School of Electrical Engineering and Telecommunications &
Real-Time Digital Simulations Laboratory (RTS@UNSW)

Real-Time Simulation of Emerging Modular VSC Topologies for HVDC Applications

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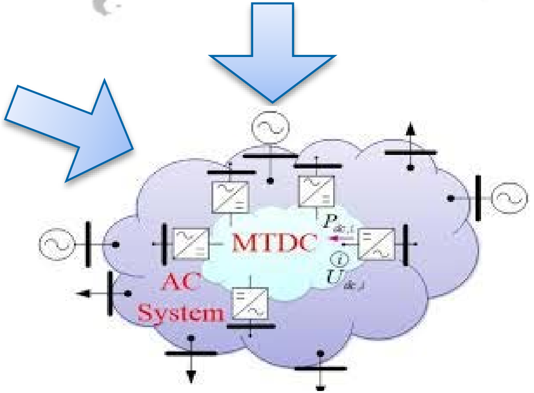
Introduction

Energy Network Transformation

- Main Driving Forces:
  - Global demand for clean energy
  - Large scale distributed energy sources
- Challenges:
  - Remote locations
  - Intermittency
  - Fast dynamics
- Multiterminal DC (MTDC) grids:
  - Long distance transmission
  - Large scale interconnections
  - Better energy utilisation

Primary energy demand, 2035 (Mtoe)

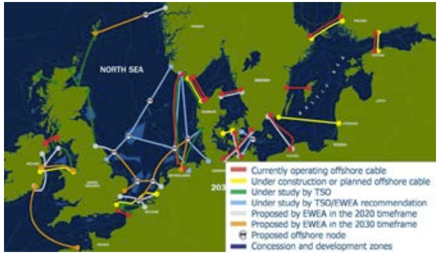
Global renewable energy zones



Multiterminal DC systems

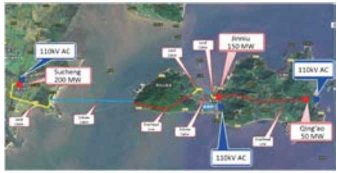
Future DC Power Systems

HVDC Links



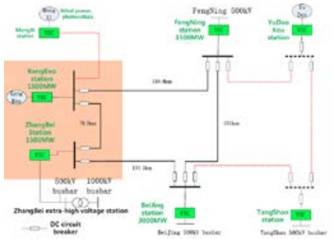
Multiterminal DC

Nan'ao



Zhoushan

Zhangbei



DC Super Grids

Modular Voltage Source Converters (VSCs)

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DC Super Grids: Enablers

Modular VSC Topologies

Modular Multilevel Converter (**MMC**)

State of the art topology

Hybrid Topologies based on Various Submodules

Alternate Arm Converter (**AAC**)

Emerging topology

DC fault tolerant capability

DC Super Grids: Barriers

- Power Flow control
- Interactions between AC and DC grids
- Stability
- DC-DC transformation
- Protection – DC Breakers & Fault tolerant converters
- Standardisation – Converter Interoperability
- Reliability & Resiliency
- Other – Security, Ownership, Management, Safety & Environmental considerations

HVDC Benchmark Test Systems

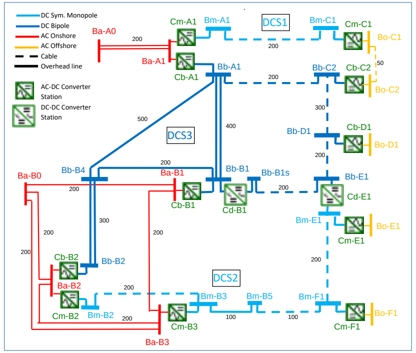
A common basis for the testing and performance of research concepts and algorithms

Detailed Benchmark models for Emerging VSC Topologies?

VSC-HVDC Benchmark Test Systems

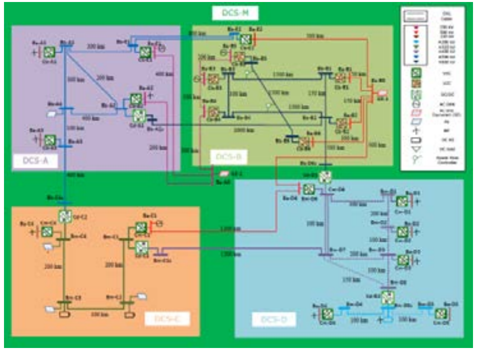
- CIGRE Working Group B4-57 (HVDC and Power Electronics)
  - 3 Subsystems
  - 11 AC/DC converters
  - 2 DC/DC converters
  - 2 DC voltages

- **Detailed studies**
- **Only MMCs**



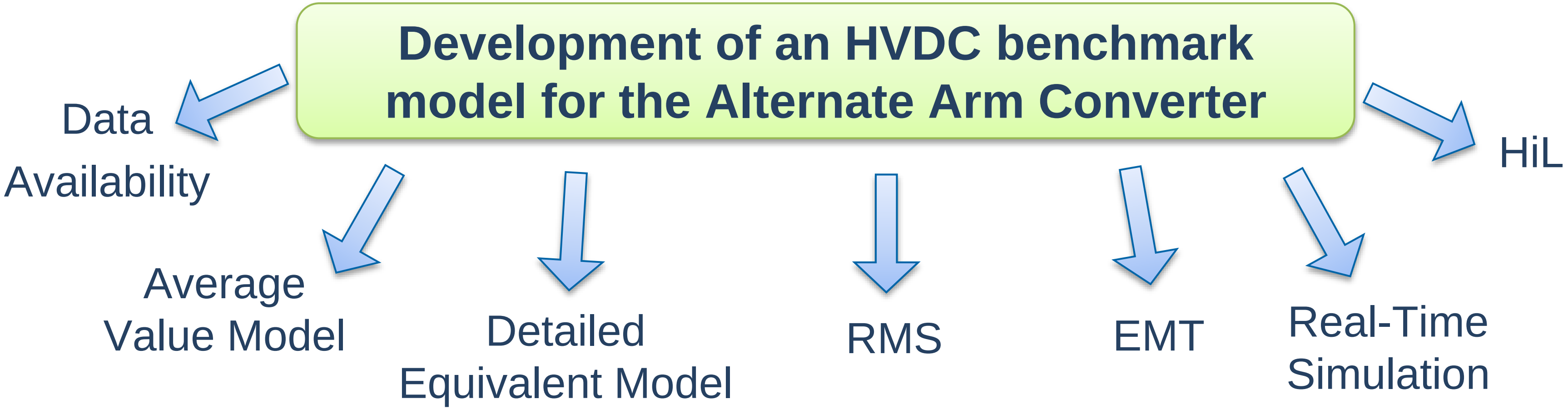
- State Grid – SGRI (Smart Grid Research Institute)
  - 4 Subsystems
  - 19 AC/DC converters
  - 5 DC/DC converters
  - 5 DC voltages

- **LCC and VSCs**
- **System level studies**



Motivation

- Development of the necessary models and benchmarks that include multiple network and converter configurations.
- Enable multiple users and vendors to have access to the network, in a fashion similar to the existing ac networks.



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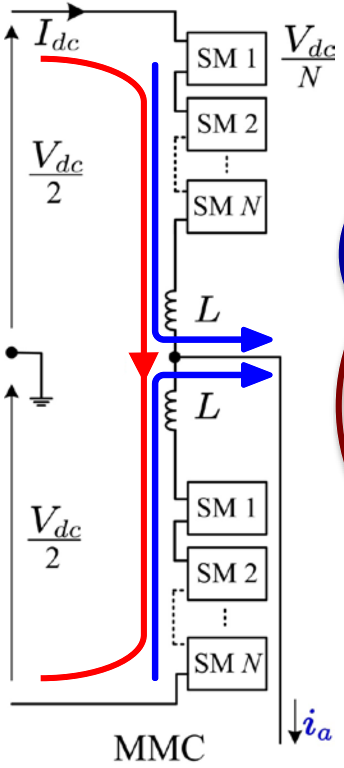
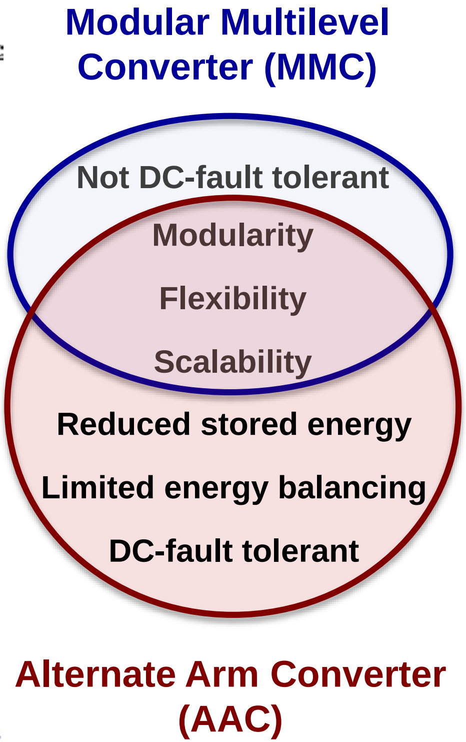
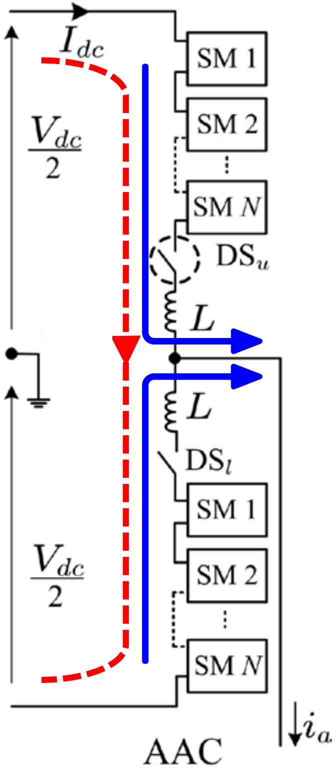
The Alternate Arm Converter (AAC)

Alternate Arm Converter (AAC)

- Emerging VSC topology
- Combines characteristics of:
  - 2-Level VSC and the
  - modular multilevel converter (MMC)
- Overmodulated operation:
  - $m_a > 1$
- Require bipolar submodules:
  - Full-bridge submodules





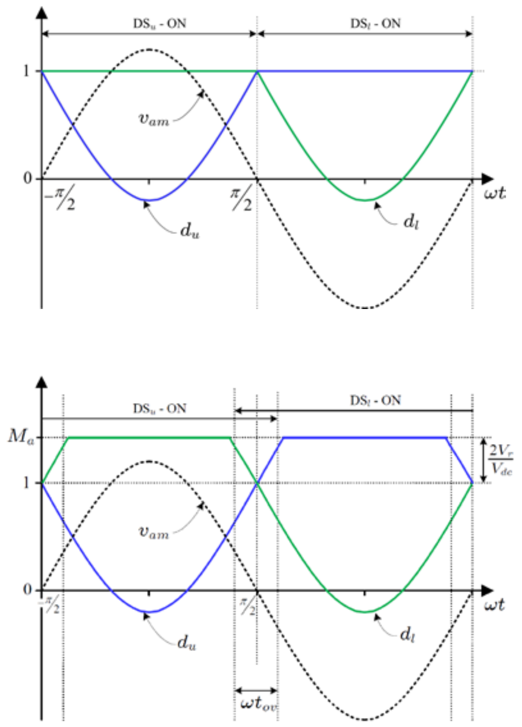


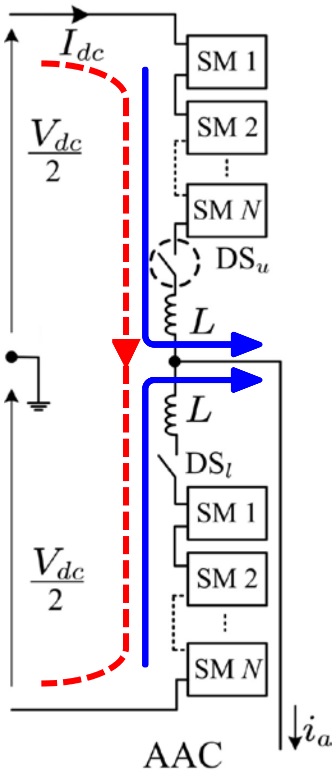
AAC Operation Modes

- "Sweet-Spot" ($m_a = 4/\pi$)
  - **Inherent energy balancing** exists
  - Net energy exchange of SM capacitors within the arms is **zero**
- Nonsweet-Spot
  - **Nonzero** net energy exchange in the SMs
  - Steady-state stored energy deviates
  - **Overlap period** for energy exchange
  - Requires active energy regulation methods

Net Energy Exchange =

$$\Delta E_{arm} = E_{dc} - E_{ac} = \frac{\pi V_{dc} \hat{I}_a \cos\phi}{4\omega}\left(\frac{4}{\pi} - m_a\right)$$

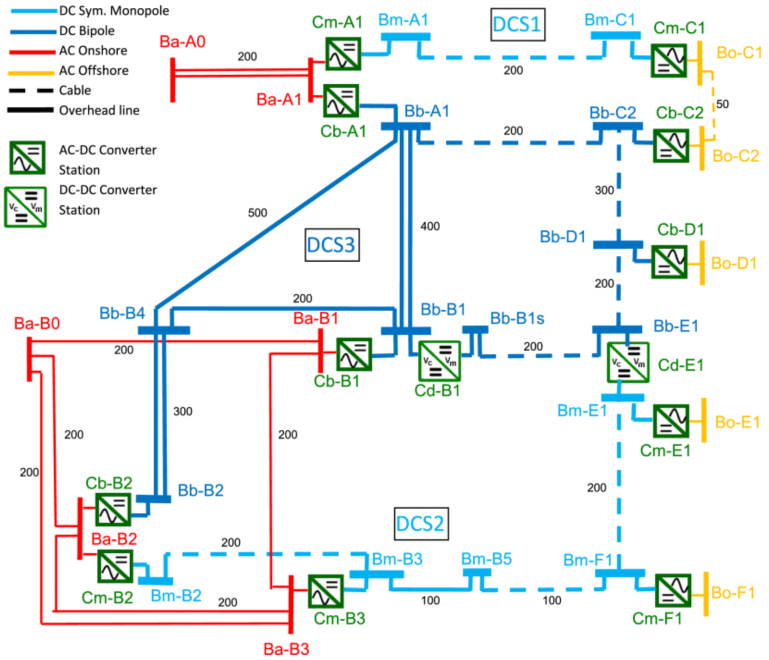


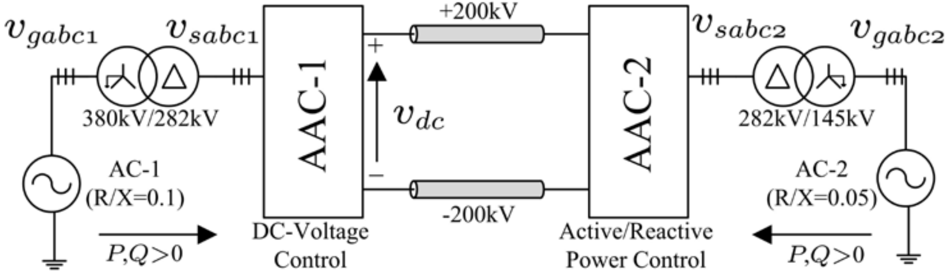


Proposed AAC-HVDC System

AAC-HVDC Station Modeling

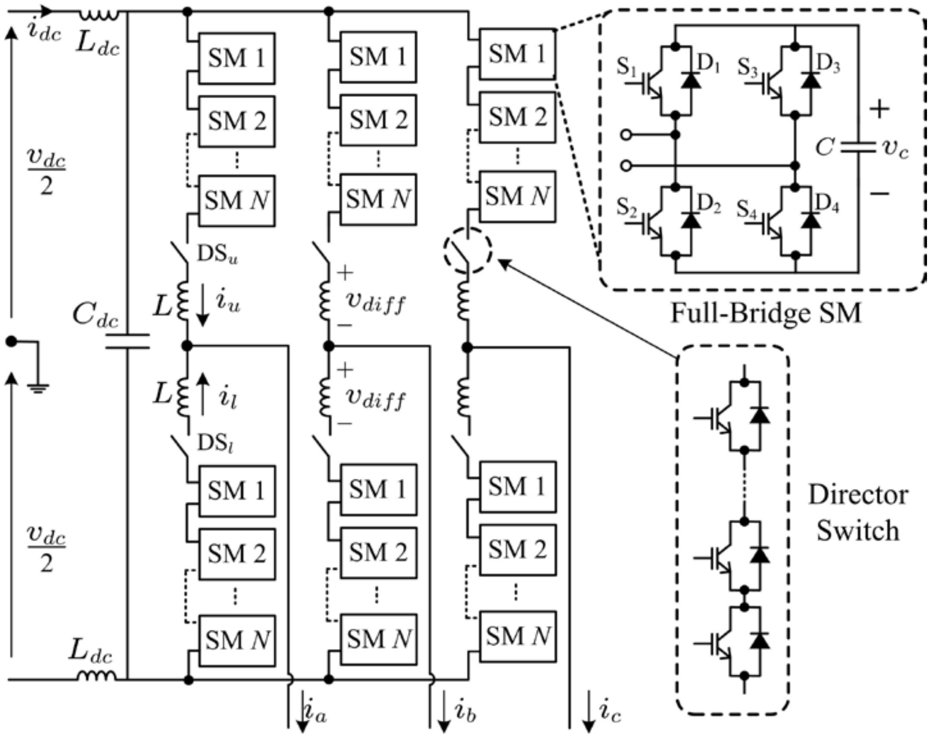
- AAC-HVDC station is modelled equivalent to the MMC-based HVDC converter of CIGRE benchmark dc system.
- The DC- and AC-side voltages and power ratings remain the same, where the AAC parameters are determined translating from the equivalent MMC parameters





AAC-HVDC Station Parameters

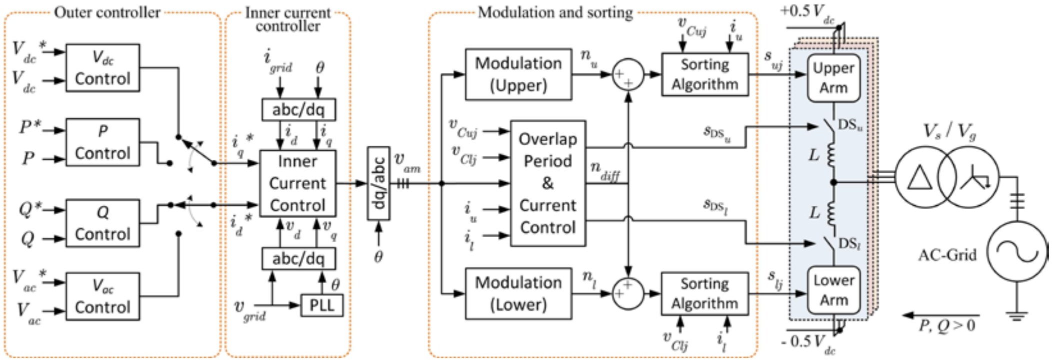
- Standard operating point
- Converter transformer
- Number of SMs per arm
- SM capacitance
- Arm inductance
- Director switch ratings
- Overlap period
- DC filter

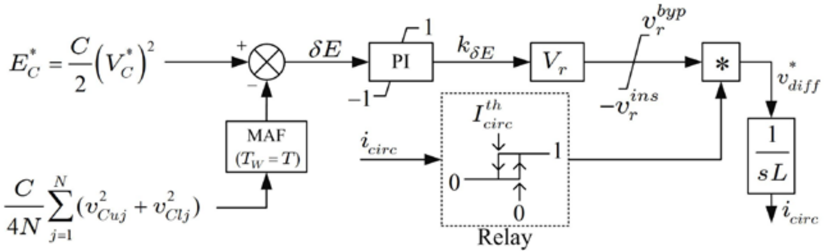


H. R. Wickramasinghe, G. Konstantinou, Z. Li and J. Pou, "Alternate Arm Converters-Based HVDC Model Compatible With the CIGRE B4 DC Grid Test System," in *IEEE Transactions on Power Delivery*, vol. 34, no. 1, pp. 149-159, Feb. 2019.

AAC-HVDC Station Control

- High-level controller:
  - Conventional grid current controller
- Low-level controller:
  - Director switch control & overlap period control
  - Overlap current & SM energy regulation
  - SM capacitor voltage sorting & balancing





H. R. Wickramasinghe, G. Konstantinou and J. Pou, "Gradient-Based Energy Balancing and Current Control for Alternate Arm Converters," in IEEE Transactions on Power Delivery, vol. 33, no. 3, pp. 1459-1468, June 2018.

Parameters

PARAMETERS OF THE AAC-HVDC STATIONS

Parameter	AAC-1	AAC-2
Rated Power	800 MVA	800 MVA
DC Voltage	±200 kV	±200 kV
Number of SMs per arm	255	255
SM Voltage	1 kV	1 kV
Stored Energy	11 kJ/MVA	11 kJ/MVA
SM Capacitance	11.5 mF	11.5 mF
Arm Inductance (p.u.)	0.016	0.016
Nominal Frequency	50 Hz	50 Hz
Nominal Operating Point (p.u.)	1.15	1.15
Transformer Resistance (p.u.)	0.004	0.004
Transformer Leakage Inductance (p.u.)	0.11	0.11
Transformer Ratio	0.778	0.297
AC-Grid Voltage	380 kV	145 kV
Short-circuit Power	30 GVA	4 GVA
R/X Ratio	0.1	0.05
DC Capacitance	88 μF	
DC Inductance	50 mH	

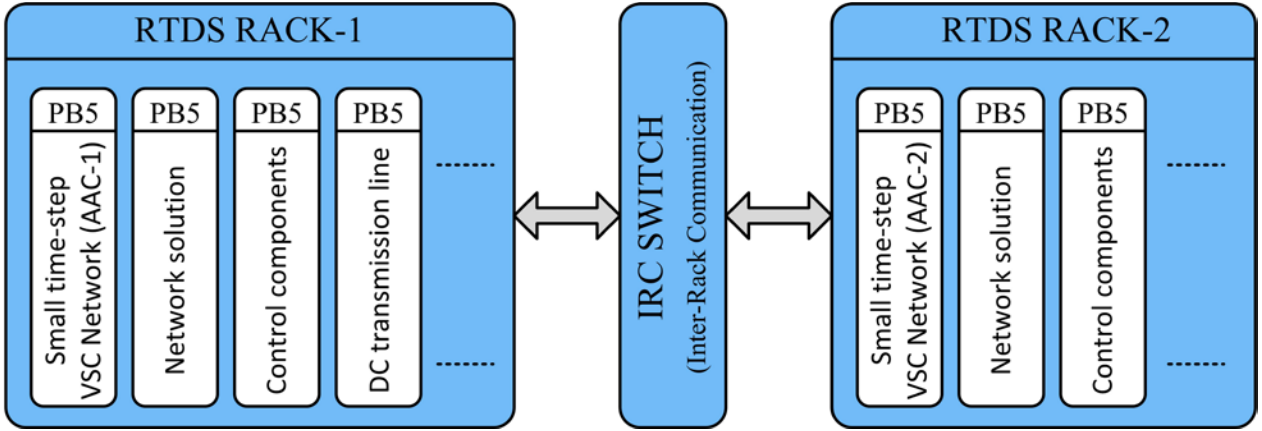
TRANSMISSION LINE AND CONTROL PARAMETERS

Transmission Line Parameters [12]	
Length	200 km
Resistance	0.011 Ω/km
Inductance	0.2615 Ω/km
Capacitance	0.2185 Ω/km
Control Parameters (Fig. 3)	
DC Voltage Control	$K_P = 8,\ K_I = 272$
Active/Reactive Power Control	$K_P = 0,\ K_I = 33$
AC Voltage/Frequency Control	$K_P = 0.2,\ K_I = 30,\ K_D = 0.0025$
Energy Balancing	$K_P = 2.9,\ K_I = 75$

H. R. Wickramasinghe, G. Konstantinou, Z. Li and J. Pou, "Alternate Arm Converters-Based HVDC Model Compatible With the CIGRE B4 DC Grid Test System," in *IEEE Transactions on Power Delivery*, vol. 34, no. 1, pp. 149-159, Feb. 2019.

RTDS Model - Computational Requirements

- Detailed equivalent model
- 7 x PB5 cards

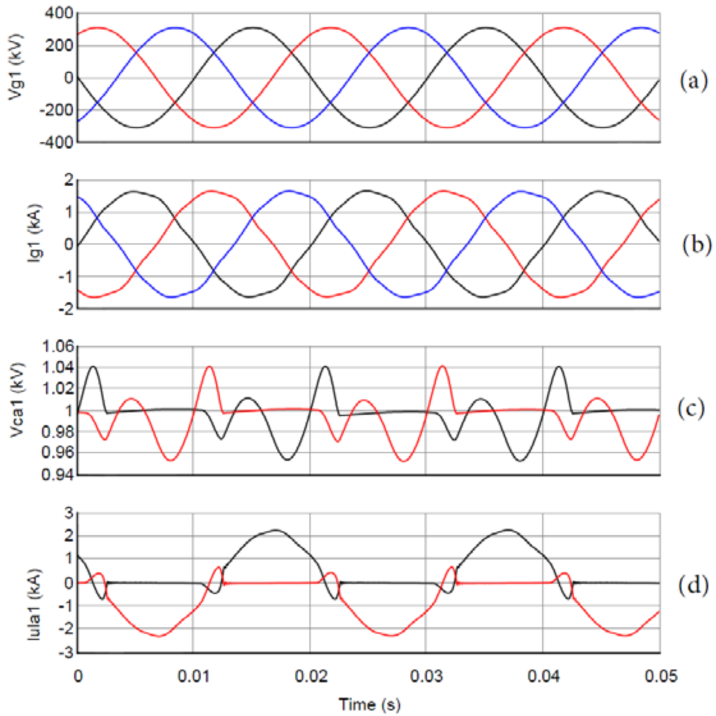


The RTDS model files of the AAC-HVDC system can be downloaded from http://bit.ly/AAC Model UNSW

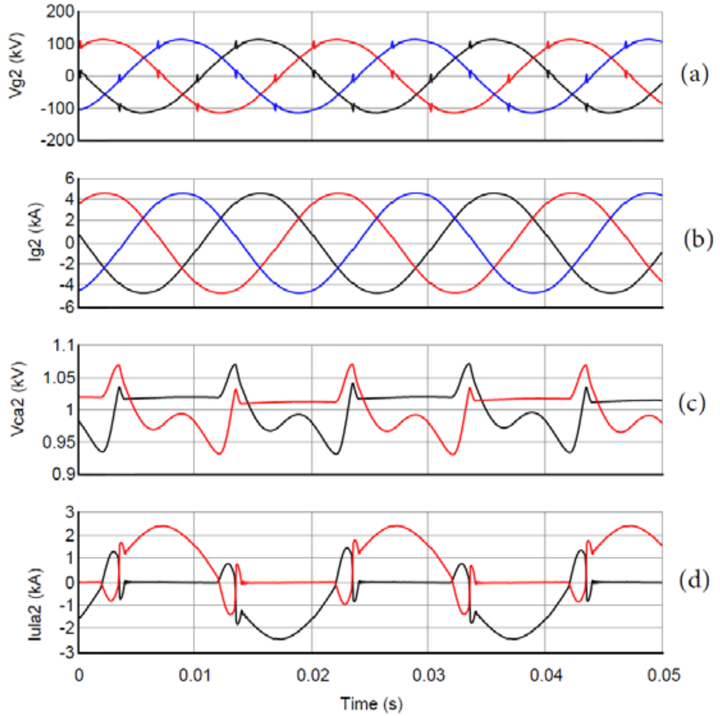
Results & Verification

Steady-state Performance

Inverter Operation

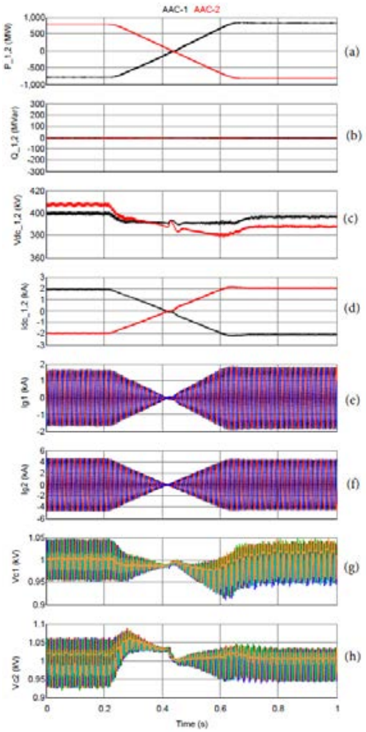


Rectifier Operation

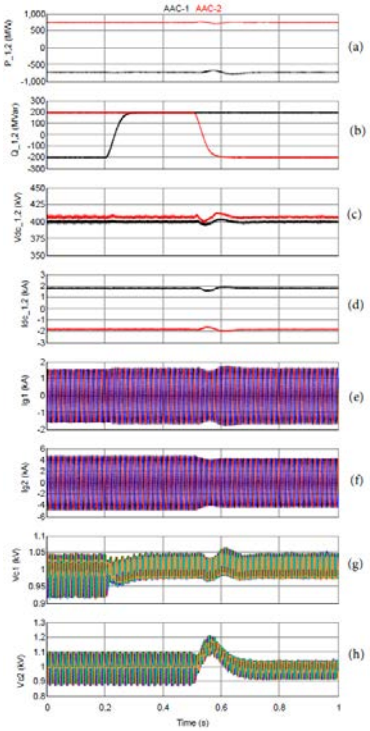


Transient Performance

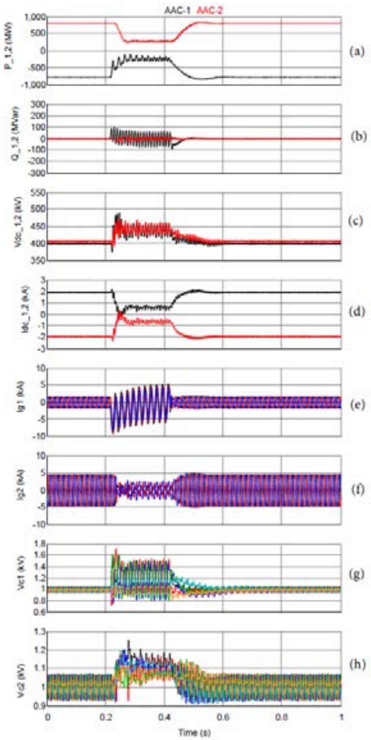
Power reversal



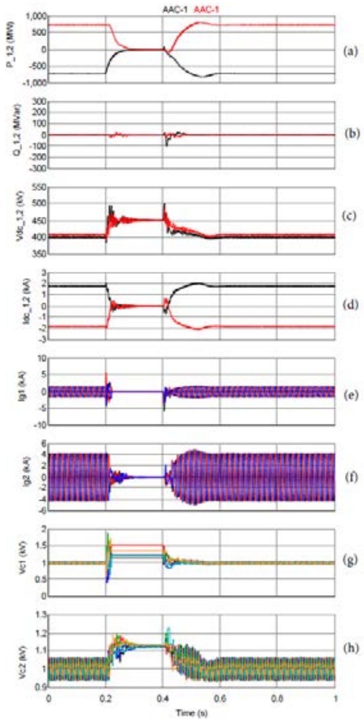
Reactive power steps



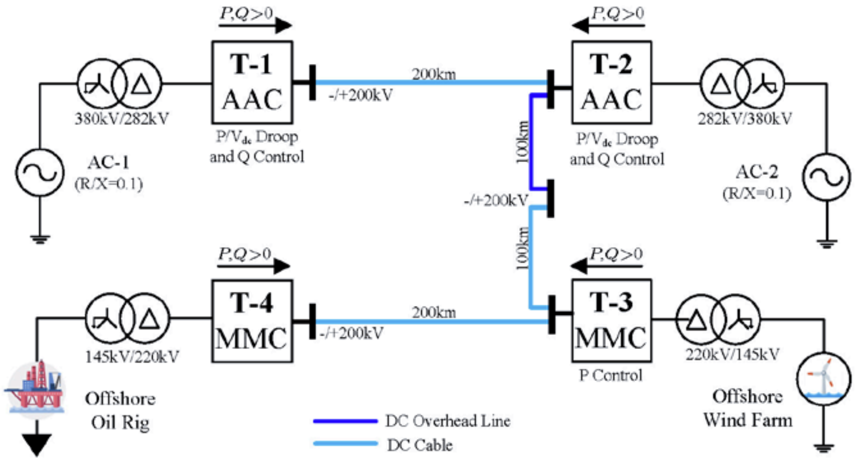
SLG fault

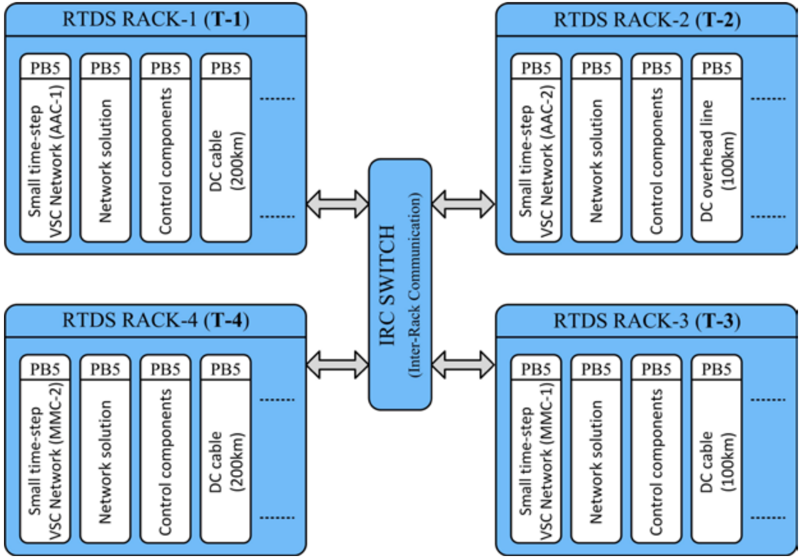


3-Phase fault

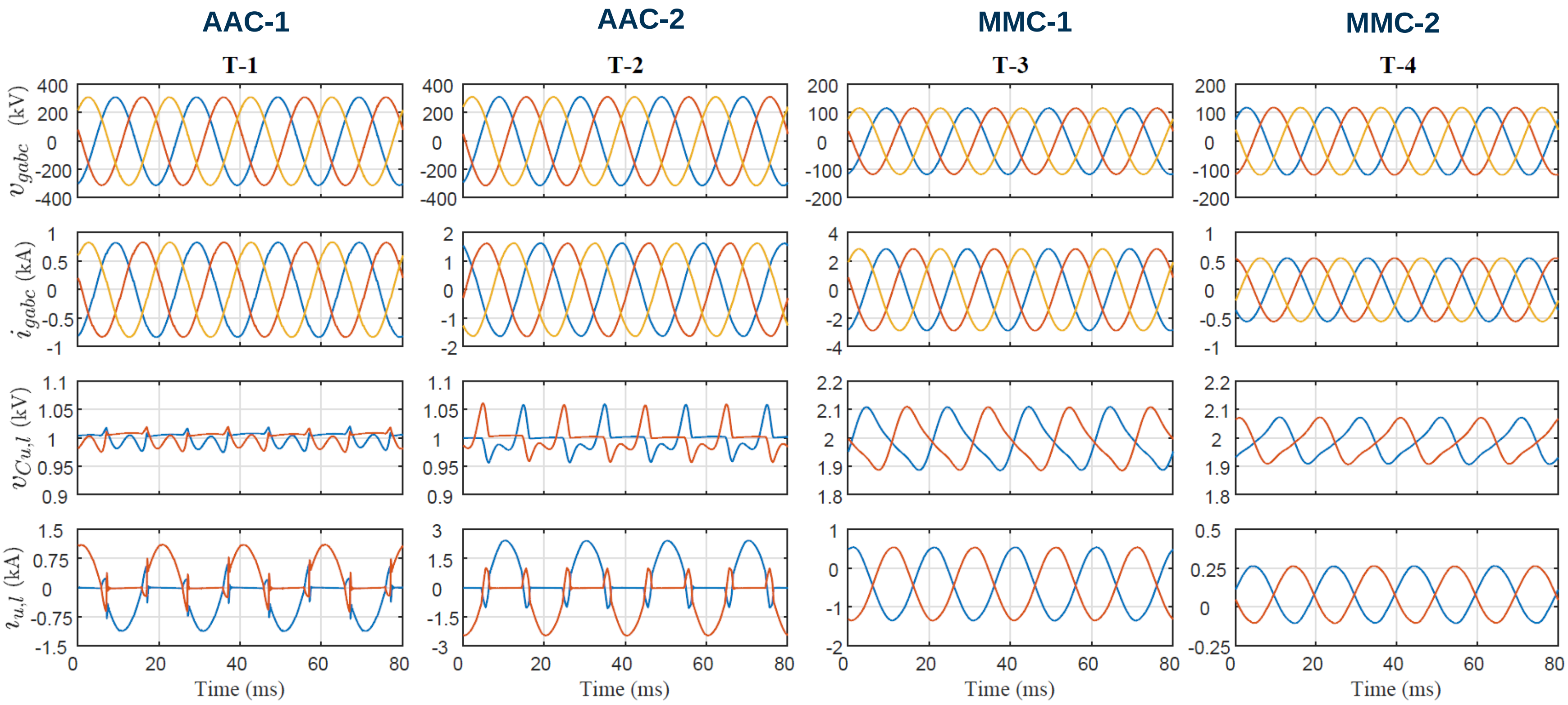


Extending to Multiterminal DC Systems



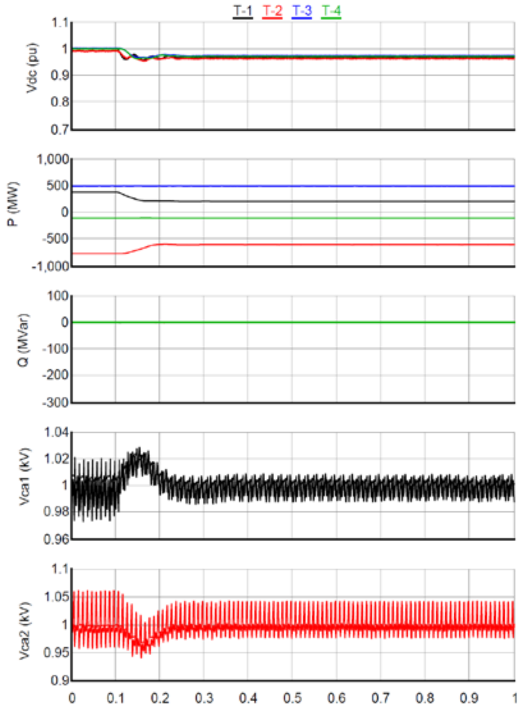


MTDC System Performance

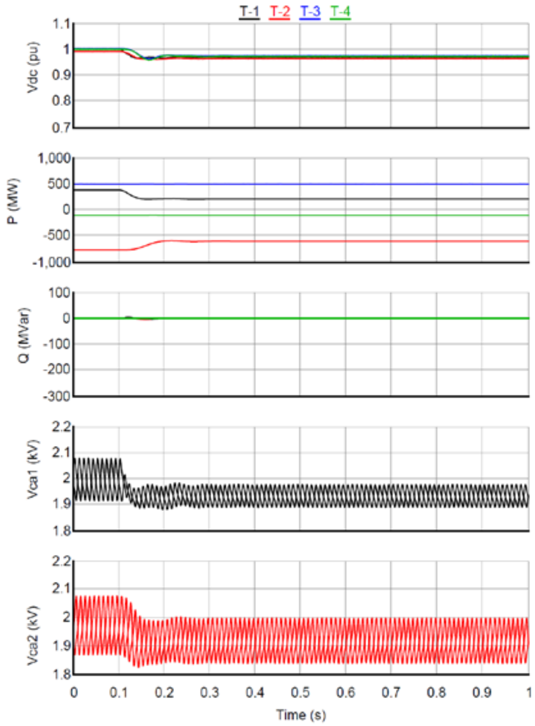


MTDC System Performance cont.

MMC-AAC Multi-converter MTDC

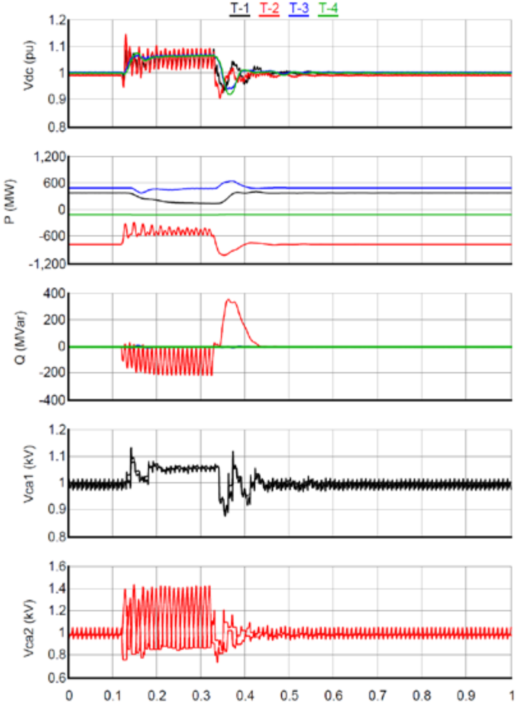


CIGRE DC test system-2 (MMCs)



MTDC System Performance cont.

MMC-AAC Multi-converter MTDC



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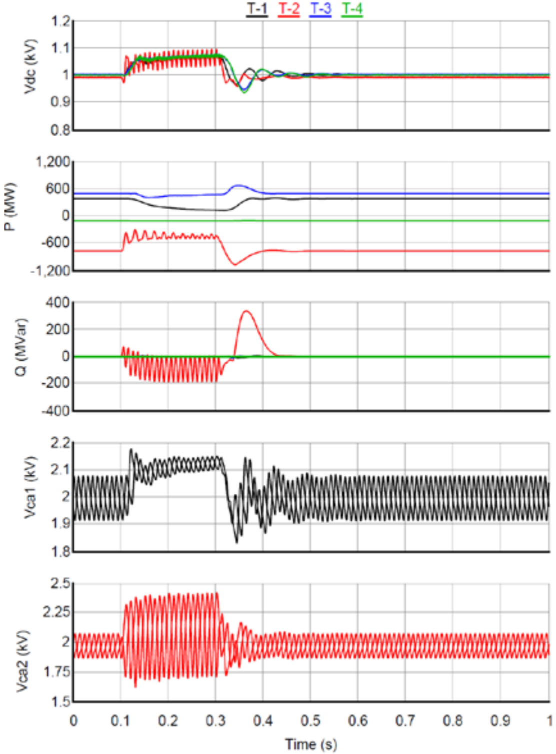
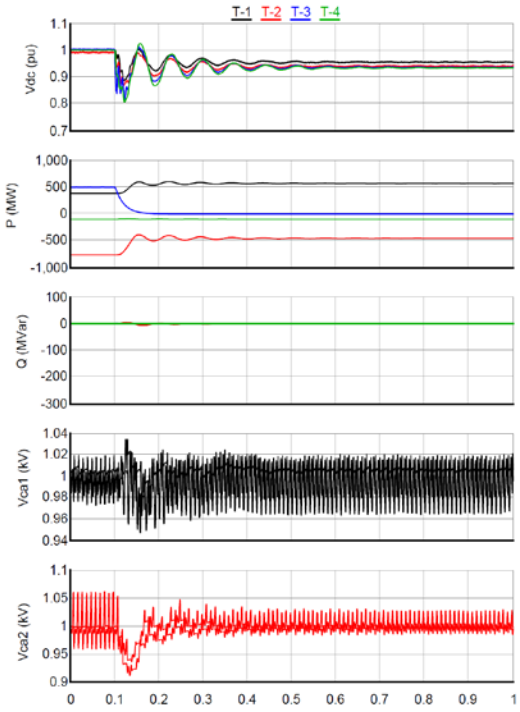


MTDC System Performance cont.

MMC-AAC Multi-converter MTDC



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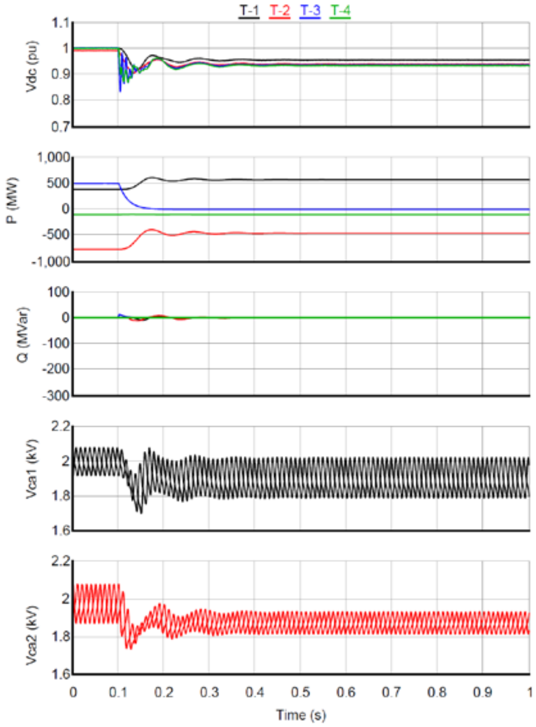

Summary

- AAC is an **emerging** HVDC converter topology.
- AAC offers **dc-fault tolerant** operation and a **potential candidate** for future HVDC applications.
- Existing benchmark HVDC test systems:
  - **Detailed** models - Limited to **MMC-based terminals**
  - **System-level** study models – Consist of **VSCs** and **LCCs**
- **Detailed** benchmark models are required for other **emerging** HVDC converter topologies.
- An **AAC-based HVDC system** is developed in equivalence with existing benchmark models & performance is verified using real-time simulations.
- Data and the RTDS model is made openly available for further research.

THANK YOU