

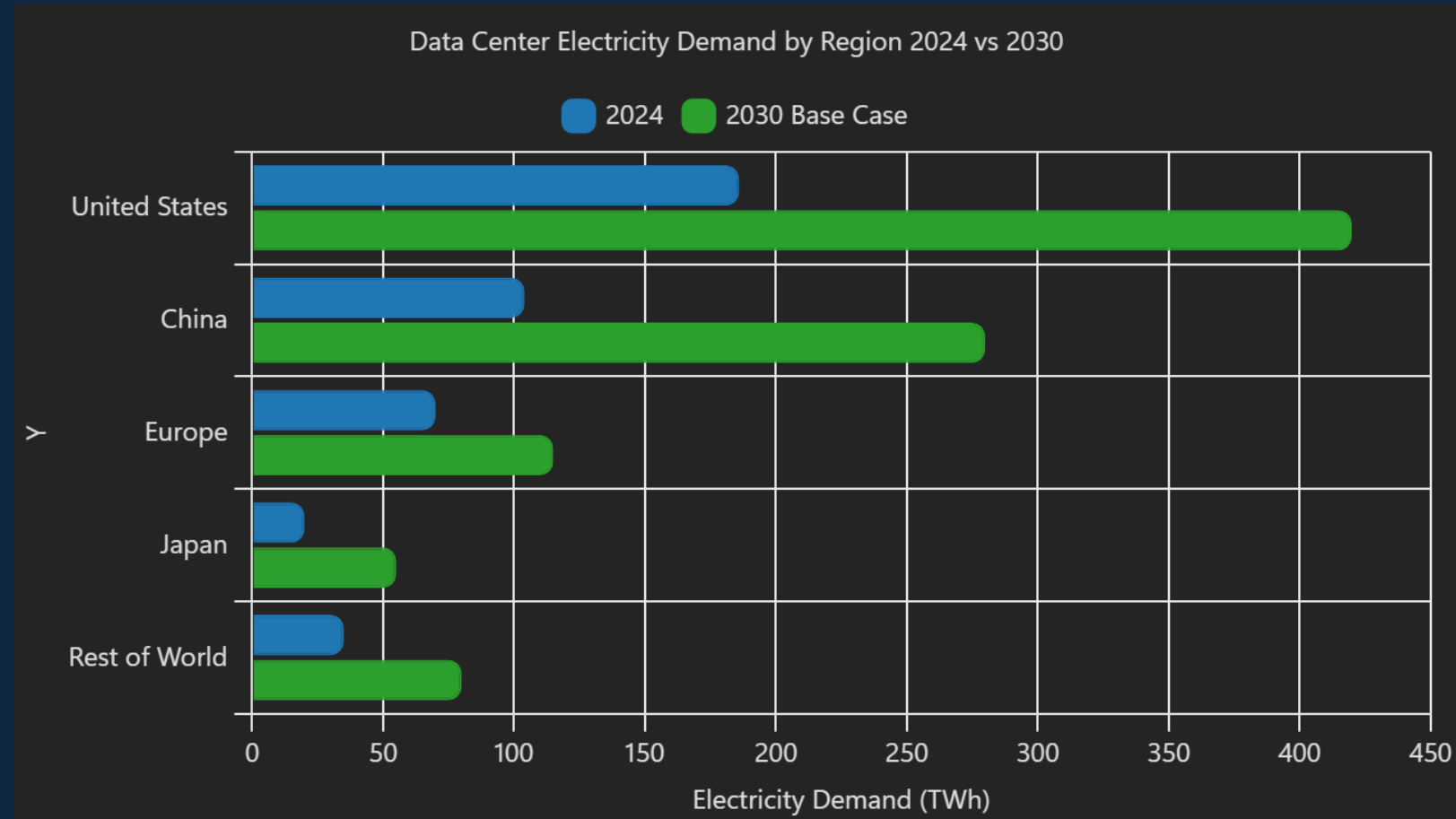
Data Center Power System Modelling: Supporting Current and Next Generation Architecture

- ▶ Sumek Elimban, Director – Product Applications
- ▶ RTDS Technologies Inc.



AI & Data Center Load Growth

- AI data center electricity demand may increase from 415 TWh (2024) to approximately 950 TWh (2030)
- AI, cloud, and digital services are driving growth
- Hyperscaler investment exceeds \$400B/year
- Higher power density is driving changes in electrical distribution architectures
- Increased grid impact and regulatory attention



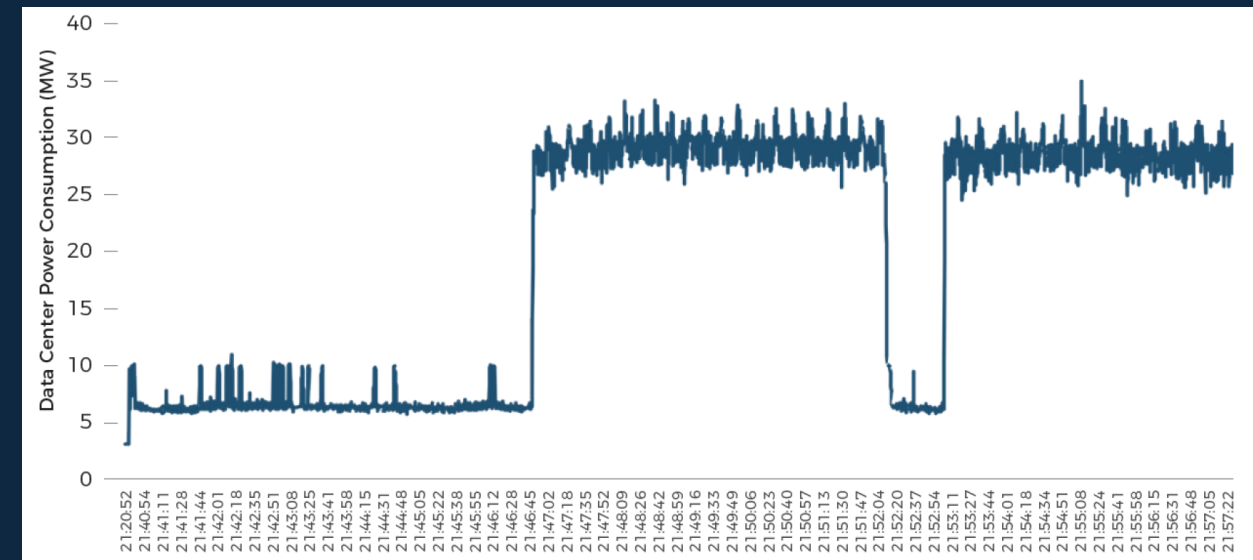
Source: IEA Report Key Questions on Energy and AI 2026

AI & Data Center Load Growth

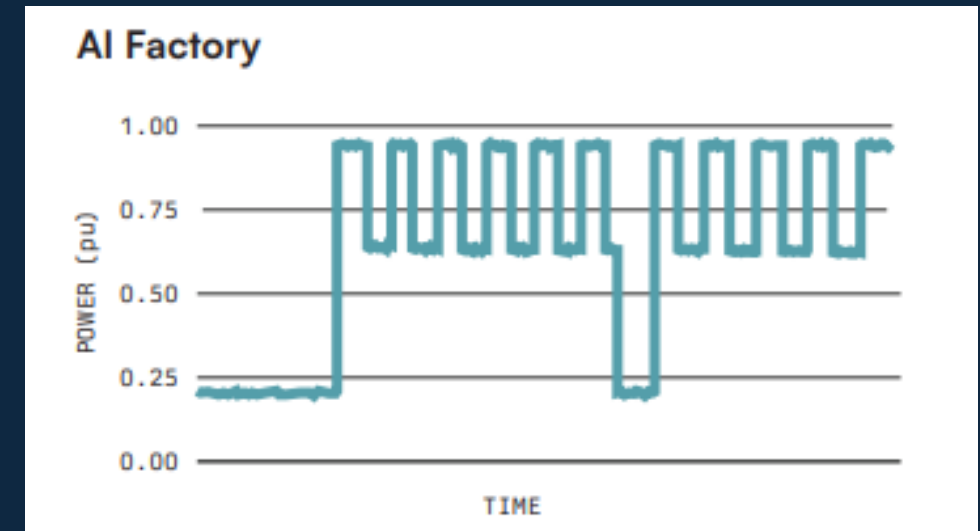
- Rapid rise in power demand at the rack level
 - 100KW → 600 KW
 - Expected to reach 1 MW racks for next generation AI (2027).
- Modern Data centers are often 100-500 MW facilities
 - 1-2 GW facilities proposed in the future
- Unprecedented performance requirements:
 - Critical loads → 99.9995% availability requirements

Key characteristics

- Power electronic interface
- Variable Consumption and fast changing loads
- Ride-through and disconnection behavior:
- Voltage and frequency interaction risks
- Geographic clusters of large loads
- Sites features co-located generation



Source: ETP



Source: Heron Power

Modelling Challenges

- Limited mature generic models available
- Limited standardization for data center EMT model
- Limited OEM EMT models
- Insufficient data availability for parameterization

Data Center Components

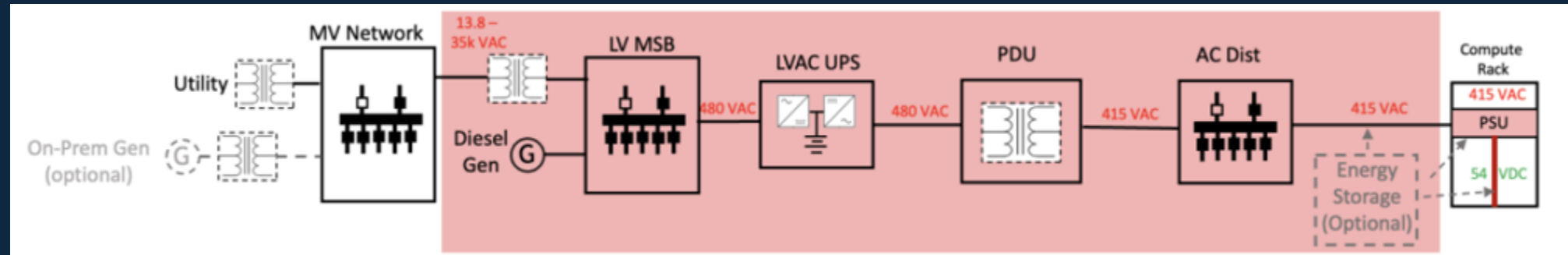
- **IT equipment:** 40–50% Energy Consumption
- **Cooling systems:** 30–40% Energy Consumption
- **Auxiliary systems:** 10–30% Energy Consumption
- Component mix drives overall electrical behavior



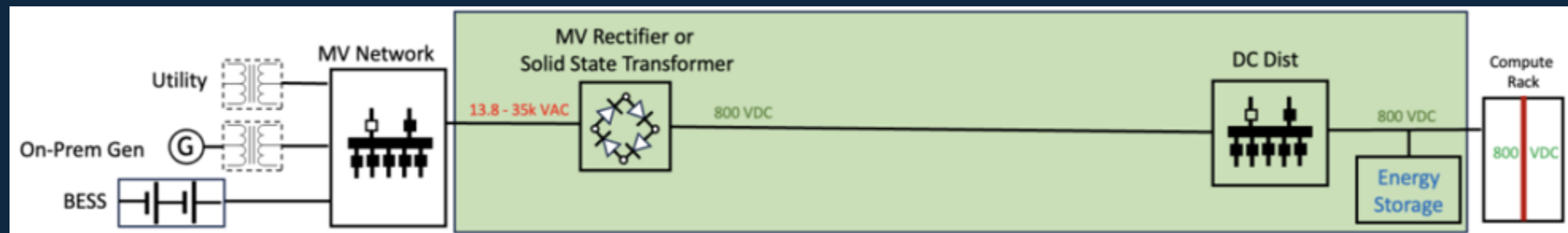
Source: TRG

Current and Next Generation Power Architecture

Today – 415 VAC distribution



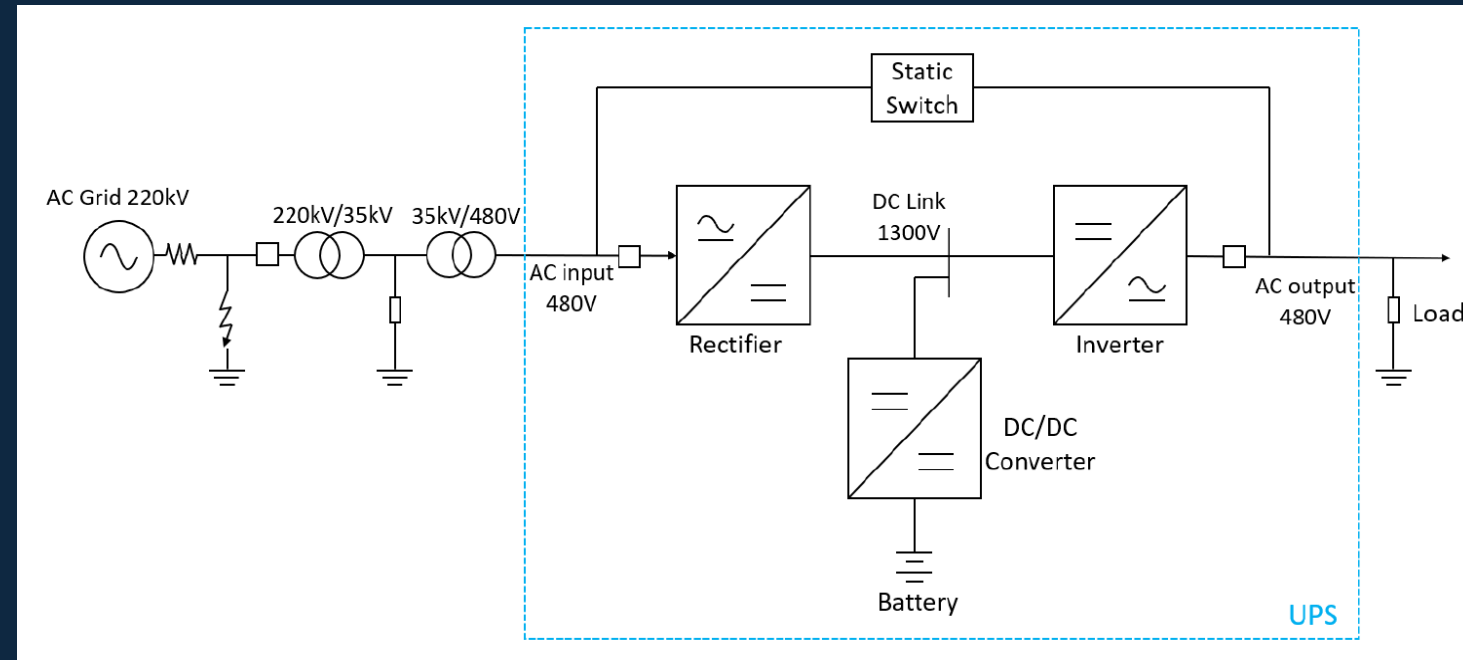
Future – 800V VDC distribution



Source: NVIDIA 800 VDC Architecture for Next-Generation AI Infrastructure

Uninterruptible Power Supply (UPS)

- Decouples grid and critical load
- Provides conditioned power to the load
- Provide temporary batter support
- Can abruptly disconnect DC load from the grid
- Key component in the modern data centers
- **Derisking protection and control system is important**



Double conversion UPS

UPS Operation modes

Double Conversion (Online) mode

- UPS switch path supports the load with conditioned power. Battery can be charged. Rectifier regulates DC link

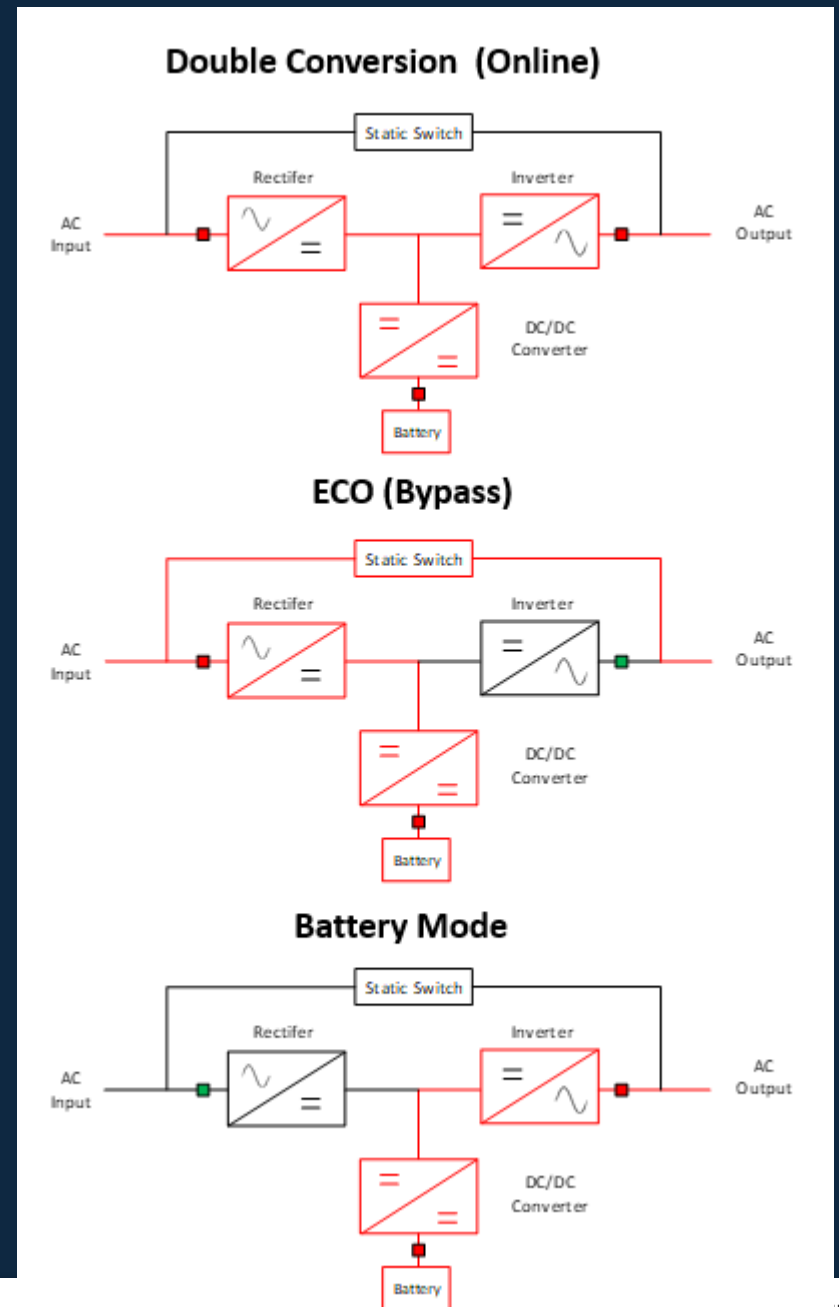
ECO (Bypass) mode

- Static switch is “closed” and load is supplied directly from Input (grid). Can reduce energy loss. Battery can be charged

Battery mode

- UPS disconnects (e.g. supply failure) from input and transfer to battery to supply load with conditioned power. DC/DC converter regulates DC link

Mode transitions are a key study event



Cooling System

Do we need to represent the cooling system?

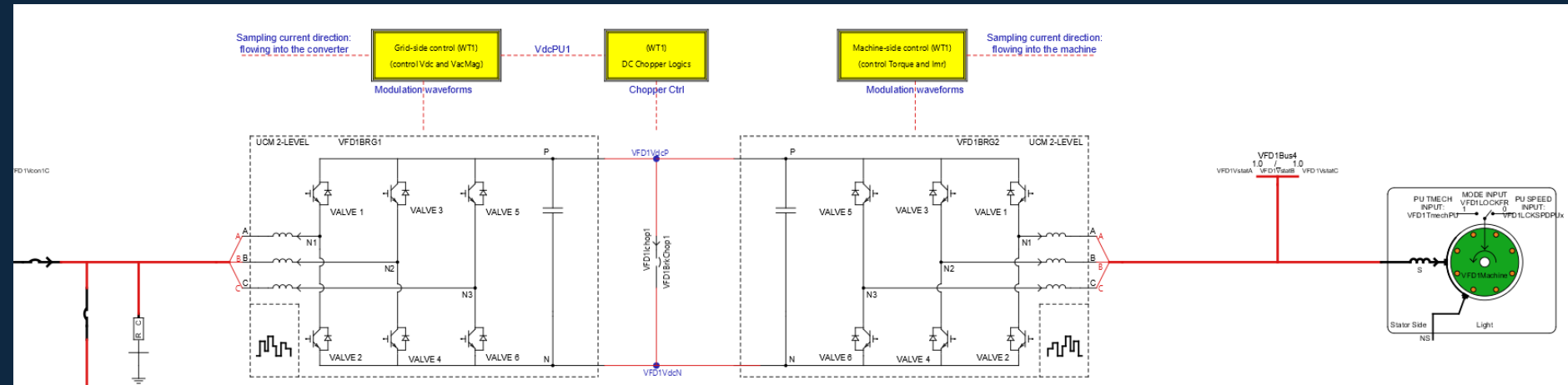
- Cooling system → 30-40% of energy consumption (PUE → ~1.3-1.4)

Chiller

- Introduce motor load behavior

Control Room Air Handler (CRAH)

- Often use variable frequency drives (VFD)
- VFD can affect transient responses

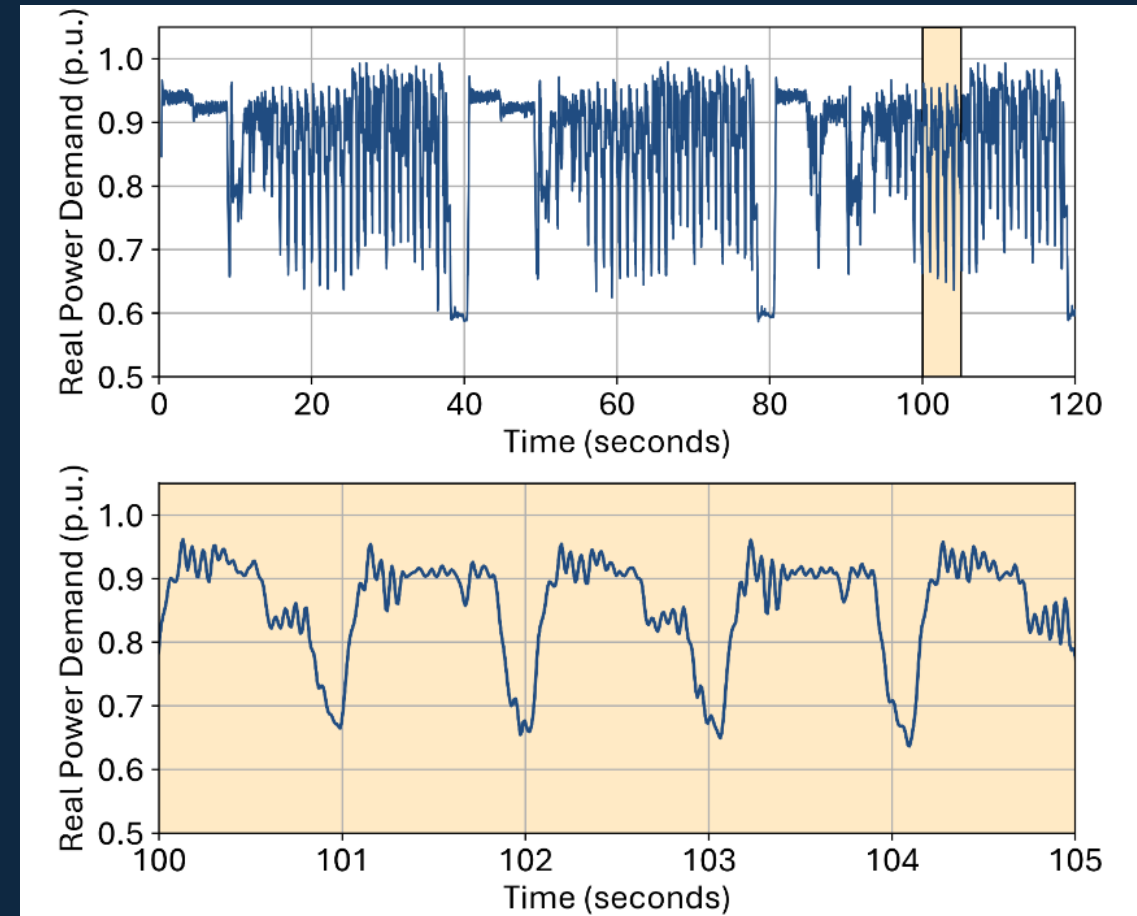


Variable Frequency Drive

AI Load

New generative AI load

- Fast transients and higher ramp rates
- Voltage fluctuation
- Possible sub-synchronous
- Modelling AI profiles is a major challenge
- Managing hundreds of MWs of load in fraction of a second is a major challenge.
 - Historic generation cannot support such swift changes; ramp rates are too slow.
 - IBR generation such as Wind and PV are intermittent



Ref: NERC whitepaper Characteristics and Risk of emerging Large loads

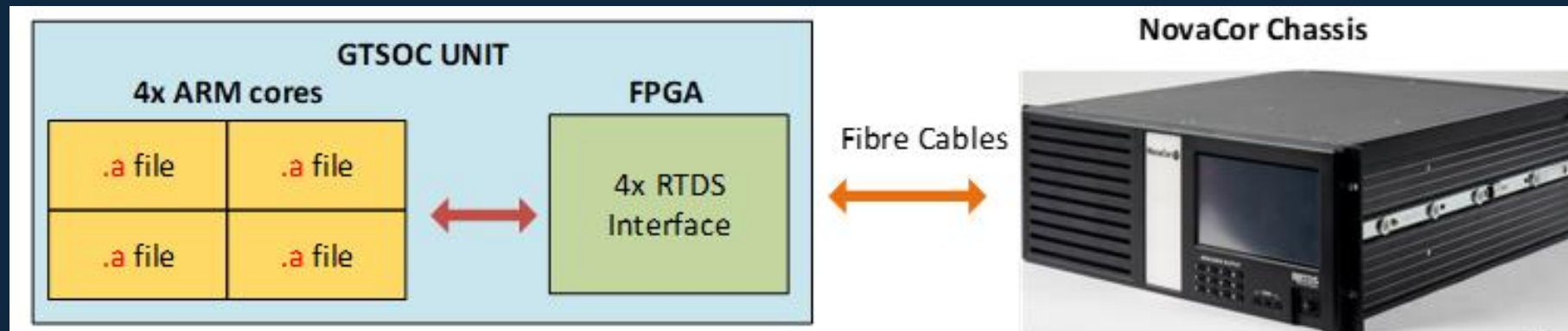
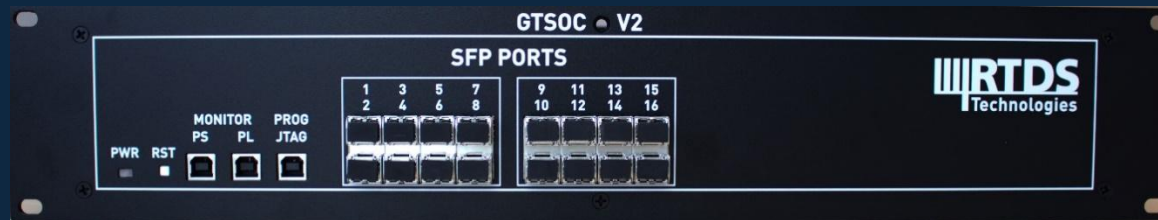
Energy Storage

- Co-located energy storage can provide grid support
 - Voltage and frequency support
 - Islanding support to data center (if needed)
 - Protect grid against oscillation and load surges from AI load
- BESS and/or E-STATCOM are possible solutions.
- Access to vendor models is important for accurate results



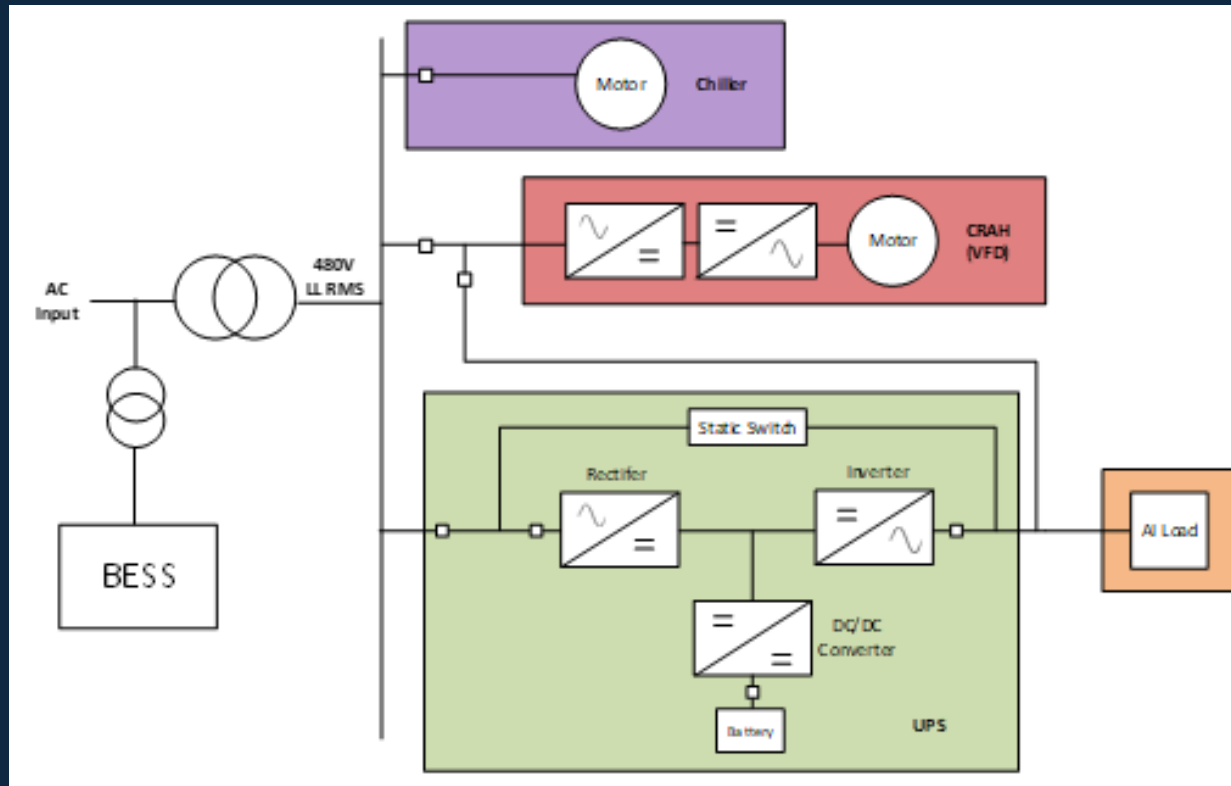
Software in the loop (SIL) black box models

- Useful when HIL is unavailable.
- Captures vendor control behavior
- Supported IBR and storage model accuracy.



Data Center modelling

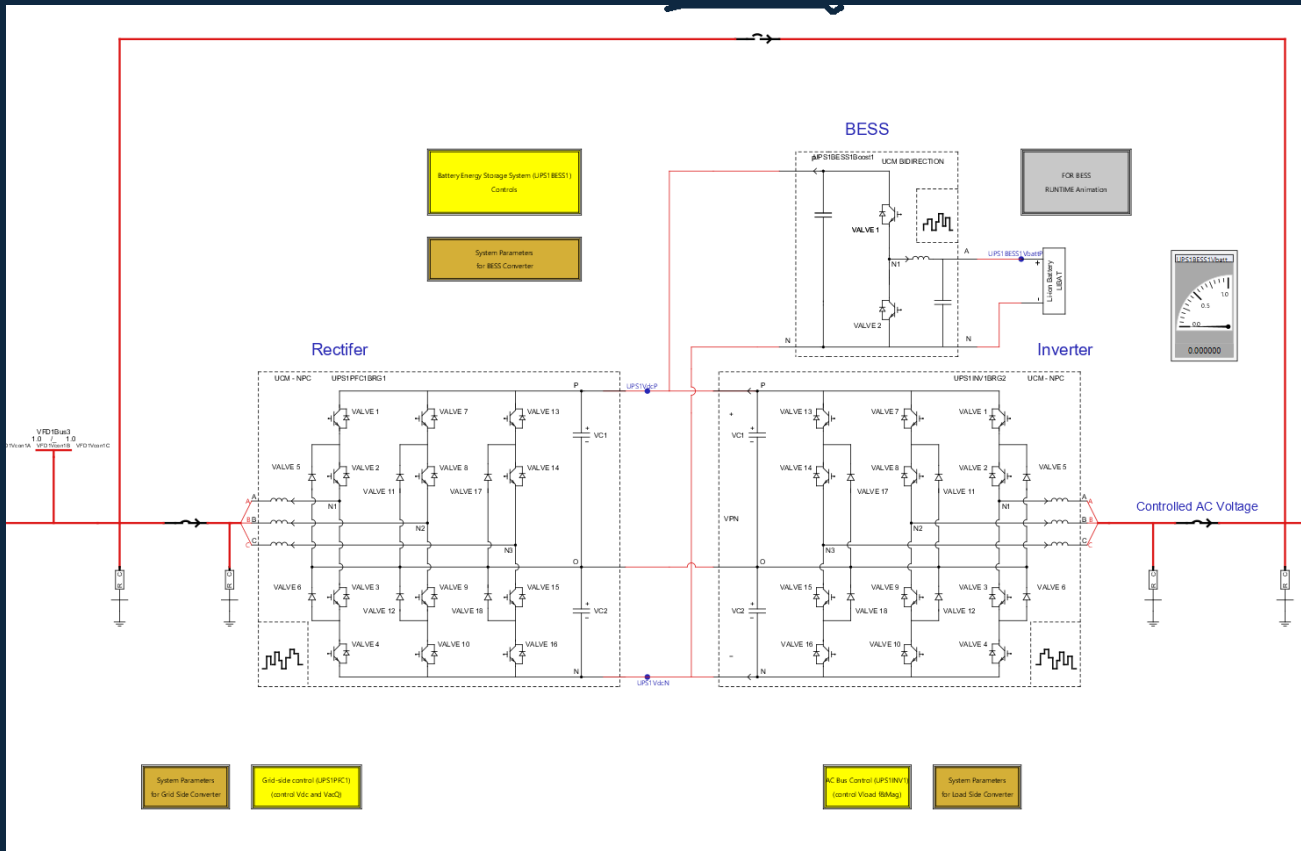
- No single standard model architecture
- Generic models may fit selected studies
- RTDS develop Data Center example model
 - Chiller
 - VFD CRAH
 - UPS
 - AI load
 - Co-located BESS (GFM controls)
- Aggregation for large facilities
- Continue development as the architecture evolves



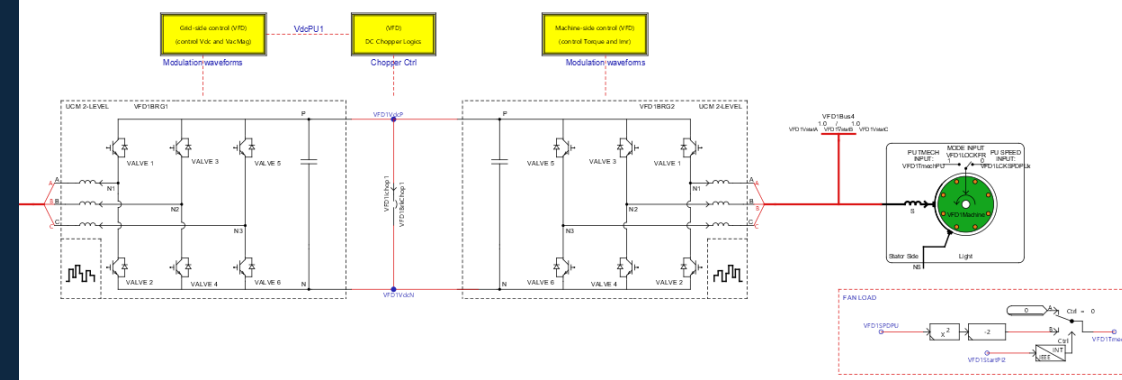
J. Sun, S. Wang, J. Wang and L. M. Tolbert, "Dynamic Model and Converter-Based Emulator of a Data Center Power Distribution System," in *IEEE Transactions on Power Electronics*, vol. 37, no. 7, pp. 8420-8432, July 2022

RTDS Data Center Modelling

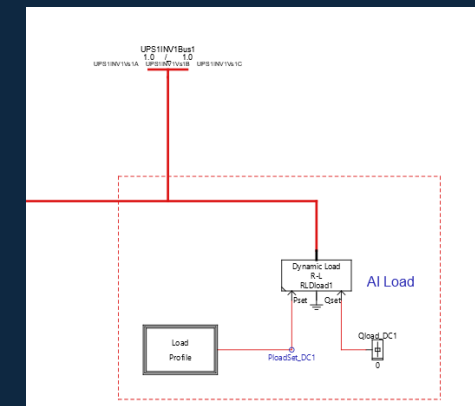
UPS



VFD (Cooling)

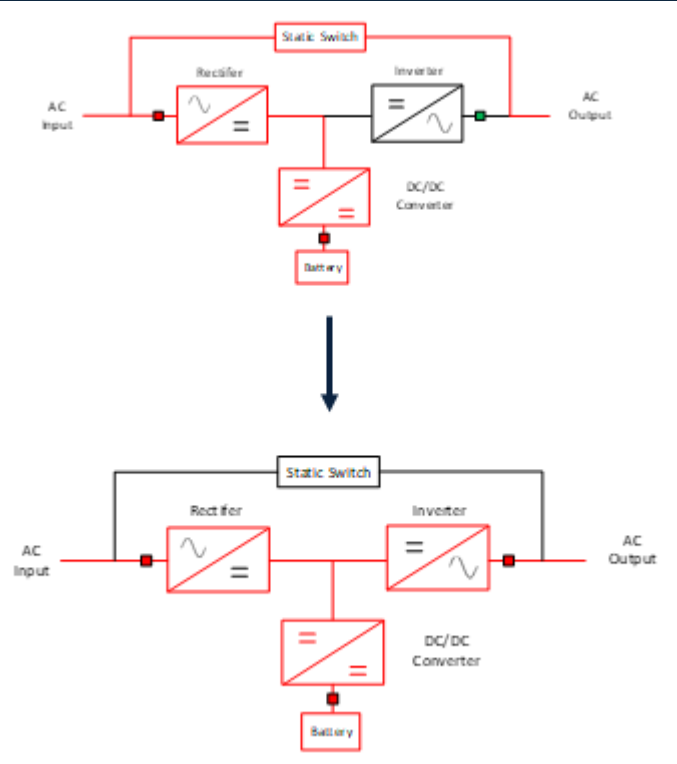


AI Load



Simulation Results

Testing functionality of the UPS control/protection

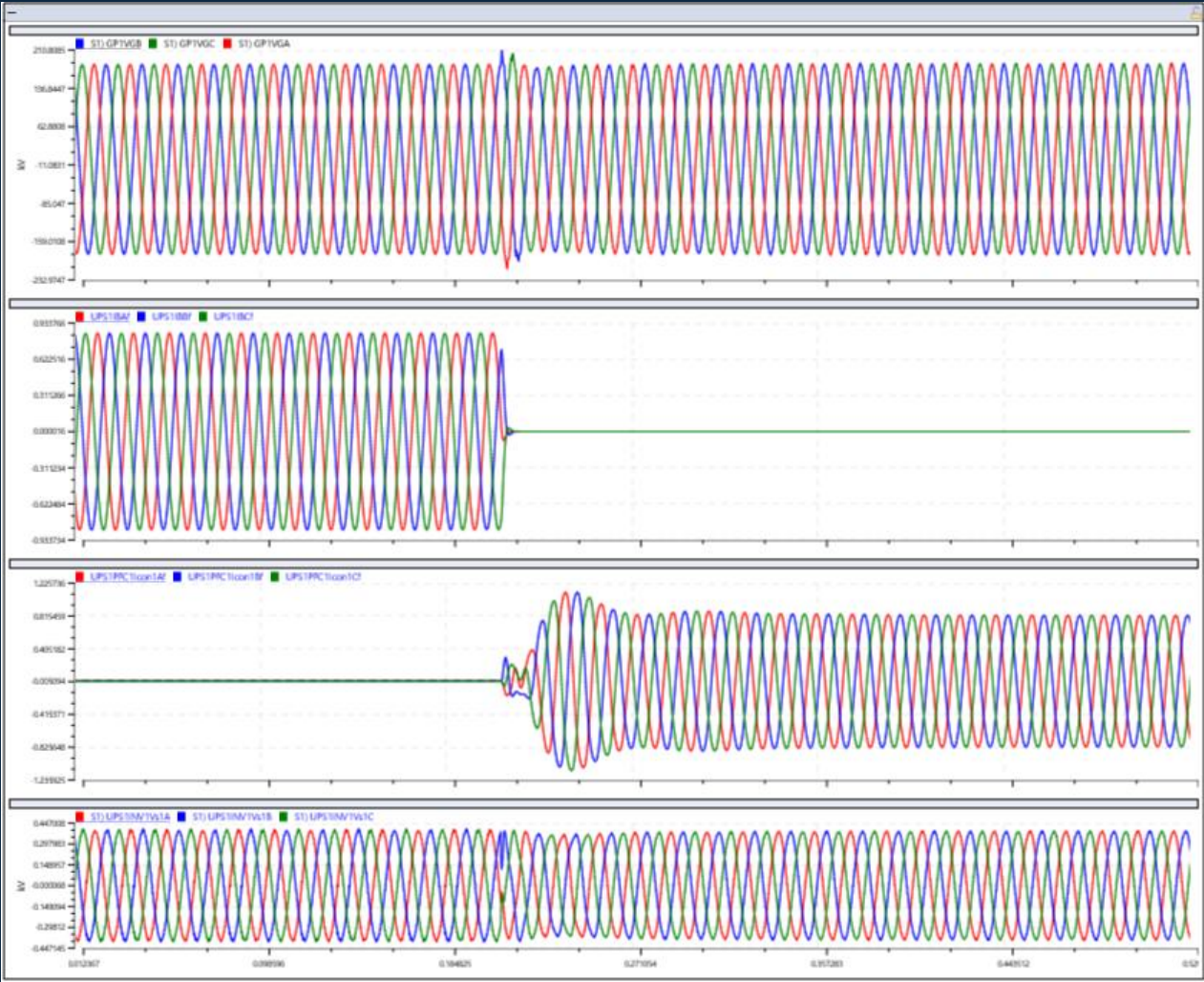


Grid Voltage (POI)

Bypass Current

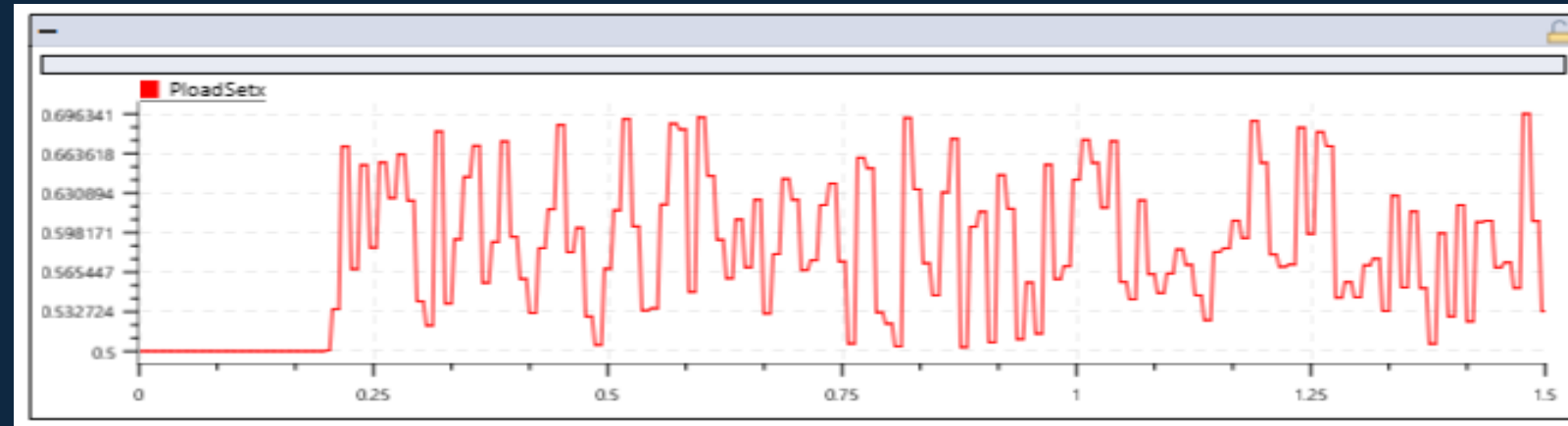
Online Current

Load Voltage

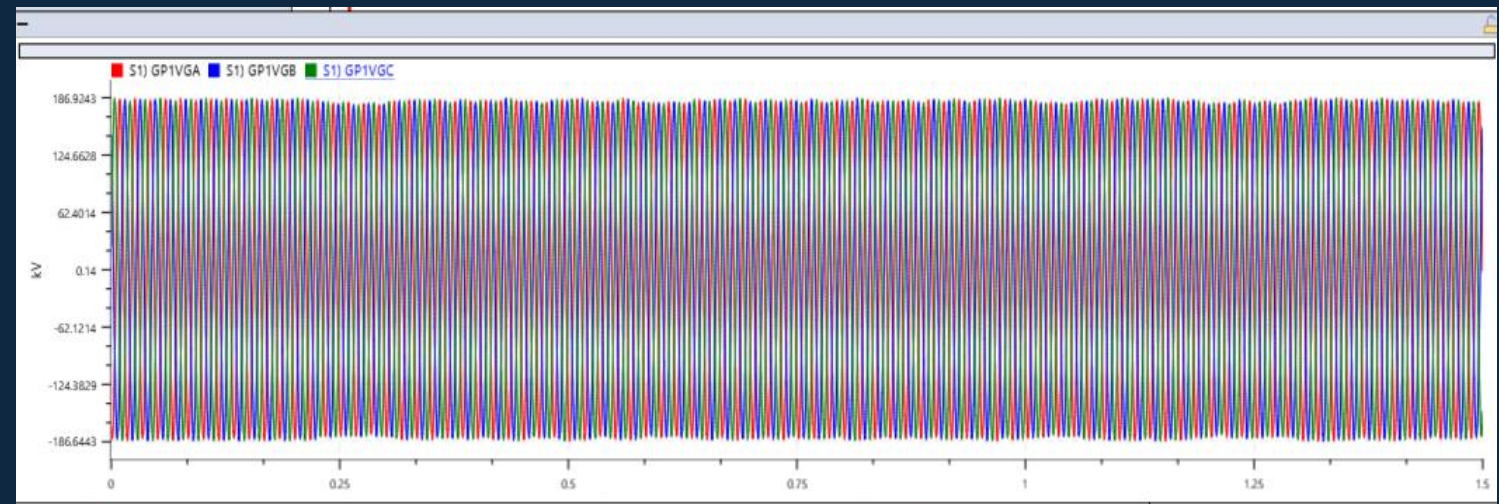


Simulation Results

- User defined load profile
- Sub-synchronous oscillations observed
- Playback of measured load profile

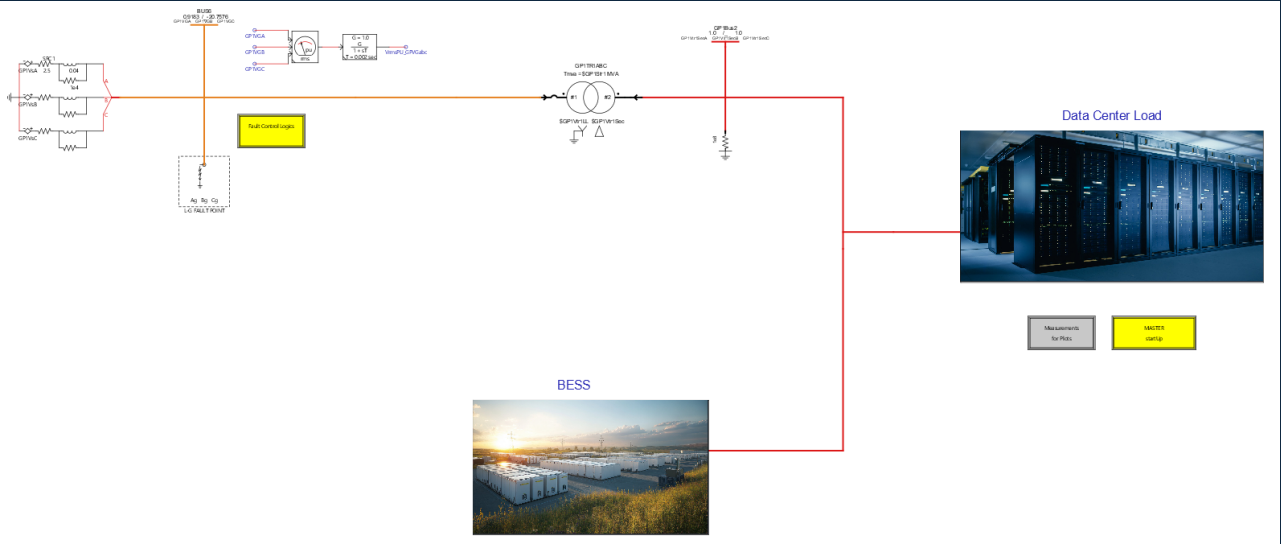


Load Profile

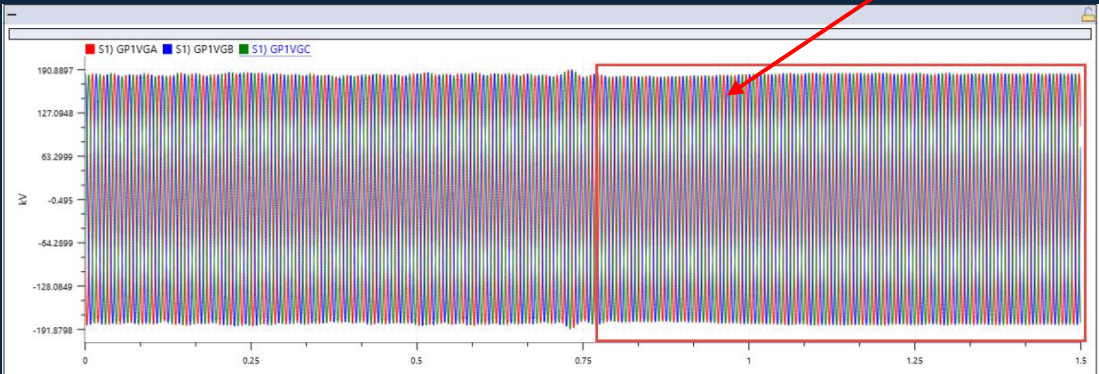


Simulation Results

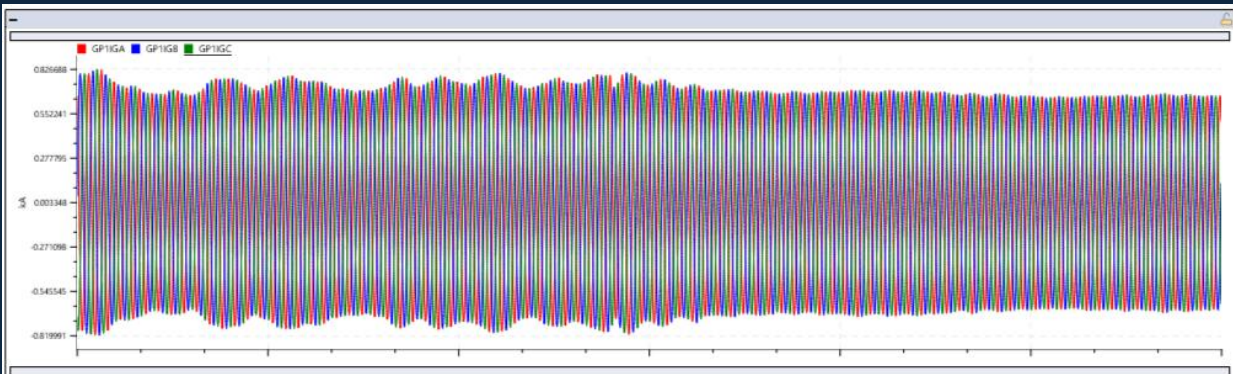
- GFM BESS can reduce load drive oscillation
- Inject or absorbed active/reactive power
- Voltage/Frequency support
- Reduces oscillation seen from the grid
- Can support surges from the load



**BESS
Enabled**



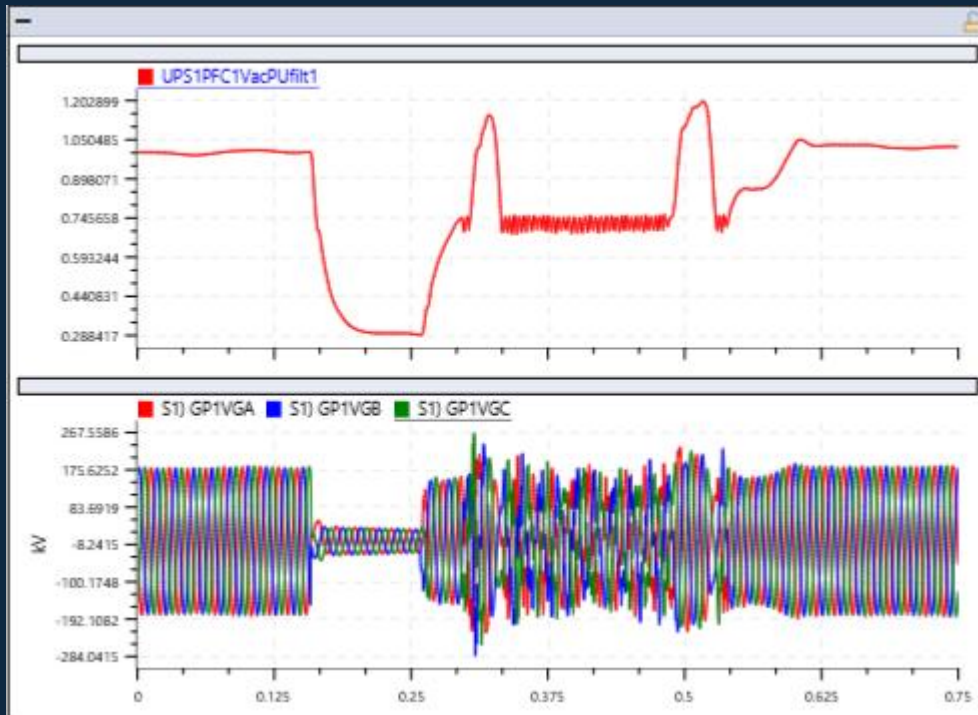
Grid Voltage (POI)



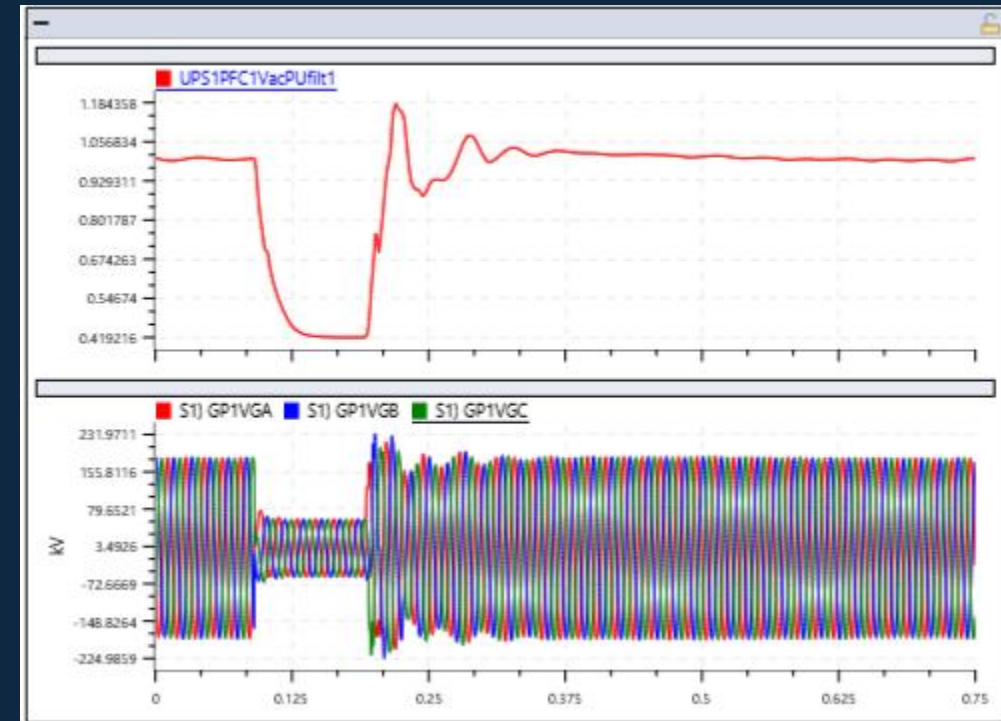
Current (POI)

Simulation Results

Severe fault at POI



Without GFM BESS



With GFM BESS

Applications

- Real time simulation helps identify design issues physical
 - Mal-operation of IBR controls (unexpected tripping)
 - Relay Coordination errors
 - Insufficient protection selectivity
 - Validate settings
 - Operators training



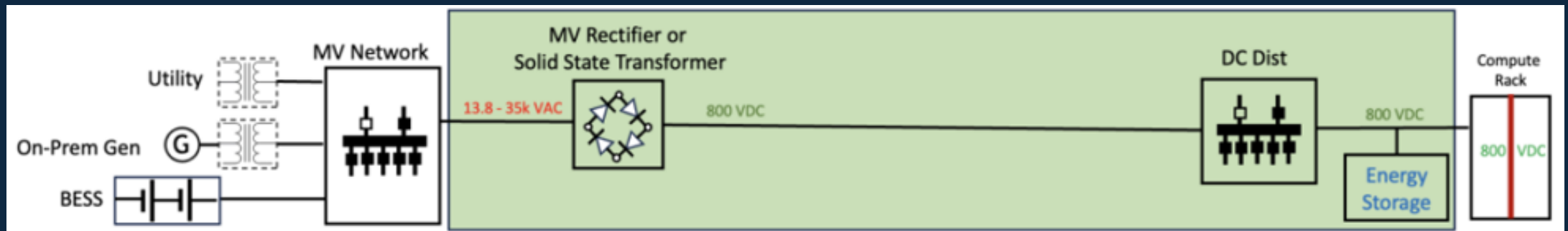
Applications

- OEM Validation energy storage and co-located generation
- HIL for SIL validation
- Test and validate software solution at the GPU rack level
 - Power hardware in the loop application
 - Stability and accuracy of interface needs to be understood



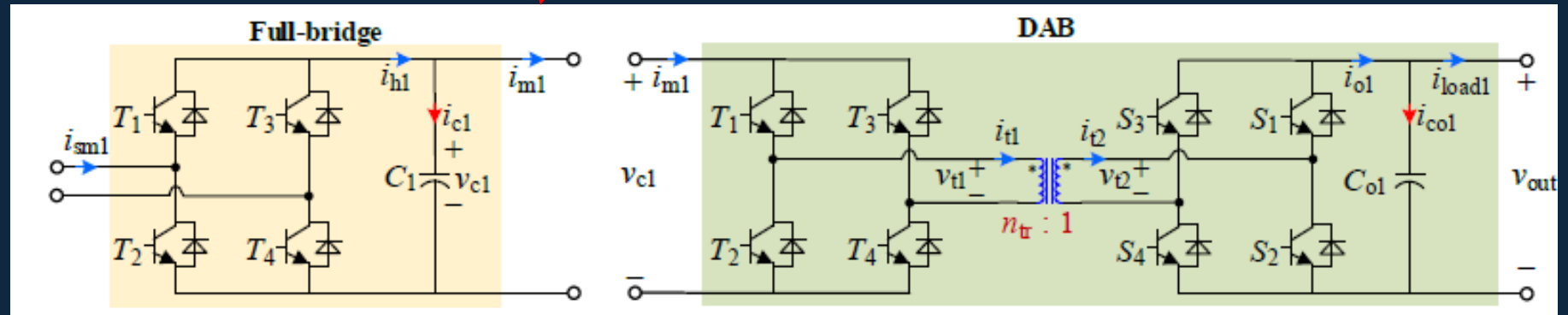
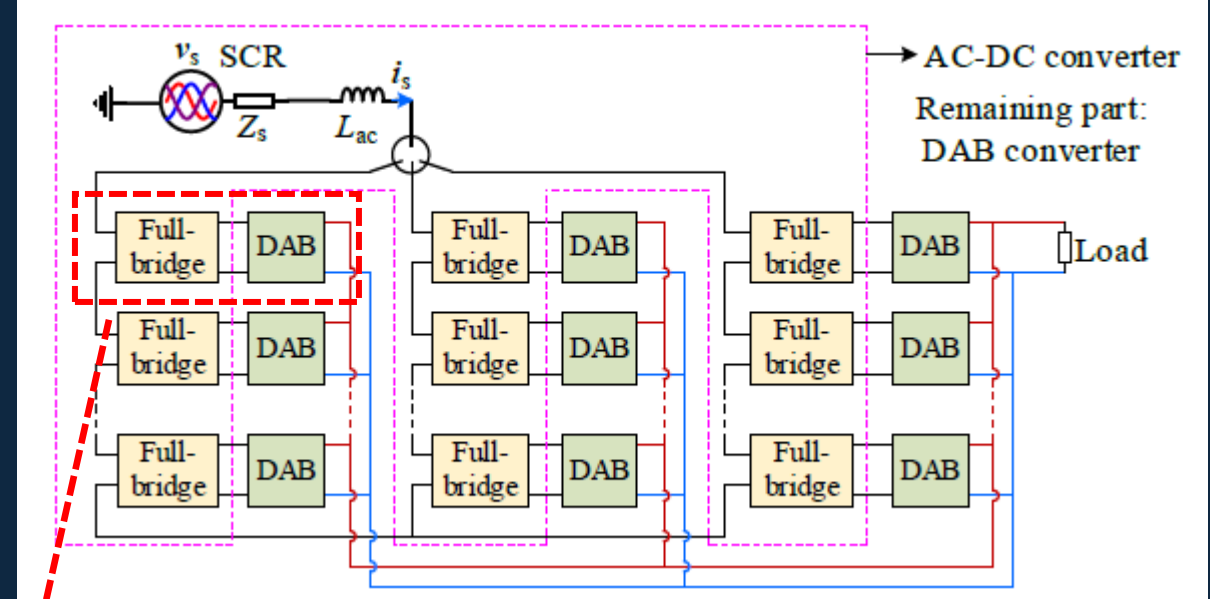
Next Generation – 800 VDC Data Center

- Direct connection to MV
- Driven by the shift is rack power demand
- Current architecture has several conversion stages
 - Adds losses, footprint, cost and failure points
- Energy storage can connect directly to the DC link
- **Solid State Transformer (SST)** is the key technology to enable shift to 800 VDC



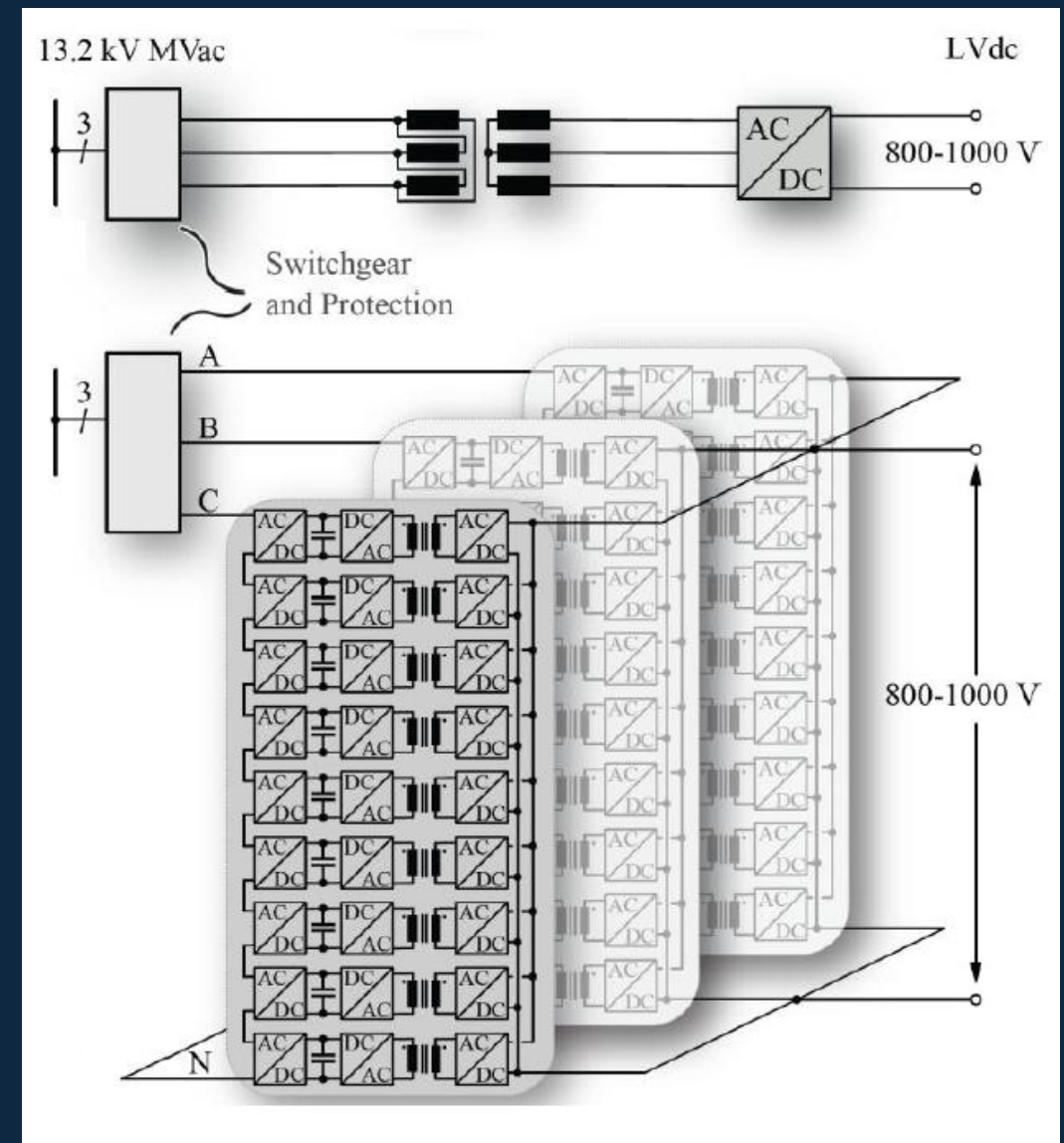
Solid State Transformer (SST)

- Power electronics based transformer that converts AC voltage to DC
- Multi- stage conversion process
 - Input Rectifier stage (AC to DC)
 - DC to DC stage (DC-AC-DC)
 - 10-100KHZ
- Modular structure
 - Cascaded H-Bridge & Dual Active Bridge (CHB-DAB)



SST Modelling

- **Scalability of Modular SSTs**
 - More cells means more complexity and heavier computation
 - Detailed switching models can exceed real-time limits
 - Simplified models or FPGA acceleration
- **Similar challenges compared to MMC modelling**
 - Modular converter-based architectures with large numbers of power electronic devices
 - Potential high computational burden for EMT and real-time simulation
- **SST has additional challenges**
 - CHB + DAB
 - DAB has high switching frequency requirements



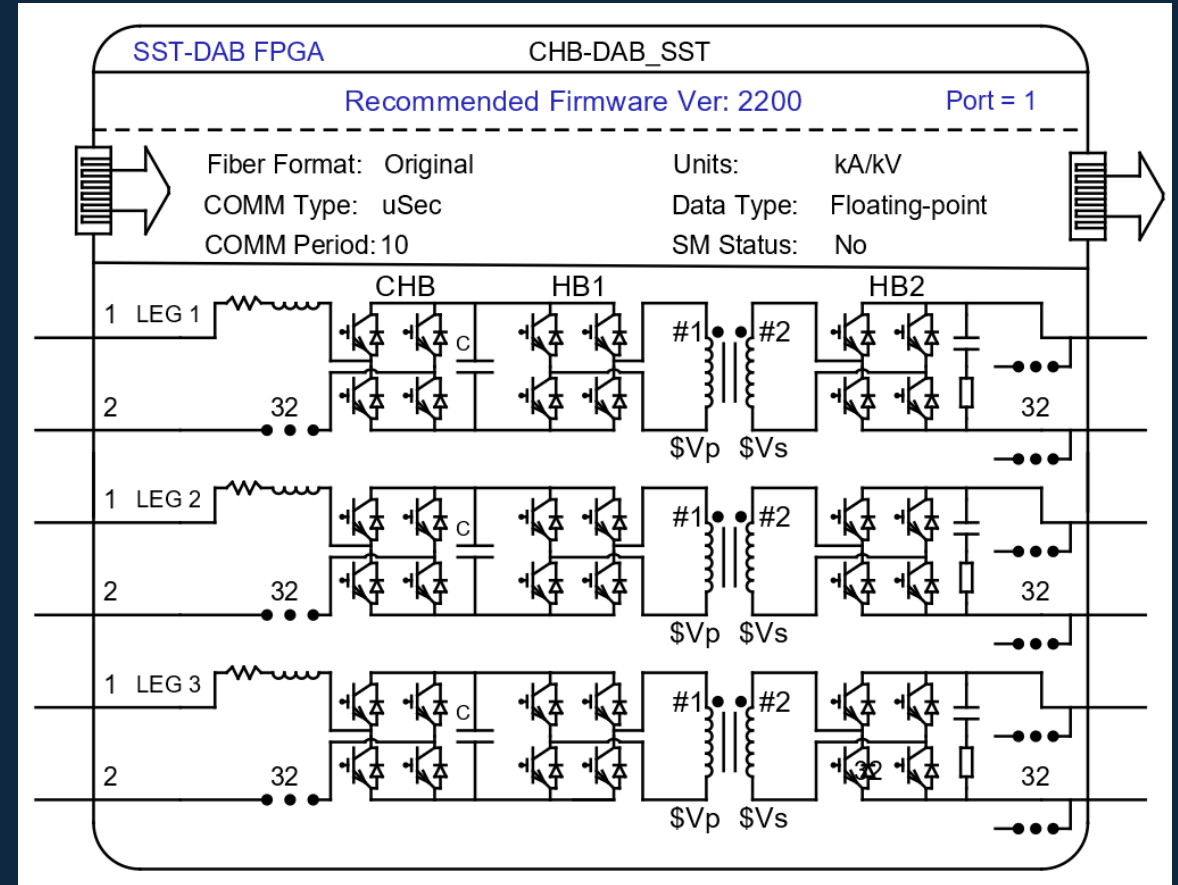
Source: 99+% Efficient Ultra-Compact Solid-State Transformers for Future Datacenters, Kolar et al.

RTDS SST model overview

- Cascaded H-Bridge & Dual Active Bridge (CHB-DAB) Model
- Common High-Frequency-Link Series-Resonant SST Model
- Both models have two implementations
 - FPGA based
 - Processor based

CHB-DAB: FPGA Component Model

- Modelled using GTSOCV2 Hardware
- 1-3 legs per component
- Maximum of 128 cells per leg
- Cascaded H-Bridge (CHB)
 - 4-bit firing pulse input (1 bit per switch)
 - Aurora communication
- Dual Active Bridge (DAB)
 - Two input options
 - Improved firing pulses (1 per switch)
 - Phase shift with initial phase offset (1 per DAB)
- Scaling function
 - One SST can be scaled to appear as multiple SSTs

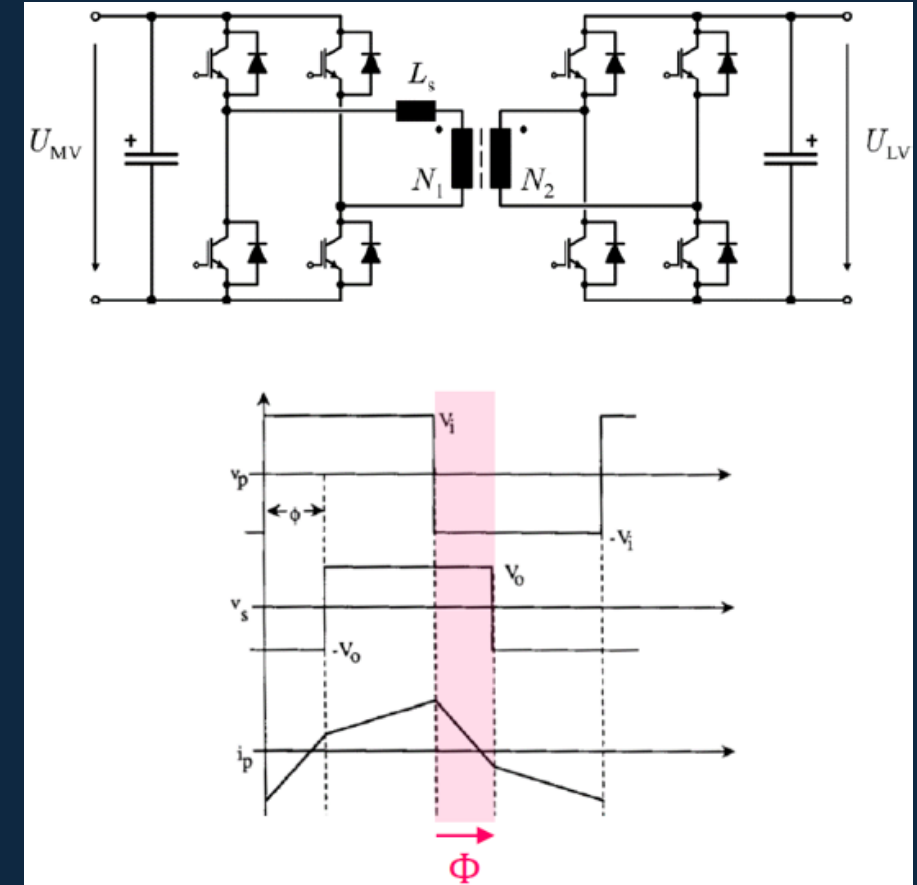


CHB-DAB: FPGA External Controller Interface

- The interface requirements for the **CHB** and **DAB** portions are different
- The CHB is identical to a MMC HVDC/STATCOM leg.
- The requirements for the **CHB** are identical to those for one of our existing MMC models (GMMX6VLV)
 - Aurora interface
 - Existing documentation and technical specifications available

CHB-DAB: FPGA External Controller Interface

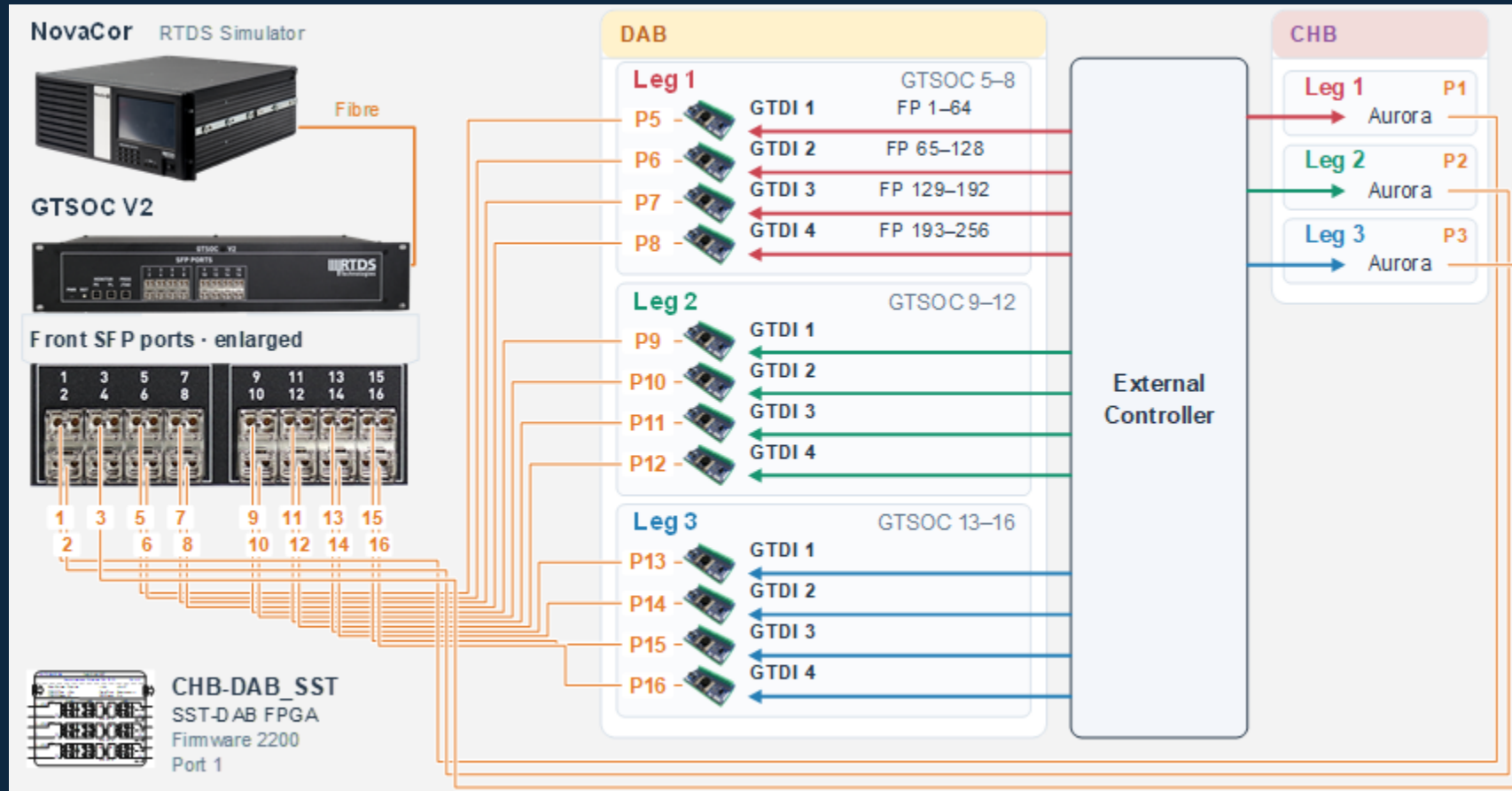
- For DAB, multiple controller interface option supported
- Each interface option has a different levels of fidelity
- The interface options in order of decreasing complexity are
 - Firing Pulse Interface
 - Aligned Firing Pulse Interface
 - Phase Shift Interface



Source: ETH Zurich, The Essence of Solid-State Transformers: Fundamentals, Design Challenges, R&D Overview, Comparative Evaluation, Outlook

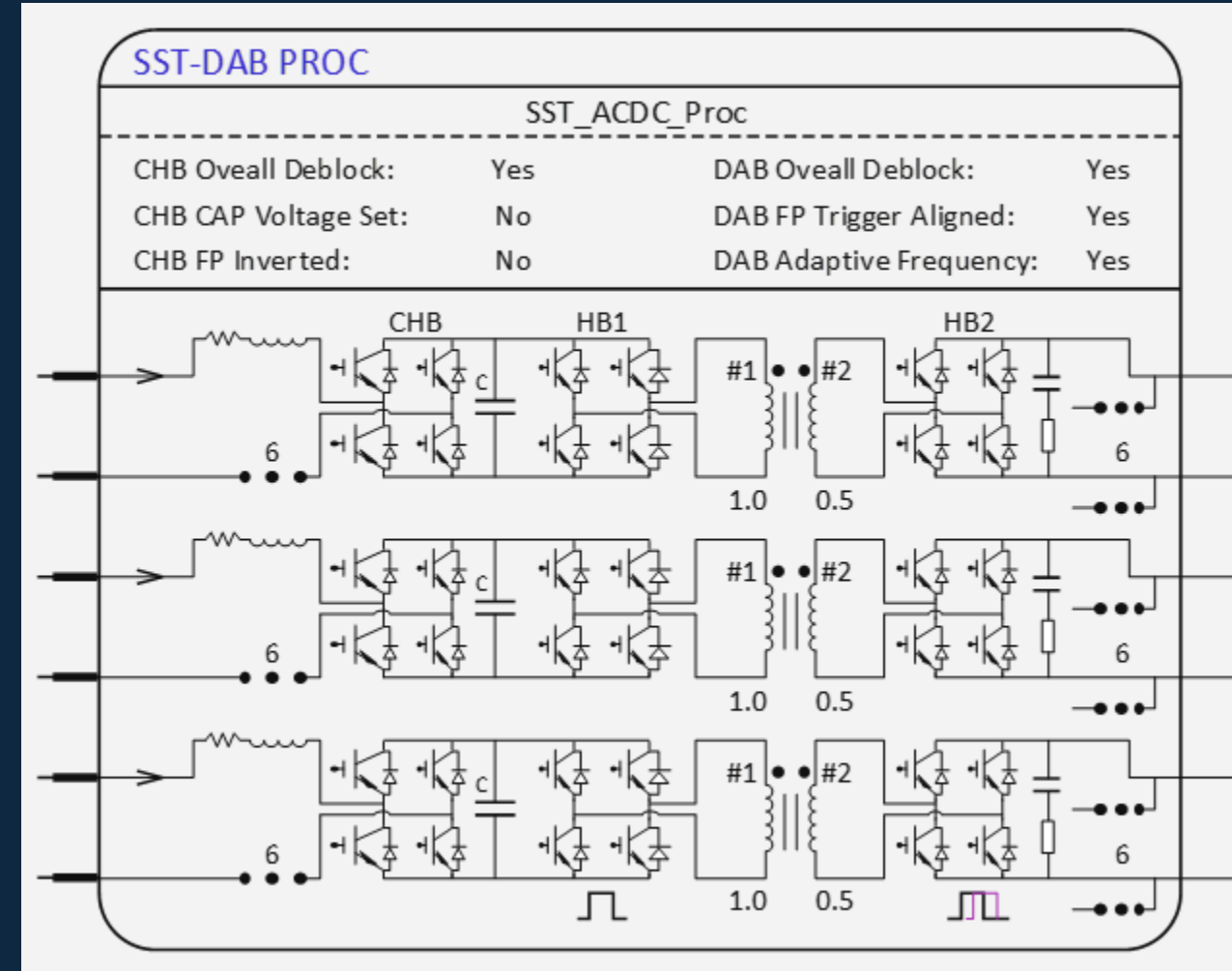
CHB-DAB: FPGA External Controller Interface

DAB Firing Pulse Interface



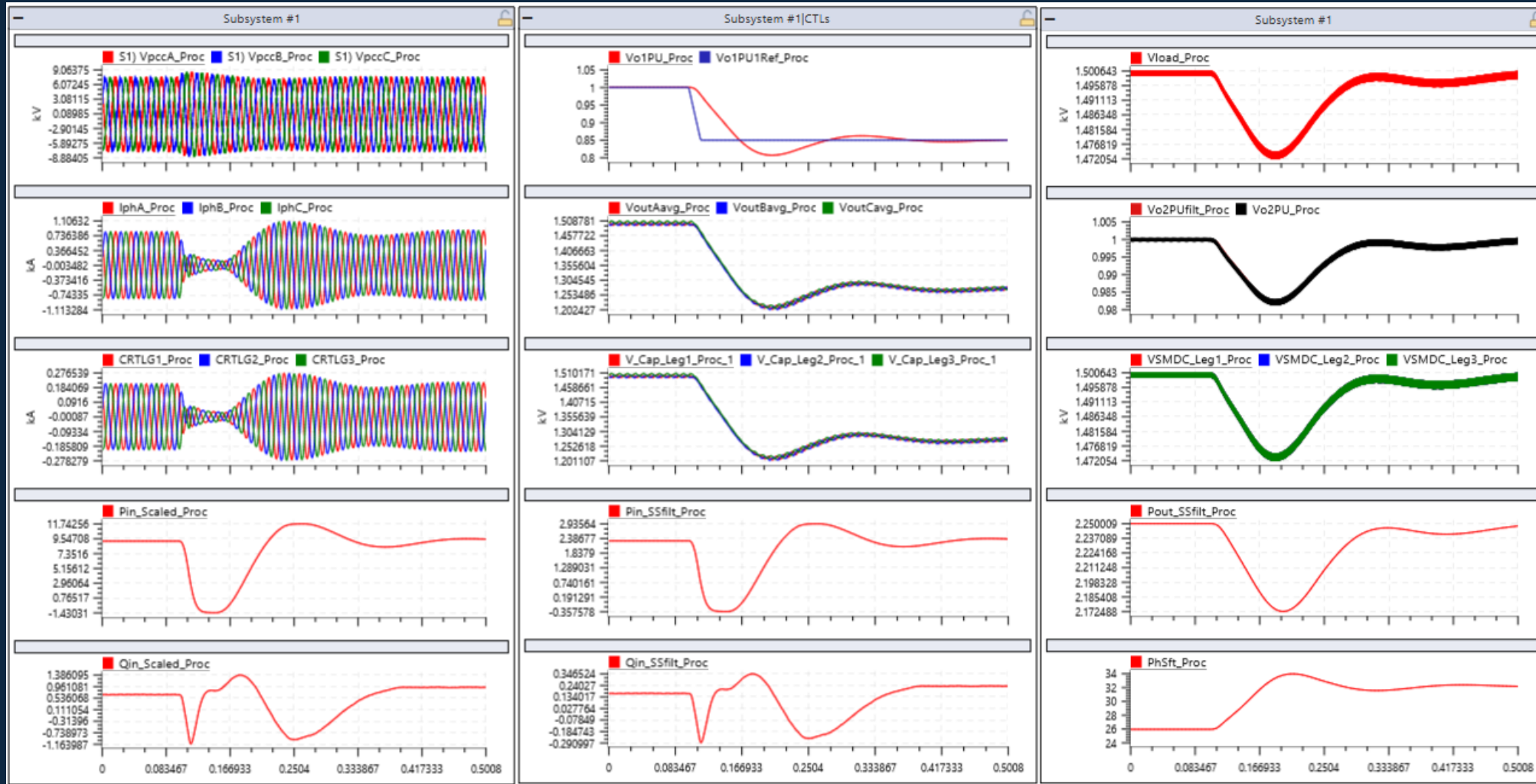
CHB-DAB: Processor Component Model

- 3 legs per component
- **Maximum of 56 cells per leg**
- Cascaded H-Bridge (CHB)
 - 4-bit firing pulse input (1 bit per switch)
- Dual Active Bridge (DAB)
 - Two input options
 - Improved firing pulses (1 per switch)
 - Phase shift with initial phase offset (1 per leg)
- Scaling function
 - One SST can be scaled to appear as multiple SSTs



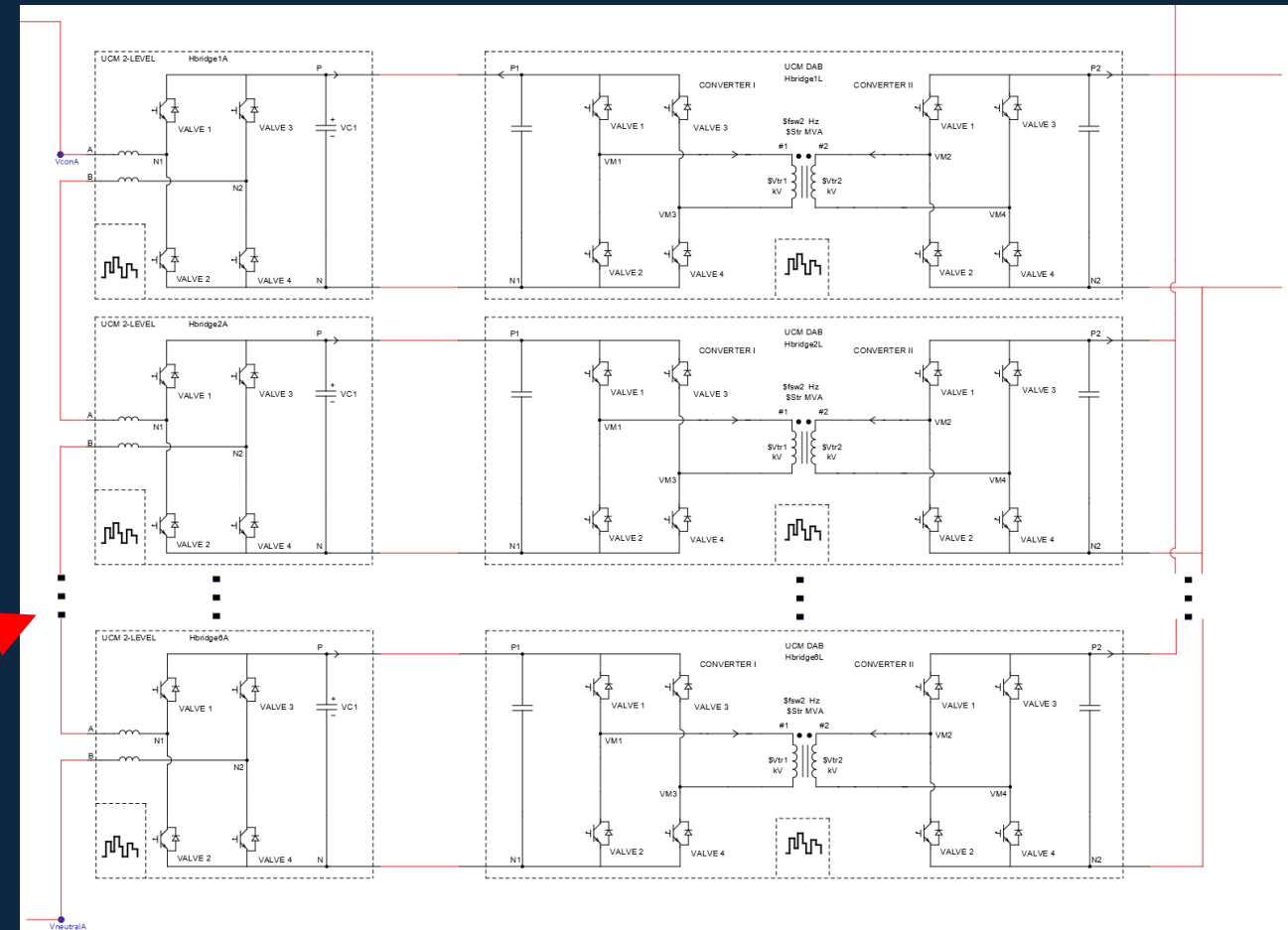
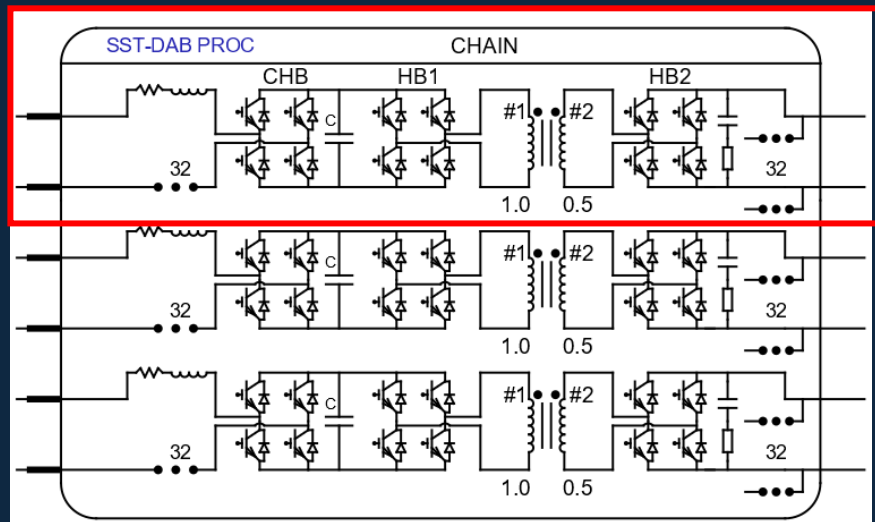
Example Cases: CHB-DAB SST

Voltage reference change



Model Validation

- Validated SST component models against detailed individual component models
- SST component models preserve the behavior and performance characteristics of the underlying detailed implementations



Key Takeaways

- The load is growing and changing
- AI workloads create fast-changing power demand
- Simulation is how we manage the risk
- Real time simulation de-risk controls and protection
- The architecture is evolving

Thank you!

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