Webinar and demo: Real-time simulation of MMC-HVDC integration of offshore wind

RTDS Technologies
AMETEK

RTDS.COM

AGENDA

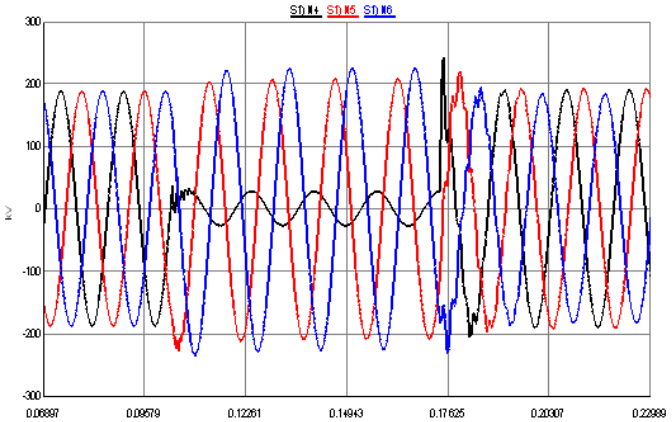
- General introdocution, including review of Universal Converter Model
- Overview of MMC-HVDC modelling options
- Overview of aggregated windfarm modelling
- Case demo in RSCAD FX software
- Q&A

About RTDS Technologies

- Headquarters in Winnipeg, Canada
- Pioneered real-time power system simulation in the 1980s
- The RTDS Simulator is the industry standard for real-time simulation and closed-loop testing, used by utilities, manufacturers, research and educational institutions, and consultants worldwide
- Learn more at www.rtds.com or the large library of videos on the RTDS Technologies YouTube channel

EMT power system simulation

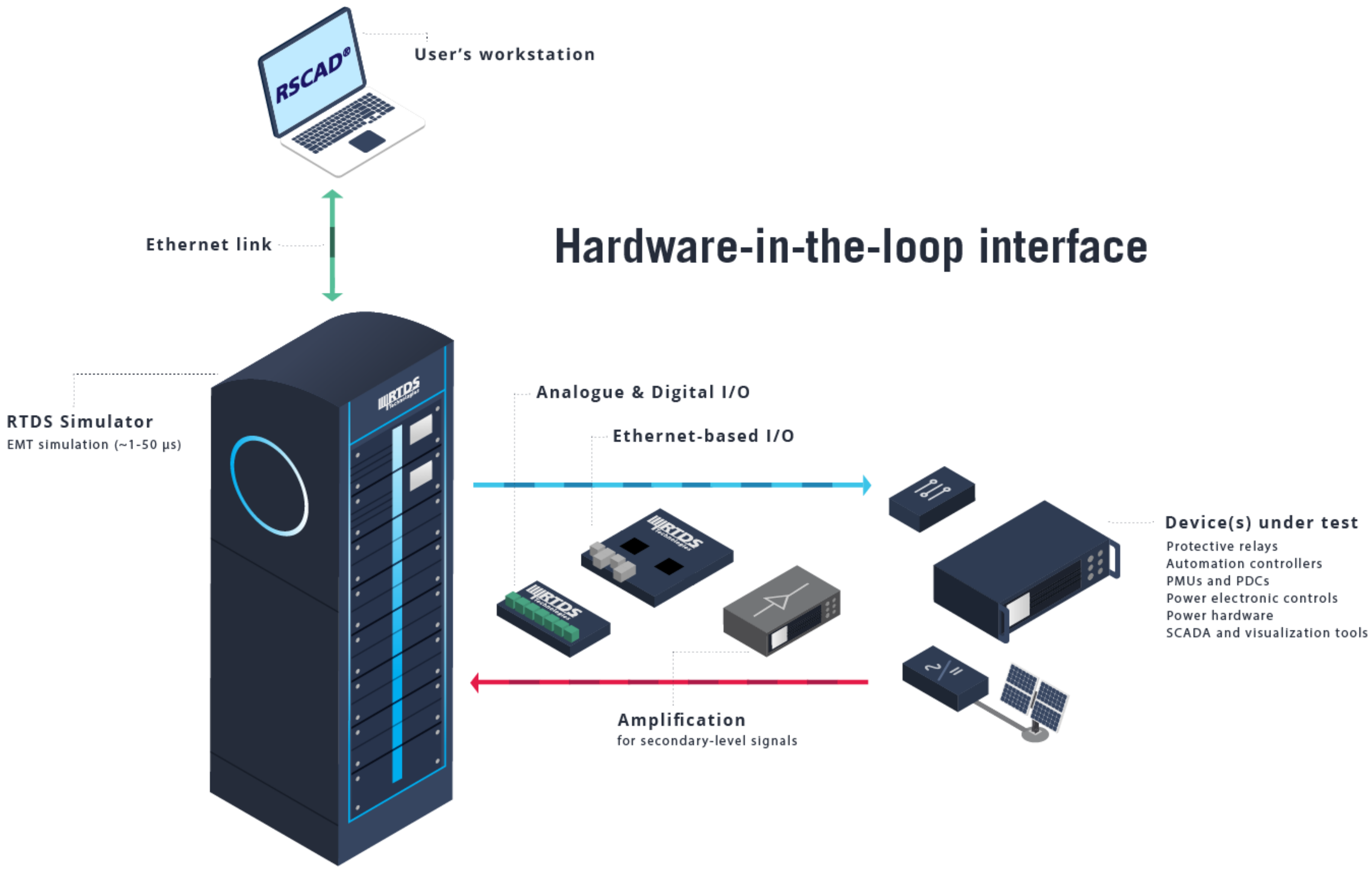
Type of Simulation	Load Flow	Transient Stability Analysis (TSA)	Electromagnetic Transient (EMT)
Typical timestep	Single solution	~ 8 ms	~ 2 - 50 μs
Output	Magnitude and angle	Magnitude and angle	Instantaneous values
Frequency range	Nominal frequency	Nominal and off-nominal frequency	0 – 3 kHz (<15 kHz)



- Greater depth of analysis than traditional phasor domain (RMS) representations
- EMT models are needed to represent inner loop controls of inverter-based resources and related stability issues

HIL testing with a real-time simulator

- **True closed-loop testing** is only possible with a real time simulator
  - Test multiple devices (and entire schemes) at once
  - Much more detailed system representation than open-loop test systems provide (e.g. modelling power electronics)
  - Provides unique insights on interactions & dependencies that traditional modelling/ testing may be blind to



CHIL for MMC-HVDC and wind

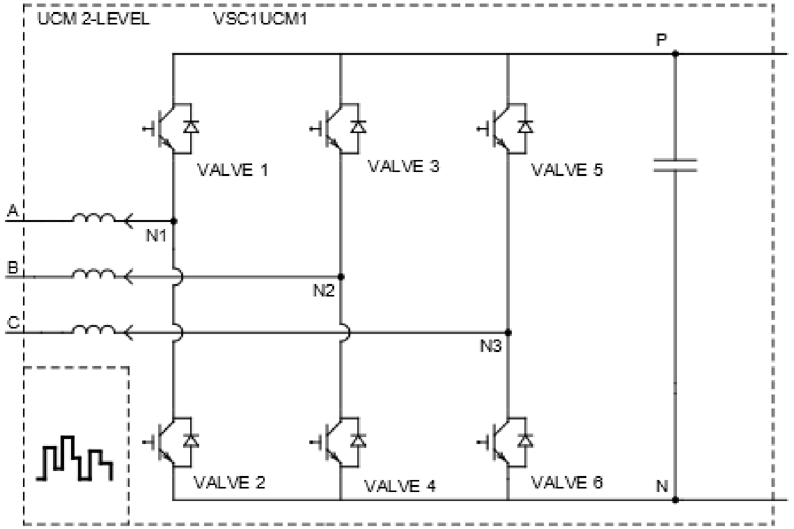
- In today's demo, our MMC-HVDC controls are implemented on the GTSOC V2 and interfaced via fibre, but it's possible to connect external controls via conventional I/O as well

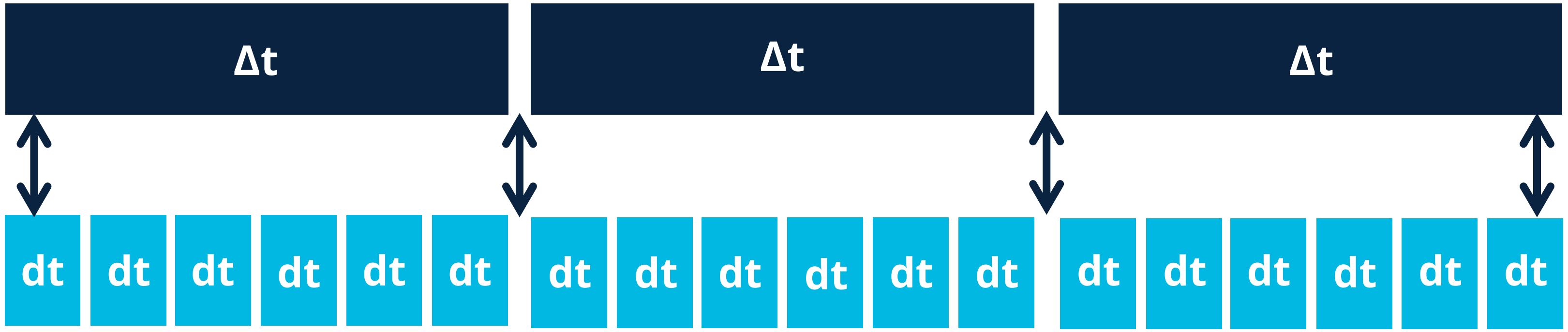
- Vendor control replicas for MMC-HVDC are standard for new projects

- Generic wind farm controls are simulated in RSCAD FX, but it's possible to connect a physical controller or a black-boxed vendor control model

Universal converter model (UCM)

- The sample case we'll look at today uses the UCM for modelling the power electronics
- The UCM works in both the Mainstep and Substep environments, so cases are built in Mainstep but can be easily converted to Substep if needed





Mainstep
Δt
e.g. 30 μs

Substep
dt = Δt ÷ n
e.g. 3 μs

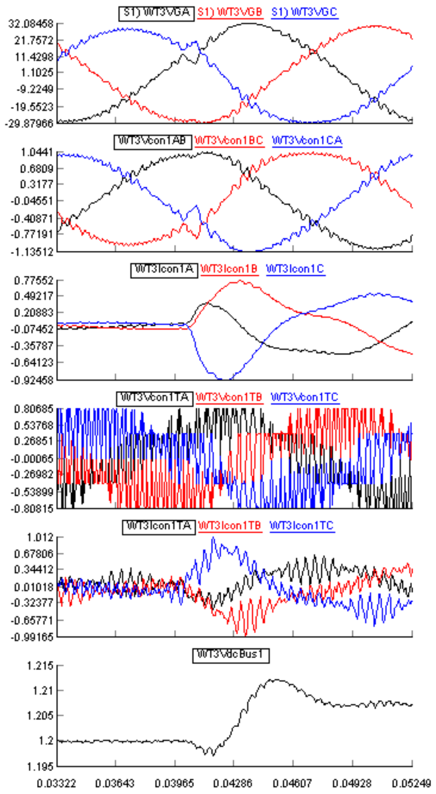
Universal converter model

- **Improved Firing Input**
  - When used in Substep environment, supports PWM firing in the ~200 kHz range
  - When used in Mainstep environment, supports PWM firing in the ~10 kHz range

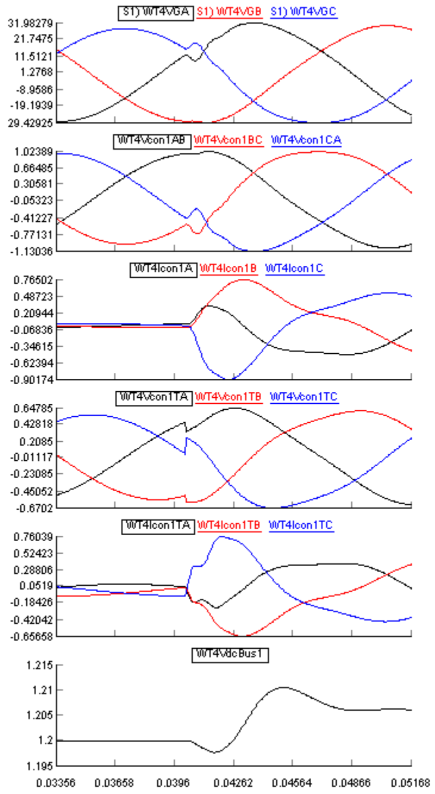
- **10 load units per converter** in Mainstep – very lightweight, detailed power electronics modelling

- Excellent performance when it comes to numerical stability, block/de-block transition, switching losses, noise

50 us timestep -
"Improved Firing" input



50 us timestep -
Modulation waveform input



Real-time Simulation of MMC-HVDC Integration of Offshore Windfarm

RTDS Technologies
AMETEK

RTDS.COM

AGENDA

- **Introduction**
- **EMT Simulation of MMCs**
- **MMC Simulation in RTDS**
  - Overview of MMC Models in RTDS
  - New Embedded MMC Valve Models
- **Sample Case: MMC-HVDC Offshore Windfarm**
  - System Overview
  - Aggregated Windfarm Modeling
  - Stability Analysis
  - Case Demonstration

EMT Simulation of Modular Multilevel Converters (MMCs)

RTDS Technologies
AMETEK

Offshore Windfarm Structure

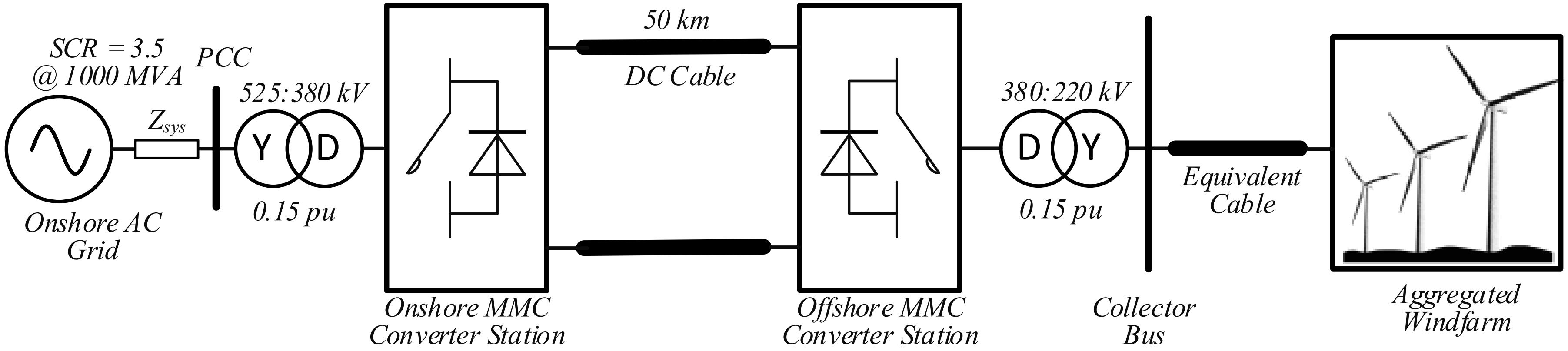


Figure 2-1 MMC-HVDC Offshore Windfarm

Why do we need EMT Simulation?

- **EMT simulation can help [1]:**
  - **Typical EMT Studies:** switching transients, system energization, insulation coordination, parallel resonance, current zero-missing and so forth…
  - **Dynamic Response Studies:** fault ride-through capabilities, control interactions, SSTI, impedance measurement, harmonics, grid code compliance and more…
- **Real time EMT simulation:**
  - **The beauty of real-time EMT simulation is to allow testing physical devices in EMT environment and provide further validation for equipment under tests.**

Overview of MMC Topologies

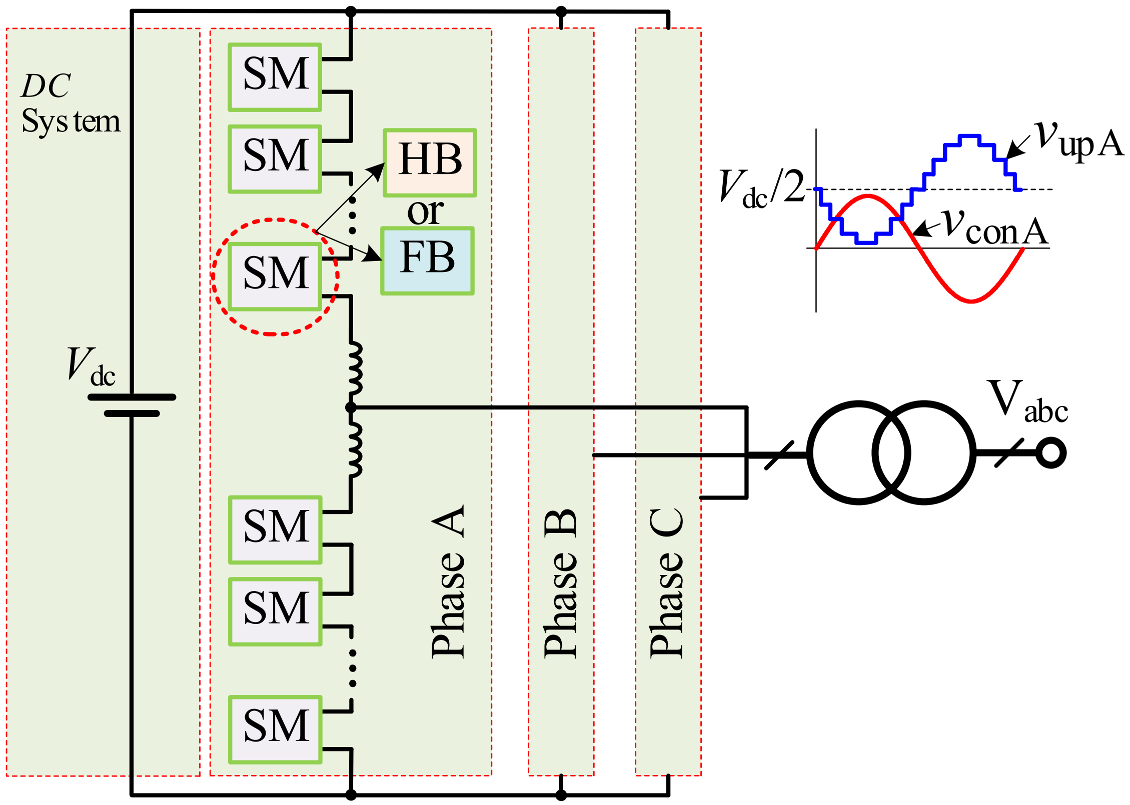


Figure 2-2 General Overview of MMC Topology [2]

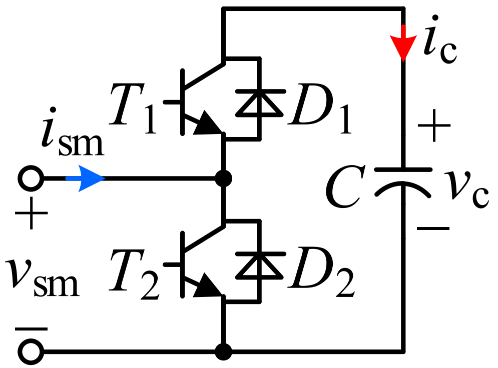


Figure 2-3 Half-bridge Submodule (SM)

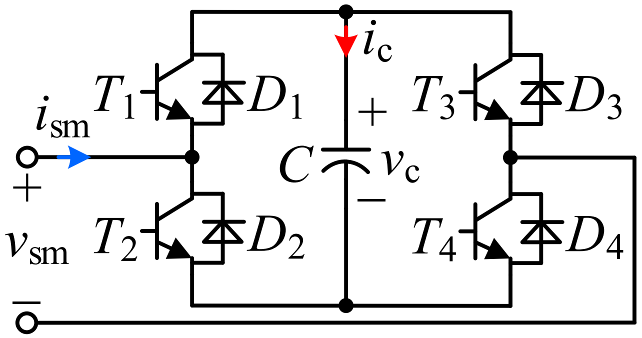
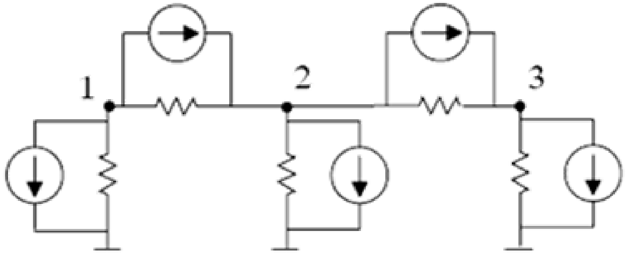


Figure 2-4 Full-bridge SM

Challenges in EMT Simulation

- All power system components are represented as **equivalent current source and resistor**
- Formulate conductance matrix for equivalent network, and the size of the G matrix is determined by the number of nodes in the simulated network.



$$\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} = \begin{bmatrix} G11 & G12 & G13 \\ G21 & G22 & G23 \\ G31 & G32 & G33 \end{bmatrix}^{-1} \begin{bmatrix} I1 \\ I2 \\ I3 \end{bmatrix}$$

- Using data from previous timestep (or initial conditions for first timestep), compute new [I] values; solve for [V] using new values of [I]
- Calculate branch currents with [V] and [I] **and repeat…**

In real-time EMT simulation, the primary challenge lies in inverting the G matrix within a very short timeframe. MMCs typically contain a large number of nodes, making the inversion of the G matrix extremely computationally expensive. Consequently, it is nearly impossible to simulate in an EMT environment using traditional methods.

CIGRE Classification of MMC Modeling

- CIGRE MMC valve type definition (TB604 by CIGRE WG B4.57) [3]

Type 1- Full Physics Based Models

Type 2- Full detailed Models

Type 3- Models based on simplified switchable resistances

Type 4- Detailed Equivalent Circuit Model

Type 5- Average Value Models based on switching function

Type 6- Simplified average value models

Type 7- RMS Load Flow Models

Type 5: Average Value Model with Switching

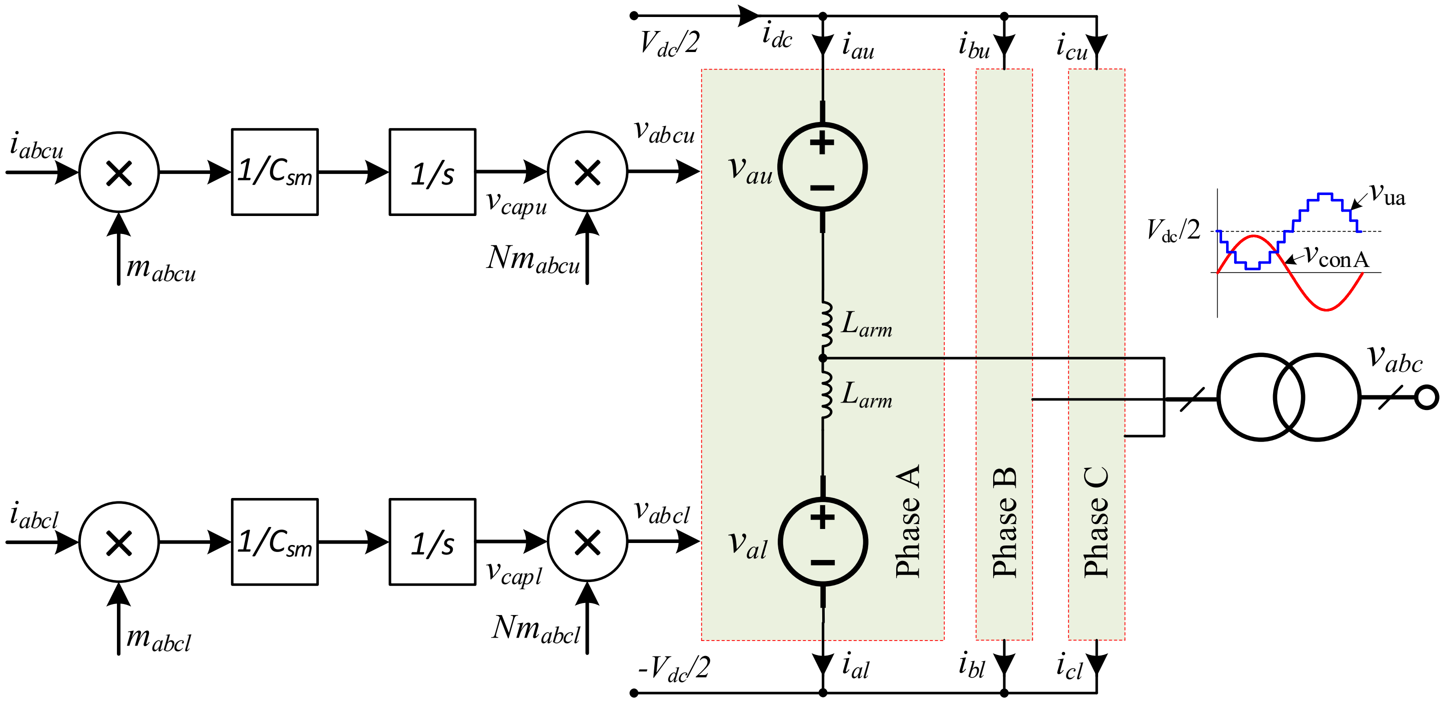


Figure 2-5 Type 5: Average Value Model [2]

Unlike typical average value models, this model can still represent the harmonic contents at the output of the MMC, but it ignores the detailed switching, and it cannot provide the charging or discharging information of individual SM.

Type 4: Detailed Equivalent Circuit Model

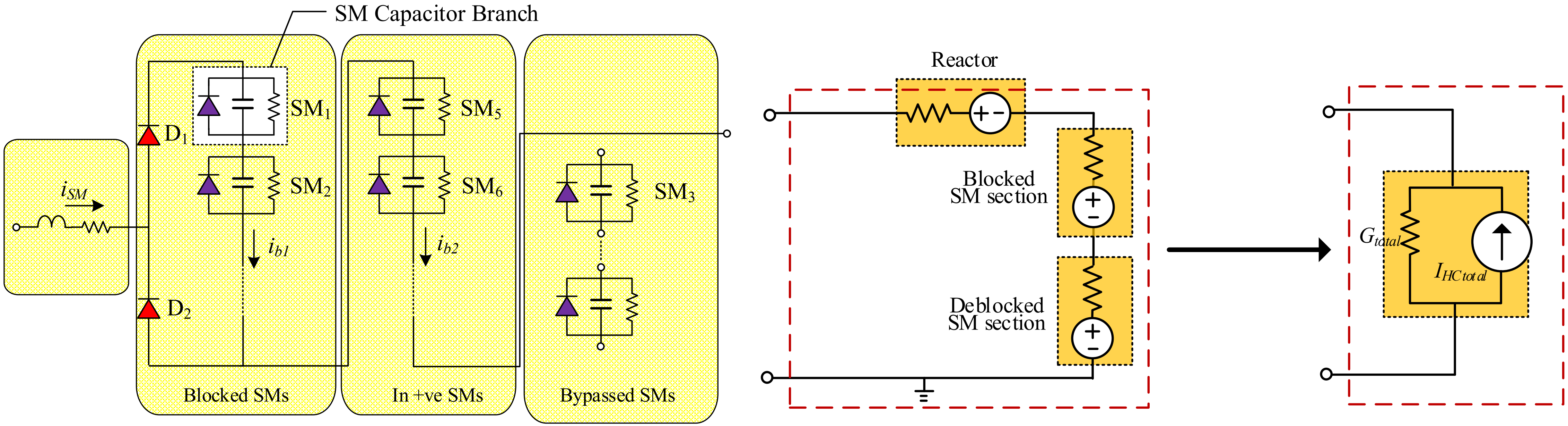


Figure 2-6 Type 4: Detailed Equivalent Model

Detailed Equivalent Circuit Model can accurately represent the charging or discharging behavior of individual SM with significantly reducing the number of nodes in the EMT modeling process.

Introduction – Structure of MMC Controller

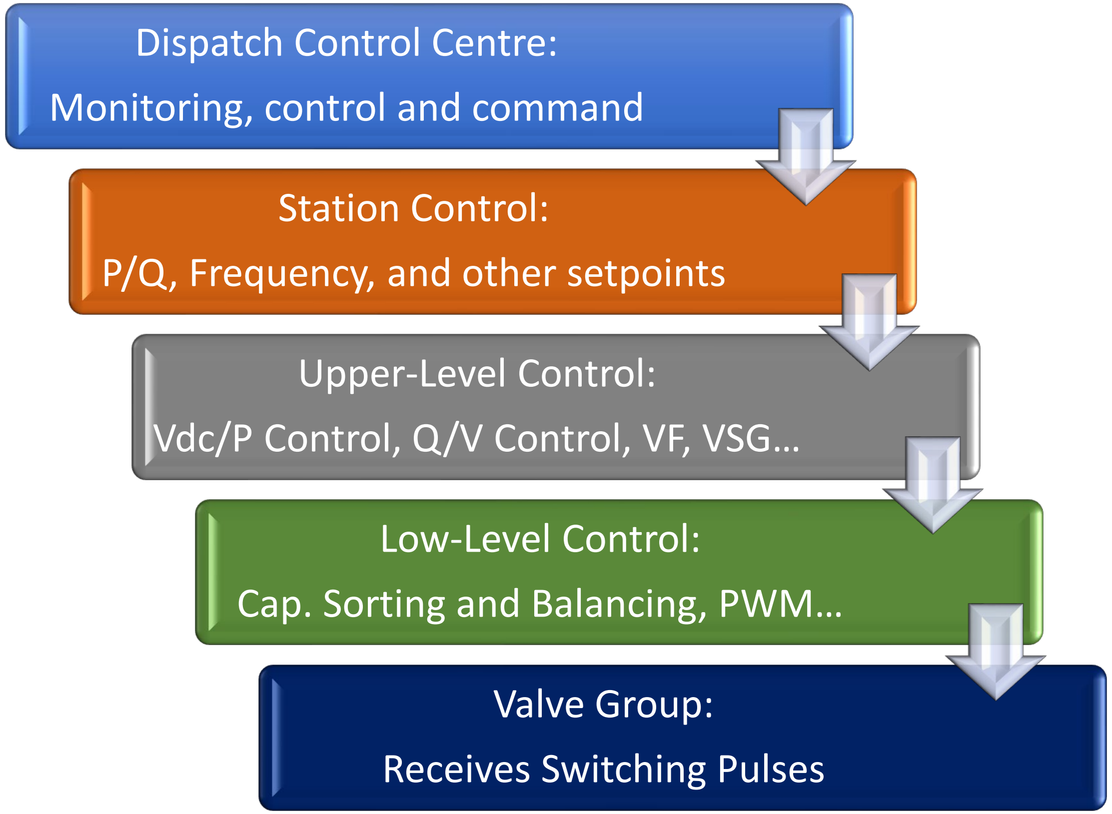


Figure 2-7 Hierarchy Structure of MMC Control [3]

In RTDS CHIL simulation:

- Typically, the value groups are modelled inside of the real-time simulator, and the controller is a physical device.
- Large volume of data, including capacitor voltage/current, switching pulses, and others, needs to be exchanged between the RTDS and the controller within a short period of time.
- Aurora communication protocol is used to optimize the communication between the valve groups and the controller.

MMC Models in RTDS

RTDS Technologies
AMETEK

RTDS.COM

MMC Library in RSCAD

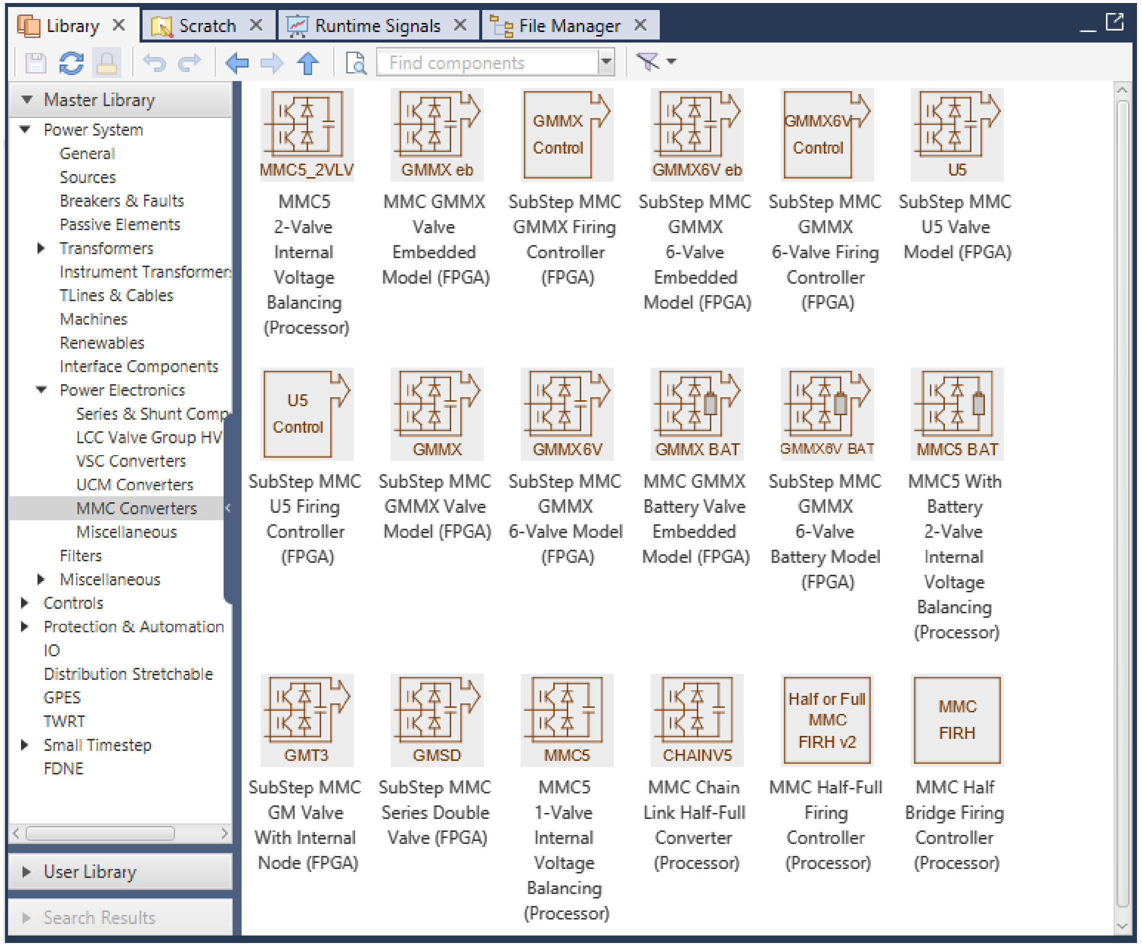


Figure 3-1 RSCAD FX MMC Library

Table 3-1 Summary of MMC Models in RSCAD

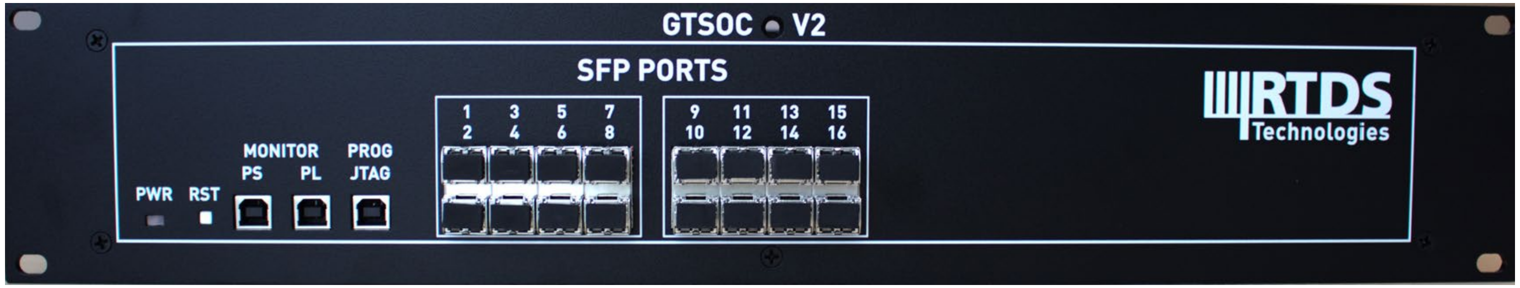
	Processor-Based (NovaCor CPU)	FPGA-Based (GTFPGA or GTSOC V2)
AVG Model with Switching Function	**MMC5 Family:** MMC5, MMC5 BAT	
Detailed Switching Model	CHAINV5	**GM Family:** GMMX, GMMX eb, GMMX6V, GMMX6V eb, GMMX BAT, GMMX6V BAT, GMT3, GMSD **U5 Family:** U5, U5 eb

	Mixed Topology	Low Level Control	Internal Faults	Maximum No. of SMs per arm
MMC5	Yes	No	No	1280
GMMX	Yes	Yes	Yes	768
U5	No	Yes	Yes	512
CHAINV5	No	Yes	No	56

Platform for FPGA-based MMC Simulation

GTSOC V2

- Combined **GTFPGA and GTSOC V1** into one single platform
- **Modular Multilevel Converter (MMC) Valve and Control**
- Sampled Values (IEC 61850-9-2/61869-9)
- Small timestep frequency dependent transmission line and cable (12 conductors)
- Generic Power Electronics Solver (GPES) for customized topology converters
- Black Box Vendor Control Model Simulation



Hardware Configuration

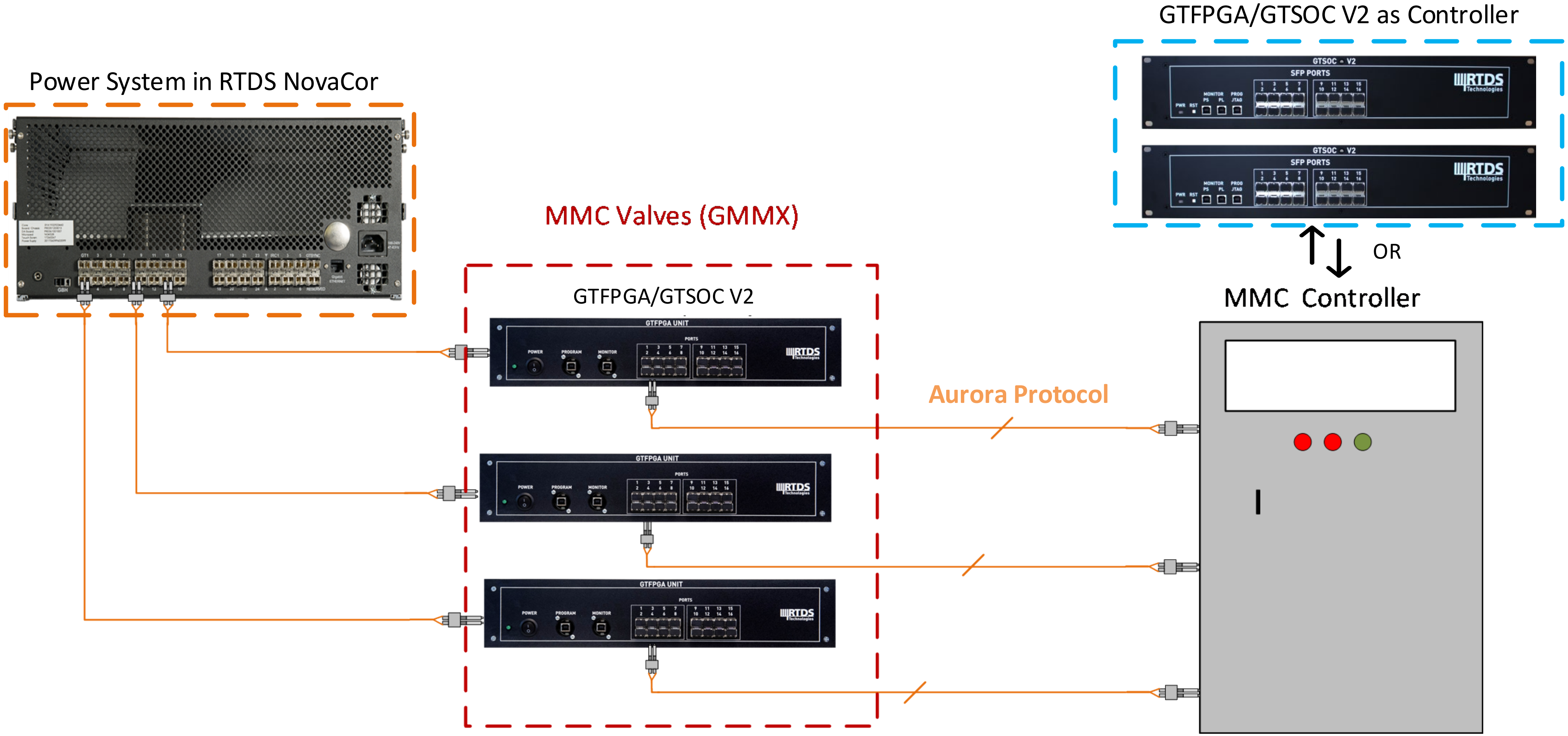
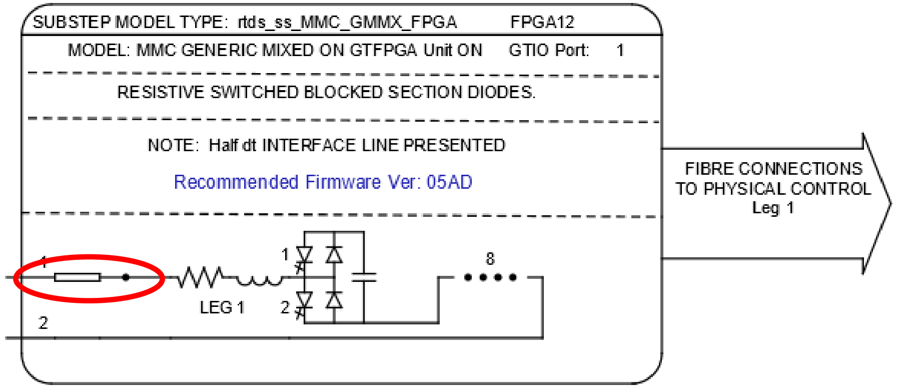


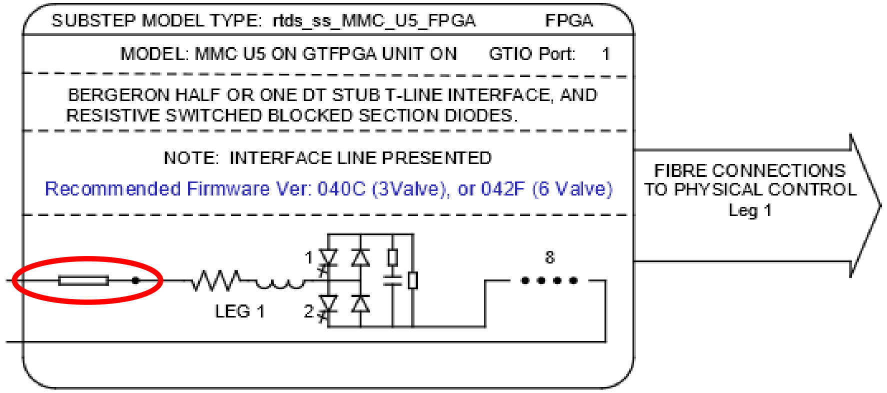
Figure 3-2 MMC CHIL Testing Connection Diagram

FPGA-Based Models with T-Line

GMMX



U5



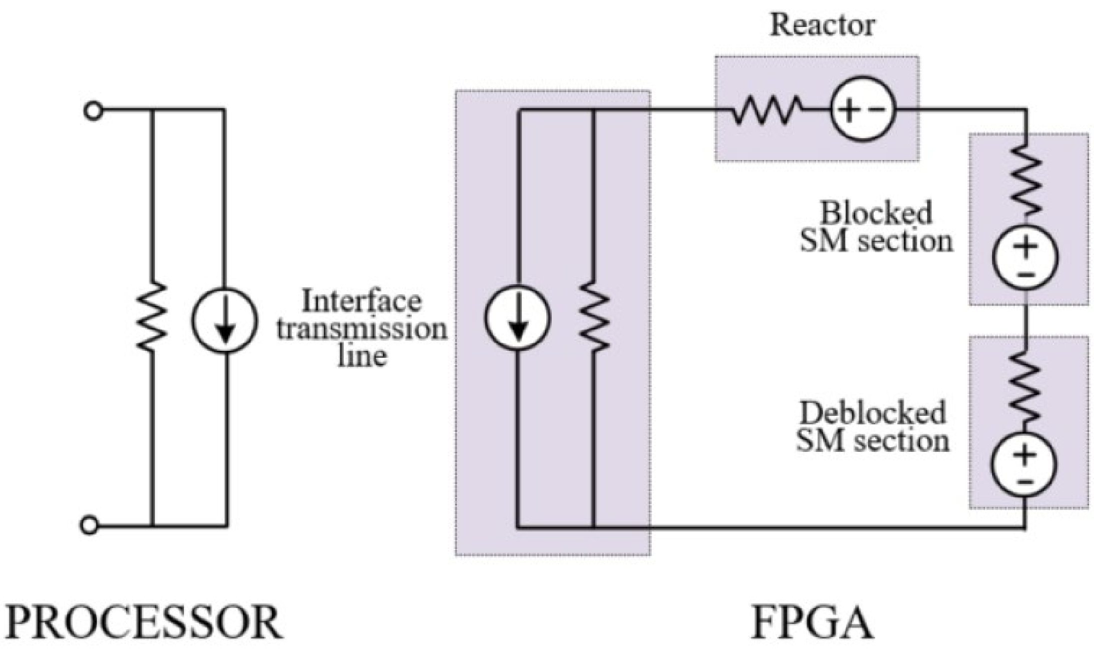
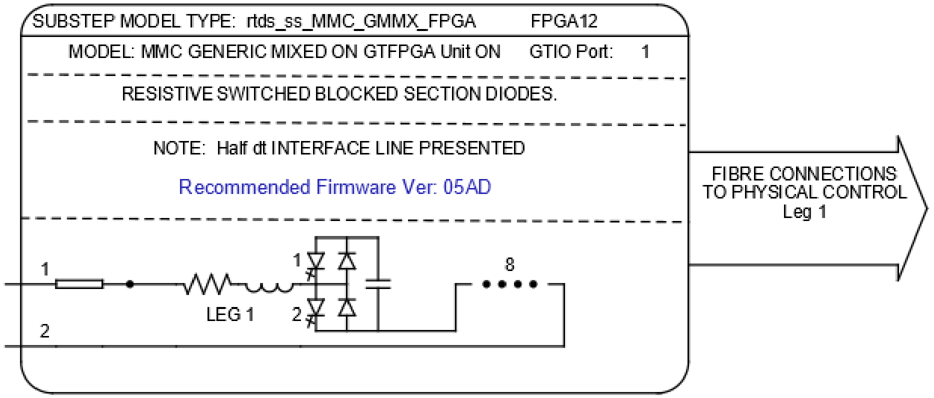


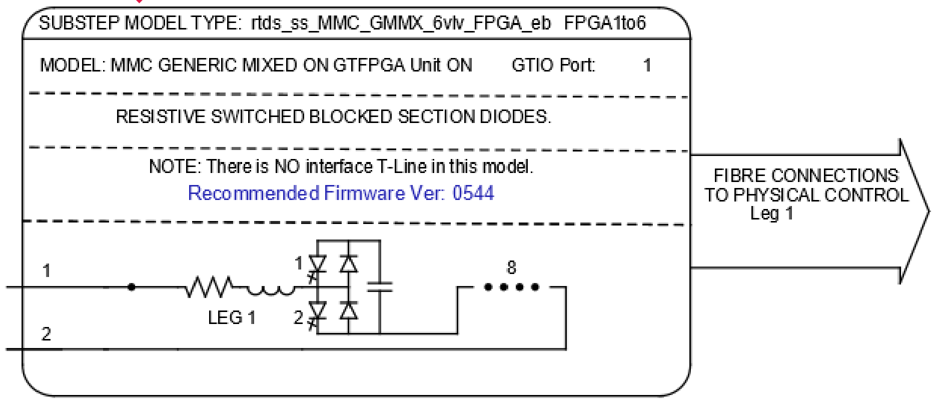
Figure 3-3 Equivalent of Surrogate Network

New Embedded MMC Valve Models

GMMX



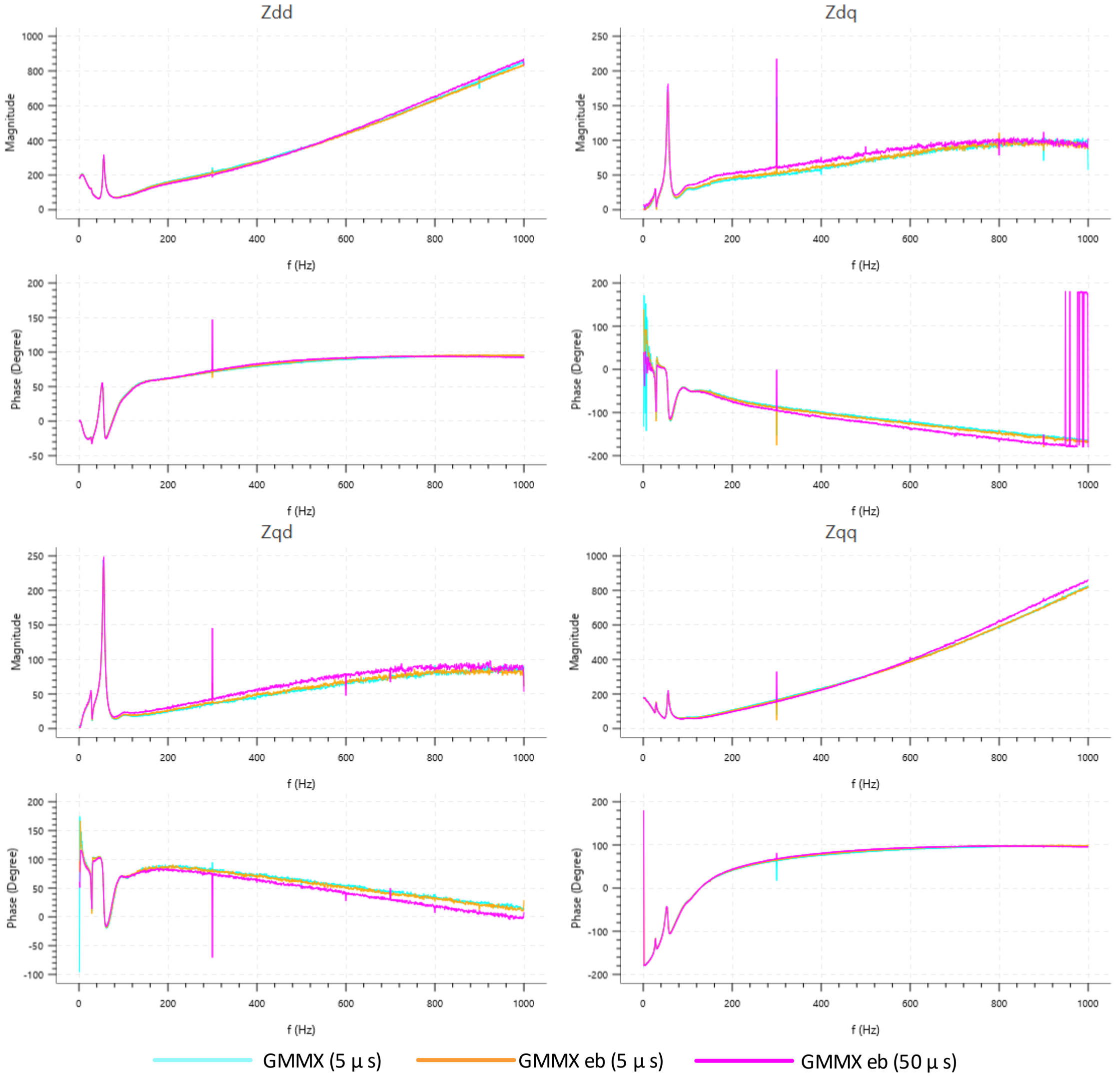
GMMX eb



Features of Embedded MMC Valve Models

- No interfacing transmission line is needed.
- Capable to run simulation at both main timestep (10 - 50 μs) and substep environment (< 10 μs) in real-time.
- In substep environment, it maintained accuracy to represent high frequency harmonic contents.
- In main timestep, it allows CHIL simulation to test physical controller with low level controls that include detailed switching pulses.
- In main timestep, no interfacing components is required, and it also reduces the computational resources needed to run the simulation.

Impacts of the Additional T-Line



Studied Case: CIGRE Benchmark Case DCS1

- In substep environment (5 μs), both GMMX and GMMX eb models showed identical impedance characteristics.
- The additional T-line have negligible impacts to the simulation results when timestep is small.
- In main timestep (50 μs), GMMX eb model can still represent very similar impedance characteristics compared to the results in substep.
- Overall, GMMX eb model is suitable for system level study in main timestep and eliminates the potential impacts from the interfacing components, which need to be carefully constructed.

MMC-HVDC Offshore Windfarm Sample Case

RTDS Technologies
AMETEK

RTDS.COM

Offshore Wind farm Structure

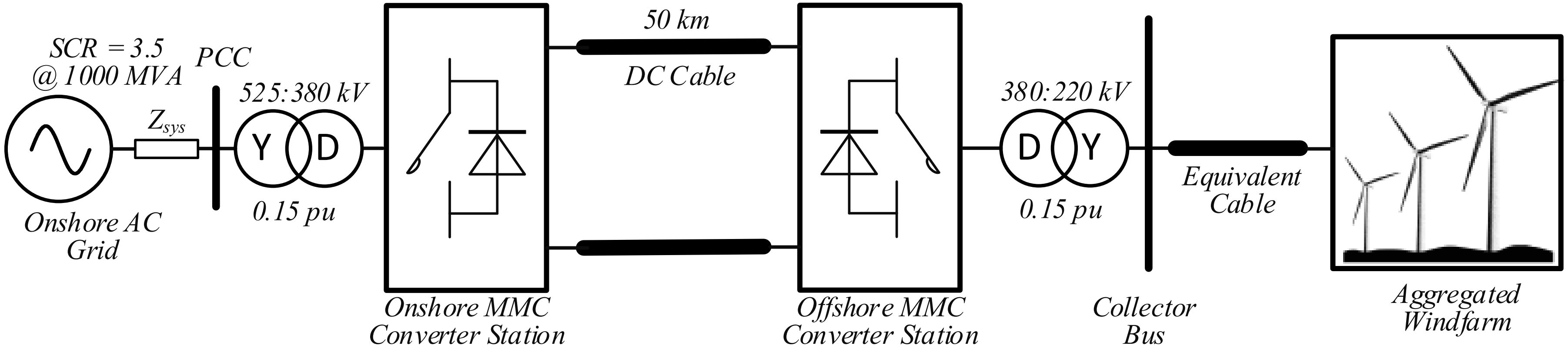


Figure 4-1 MMC-HVDC Offshore Windfarm

Table 4-1 Parameters of MMC Converters

Parameters	Onshore MMC	Offshore MMC
Topology	*Symmetrical Monopole, half-bridge SMs*	
DC Voltage	*±320 kV*	
Rated Power	*1 GW*	
Number of SMs	*320 per arm*	
SM Capacitance	*12500.0 µF, EoP of 48 kJ/MW*	
Arm Inductance	*0.06895 H or 0.05 pu*	
High-level Control	*DC Voltage, V_{ac} or Q @ PCC*	*AC Voltage and Frequency*

Wind Turbine Generators

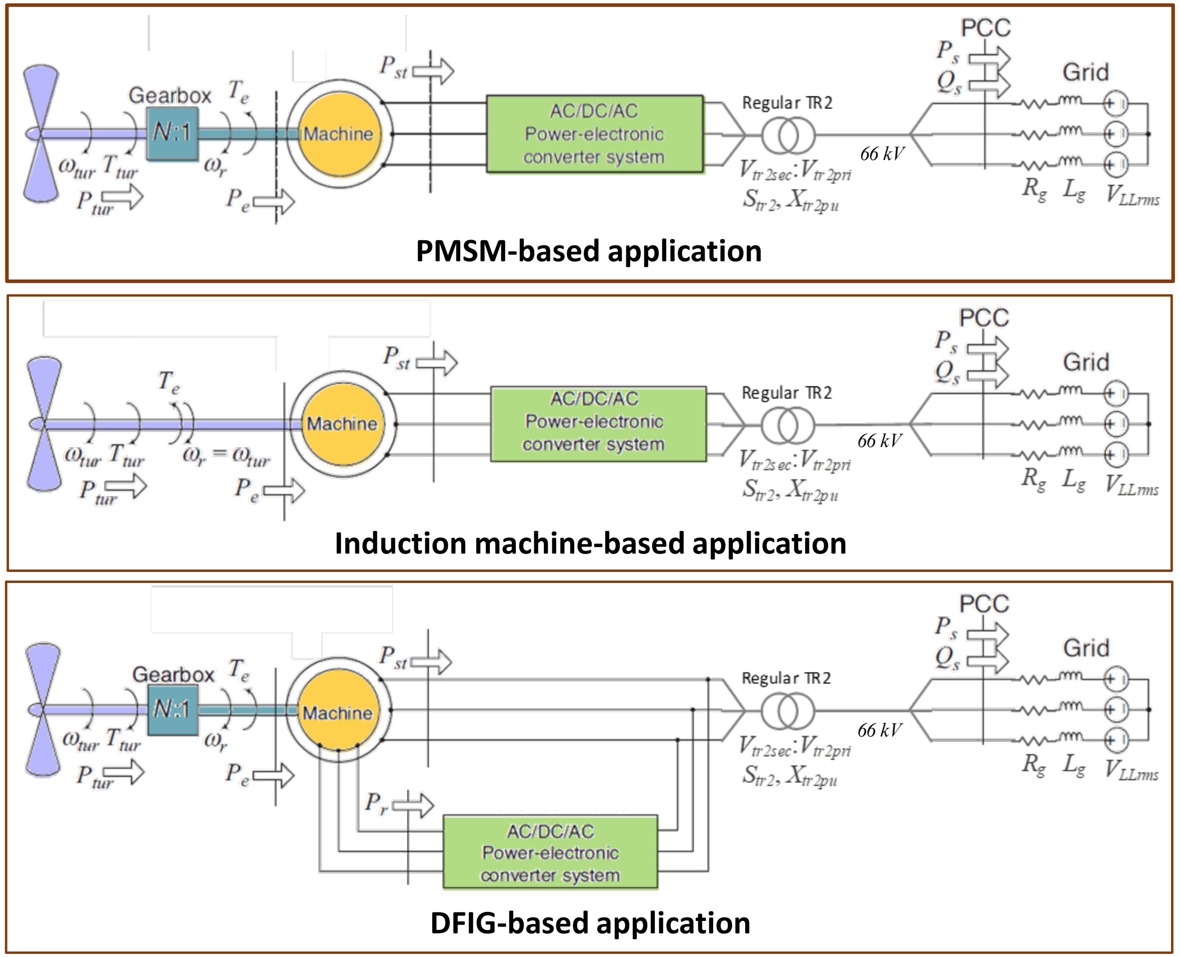


Figure 4-2 Typical Types of Wind Turbine Generators

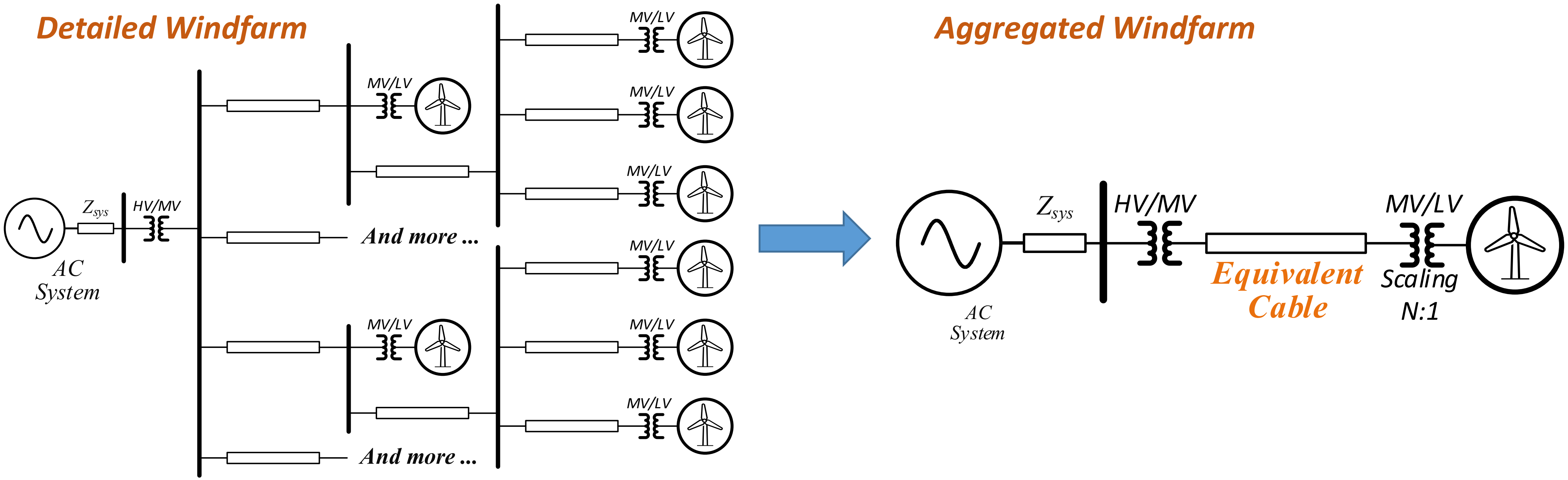
Table 4-2 Parameters of WTG

Wind Turbine Generators Parameters	
WTG Type	*Type – 4 PMSM-based*
Regular TR2	*66 kV: 3.3kV, 10 MVA, 0.1 pu*
Machine	*66 kV: 3.3kV, 10 MVA* *PMSM: 12Hz* *Stator Leakage 0.1 pu* *Inertia Constant 3.5 s*
Wind Turbine	*10 MW, 12m/s rated wind speed*
PE Topology	*Back-to-Back 3L-VSC (ANPC)*

For WTG Modelling:

- Machine Model
- Wind Turbine Model
- System Control →
  - Grid-side control
  - Motor-side control
  - MPPT for WTG

Aggregated Windfarm



❑ Windfarm Aggregation:

- **Methodology:** Model one wind turbine with real system parameters, and scale up the power by the scaling transformer
- **Equivalent Cable:** the RXB values of the equivalent cable should match the detailed windfarm at studied frequency range
- **Advantages:** Significantly reduced the computational load and can still provide adequate accuracy for system level studies

Validation of Scaling Transformer

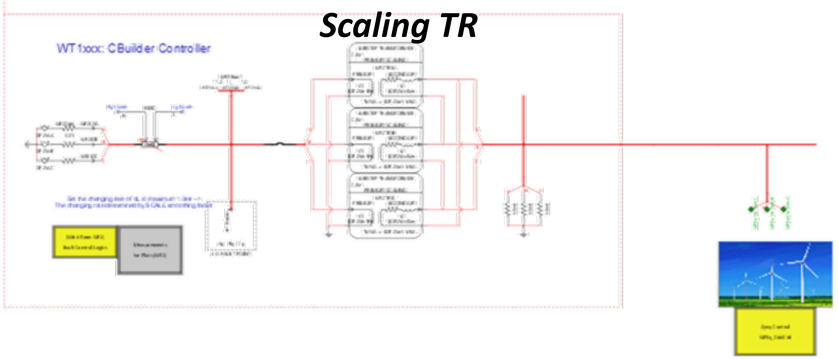
PMSM-based Wind Farm Simulation in Mainstep

Two system are compared (both use the scaling transformer model)

– Case 1 system uses only ONE wind turbine system

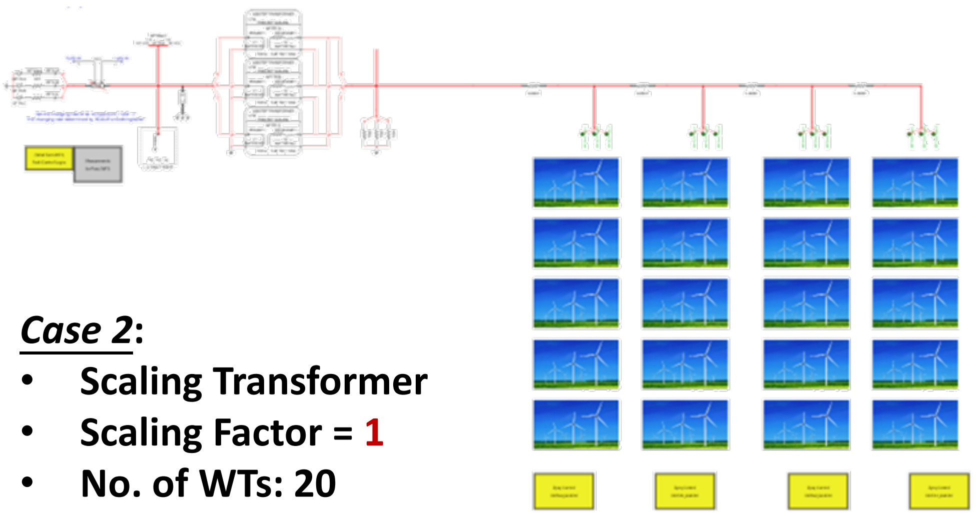
– Case 2 system uses 20 wind turbines

To validate the use of
ONE wind turbine + Scaling
to equivalent
multiple wind turbines



f_{sw} = 2 kHz

***Case 1*:**
- **Scaling Transformer**
- **Scaling Factor = 20**
- **No. of WTs: 1**



***Case 2*:**
- **Scaling Transformer**
- **Scaling Factor = 1**
- **No. of WTs: 20**

Validation of Scaling Transformer

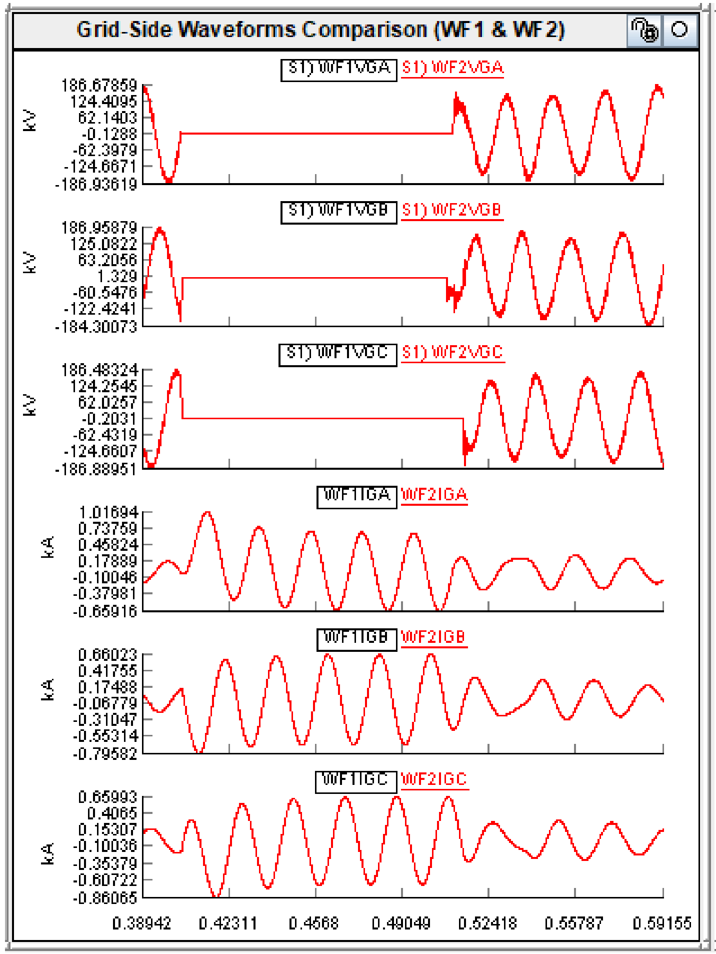
Testing PMSM-based Wind Farm: Simulation timestep *50 µs*, f_o *= 50 Hz*, one WTG P_{base} *= 2.5 MW*
Three phase to ground fault

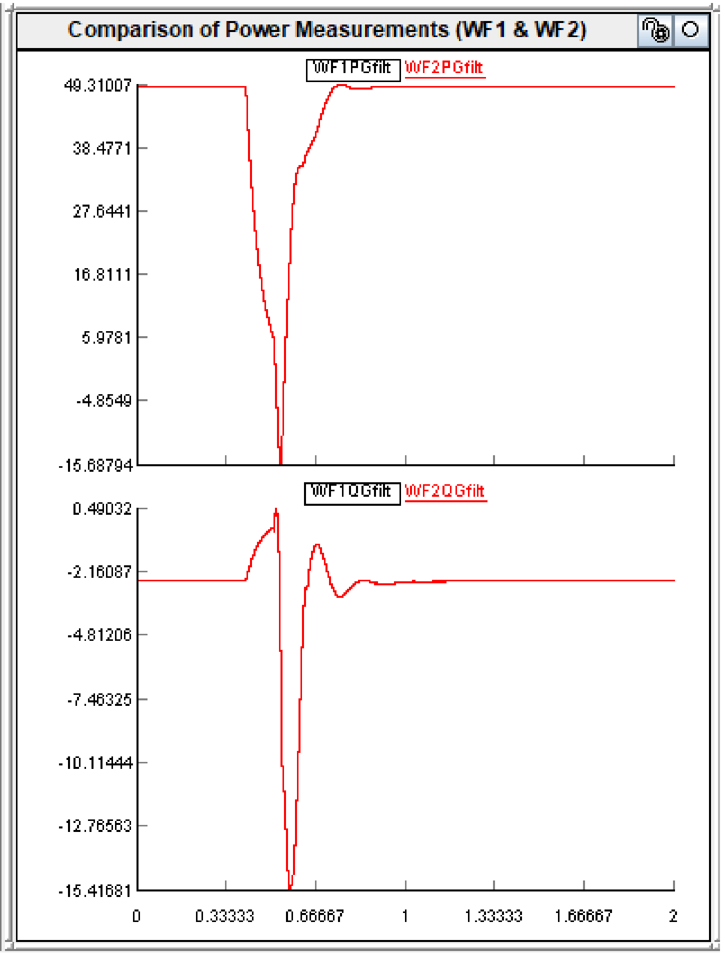
WF1: Scaling system
(Scaling TR Scale = 20 + 1 WTG)
WF2: Detailed system
(Scaling TR Scale = 1 + 20 WTGs)

<u>Observation:</u>

The results of the two systems are the same from observation.

Therefore, it is effective to use one wind turbine and scaling to represent multiple wind turbines.



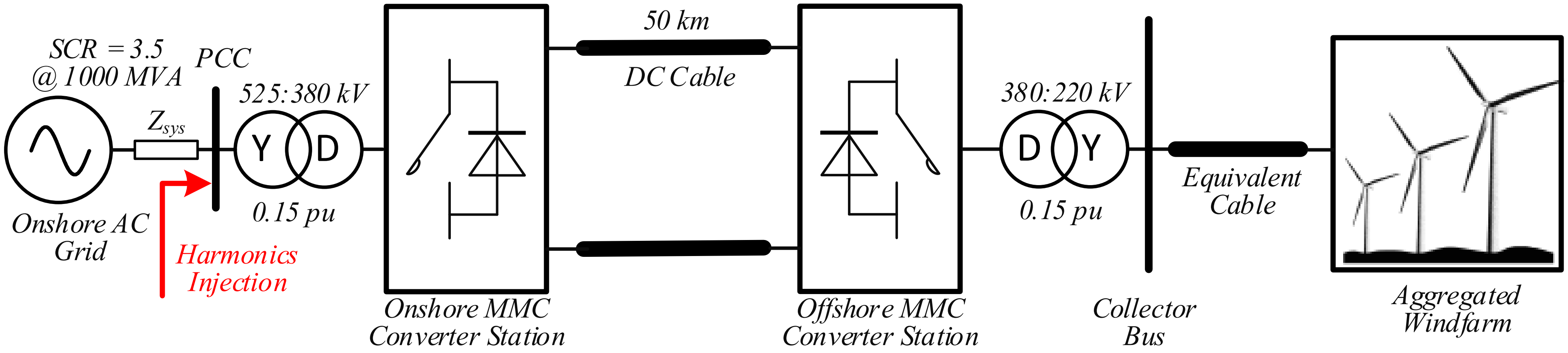


Simulation Requirements

Figure 4-3 Hardware Setup

Simulation Requirements	
Timestep	*50 µs for the entire case*
Hardware	*2 Cores on RTDS NovaCor 1.0 or 2.0* *3 GTSOC V2 for MMC Valves Models* *2 GTSOC V2 for MMC Valves Controller*
Converter Models	*Onshore MMC: MMC5_2VLV* *Offshore MMC: GMMX_eb* *WTG VSCs: rtds_ss_UCM_NPC*

Stability Analysis – Frequency Scan



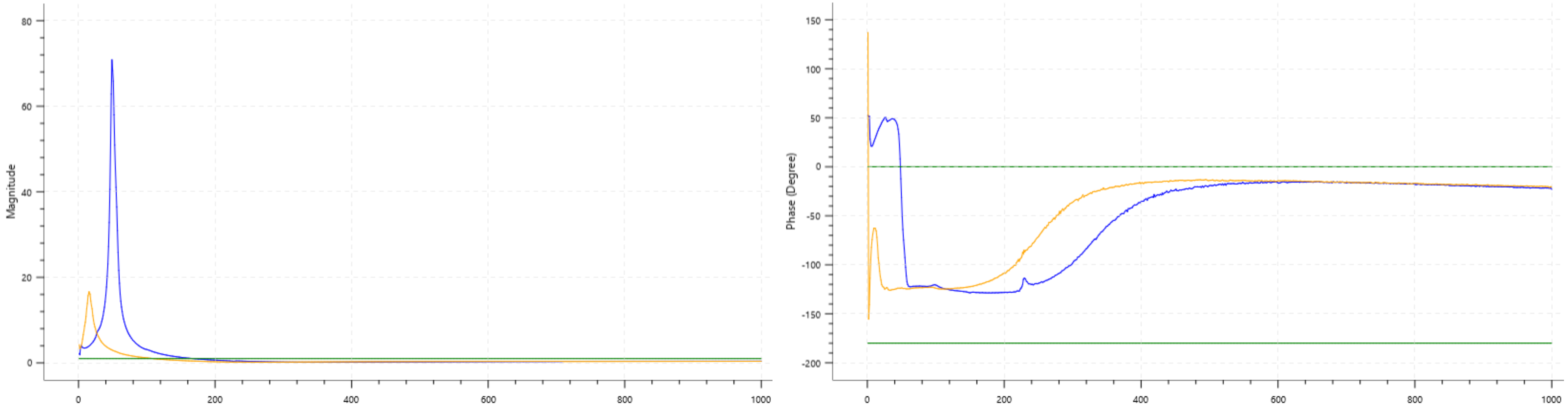
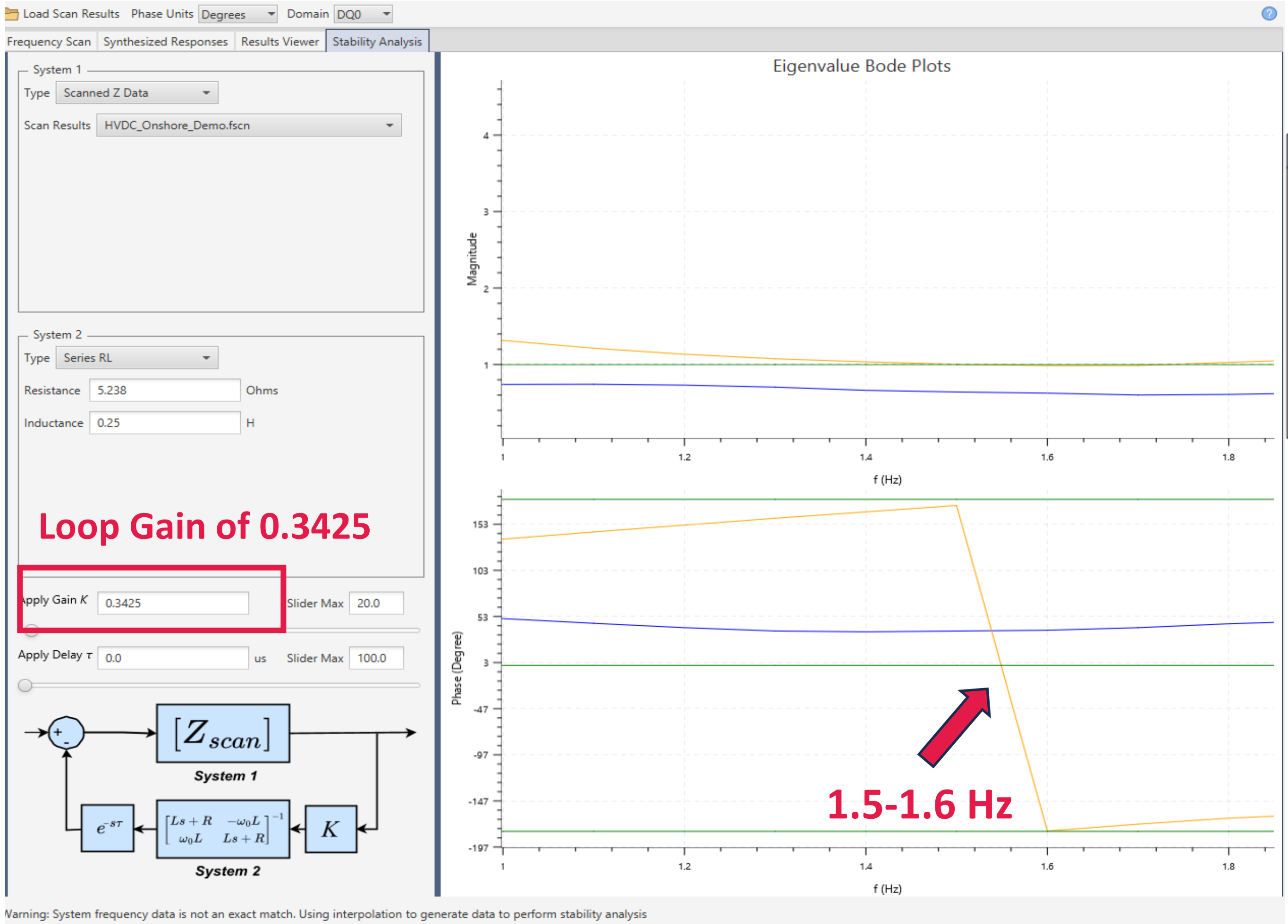
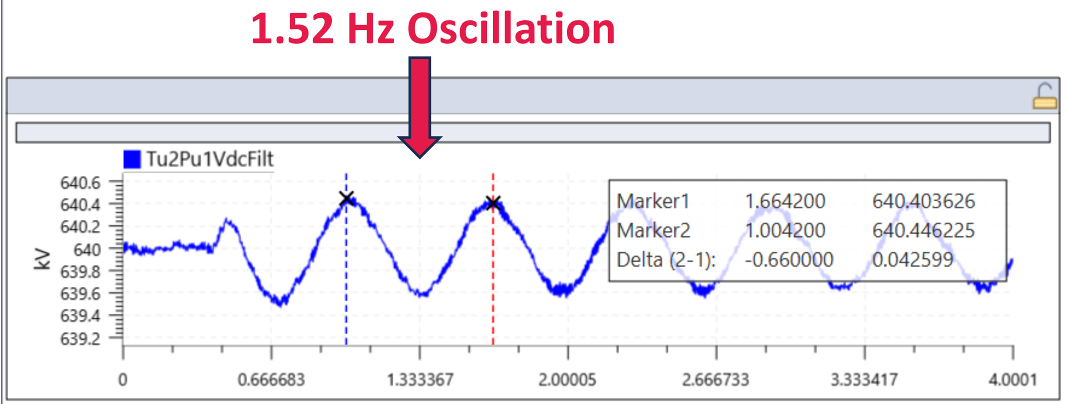


Figure 4-4 Bode Plots of Eigenvalues

Stability Analysis – Frequency Scan





By adjusting the loop gain K to 0.3425, which means the SCR was adjusted to 1.2, the DC link voltage showed an oscillation frequency of 1.52 Hz at the same operating point. This result matches to what we have observed from the simulation

Thank you!

Bruce Liu bruce.liu@ametek.com

1. *PSCAD, "Modeling and Simulation Studies to Facilitate Offshore Wind and HVDC Systems," 2021.*
2. *S. Filizadeh, "Modular Multilevel Converter Systems and Applications," Graduate Course, University of Manitoba, 2020.*
3. *Working Group B4.57, CIGRE, "Guide for the Development of Models for HVDC Converters in a HVDC Grid," December 2014.*

RTDS Technologies
AMETEK®

RTDS.COM