A Scalable and Flexible Co-Model and Monitoring System for Advanced Transformer Considering Interactions with Power Electronics Assets

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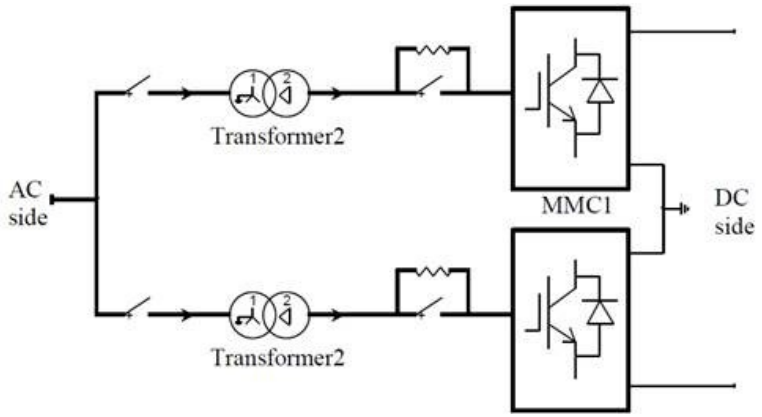
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Project Overview

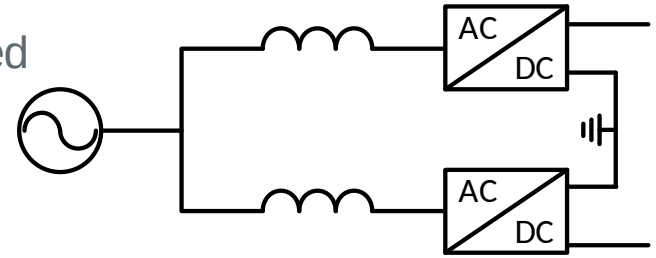
- Project Description: To Develop a comprehensive modeling framework to address the major gaps in the current power system dynamic and stability analyses spanning from fundamental transformer representations to large-scale, modular co-models and digital twins
- Period of Performance: 10/01/2025 to 09/30/2027
- Award Amount: $800,000
- Prime Awardee: Brookhaven National Laboratory (BNL)
- Partners: Tianqi Hong, University of Georgia, Franscisco de Leon, New York University, and Tianqiao Zhao, University of Texas Arlington
- Technology Area:
  - Advanced Transformers
  - Advanced Power Electronics
- Alignment/Supports strategic pathway:
  1. **Stabilize** the grid to address the immediate, acute conditions that strain reliability
  2. **Grow** the grid by enabling innovation, advancing new technologies, and building capacity for a future-ready electricity system

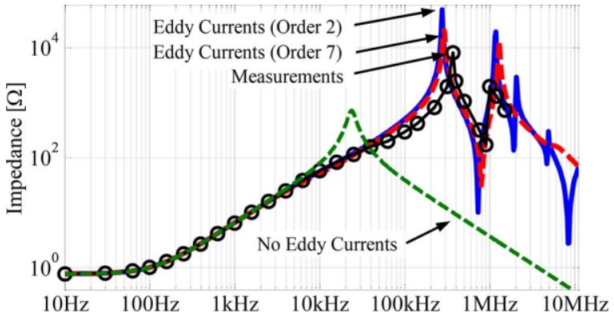
Project Details: Problem Statement

- Increasing integration of power electronics (PEs)
- Interactions between PEs and transformers often neglected, leading to incomplete or inaccurate assessments of system behavior, particularly under disturbances.
- Existing transformer models frequently lack the necessary detail to represent PE-introduced complex bi-directional dynamics (reversible model)
  - Can be misleading by obscuring potential risks and diminishing the ability to understand the true impact on the host grid.



Oversimplified

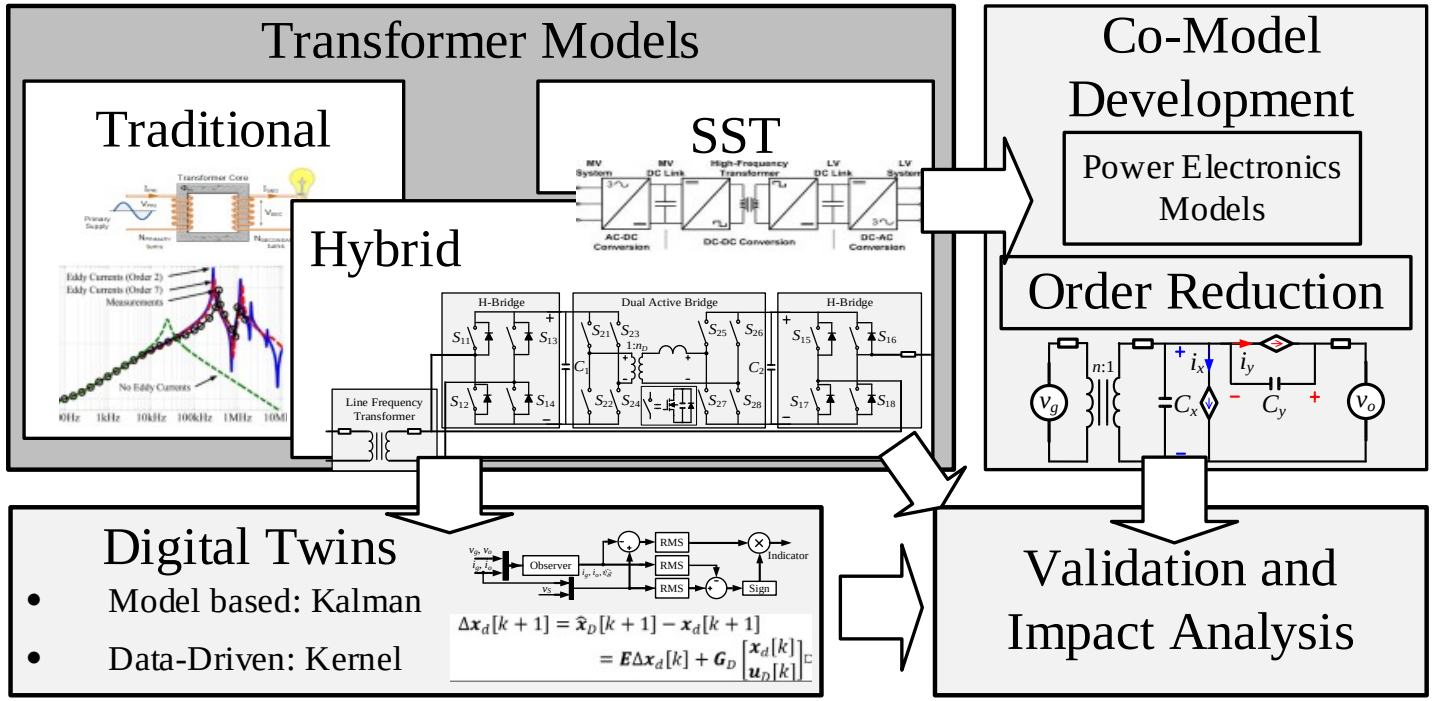




Oversimplification induced incomplete/inaccurate assessment of system behaviors

Project Details: Technical Approach/Innovation

- Phase 1
  - Thrust 1: Development of Advanced Transformer Models
  - Thrust 2: Co-Modeling Framework Establishment
- Phase 2
  - Thrust 3: Digital Twin System Development
  - Thrust 4: Model Validation and Impact Analysis



The overall technical approach

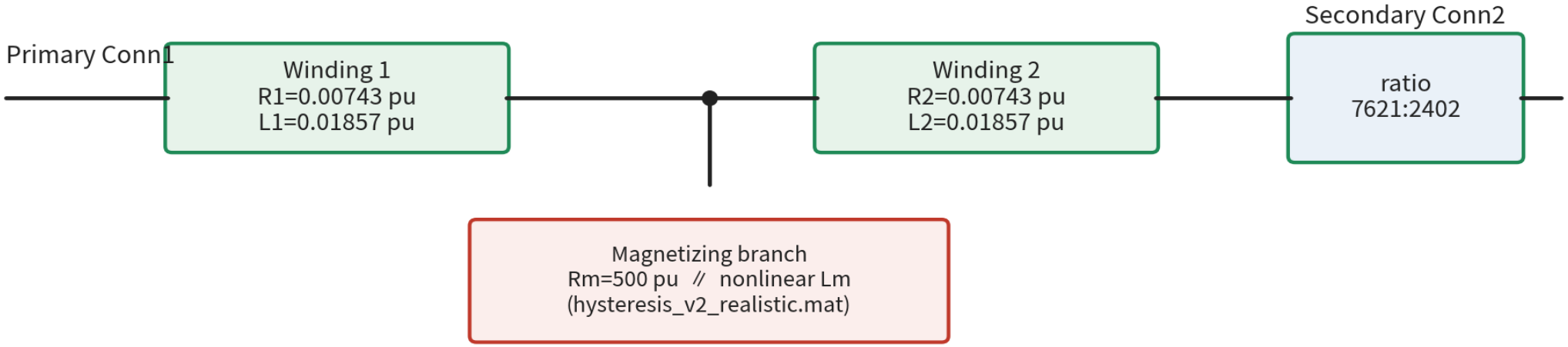
Project Details: Technical Approach/Innovation (cont'd)

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- Thrust 1: Development of Advanced Transformer Models
  - Line frequency transformer modeling: Duality, Medium and high frequency transients
  - Solid-state transformer: Two H-bridges + Dual active bridge circuit, Control for wide-range operation including unity power factor condition
  - Hybrid transformer: 90% on line-frequency transformer
- Thrust 2: Co-Modeling Framework Establishment
  - Major signature extraction of joint model of transformer and power electronics
  - Model reduction and modularized design: Singular Perturbation + Modal Analysis
- Thrust 3: Digital Twin System Development
  - Observer design – Kalman observer: Model-based method, Robust to sensor noise
  - Data-Driven model corrector: Kernel-learning method for a lightweight solution
  - Reinforcement-learning technique for dynamic adaptability and robustness to uncertainty
- Thrust 4: Model Validation and Impact Analysis
  - Model and digital twin validation using IEEE Test system with different power electronics penetration levels
  - Impact analysis: Fault, Black Start, and Geomagnetically induced current (GIC)

Project Details: Results

- Traditional transformer modeling
  - Developed a multi-fidelity distribution-transformer modeling library specifically targeted for SST interaction studies.
    - **T_linear** or T-equivalent linear model, **T_non** or T-equivalent nonlinear model
    - **π_linear** or π-equivalent linear model, and **π_non** or π-equivalent nonlinear model



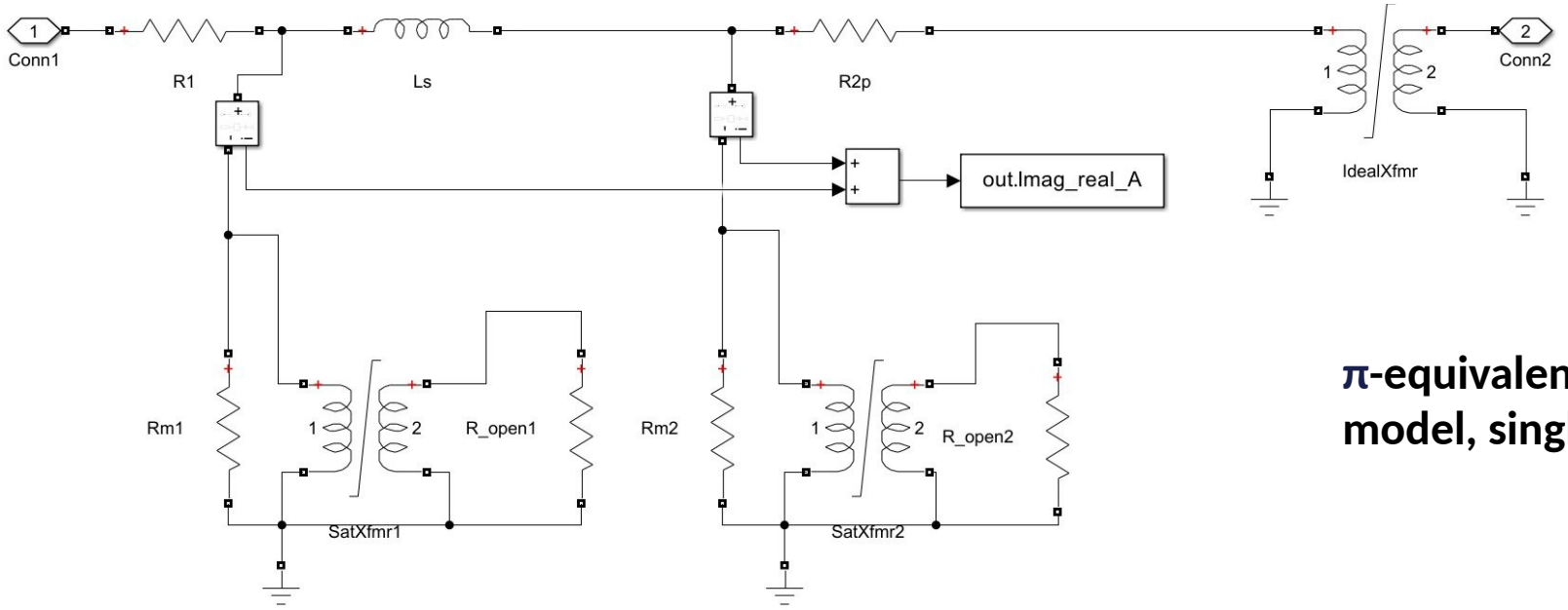
Single block: leakage inside windings 1/2, one central magnetizing branch; turns ratio 7621:2402 built in. Measurement Imag + IRm.

This is one phase (phase A); three phases use three identical single-phase blocks, each with Conn1/Conn2 on that phase's primary/secondary.

T-equivalent transformer model, single phase

Project Details: Results

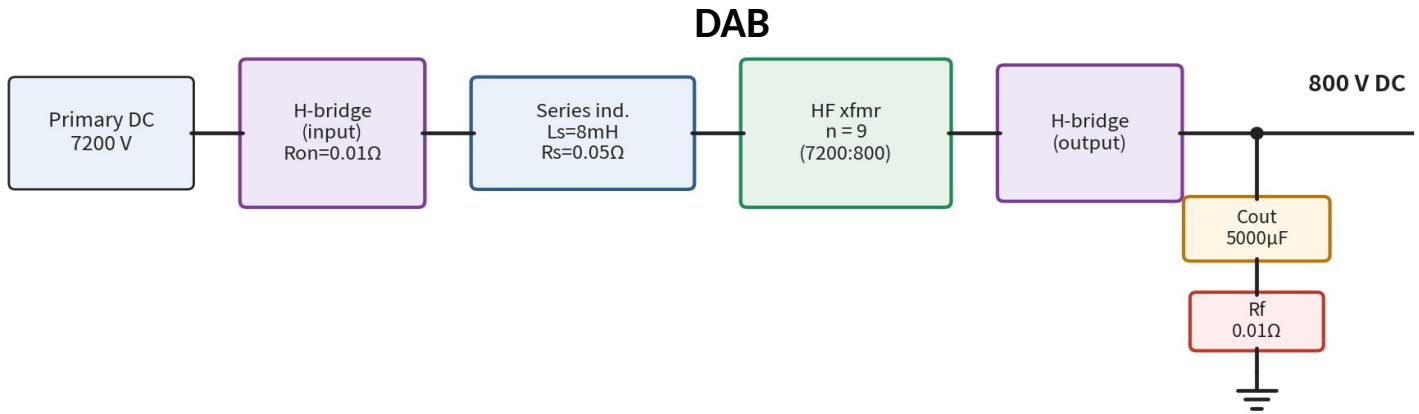
- Traditional transformer modeling (cont'd)
  - For T- or pi-equivalent model:
    - Sharing identical winding parameters but differ only in the level of magnetic detail, i.e., the constitutive law on magnetization branch
  - π-model hysteresis data is converted from the T-model data

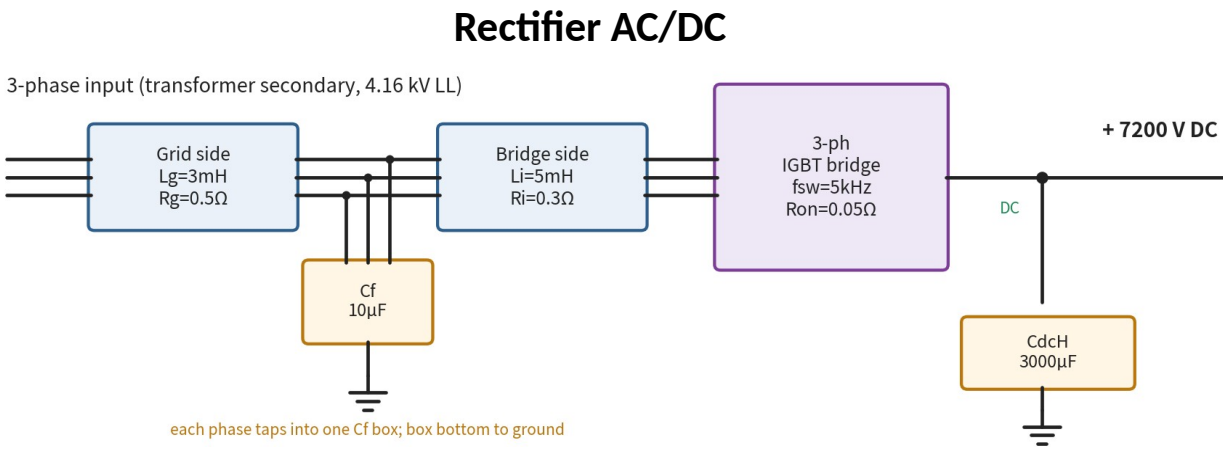


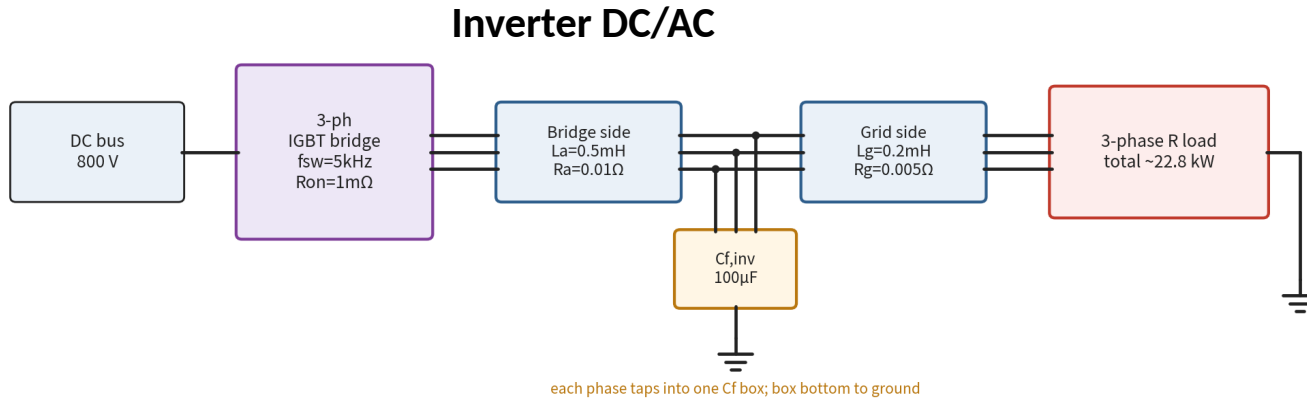
π-equivalent transformer model, single phase

Project Details: Results (cont'd)

- Solid-state transformer modeling
  - Follows a three-stage cascade:
    - A three-phase PWM rectifier (AC/DC),
    - A dual-active-bridge isolated DC/DC converter (DAB),
    - A three-phase grid-connected inverter (DC/AC)
  - Dual-active-bridge (DAB)-based SST models with decoupled control strategy





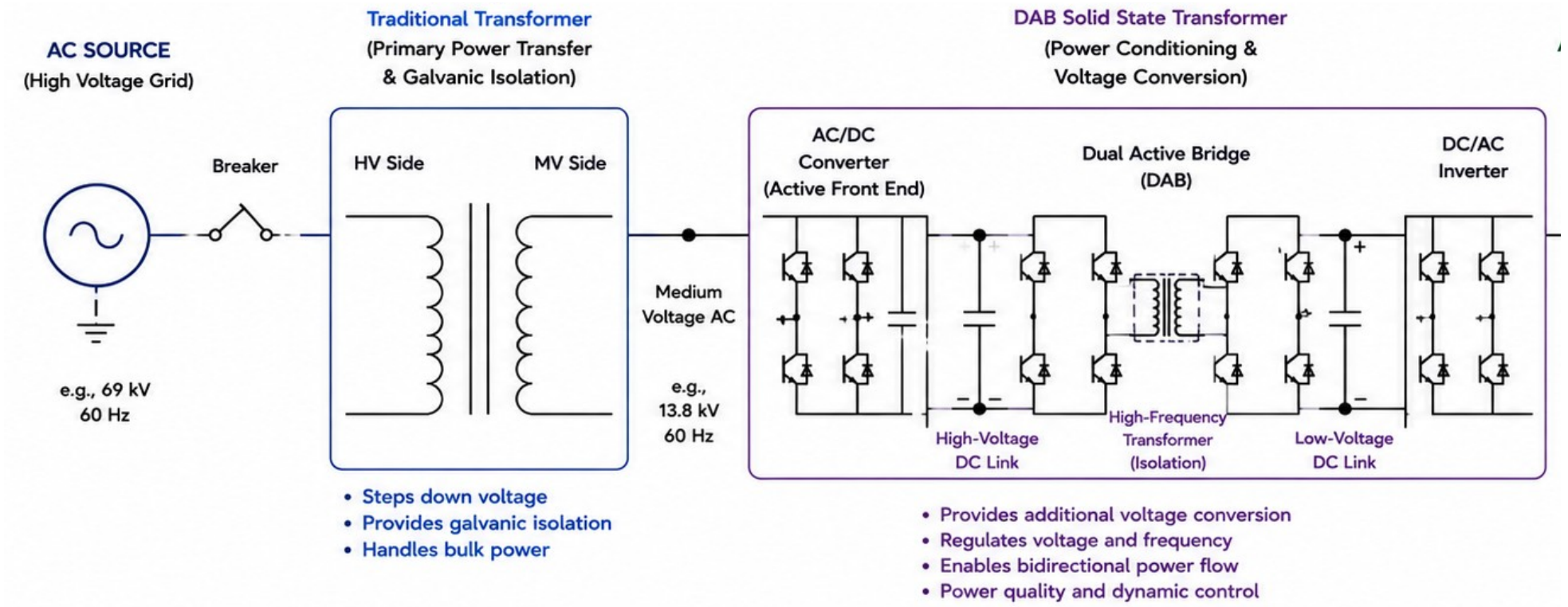


A three-stage cascade for SST

Project Details: Results (cont'd)

- Hybrid transformer modeling
  - The SST model and three types of transformer models (T_non, **π**_linear, and **π**_non)

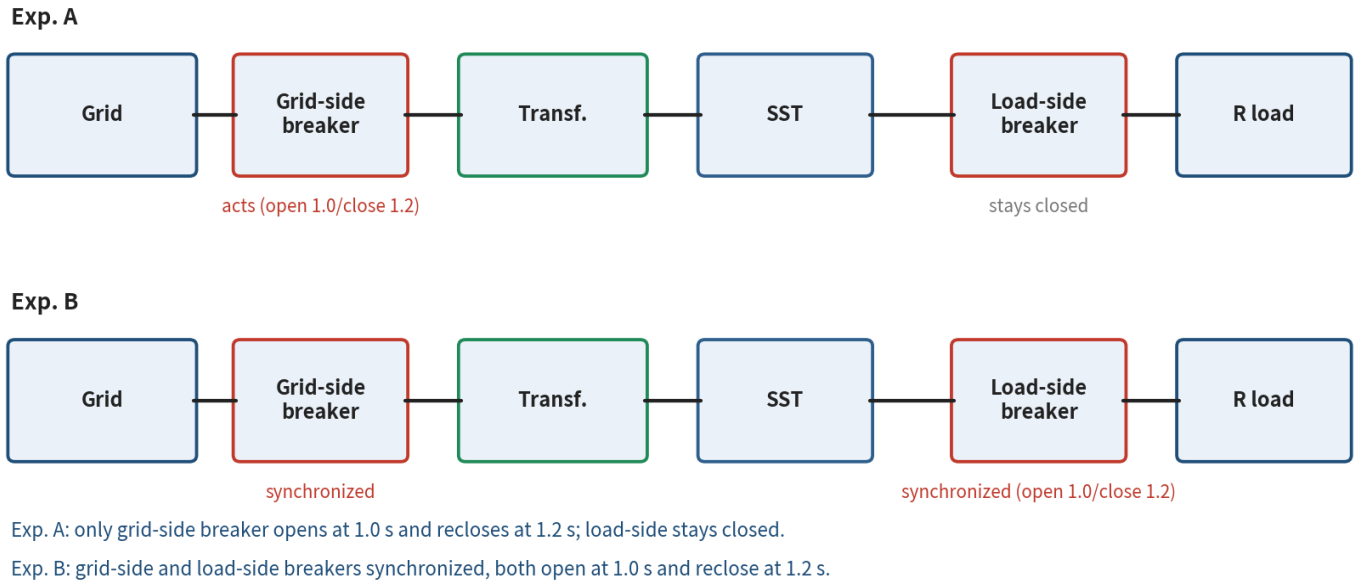
An example architecture of hybrid transformer



Project Details: Results (cont'd)

- Hybrid transformer modeling (cont'd)
  - Two different experimental setups
    - ExpA: Only grid-side breaker operates. The load-side breaker stays closed and the resistive load remains connected to the inverter output terminal during all the simulations.
    - ExpB: the load-side breaker is synchronized with the grid-side breaker: both of them open at 1.0 s and reclose at 1.2 s

Experimental setups



Exp. A: only grid-side breaker opens at 1.0 s and recloses at 1.2 s; load-side stays closed.

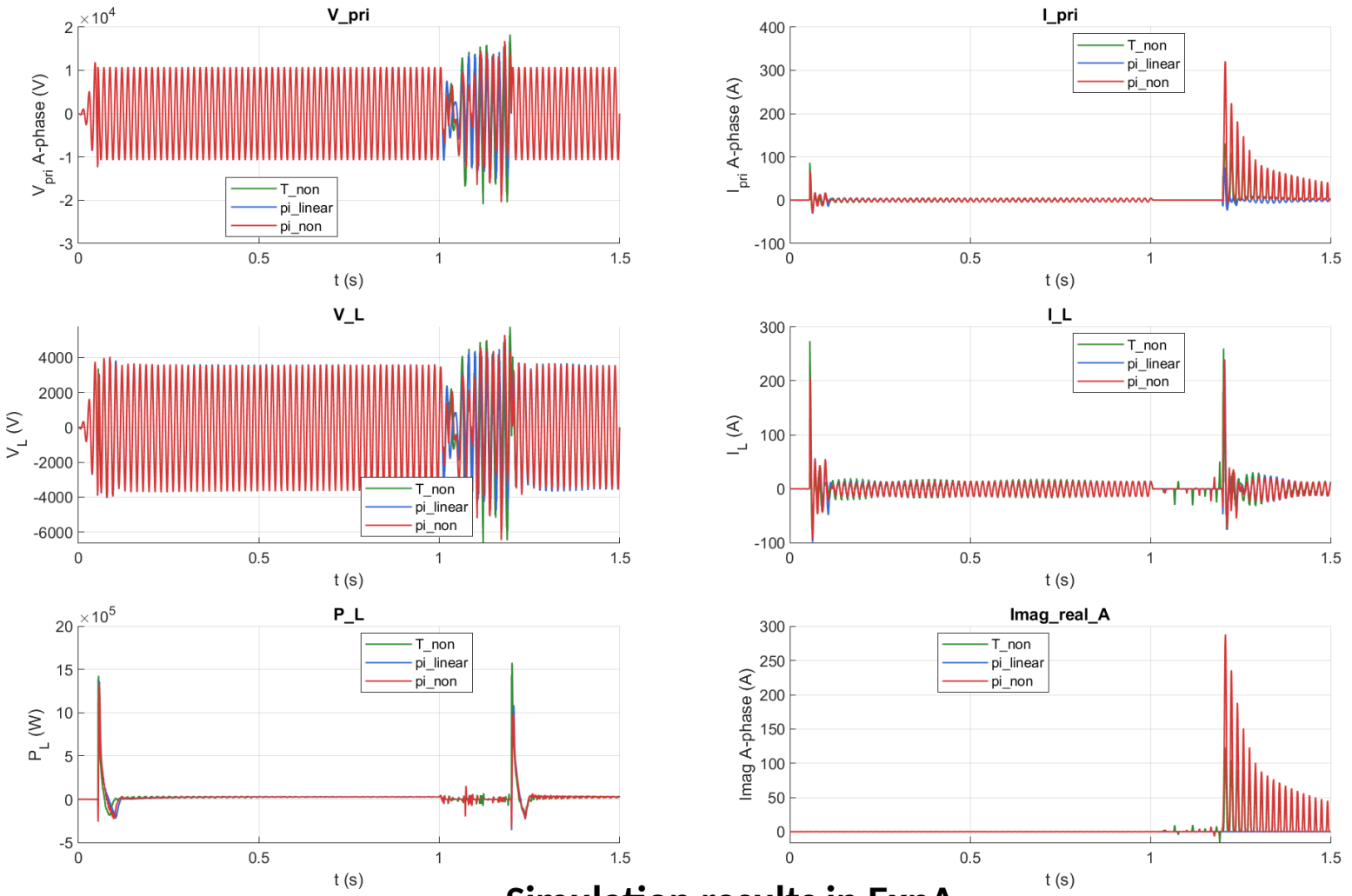
Exp. B: grid-side and load-side breakers synchronized, both open at 1.0 s and reclose at 1.2 s.

Event Switching Sequence



Project Details: Results (cont'd)

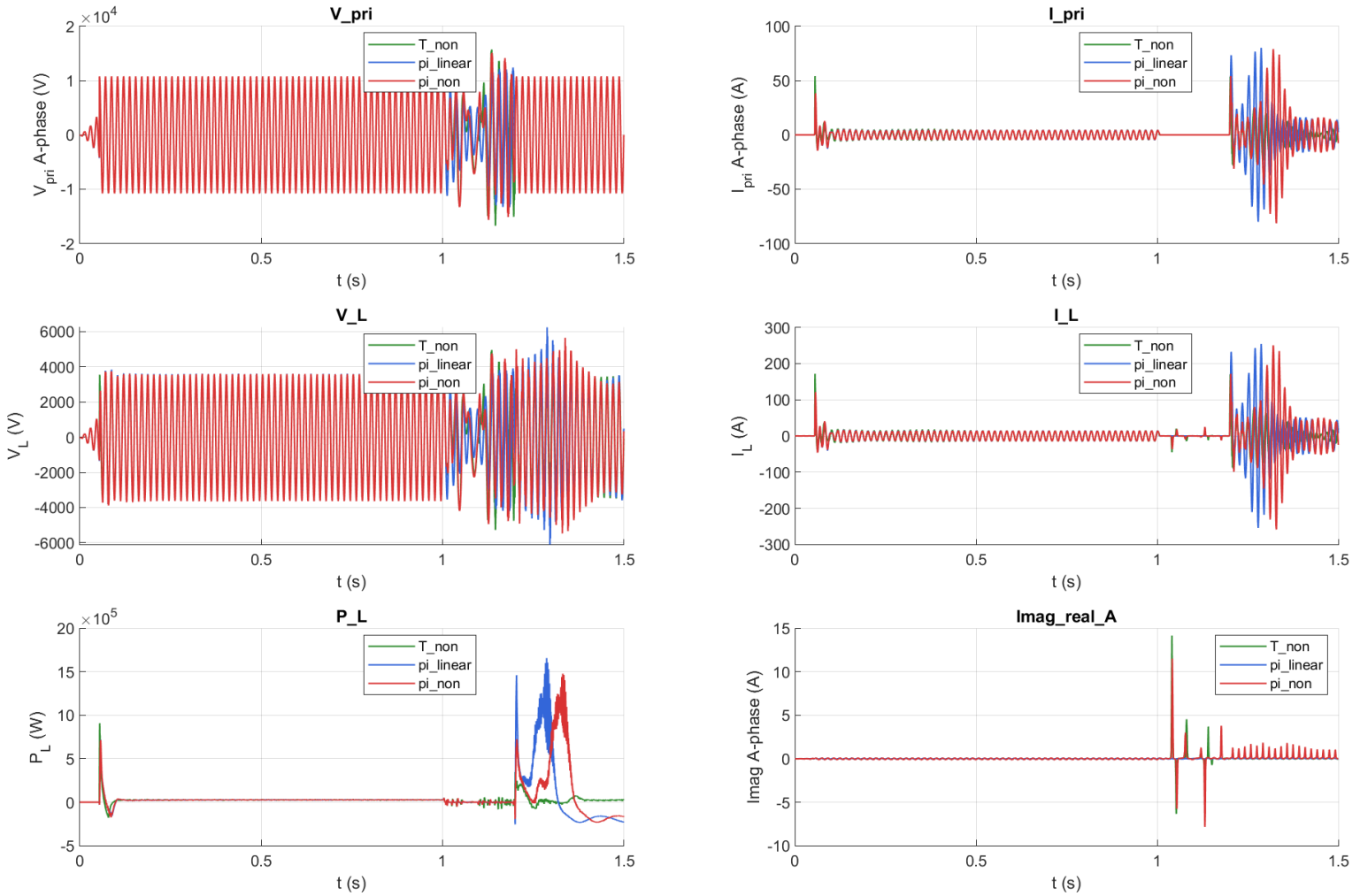
- Hybrid transformer modeling
  - In ExpA, all three types of transformers have very close steady state performance but different dynamic performance
  - The π_non model
    - Highest inrush current among all types of transformer models, which can easily damage the protective device and the SST system
    - Highest magnetizing current peak at steady-state and post-reclose



Simulation results in ExpA

Project Details: Results (cont'd)

- Hybrid transformer modeling
  - In ExpB, the load-side breaker synchronizes with grid-side breaker, and the transient inrush current still exists with a much smaller amplitude
    - The synchronization between legacy transformers and SST is very challenging
    - Small mismatch may also induce high current on the SST side which we plan to perform further investigation in the future.



Simulation results in ExpB

Project Details: Results (cont'd)

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- Scalable co-modeling framework development
  - Major Signature Identification of Joint Model between Transformers and Power Electronics Assets
    - Through time-series and frequency-domain analysis, we have identified the following signatures
      - Switching ripple propagation into transformer currents
      - Voltage distortion versus transformer excitation current
      - Dynamic response following converter mode transitions
    - The impacts have been validated in simulation but the mechanisms are still being investigated
  - Model Reduction and Modularized Design
    - A preliminary model reduction method has been developed by converting the switching stage to the average model for the SST
    - The original high-frequency piece-wised linear structure is converted to a controllable gain with a dc voltage source

Project Details: Results (cont'd)

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- Scalable co-modeling framework development
  - Model Reduction and Modularized Design
    - The same ExpA and ExpB were simulated
      - The inverter, the DAB, or both are replaced by average models and compared against full switching models.
    - The average model has the same steady-state behavior as the switching model.
      - However, when the rectifier model is changed from switching model to average model, large discrepancies can be found during transition.
      - The large discrepancies are mainly introduced by transformer inrush currents

Comparison of alternative models

Configuration	Inrush peak	Rectifier island current (pk-pk)	Note
Full switching (reference)	307.6 A	96.7 A	Engine fully on
Inverter → AVM	290.9 A	89.1 A	≈ reference; inverter transparent
DAB → AVM (lossless)	10.1 A	99.5 A	9% power deficit suppresses driver
DAB → AVM (power-matched η=0.90)	168.7 A	—	recovers m_a DC + 55% inrush
DAB + inverter → AVM (lossless)	69.1 A	96.1 A	same power deficit
Rectifier blocked (control)	6.1 A	17.5 A	engine off (real SST)

Project Details: Conclusions and Impact

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- Developed modeling library for traditional, solid-state, and hybrid transformers that are suitable for studying EMT interactions with the power grid
  - Addressed the oversimplification of transformer and PE models in the existing studies
- Identified the major signatures of the joint model between the transformer and power electronics through singular – perturbation-based modal analysis
- Developed preliminary model reduction method for the joint model
  - Identified the gaps of the preliminary model reduction method

Project Details: Future Direction/Next Steps

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- Continue the scalable co-modeling framework development
- Start the development of digital-twin system for continuous situational awareness and predictive capability for transformer operations
  - A hybrid framework using observer-based method, Kalman filter, augmented by a reinforcement learning for re-tuning model parameters
  - Different indicators for operating status of transformers for identification of potential risks and instabilities
- Continue the development and validation of the integrated so-modeling framework against benchmark power grids
- Continue to reach out to the power industry and other stakeholders for technology dissemination and adoption

Acknowledgements (Required)

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