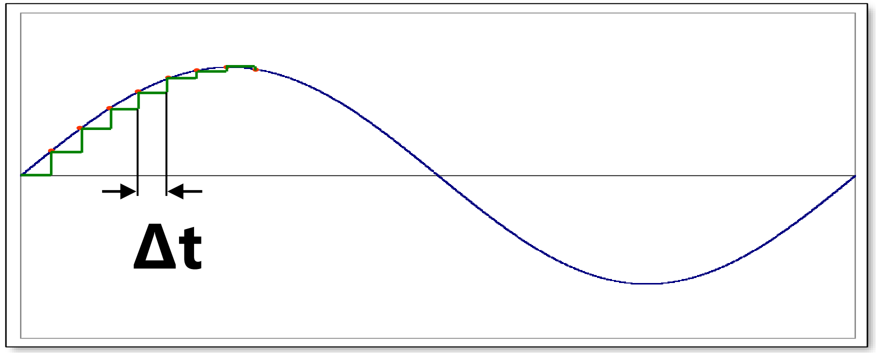
- HVDC and FACTS.
- Energy conversion.
- Drives.

Protection

- Digital substations.
- Travelling wave testing.

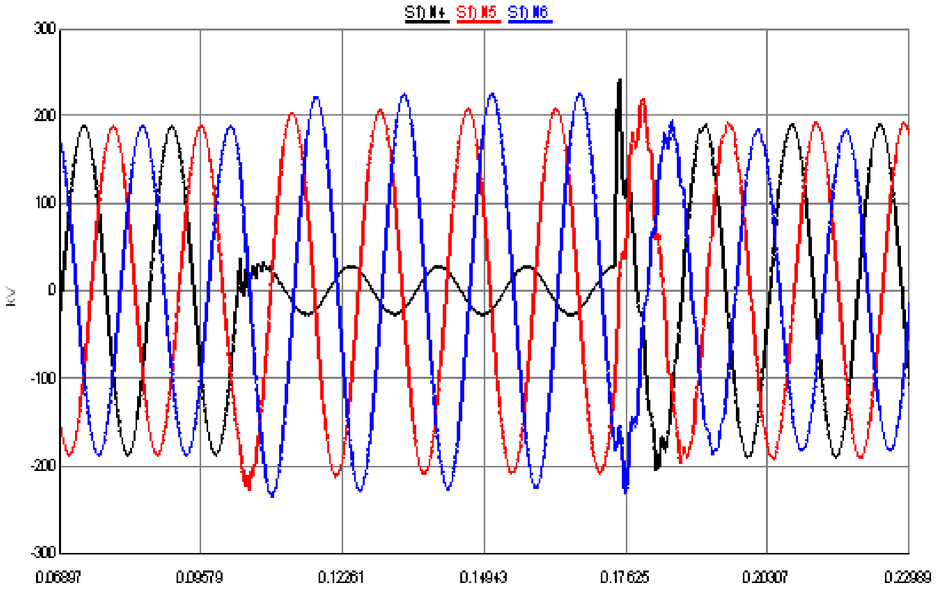
WHAT IS EMT SIMULATION?

Type of Simulation	Load Flow	Transient Stability Analysis (TSA)	Electromagnetic Transient (EMT)
Typical timestep	Single solution	~ 8 ms	~ 2 - 50 μs
Output	Magnitude and angle	Magnitude and angle	Instantaneous values
Frequency range	Nominal frequency	Nominal and off-nominal frequency	0 – 3 kHz (<15 kHz)



Dommel algorithm of nodal analysis used in RTDS, PSCAD, EMTP, etc.

ADVANTAGES OF EMT SIMULATION



- Allows for a greater depth of analysis than phasor domain (RMS) representations such as load flow or transient stability analysis
- RMS models lack the ability to capture fast network dynamics during transient conditions and often provide optimistic results [1]
- Important for systems with many power electronic converters [1]

WHAT IS REAL TIME?

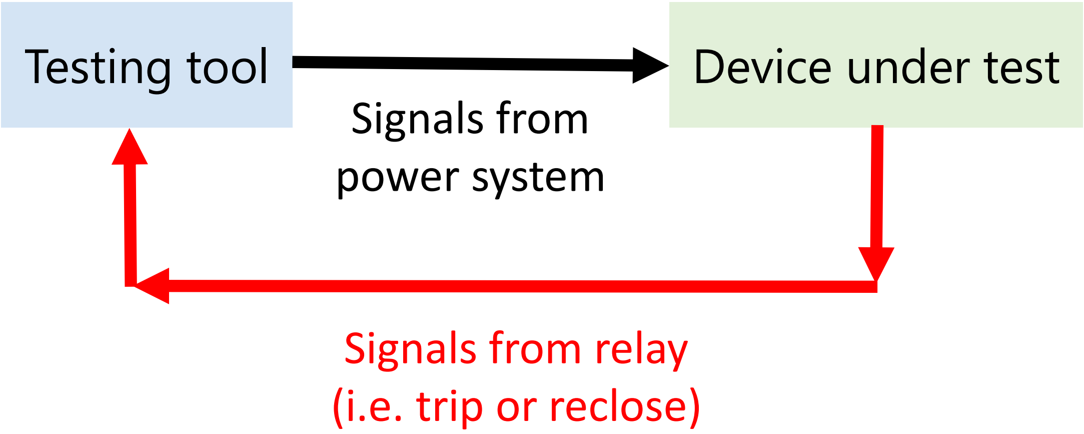
- **Real time it takes for an event to occur = Simulation time of an event.**
  - E.g. 3 cycle fault for 60Hz system = 0.05 seconds. RTDS simulates this fault in real time i.e. 0.05 seconds
  - Non-real-time simulations will simulate events faster or slower than real time depending on case complexity
- **Values updated each timestep**
  - All calculations and servicing I/O completed within a timestep.
  - Every timestep has same duration and is completed in real time
- **Requires dedicated parallel processing hardware**

ADVANTAGES OF CLOSED-LOOP TESTING

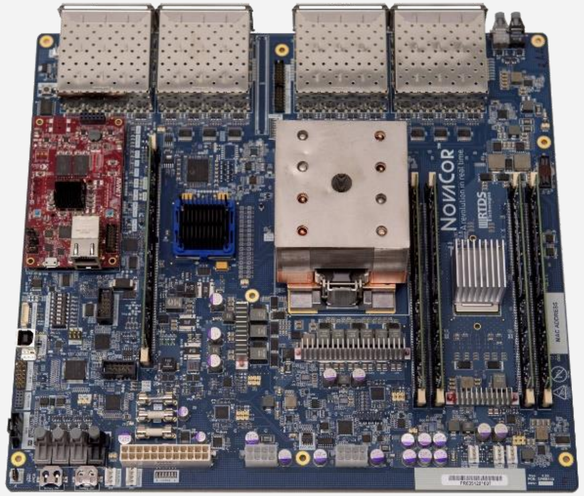
Significantly **more efficient** than offline (non real-time) simulation – save time

Real time operation is what allows us to connect physical devices in a **closed loop** with the simulated environment

- Test continues after the action of the protection/control device, showing dynamic response of the system
- Test multiple devices (and entire schemes) at once
- Much more detailed system representation than open-loop test systems provide (e.g. modelling power electronics)
- No need to bring equipment out of service

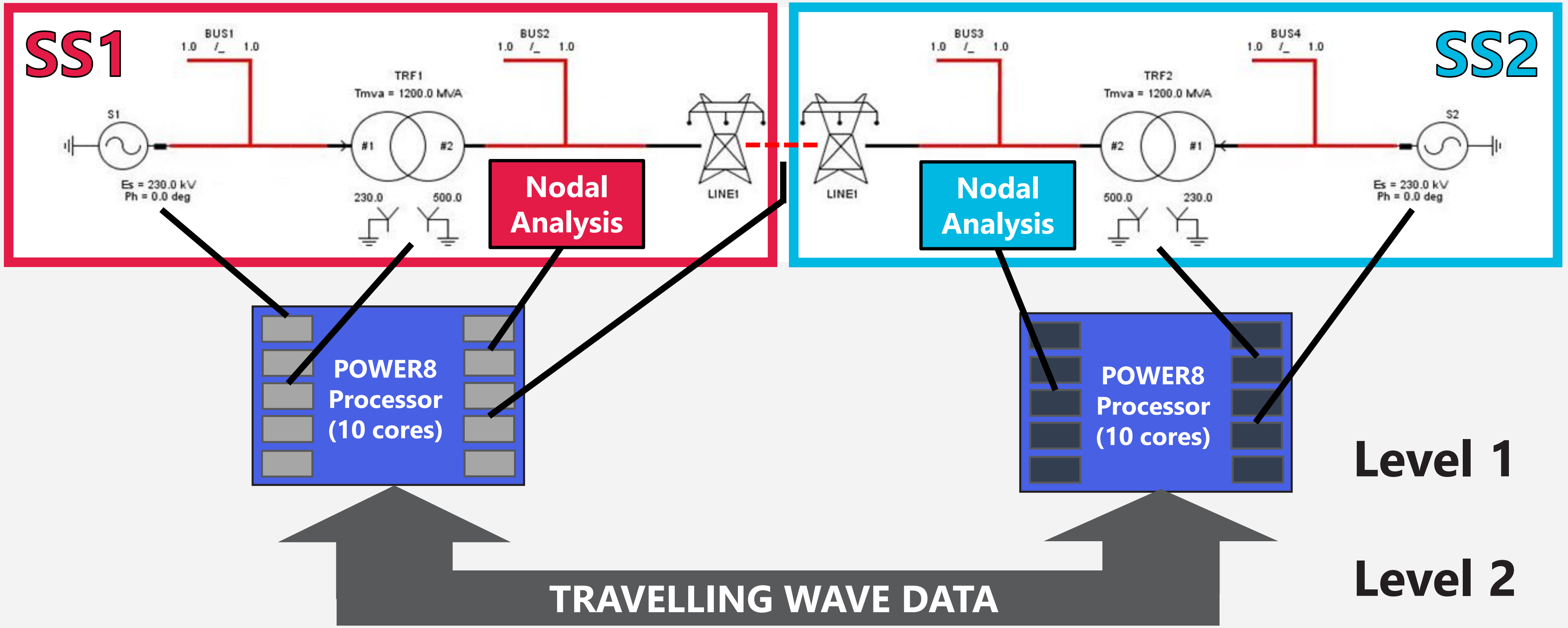


MAINTAINING REAL TIME: HARDWARE



- Parallel processing platform based on a IBM™'s POWER8® multicore processor
- Custom integrated, runs bare-metal (no OS)
- Modular design
- Main interface is through user-friendly software
- Ample I/O to connect physical devices

PARALLEL PROCESSING ON TWO LEVELS

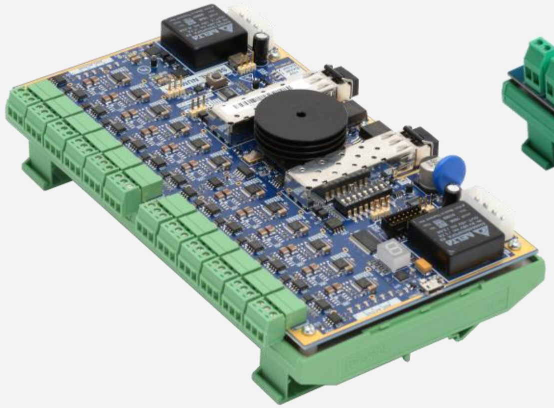


INTERFACING EXTERNAL EQUIPMENT: I/O

Modular digital and analogue I/O cards

- 12 channel, isolated 16-bit analogue input/output cards
- 64 channel, isolated digital input/output cards

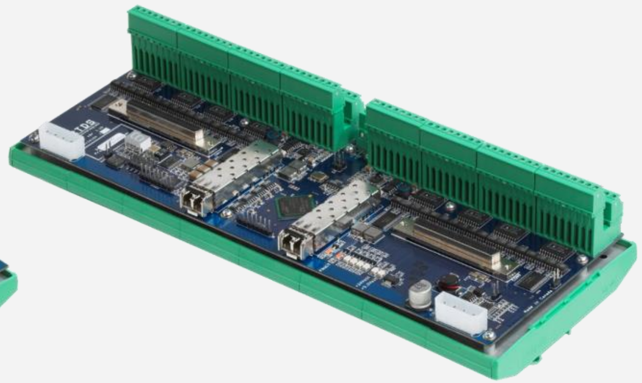
GTAI



GTAO

GTDI

GTDO



INTERFACING EXTERNAL EQUIPMENT: I/O

Network Interface Card

- Communication with external devices over Ethernet.
- Card has two "modules" and can have two network protocols operating simultaneously.

IEC 61850

GOOSE Messaging
IEC 61850-9-2LE, IEC 61869-9

SCADA

DNP3 and IEC 60870-5-104

Large data playback

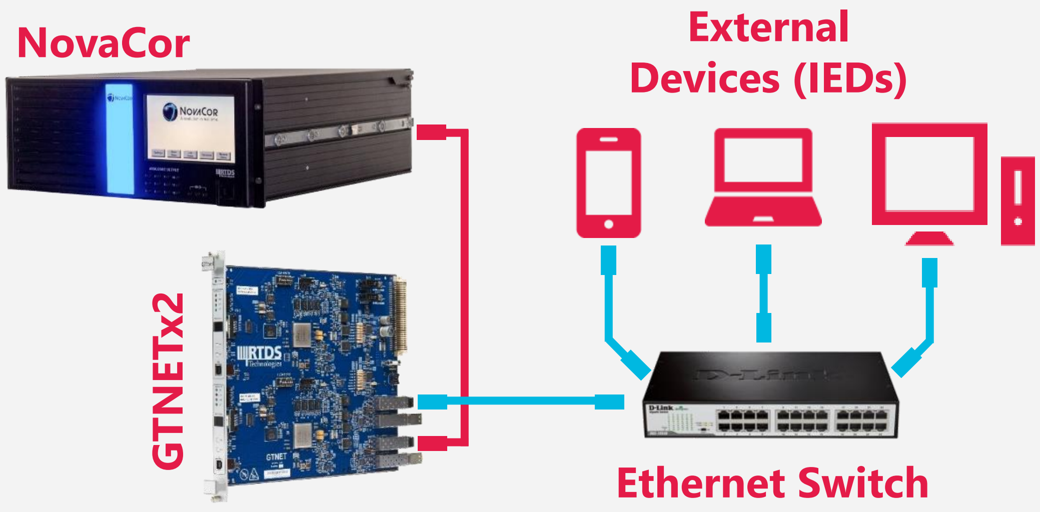
PMU

IEEE C37.118

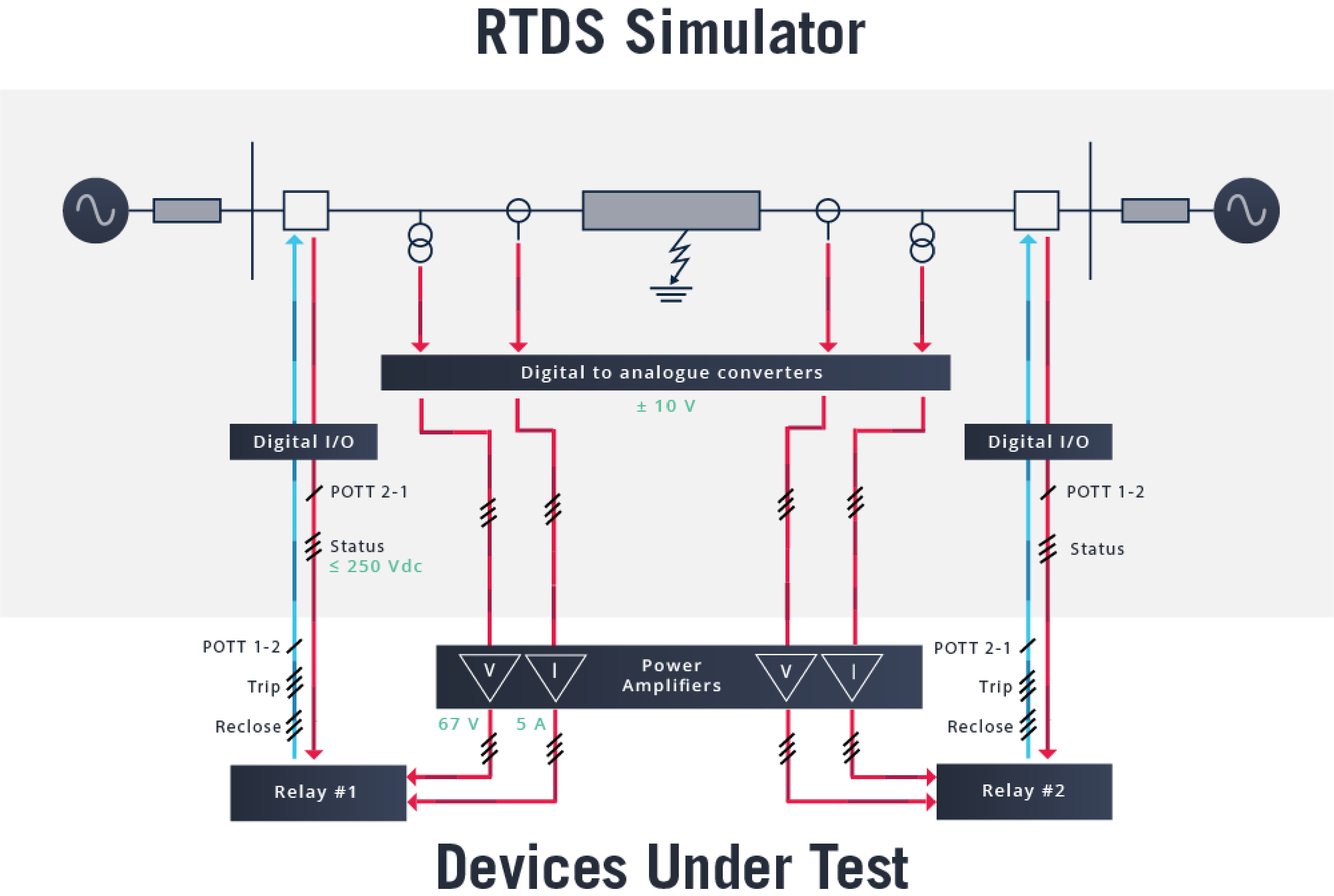
MODBUS

TCP, RTU over TCP,
ASCII over TCP

Generic TCP/UDP Sockets

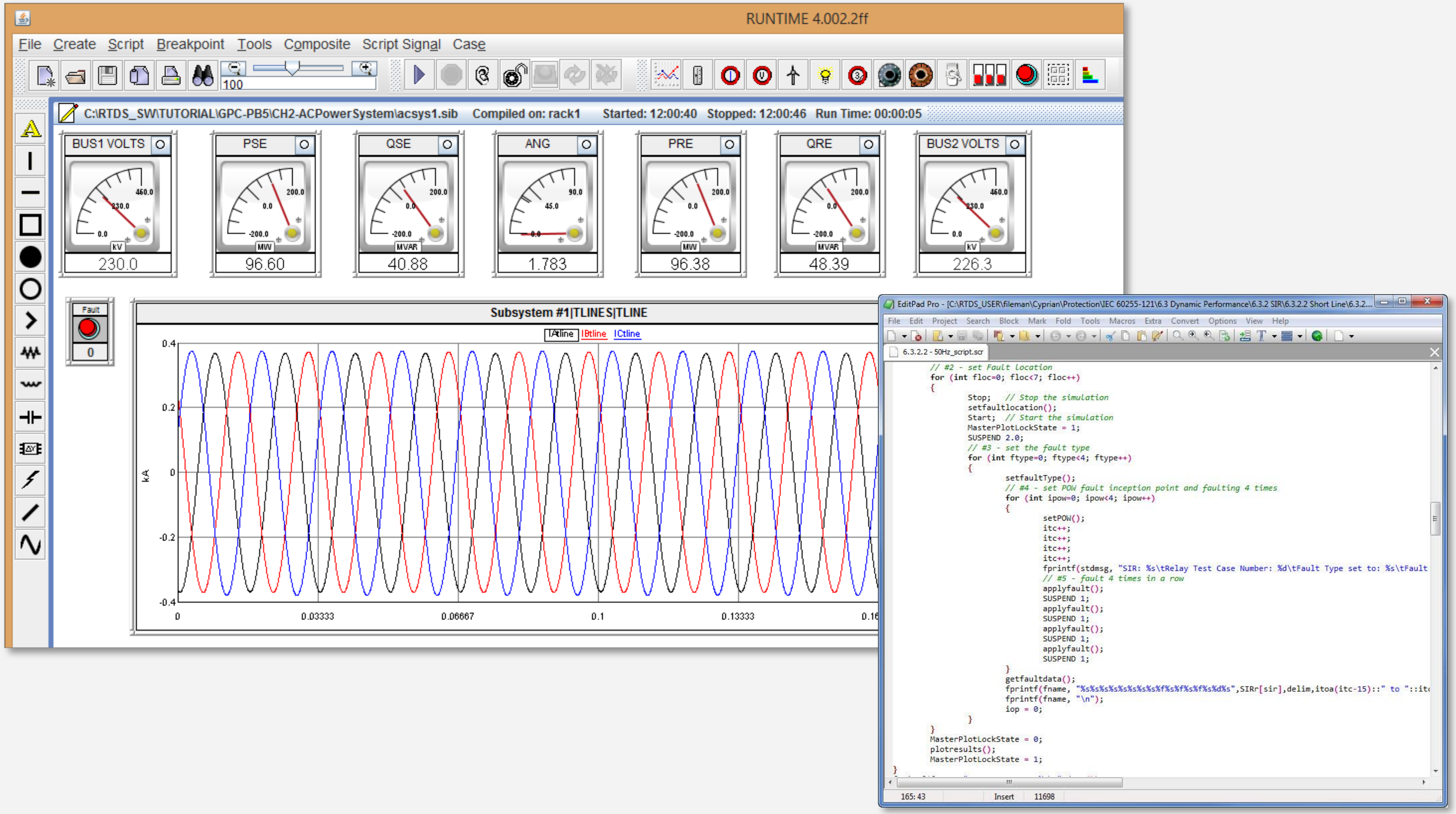


CLOSED-LOOP PROTECTION TESTING



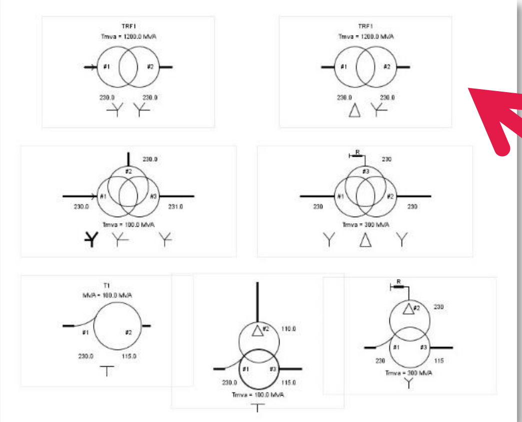
REAL-TIME SIMULATION SOFTWARE: RSCAD®

- Real-time performance provides ability to operate the simulated power system interactively
- Simulator control
- Monitoring
- Data acquisition
- **Scripting for automated batch mode testing**



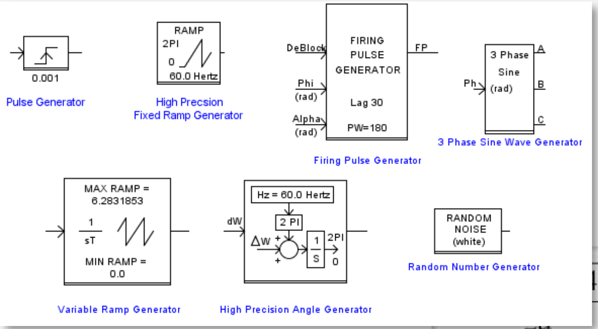
COMPONENT LIBRARIES

- Large established library, plus CBuilder module for creating custom, user-written components



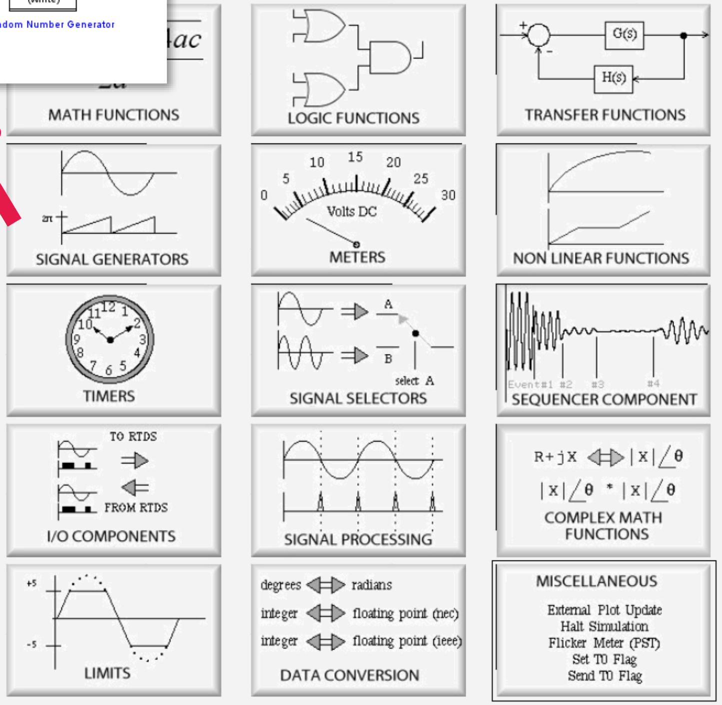
Transformer Models

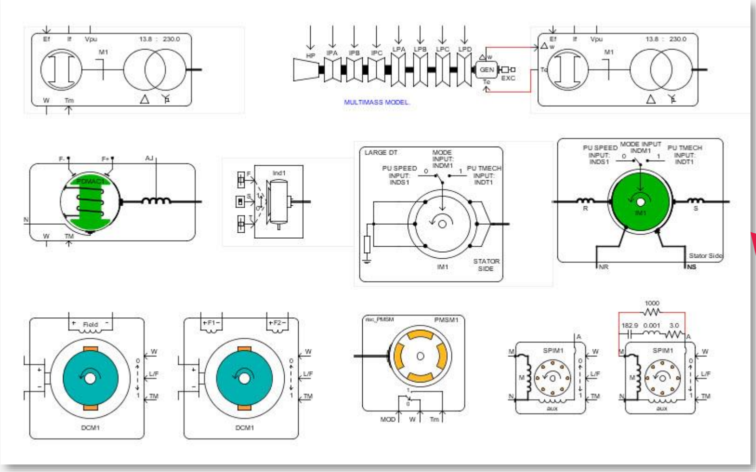
Fault and Breaker Models



Valve Group and SVC Models

RLC Components



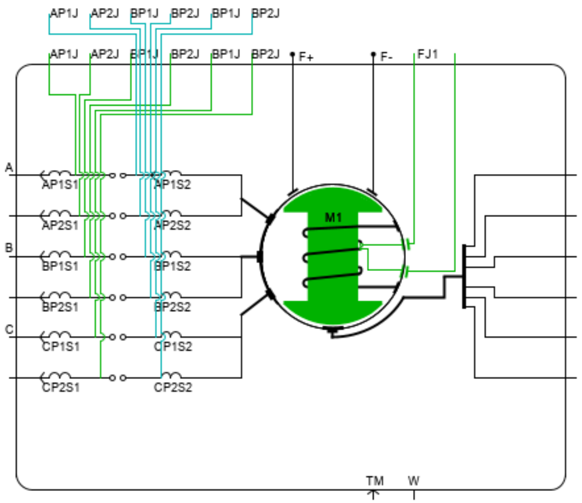


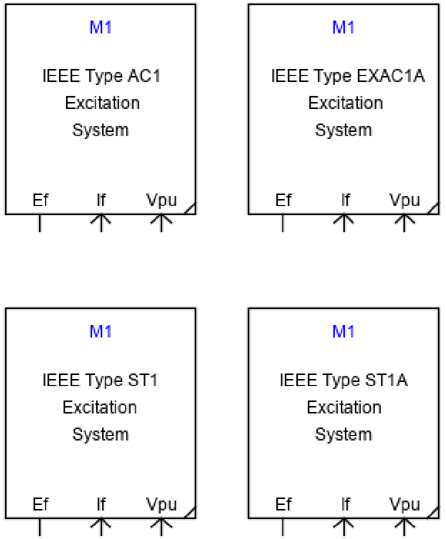
Machine Models

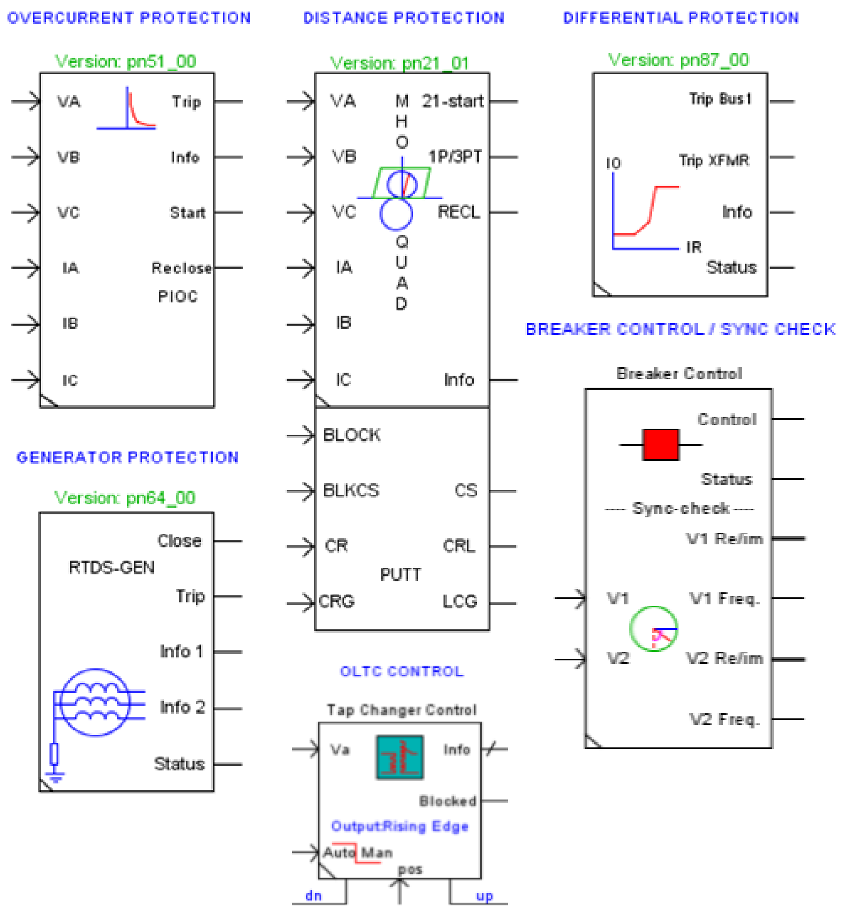
Transmission Line and Cable Models

COMPONENT LIBRARIES

- Industry leading power systems models:
  - Faulted phase domain synchronous machine
  - Faulted terminal-duality transformer
  - Small timestep frequency-dependent T-line
- Various protection and automation models based on standards (IEEE, IEC, etc.)
- IEEE generator control block models

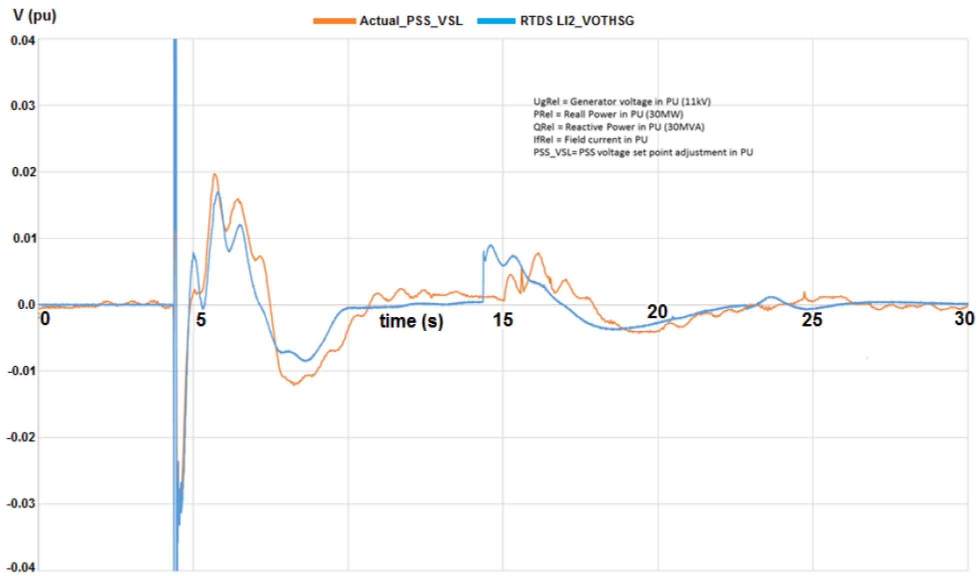




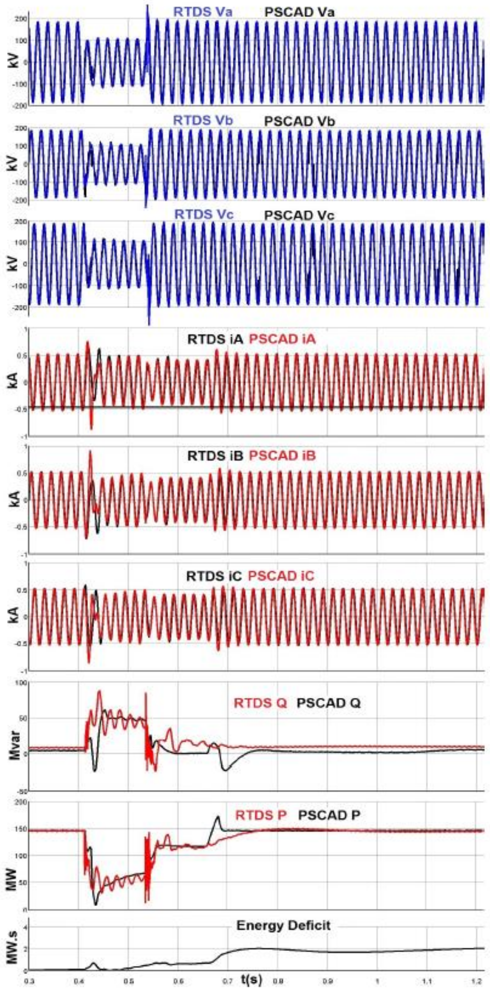


MODEL VALIDATION/BENCHMARKING

- **In-house**
  - Offline EMT programs
  - Transient stability and load flow
  - Benchmark cases (CIGRE, IEEE)
- **Independent customer validation**
- **Power system measurements**

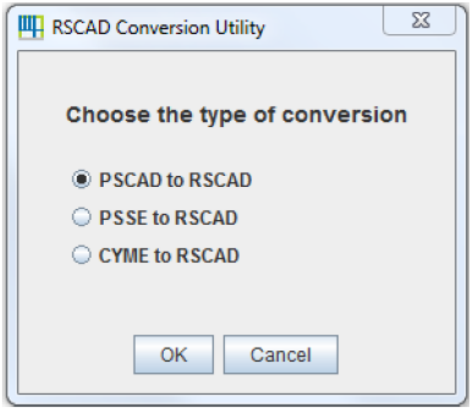


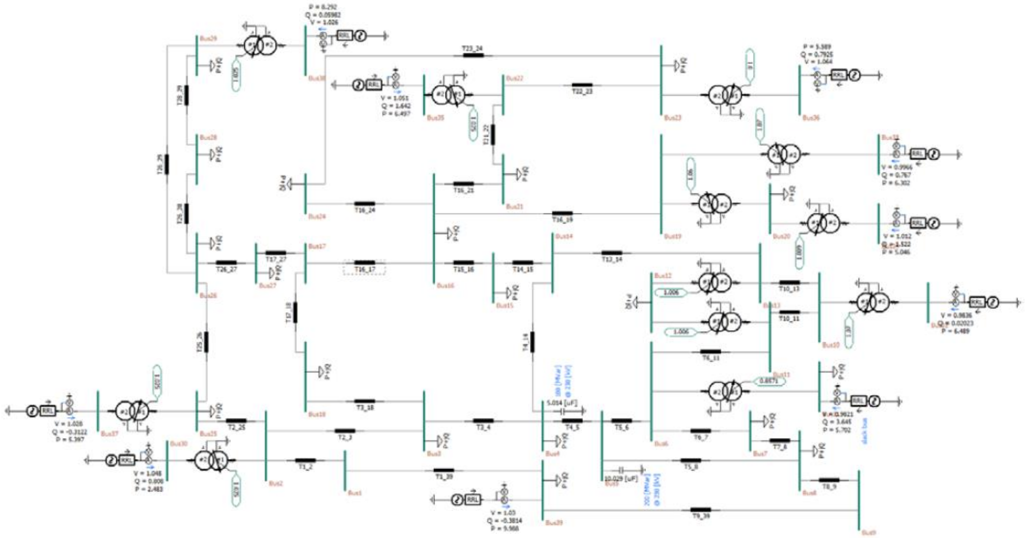
Source: [2]

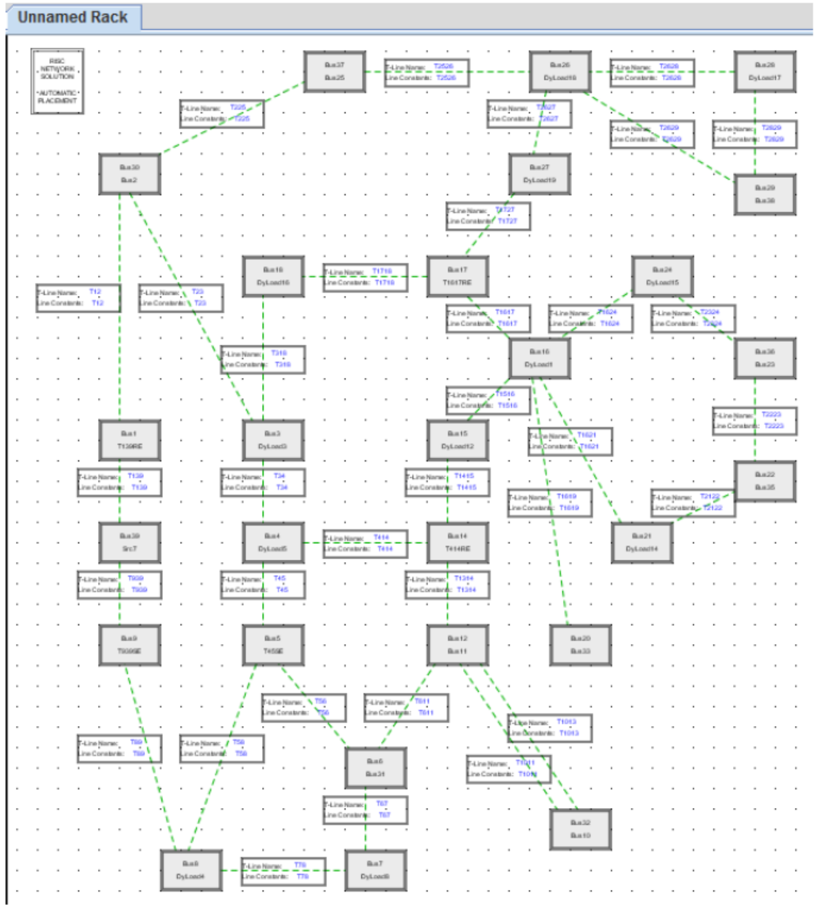


BRINGING OFFLINE MODELS INTO REAL TIME

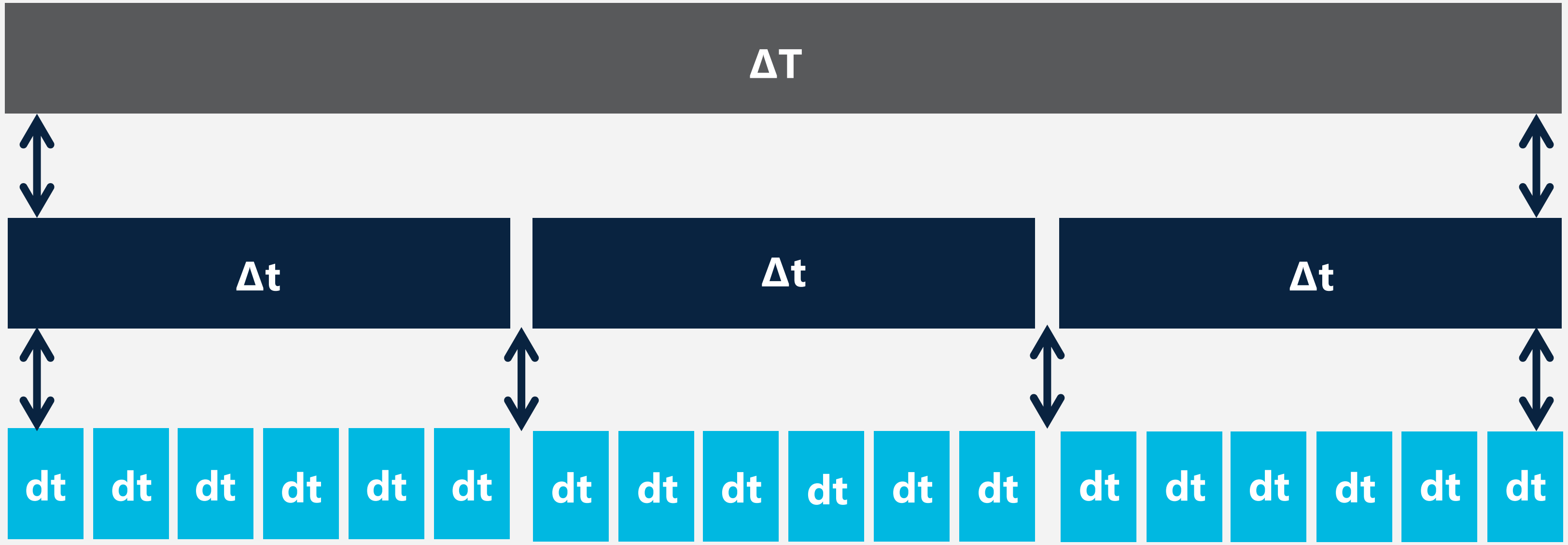
PSCAD to RSCAD Conversion Tool







MULTI-RATE SIMULATION



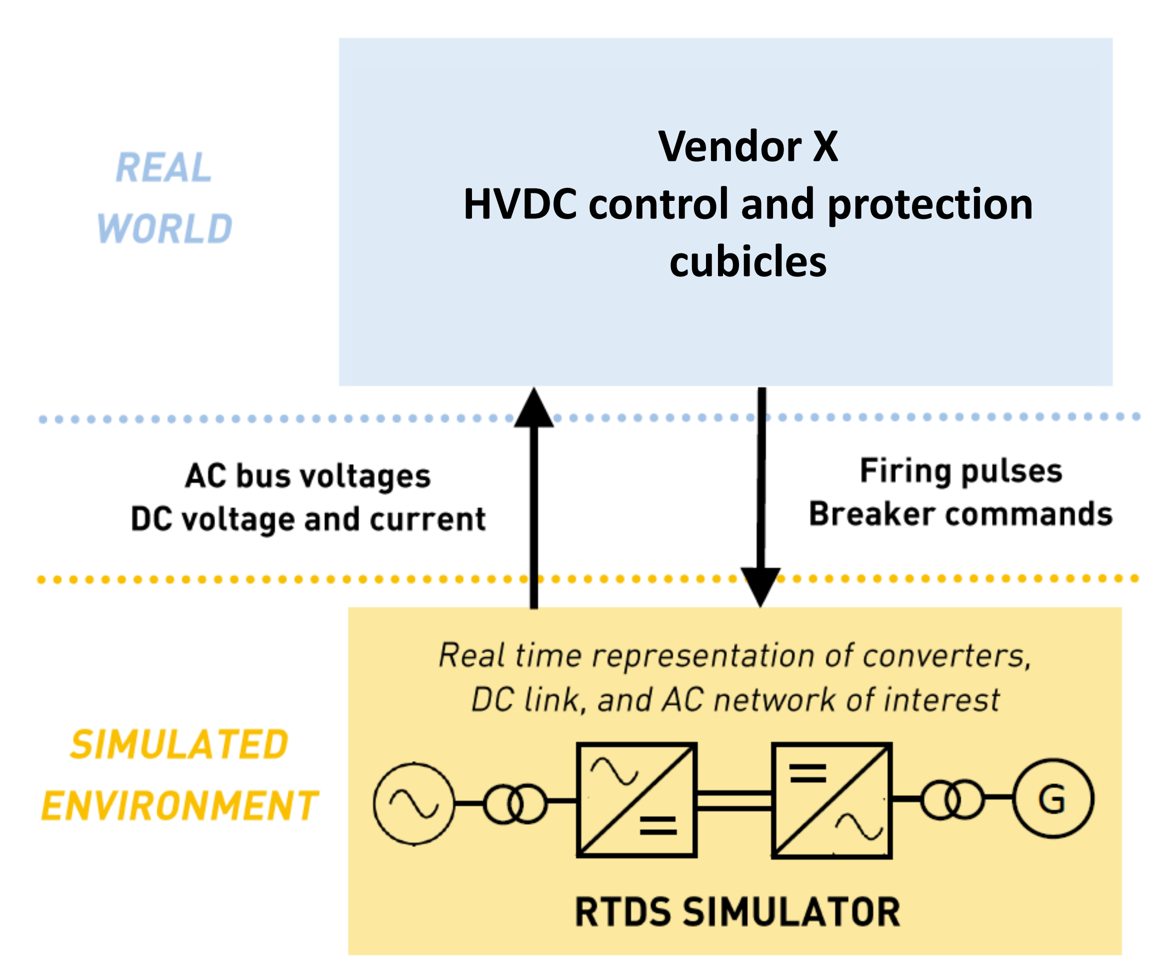
Superstep
$\Delta T = N \times \Delta t$

Mainstep
Δt

Substep
$dt = \Delta t \div n$

FACTORY ACCEPTANCE TESTING (FAT)

- Used by all manufacturers of HVDC for FAT
- Vendor builds up a model of their scheme and equivalent of the network where the scheme will be installed
- Tests include standard operating scenarios (start up, shut down, etc.) and performance tests for various contingency scenarios
- Simulations run for hours or days for comprehensive testing



REPLICA SIMULATORS

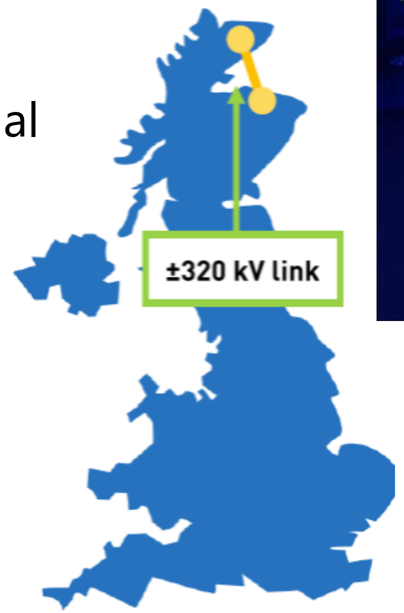
- Assist during commissioning.
- Investigate proposed network changes.
- Investigate proposed control modifications.
- Test scheme upgrades and refurbishment.
- Train personnel on scheme theory and operation.

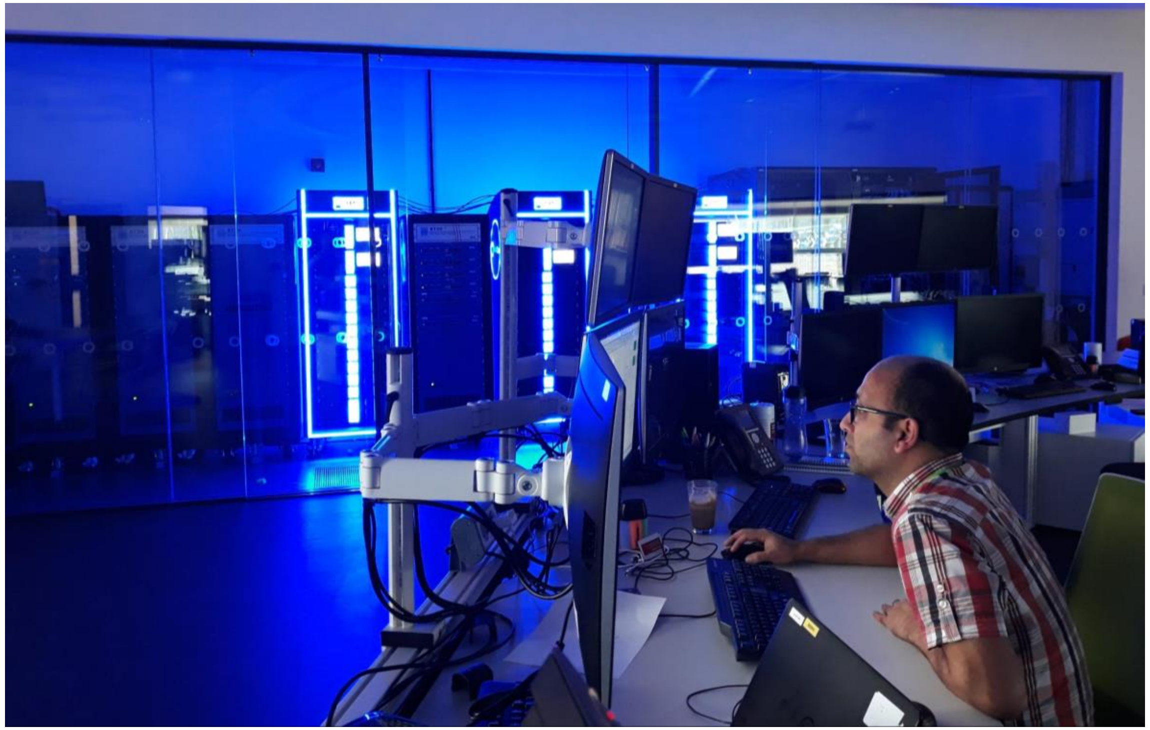
Furnas (Brazil)
TNB (Malaysia)
CSG (China)
SEPC (China)
ESKOM (South Africa)
SEC (Saudi Arabia)
Power Grid (India)
Powerlink (Australia)
REE (Spain)
Equinor (Norway)

DEWA (UAE)
ONS (Brazil)
NamPower (Namibia)
RTE (France)
BPA (USA)
Manitoba Hydro (Canada)
Transpower (New Zealand)
SHE Transmission (UK)
Zhejiang EPRI (China)
Amprion (Germany)

THE NATIONAL HVDC CENTRE

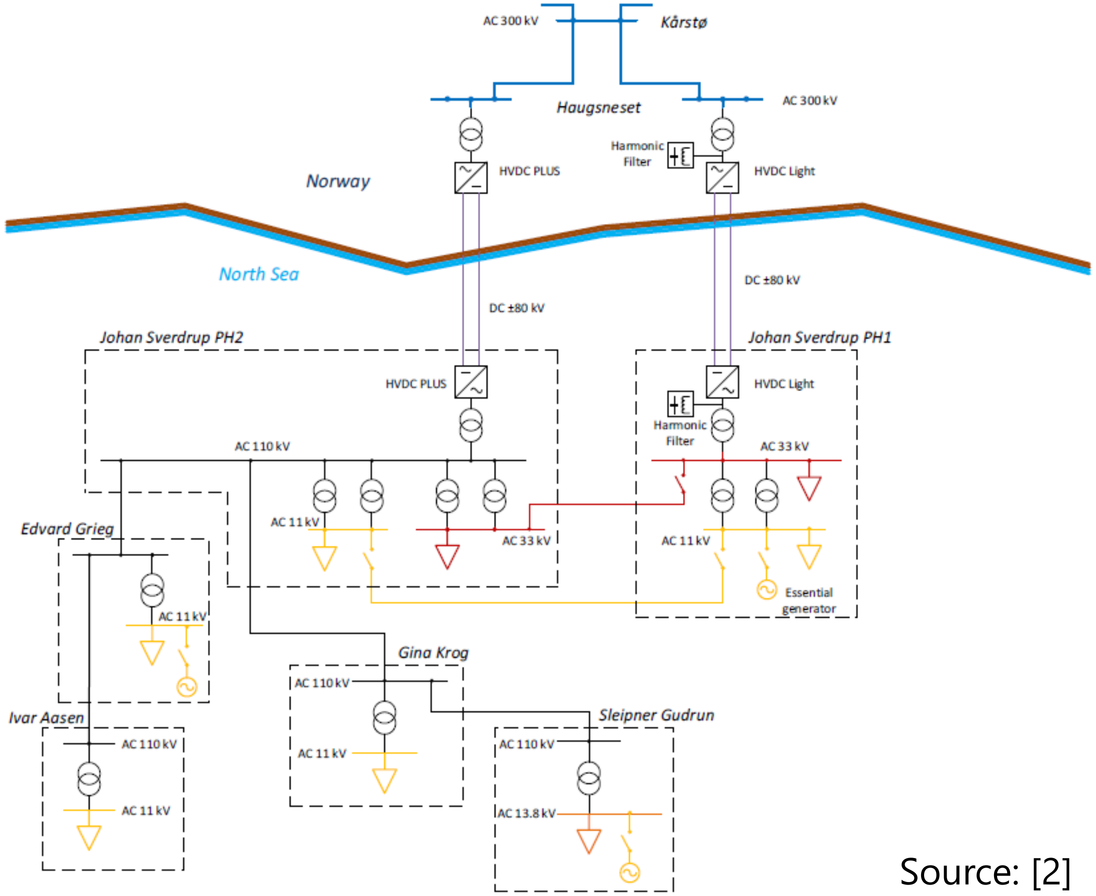
- First ever NovaCor installation worldwide (6 chassis, 3 racks)
- Vendor-supplied HVDC replica controls
- Caithness-Moray link – HIL testing addressed technical challenges and ensured timely delivery
- First project designed for multi-terminal operation in Europe





USE CASE: EQUINOR HVDC PROJECT

- Offshore platform connected to Norwegian onshore grid via two HVDC links
- 2-level VSC link supplied by ABB and MMC-VDC link by Siemens
- HIL testing of C&P cubicles identified as necessary [3]
  - HVDC manufacturers do not have access to full offline model of the system
  - Slower-acting C&P are not included in offline models due to time restrictions
  - Global controller to coordinate two links not available for inclusion in offline model



Source: [2]

OTHER NOTABLE HVDC PROJECTS

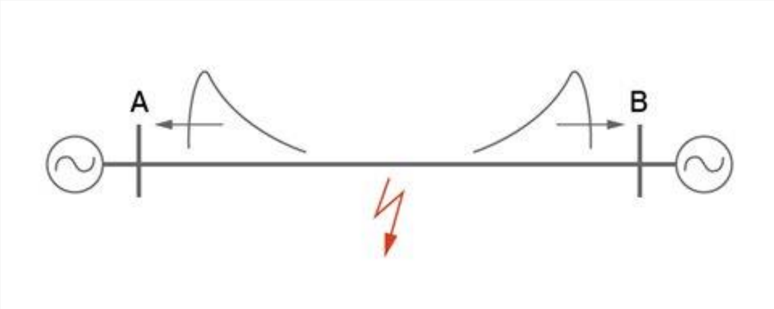
ONS (Brazil)

- At time of testing, Rio Madeira link was longest in the world (2,375 km)
- Multi-vendor controls from NARI Relays, ABB, Siemens, GE/Alstom
- Belo Monte link is 2 bipoles with multi-vendor control plus a master controller

USE CASE: TRAVELLING WAVE PROTECTION

Public Service Company of New Mexico

- Division of line resulted in ~150% overcompensation– issues for existing impedance-based protection schemes
- SEL Engineering Services proposed new travelling wave-based protection
    - Technology currently used for fault location
    - Increased accuracy
    - Faster tripping – improved stability, safety, reduced equipment damage
    - Secure protection for compensated lines



Source: [4]

USE CASE: TRAVELLING WAVE PROTECTION

- Original plan to use current differential for main protection and T400L for monitoring
- Factory Acceptance Testing at SEL with the RTDS Simulator

SEL-T400L and SEL-411L relays ⟷ RTDS Simulator

USE CASE: TRAVELLING WAVE PROTECTION

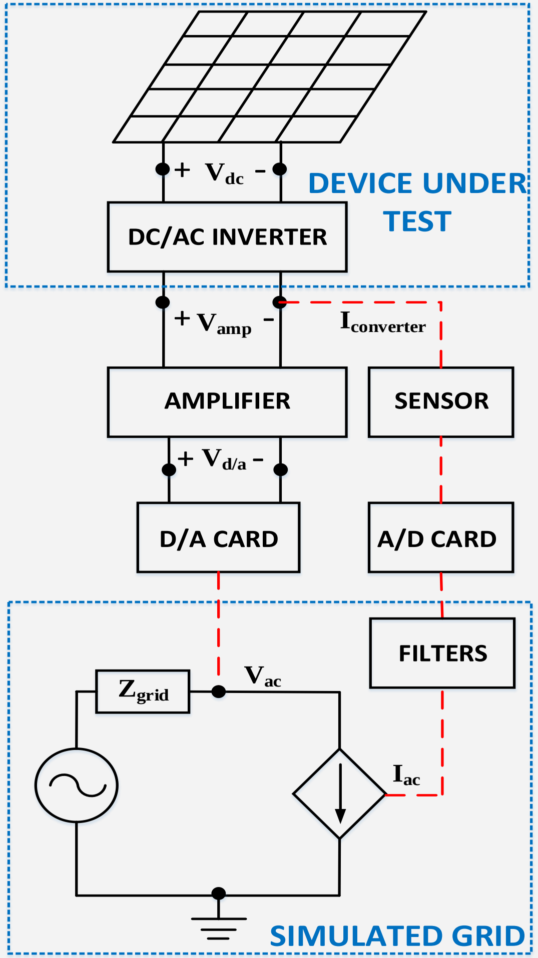
- HIL testing revealed 600 microsecond operation time for a midline single-phase fault
- Traveling wave fault locator reported the fault location to within 0.02 miles on a 33.1 mile line
- First utility in the world to deploy traveling-wave based protection with live tripping to CBs [3]

T400L relays installed in the substation

Source: [4]

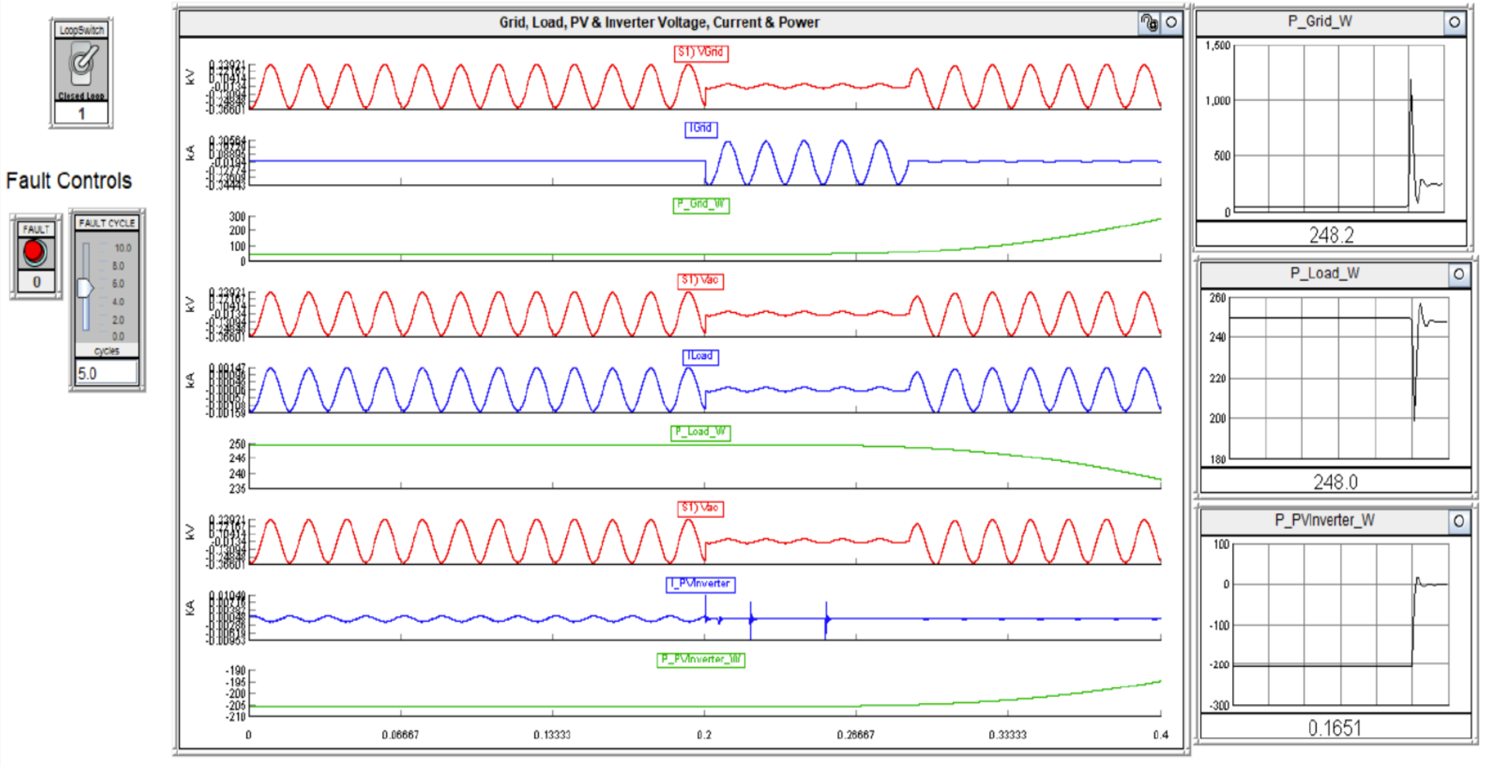
POWER HARDWARE IN THE LOOP (PHIL)

- Simulated environment exchanges power with renewable energy hardware, motors, batteries, loads, etc.



USE CASE: PHIL

- Characterize inverter behaviour
- Investigate the impacts of inverter behaviour on other protection and control systems



USE CASE: LARGE-SCALE SIMULATION

- Large RTDS user base in China, including the two largest real-time simulators in the world

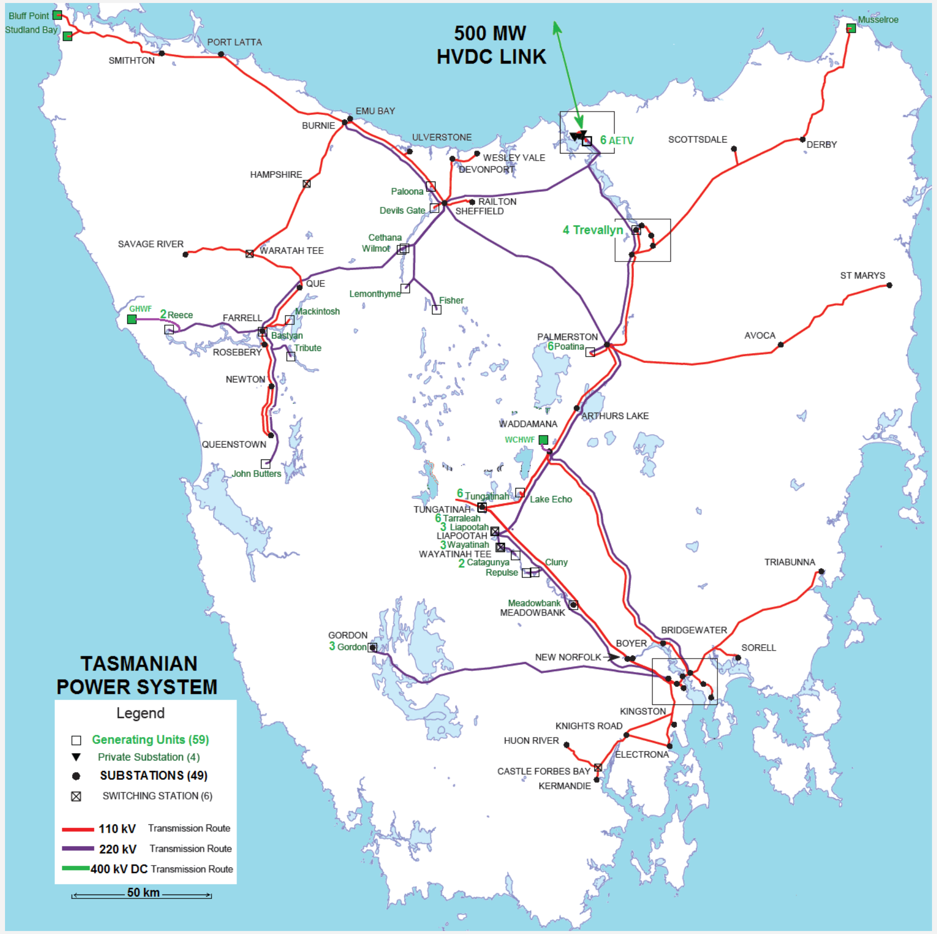
NARI/SGEPRI

- Can simulate >3600 three-phase buses and 20 HVDC links
- Validate wide area protection and control schemes, AC and multiple HVDC coordination, system stability control

USE CASE: LARGE-SCALE SIMULATION

TasNetworks

- All 110/220 kV lines modelled plus 500 kV lines on Victoria side
- Modelling existing LCC-HVDC interconnections to mainland Australia and 2 future MMC-HVDC links
- Over 2000 MW of wind power, 1000 MW pumped storage



Thank you!

References

[1] B. Badrzadeh, Z. Emin, February 2020. The need for enhanced power system modelling techniques and simulation tools. CIGRE ELECTRA No. 308.

[2] M. Davies, October 2019. Preparing for the Future Power System – Now. Presentation, RTDS Technologies Australian UGM.

[3] M. Barnes, March 2020. John Sverdrup Control and Protection Progress. VSC-HVDC Newsletter, Vol. 8 Issue 03.

[4] Schweitzer Engineering Laboratories 2019, The Modernization Story of PNM, accessed May 17 2019, <https://selinc.com/featured-stories/pnm/>.

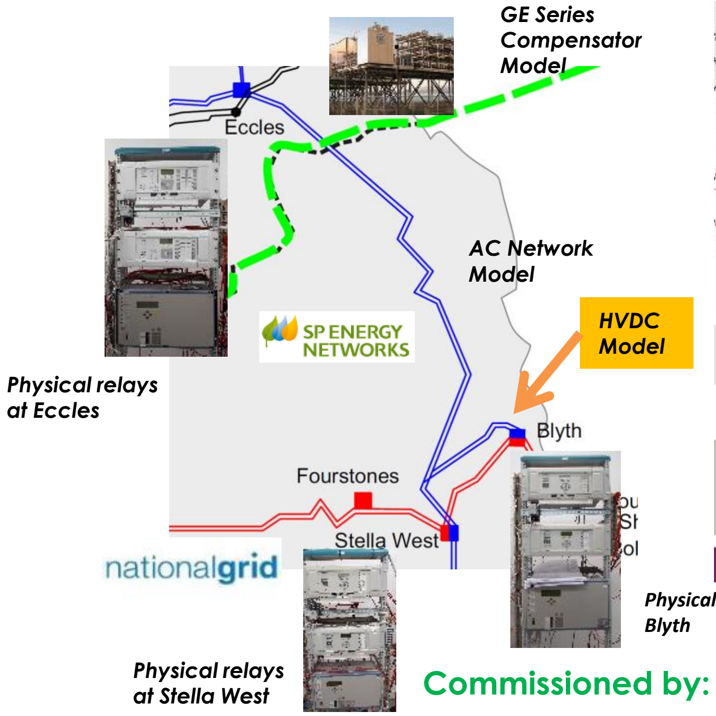
RTDS Technologies

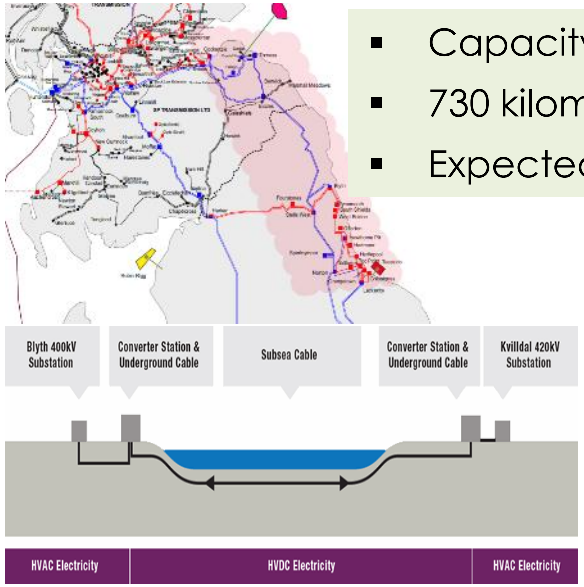
Further Applications of RTDS at The National HVDC Centre

Practical Use cases of RTS

❑ Impact of HVDC Link on AC Grid Protection Performance

NGET and SPEN commissioned the HVDC Centre to test & validate AC protection performance and co-ordination testing for a new HVDC interconnector to ensure the security and resilience of the GB electricity network.





Source: http://northsealink.com/

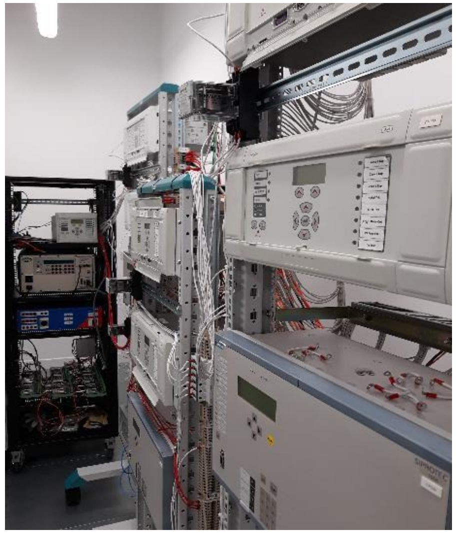
Commissioned by: nationalgrid & SP ENERGY NETWORKS

- Capacity to transmit 1,400 MW of power at DC voltage ±525kV
- 730 kilometre link will be the world's longest subsea power interconnection
- Expected to enter commercial operation in 2021.

The protection study has increased our understanding of the:

- Potential risks associated with AC protection in the presence of HVDC links & FACTs
- Practicalities of implementing multivendor protection system testing within GB Network
- Differences between modelled and actual protection behaviour.

Overview of Eccles-Blyth-Stella West 400kV Protection Performance Studies

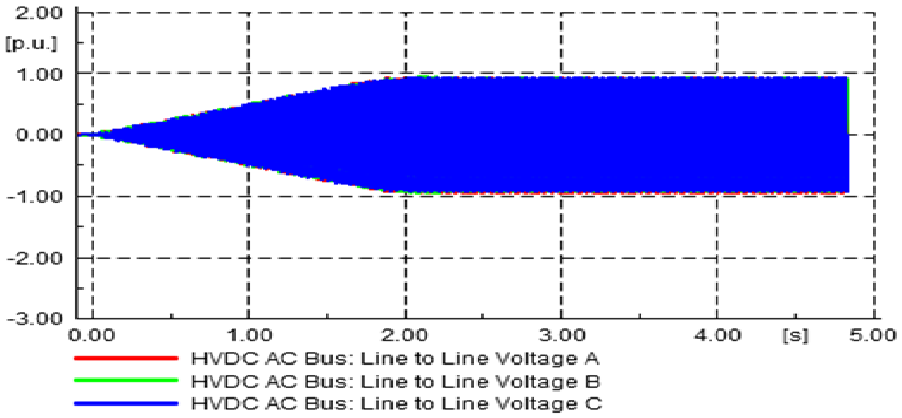


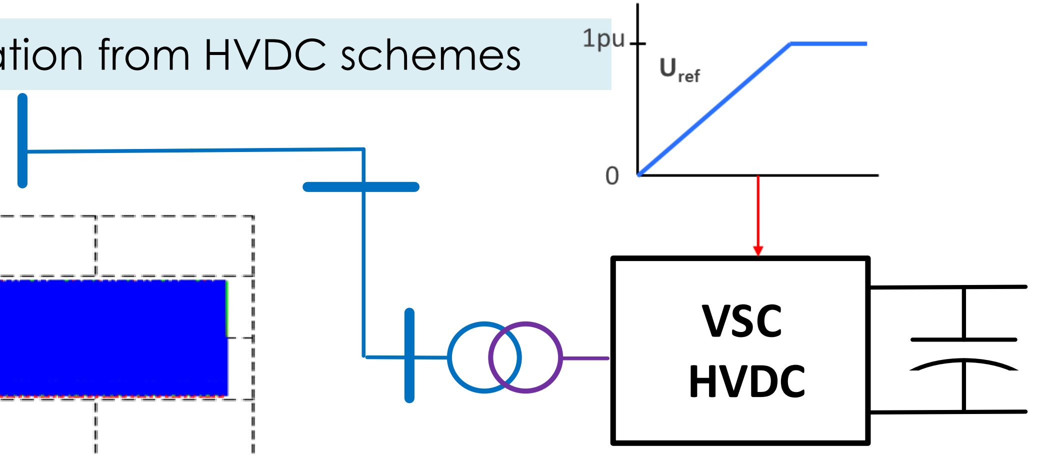
A test setup with Physical relays at our centre

Practical Use cases of RTS

❑ Grid energisation from HVDC schemes (EPRI Project)

❑ Coordination of AC network protection settings during grid energization from HVDC schemes





1,400 MW
±525kV DC voltage

Recommendations for:

- Protection settings, algorithms and relay configuration
- How to mitigate low grid strength issues during black-start/restoration
- Control system design considerations for design of the VSC HVDC incorporating black-start capability

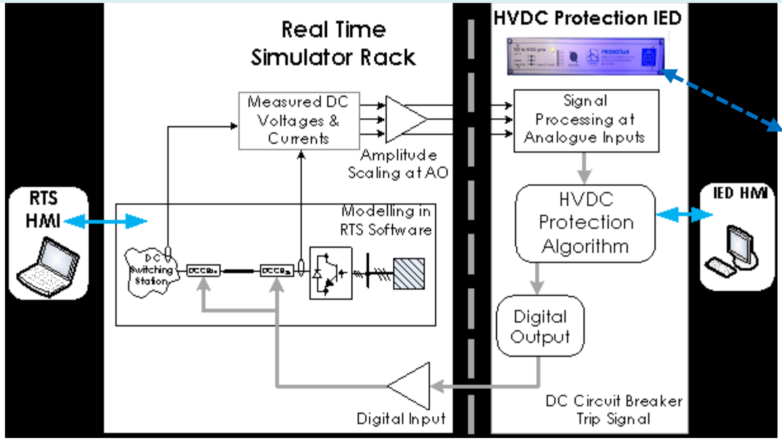
To ensure the ***security and resilience*** of the GB electricity network as more HVDC links are connected

Practical Use cases of RTS

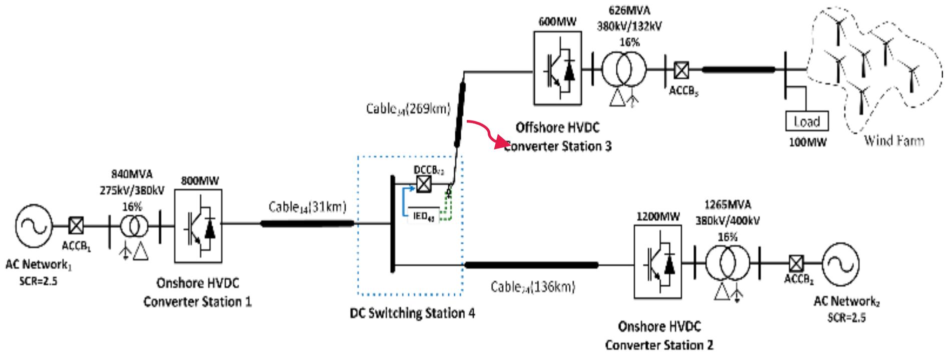
❑ DC Grid Protection Demonstration (PROMOTioN WP9)

This project has received funding from the European Union's Horizon 2020 programme.

- Hardware-in-the-loop testing & guidelines for non-selective protection systems demonstration
- Demonstration of selective protection systems interoperability and primary and back-up protection

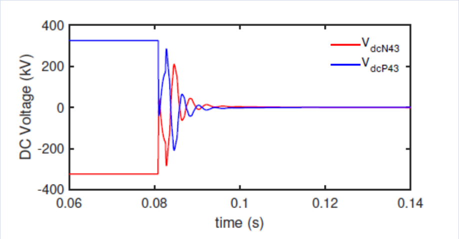
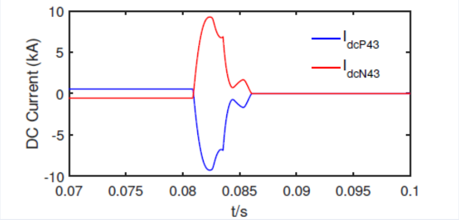


MELCO IED



Real time Simulation Test Setup & Schematic Diagram

Example Time Domain Result

DC Voltage	
DC Current	
Notes	Measurements at IED location Hybrid DCCB Mid-cable pole-to-pole fault

- Combined with the protection schemes and hardware prototypes has been integrated into a realistic radial multi-terminal HVDC system to test different protection scheme
- A mesh grid DC protection will be demonstrated
- To allow overall system performance pole re-balancing and post-fault recovery sequences will be considered

The National HVDC Centre

PROMOTioN PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

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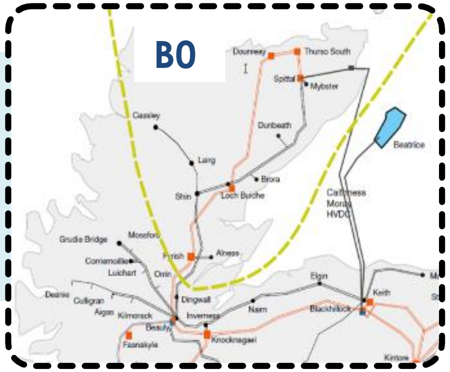
Practical Use cases of RTS

The National HVDC Centre

❑ Caithness-Moray (CM) HVDC Link

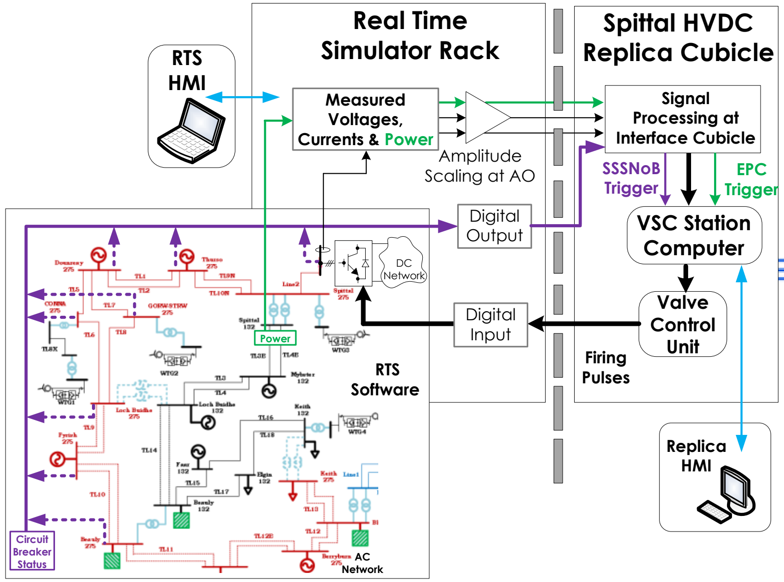
- ✓ CM HVDC link increased B0 boundary capability.
- ✓ HVAC option was slightly more expensive and had a number consenting issues.
- ✓ Weak AC network in Spittal & Embedded HVDC with parallel HVAC circuits sets operational challenges
- ✓ Symmetrical monopole configuration with standard AC transformer use & operation during temporary faults.

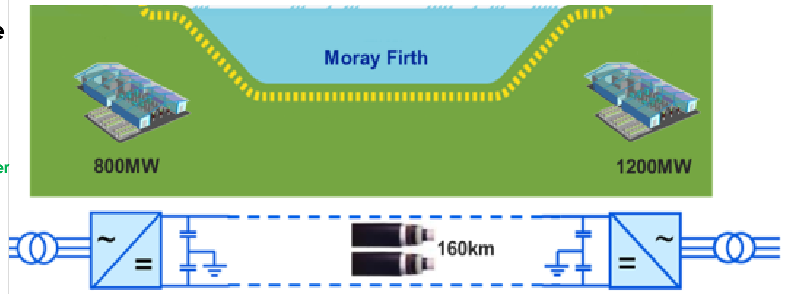


National Grid Electricity Ten Year Statement 2018

❑ Used HVDC Replica Control & Protection Systems with RTS to:

- o De-risk GB customers' investment in HVDC
- o Run additional FST
- o Provide training for engineers
- o Diagnose HVDC operating issues
- o Develop future solutions
- o Test software upgrades, or system changes
- o Test extensions to HVDC Schemes
- o Test changes to the network
- o Long-term model





Configuration of Caithness-Moray HVDC Link

Simplified Diagram showing signal transmission between RTS & Replicas

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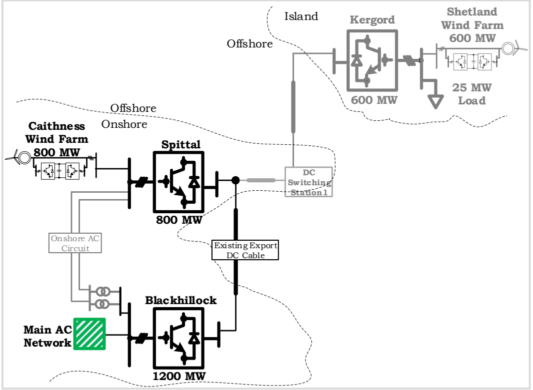
Future Use of RTS with HVDC Replicas

The National HVDC Centre

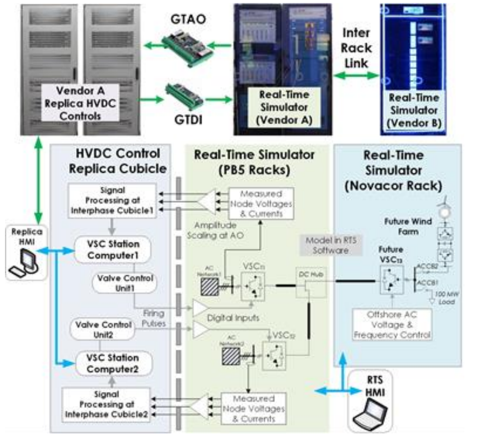
❑ Shetland HVDC Multi-terminal Extension

- De-risk multi-terminal VSC-HVDC system design, extension & operation;
- Support DPS, factory system tests, commissioning & in-service operation.



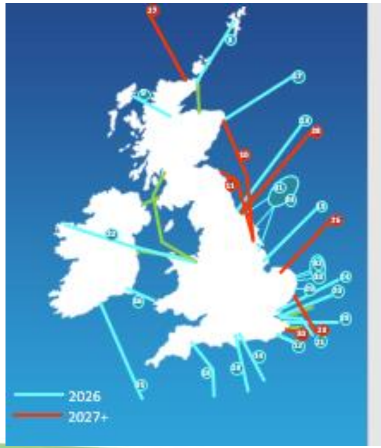
❑ Analysis of Multi-Vendor HVDC Options

- Use RTS with two hardware HVDC replicas for integration of an open-source converter model;
- Assess technical feasibility, control requirements & system testing options.



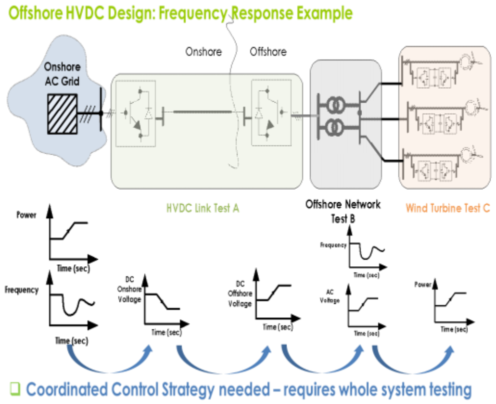
❑ New Replica Projects

- A variety of new and existing connections of Interconnectors and FACTS devices are engaged with Centre;
- Host replica, pre-commissioning tests & in-service support



❑ Composite Testing Project

- Investigate composite interactions & compliance testing of combined solutions;
- Develop RTS with Re-configurable replica concept with OEMs



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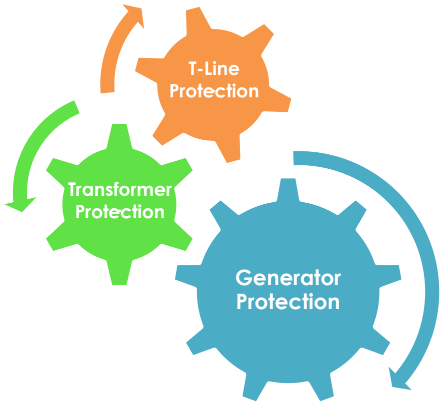
Use of RTS for De-risking Innovation Projects

The National HVDC Centre

❑ Distributed ReStart – Control HiL Testing

SP ENERGY NETWORKS

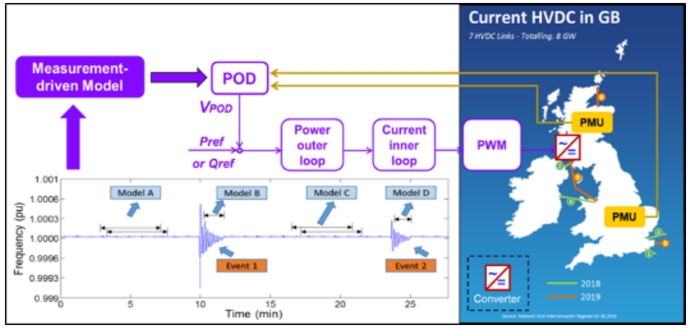
❑ Protection Assessment in Low Strength Areas



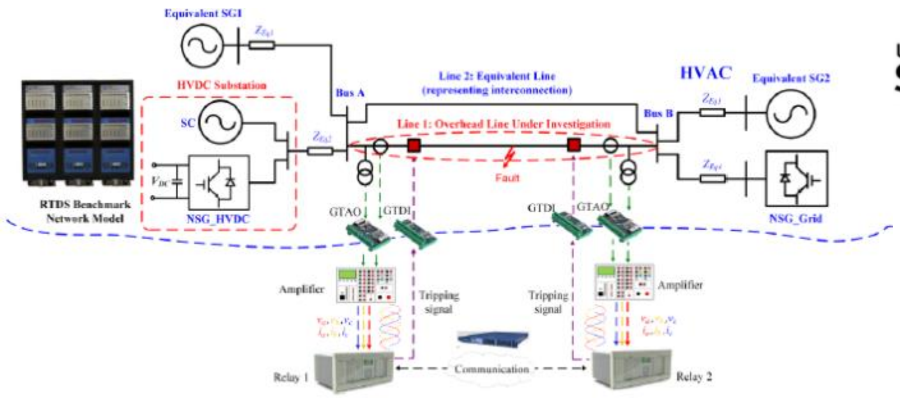
Manitoba HYDRO INTERNATIONAL

❑ HVDC Power Oscillation Damping Controls

EPRI ELECTRIC POWER RESEARCH INSTITUTE



❑ Protection Test Benchmarking & Sync. Comps



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Thanks for listening.

Any questions, please?

- **Summary of questions, answers and discussions from the webinar will be made available at:** https://www.hvdccentre.com/wp-content/uploads/2020/04/Webcast-Summary-16042020-Final.pdf
- For further information, please visit www.hvdccentre.com ; OR email: info@hvdccentre.com ; OR email: kati@rtds.com
- Upcoming Webcast 13th May. "Demonstration of DC Grid Protection – PROMOTioN WP9 Results so Far"; registration open at: https://www.ssen.co.uk/StakeholderEvent/Registration/?EventId=503

RTDS Technologies 25 YEARS

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