Submission Information

Presentation ID#: 1.1

Presentation Title: Optimal Three-Port AC-AC Module for Flexible and Scalable Solid-State Transformers

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Organizations: Sandia National Laboratories, University of Pittsburgh

Optimal Three-Port AC-AC Module for Flexible and Scalable Solid-State Transformers

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DOE OE TRAC Peer Review 2026

Sandia National Laboratories

University of Pittsburgh

U.S. DEPARTMENT of ENERGY

Project Overview

Topic Area: 1) Advanced Transformers

Project Description:

In this project we will design and demonstrate an optimal, three-port AC-AC building block module for solid state transformer (SST) applications. This three-port single-stage (TPSS) module delivers ultra-high efficiency without sacrificing power flow control capabilities, creating the lowest-cost, lowest-component count, highest reliability modular SST solution possible.

Strategic Pathway: Optimize

The proposed three-port single-stage architecture is designed to improve efficiency, reliability, and cost relative to conventional multi-stage solid-state transformer approaches. By reducing component count, eliminating large line-driven DC-link capacitors, and lowering conversion losses, the technology can enhance grid asset performance while reducing thermal management requirements and lifecycle costs.

Prime National Lab(s): Sandia National Labs

Principal Investigator(s): Jake Mueller

Major Team Participants:

University of Pittsburgh

Funding Profile:	
Sandia	$800k
University of Pittsburgh	$400k
Total	$1200k

Period of Performance: 10/01/25 – 9/30/28

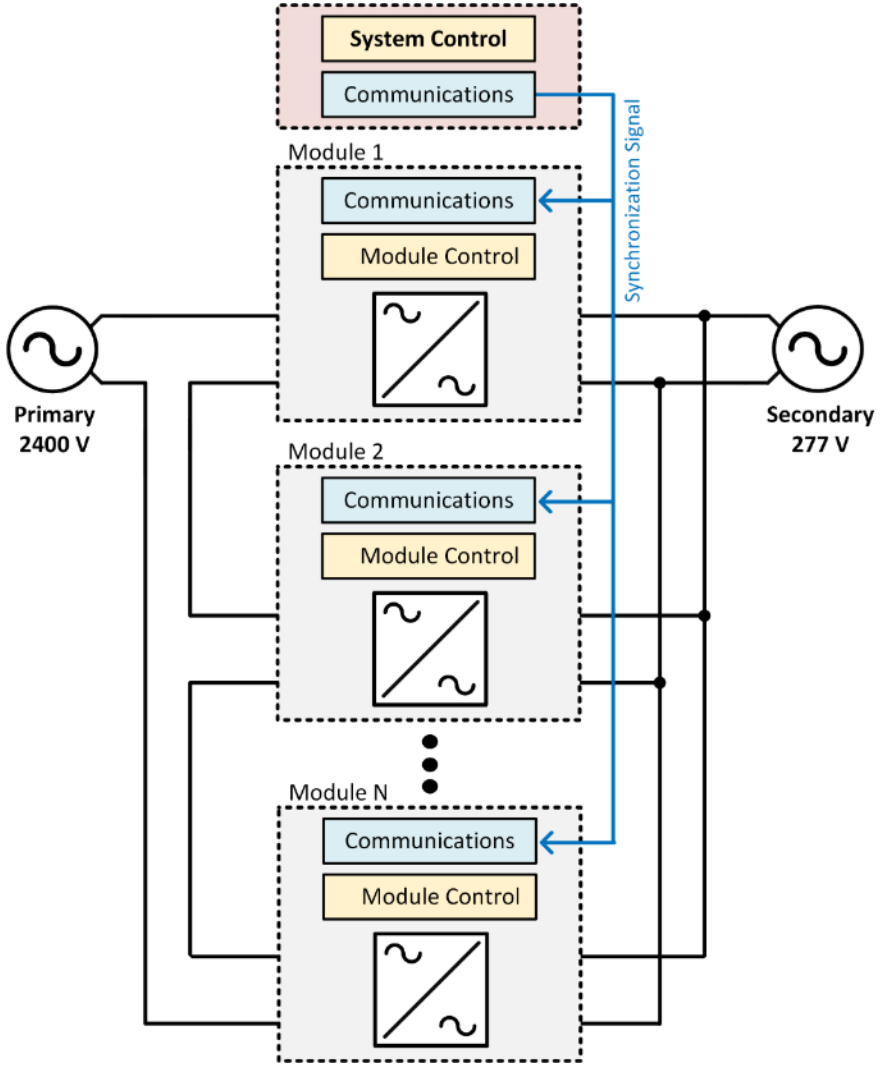
Background – SST Landscape

- Solid-state transformer (SST) and solid-state power substation (SSPS) technology is making the jump from prototype/pilot demonstration to industry-accepted solution in real time

- Modularity is key to the SST value proposition
  - Scalability, flexibility, simplification of supply chain

- Modular SSTs are constructed from stacks of isolated building block modules to scale power and operating voltage

- The attributes of a module determine system-level performance characteristics
  - Cost, complexity, efficiency, reliability

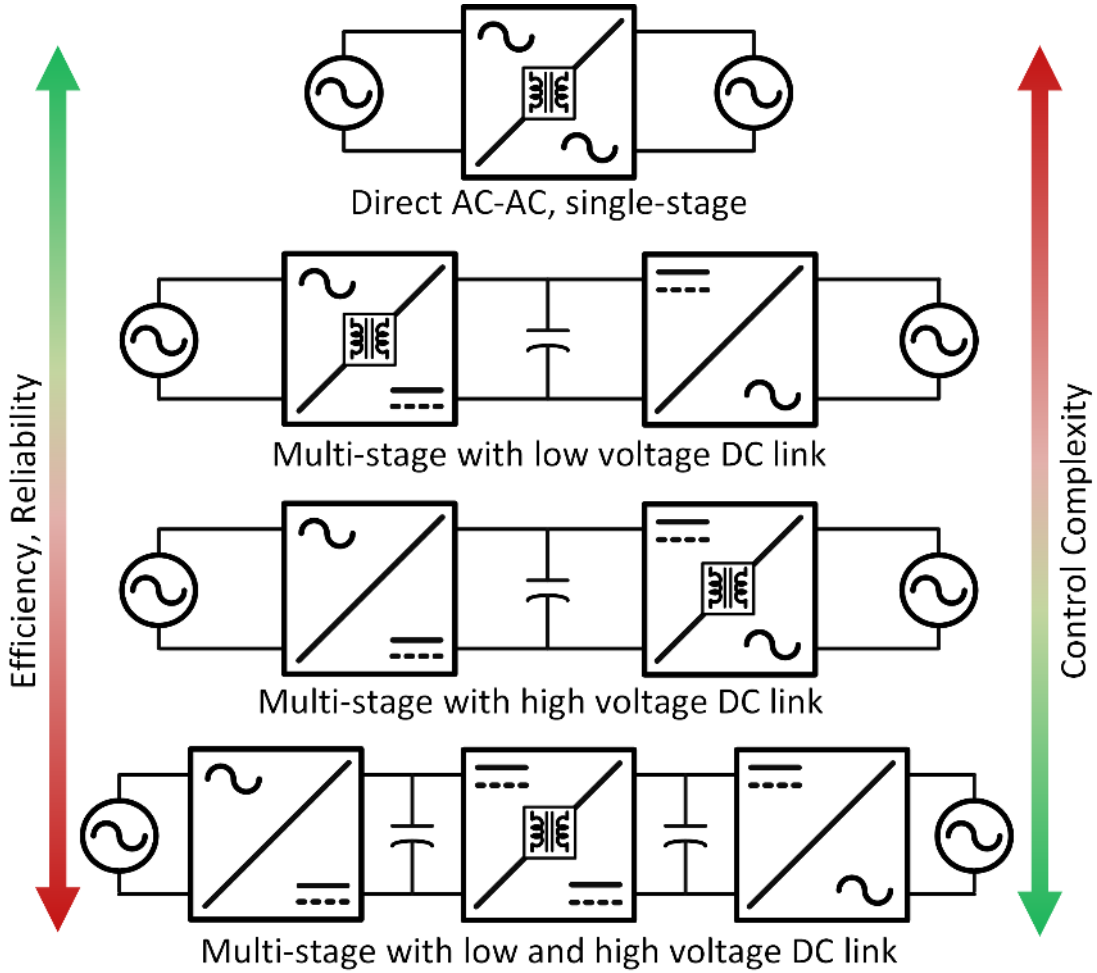


What is the gap?

- Existing SST module solutions meet **either** cost, efficiency, and reliability requirements **or** provide the necessary control functionality, ***but not both***.

- Multi-stage designs involve several distinct conversion circuits with individual functions. This simplifies control implementation at the expense of parts count, losses, and reliability.

- **Project Objective**: Develop a building-block module ideally suited to the needs of SST applications:
  - Low loss, low cost, high reliability
  - Extensive control flexibility

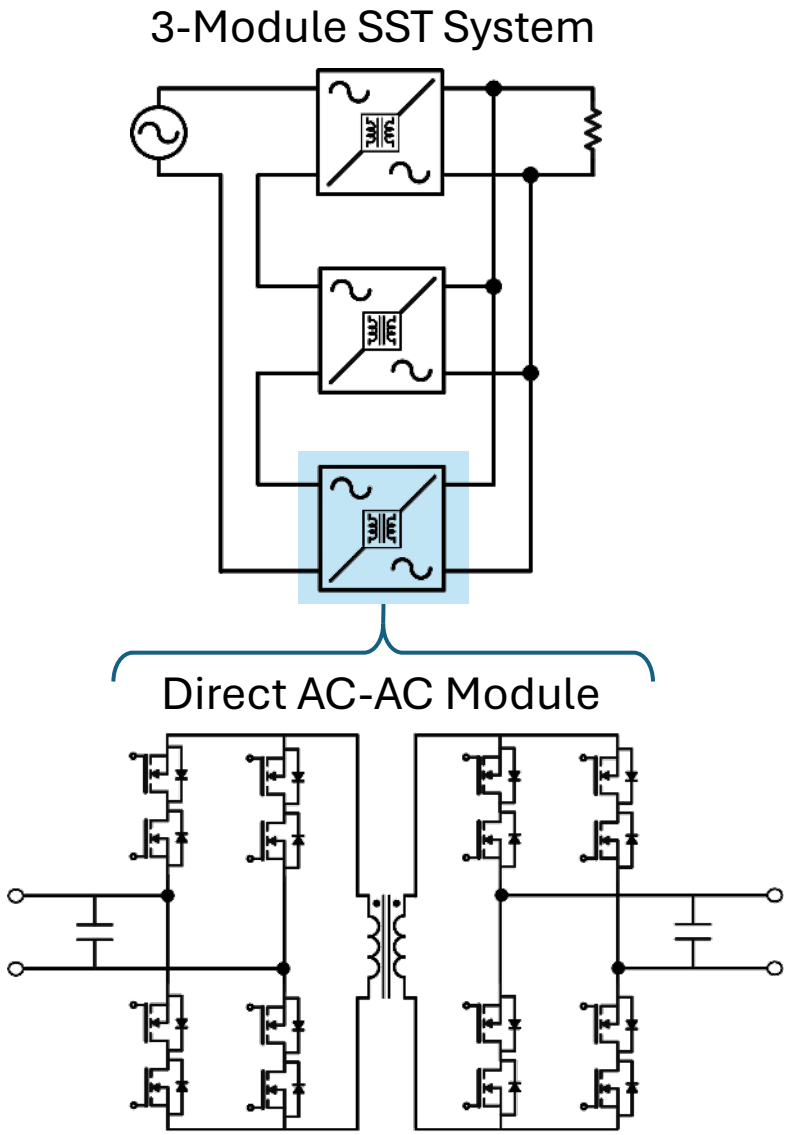


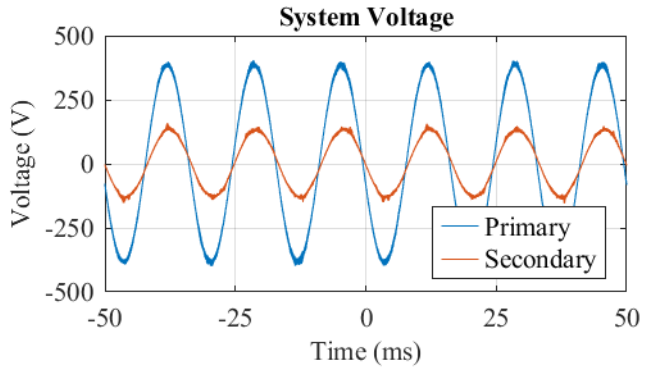
Starting Point: Direct AC-AC Conversion

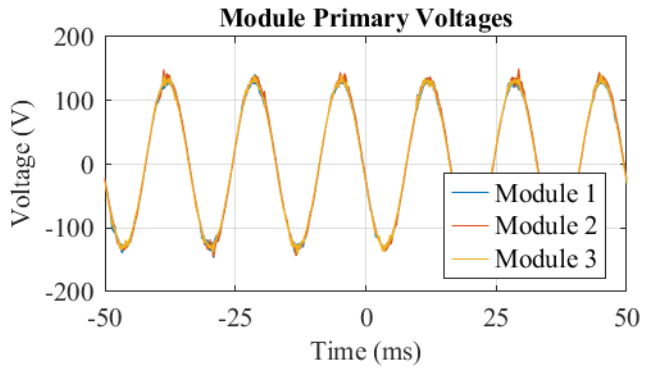
- Project builds on prior work under Sandia Lab-Directed R&D (LDRD) efforts:
  - *AC-AC SST with Bidirectional Switches (*FY22-FY25)

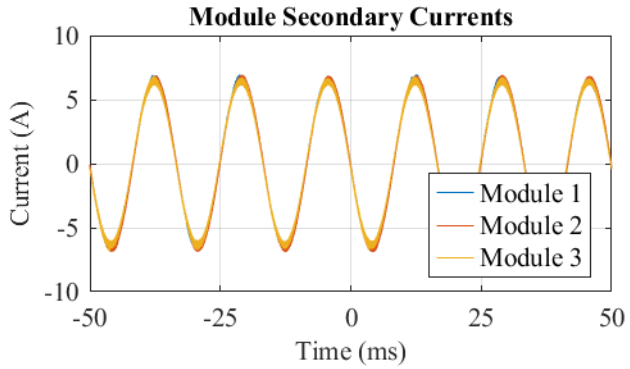
- Advantages:
  - High efficiency
  - No DC link capacitor
  - High power density

- Challenges:
  - Power flow control limitations
  - Requires semiconductors **capable of four-quadrant operation**









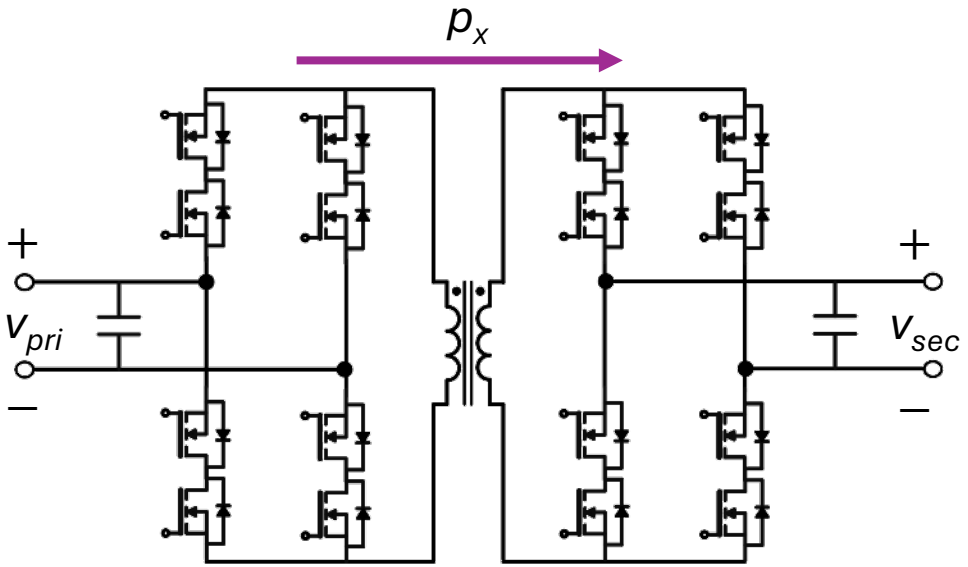
Power Transfer Limitations

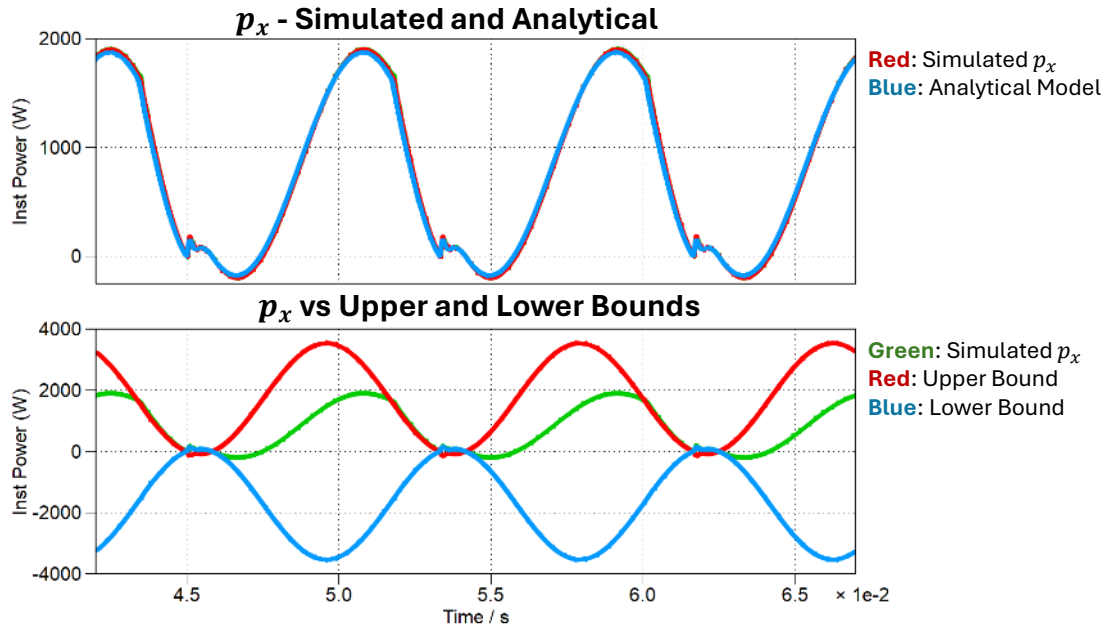
- Instantaneous power transfer p_x is subject to upper/lower bounds

$$|p_x| \leq \frac{1}{8}\left(\frac{v_{pri}v_{sec}}{f_{SW}\left(\frac{N_p}{N_s}\right)L_{lk}}\right)$$

- A practical consequence: limitations on primary-side power factor correction

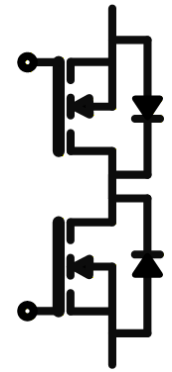
- When power transfer bounds are exceeded, voltage and current waveforms become distorted

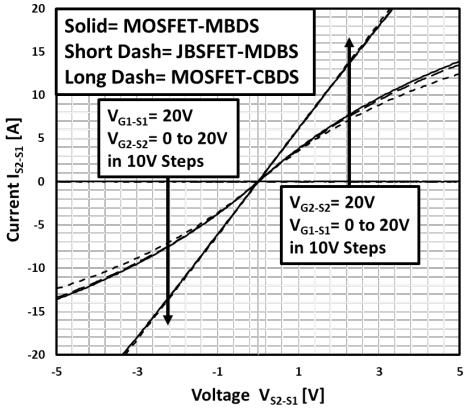




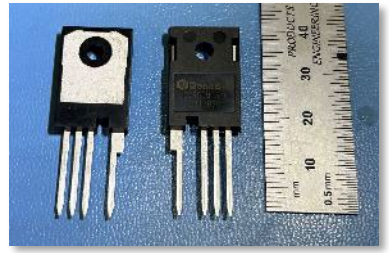
New Semiconductors Reshape Circuit Ecosystem

- Bidirectional semiconductor devices operate in all four quadrants of the current-voltage plane
  - Forward and reverse voltage blocking capability
  - Forward and reverse current conduction



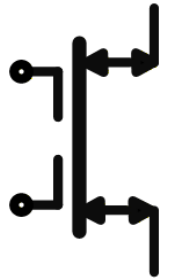


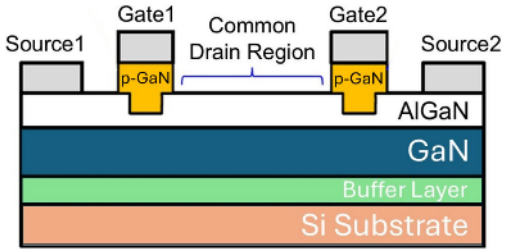
- Traditionally implemented using multiple devices
  - For example: back-to-back Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistors (SiC MOSFETs) as two discrete devices, two co-packaged devices, or two monolithically integrated devices
  - In all cases, loss penalty is high for bidirectional operation:
    - 2x devices means 2x R_{ON} (on-state resistance) and 2x conduction losses
    - 4x devices needed for bidirectional operation and equivalent conduction loss



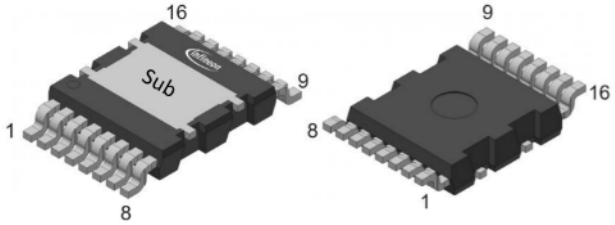


- Lateral GaN devices offer a radically different tradeoff
  - Symmetric dual gate structure with shared layer means bidirectional blocking capability without doubling R_{ON}
  - Circuit-level impact is significant for AC-AC topology, at least 2x reduction in semiconductor component count

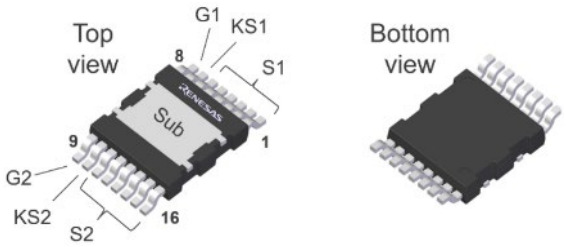


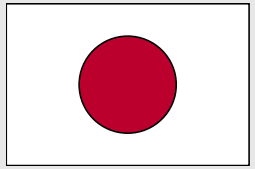


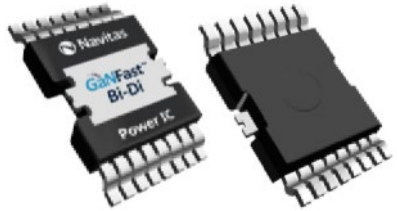
Production GaN Bidirectional Semiconductor Devices at 650V



Parameter	Value
Part Number	IGLT65R055B2 [5]
Typ. R_{ON}, 25C	55mΩ
Series	CoolGaN
Gate Structure	Gate Injection Transistor (GIT)
Package	TOLT
Manufacturer Headquarters	



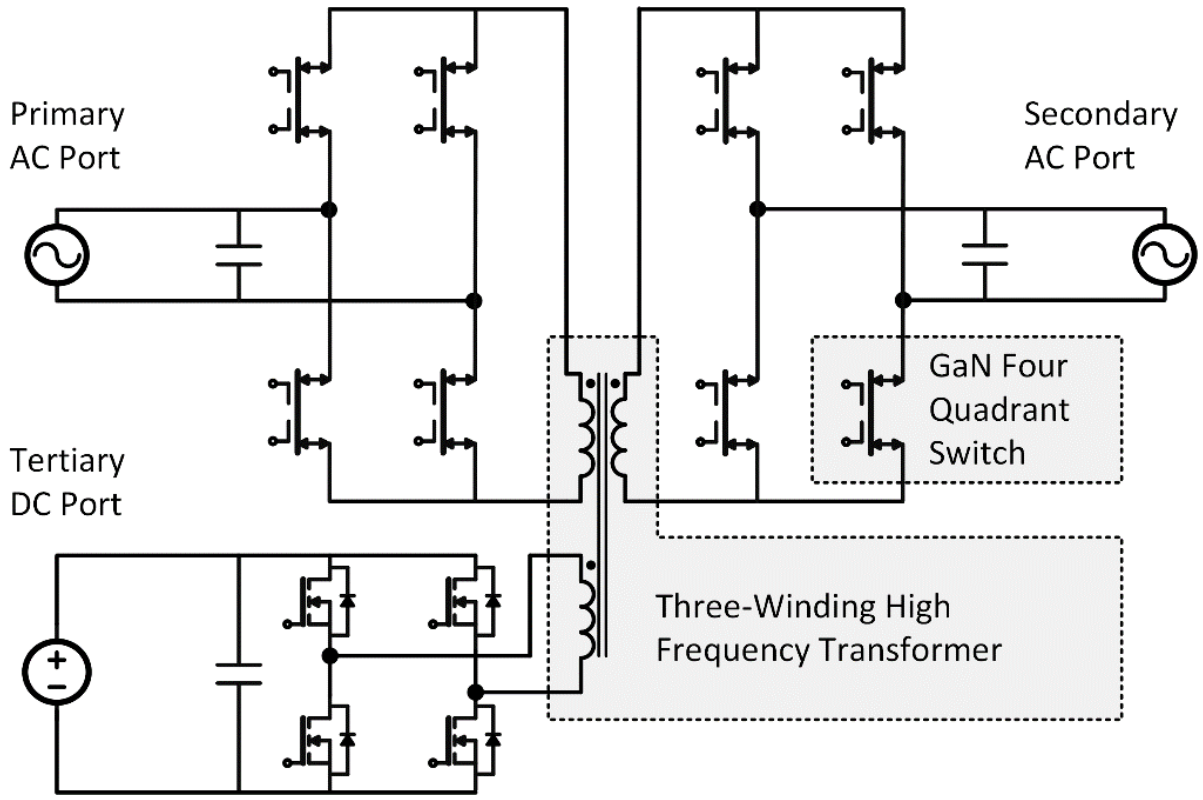
Parameter	Value
Part Number	TP65B110HRU [6]
Typ. R_{ON}, 25C	110mΩ
Series	SuperGaN
Gate Structure	Cascode
Package	TOLT
Manufacturer Headquarters	



Parameter	Value
Part Number	NV6428 [7]
Typ. R_{ON}, 25C	52mΩ
Series	GaNFast
Gate Structure	Direct Drive
Package	TOLT
Manufacturer Headquarters	

Technical Approach

- Equip direct AC-AC converter with a third DC port to provide energy buffering capabilities
- Bulk power transfer benefits from single-stage structure, third port is fractionally rated
- Challenges
  - Optimal Bi-Directional Switch (BDS) utilization
  - Three-winding high-frequency transformer design
  - Modeling and control



Project Timeline

FY26 | **2026 Peer Review** | **FY27** | **FY28**

Q1 Q2 Q3 Q4 | Q1 Q2 Q3 Q4

Subtask 2.1 – GaN BDS Device Characterization

Subtask 2.2 – Analytical Power Flow Model

Subtask 2.3 – Finalize TPSS Design Requirements

Subtask 2.4 – Benchtop Prototype Assembly/Eval

Subtask 3.1 – Three-Winding Transformer Design and Fabrication

Subtask 3.2 – Primary Control Design and Implementation

Subtask 3.3 – TPSS Power Stage Prototype Eval

Subtask 4.1 – Transformer Optimization

Subtask 4.2 – Secondary Control Design and Implementation

Subtask 4.3 – Building Block Module Prototype

V1 Prototype
Proof of Concept



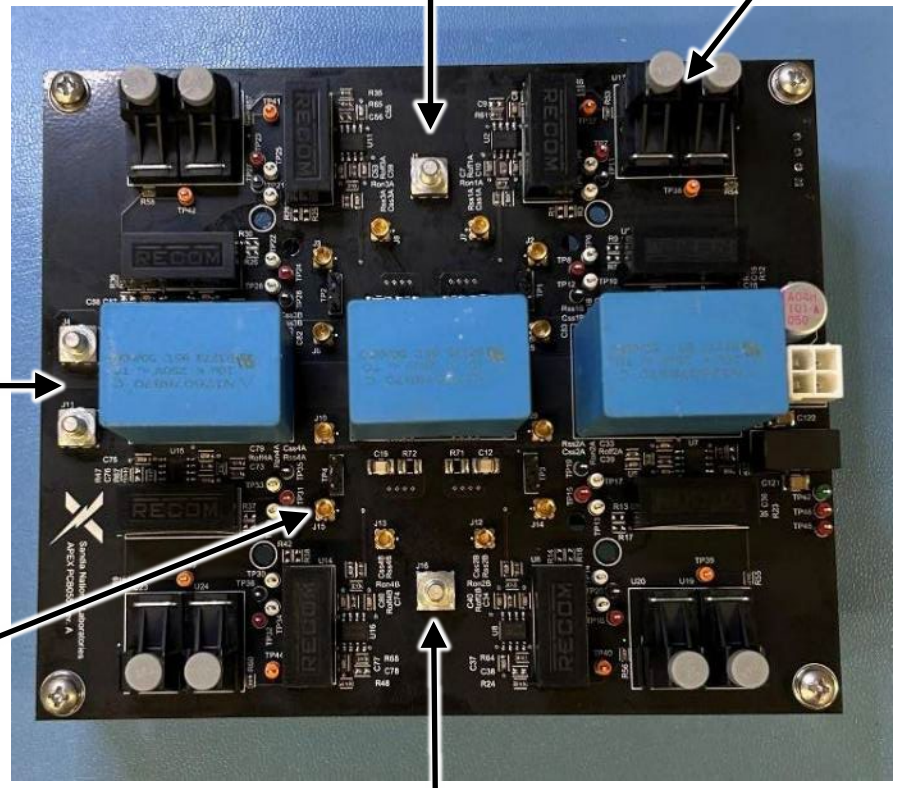
V2 Prototype
Closed-Loop Power Stage

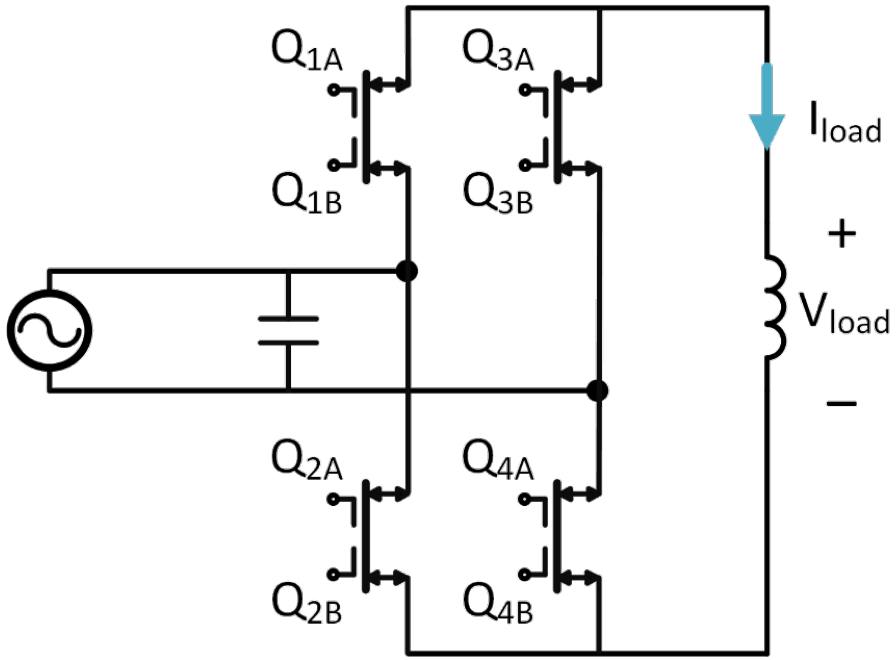


V3 Prototype
Complete AC-AC SST Module



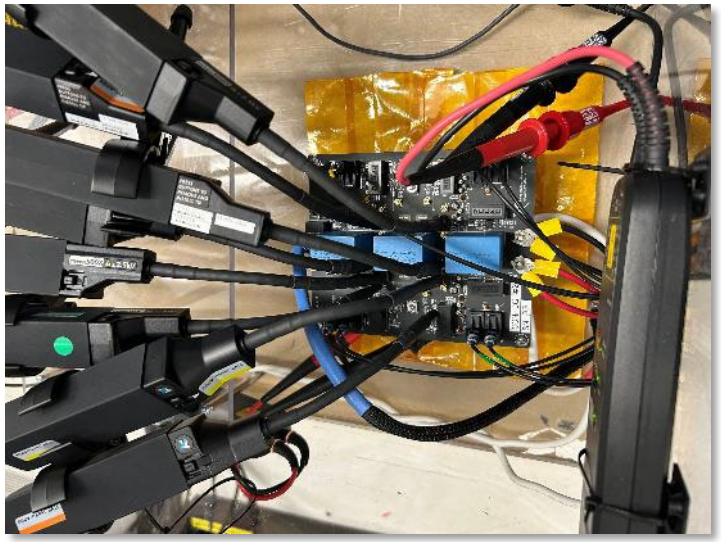
Custom BDS Characterization Board Design

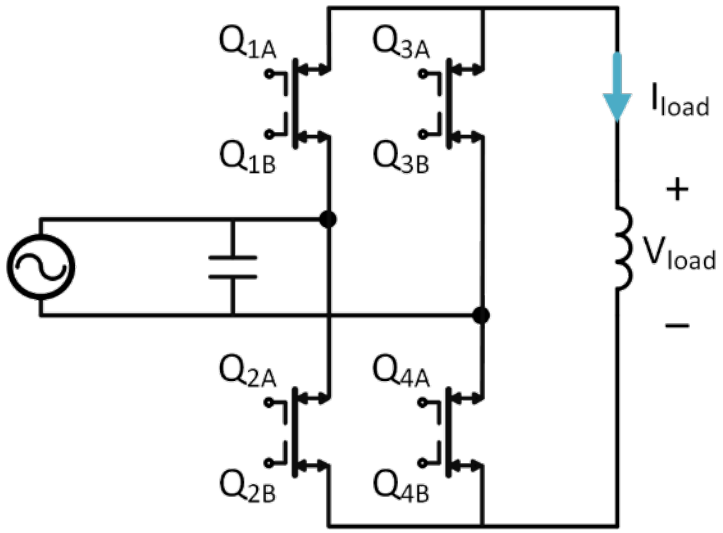


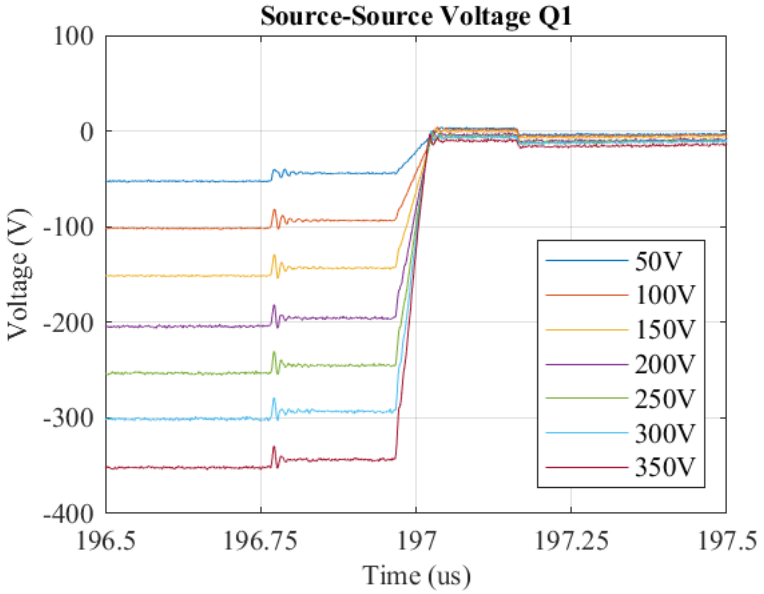


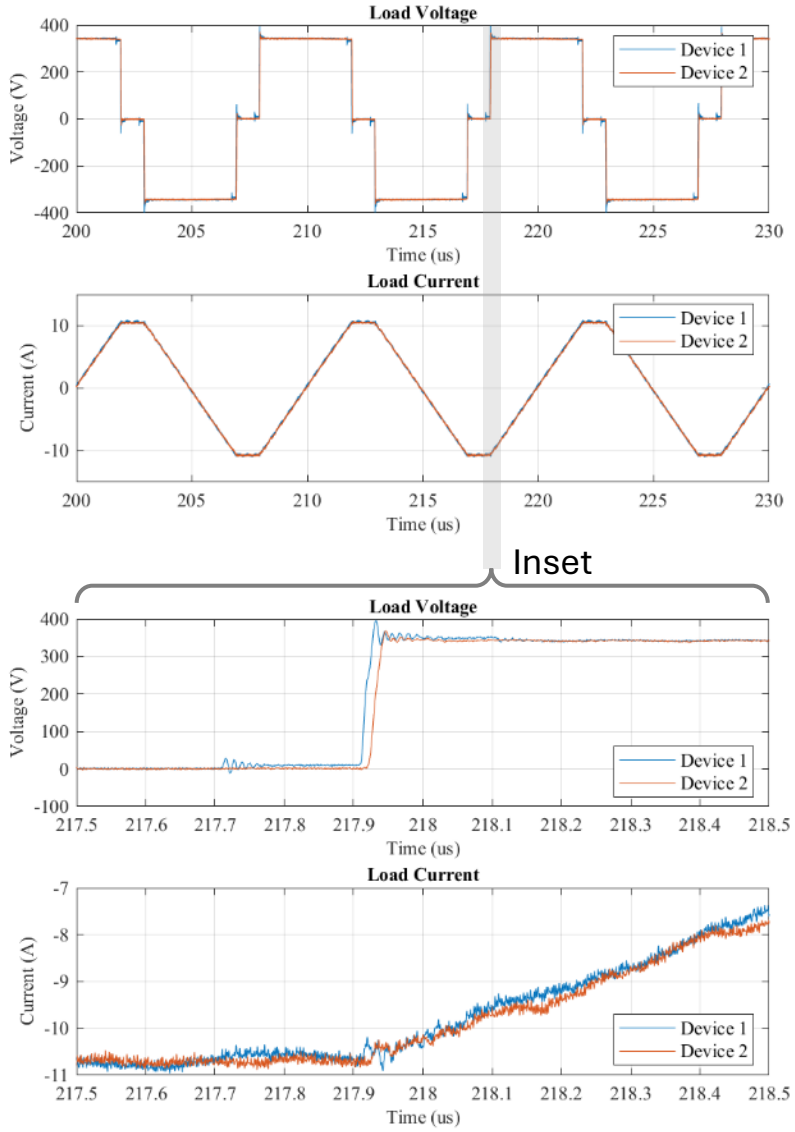
BDS Characterization Results

- Characterization completed for three types of BDS device
- 100kHz operation, multi-step commutation w/ 200ns overlap time
- Applied voltages 50V-350V
- Inductive loads 60uH to 150uH to set peak currents







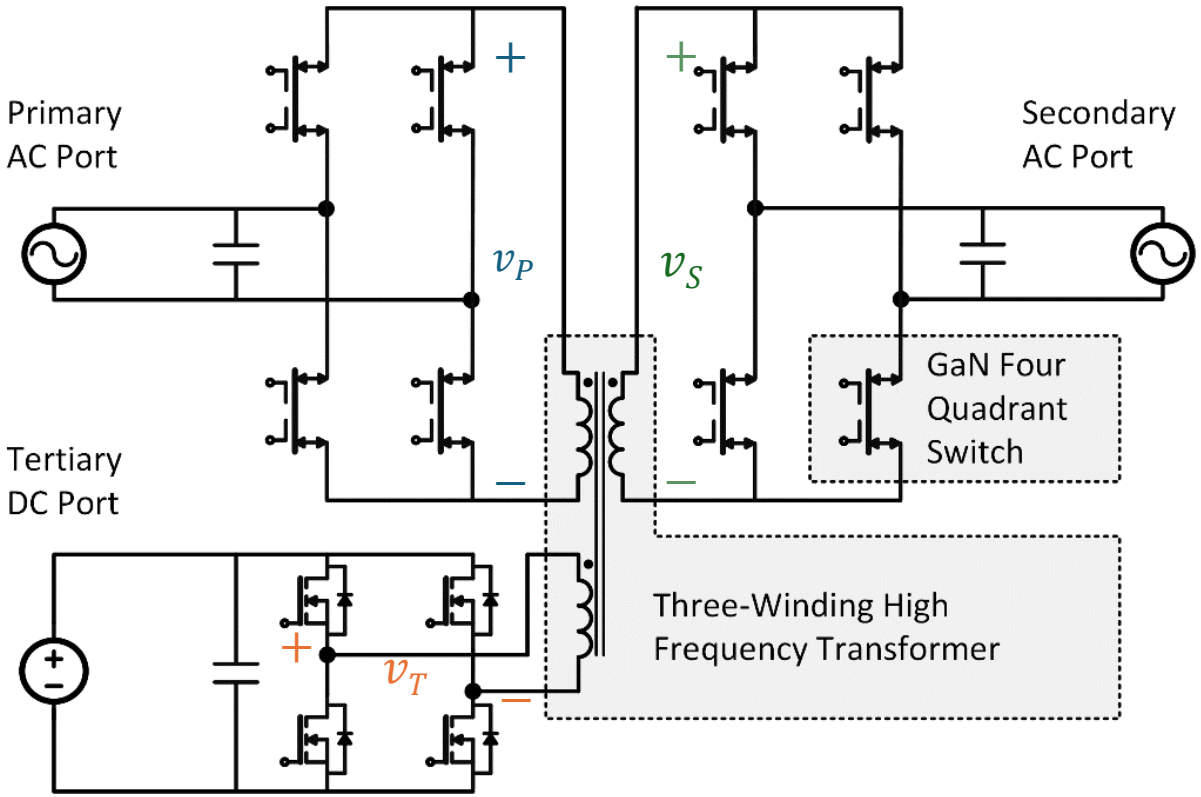


Model Development and Validation

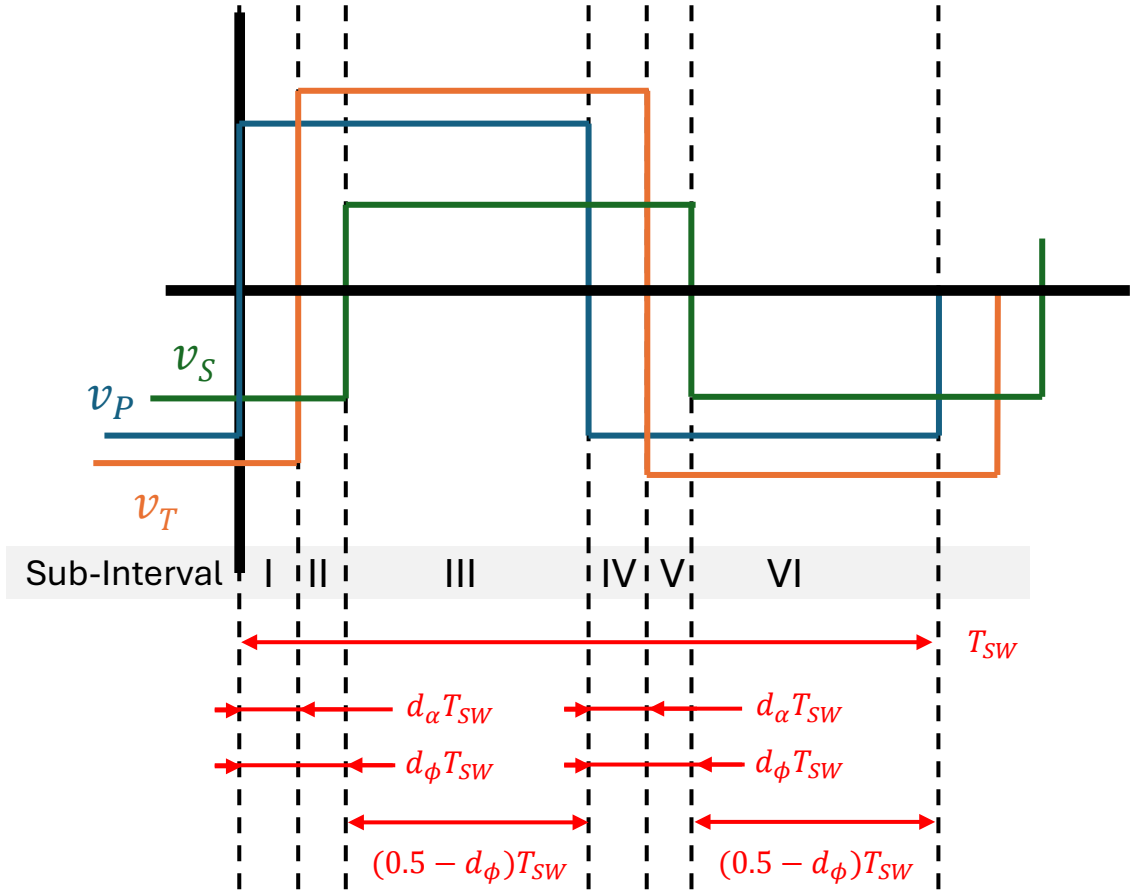
Converter operates with phase shift modulation

Power transfer is determined by phase shift control inputs:

- Primary-secondary phase shift, d_ϕ
- Primary-tertiary phase shift, d_α
- Secondary-tertiary phase shift, d_β



Switching-Cycle Transformer Excitation



Modeling Objective: Primary, secondary, and tertiary port power as function of $d_\phi, d_\alpha, d_\beta$.

Model Validation

Power Transfer Equations by Port:

$$P_P = \left(\frac{1}{f_{sw}}\right)\left(V_P V_T k_{13} d_\alpha (2|d_\alpha| - 1) + V_P V_S k_{12} d_\phi (2|d_\phi| - 1)\right)$$

$$P_S = \left(\frac{1}{f_{sw}}\right)\left(V_S V_P k_{21} d_\phi (2|d_\phi| - 1) - V_S V_T k_{23} d_\beta (2|d_\beta| - 1)\right)$$

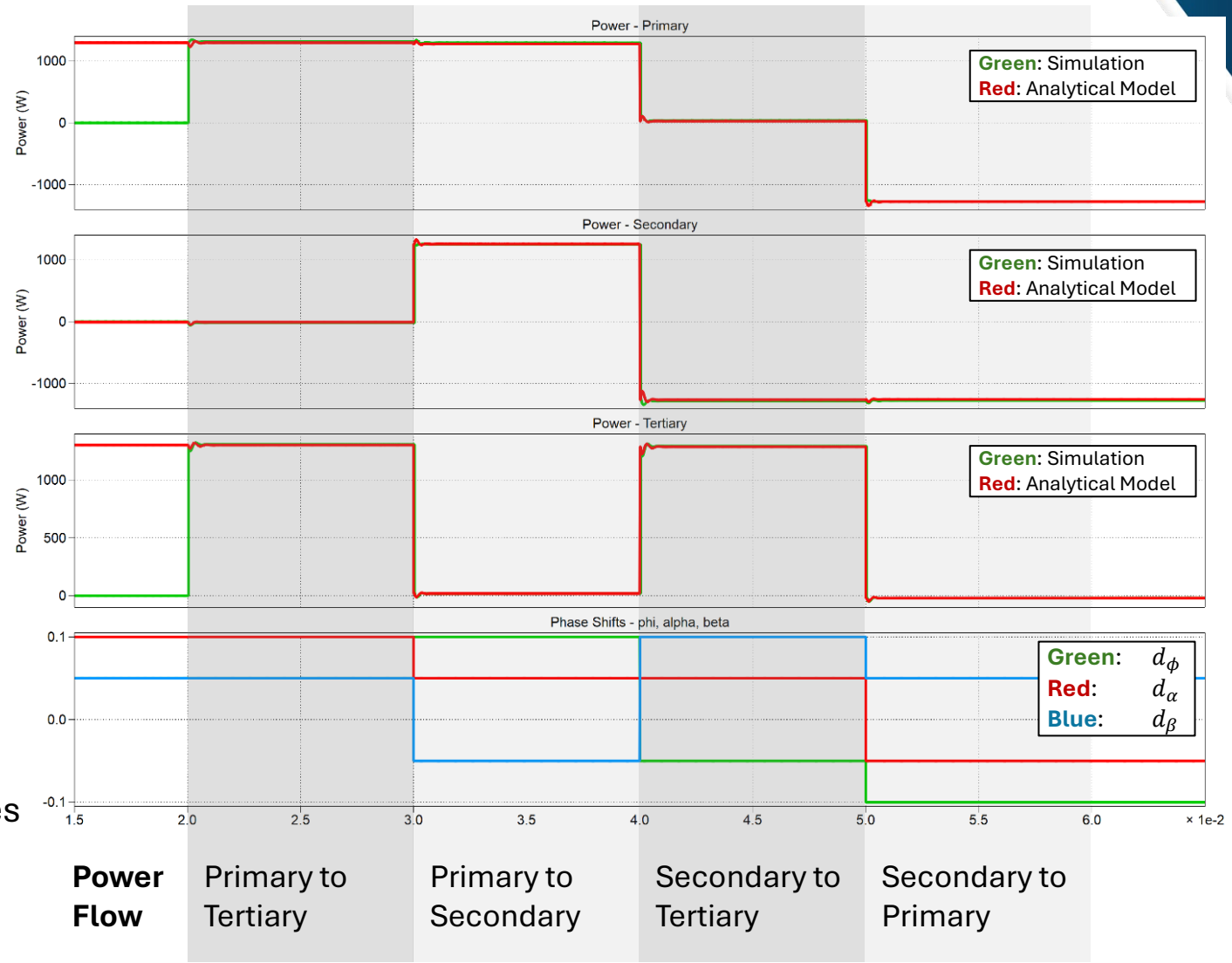
$$P_T = \left(\frac{1}{f_{sw}}\right)\left(V_T V_P k_{31} d_\alpha (2|d_\alpha| - 1) + V_T V_S k_{32} d_\beta (2|d_\beta| - 1)\right)$$

Where:

- f_{sw} is switching frequency
- V_P is primary port voltage
- V_S is secondary port voltage
- V_T is tertiary port voltage
- d_ϕ is primary-secondary phase shift
- d_α is primary-tertiary phase shift
- d_β is secondary-tertiary phase shift
- k_{xy} are normalized terms of an inductance matrix

Analytical equations validated against time-domain simulations cycling through possible power transfer cases

Validation in hardware is final FY26 objective



Control System Implementation

Control Objective: Determine control inputs needed to produce a desired combination of port power commands.

Model $[P_P, P_S, P_T] = f(d_\phi, d_\alpha, d_\beta)$

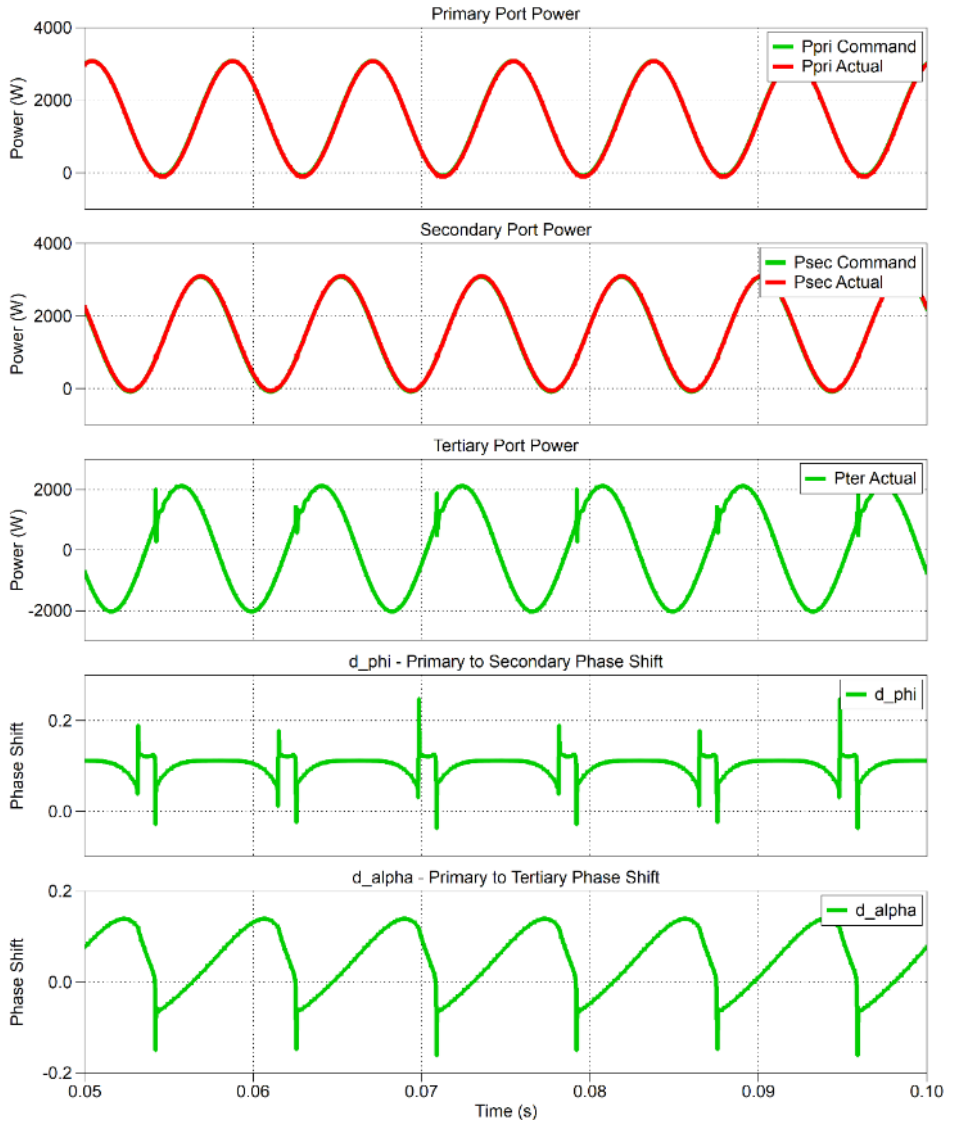
Solve Inverse Problem

Control $[d_\phi, d_\alpha, d_\beta] = f^{-1}(P_P, P_S, P_T)$

Inverse solution implemented in simulation as open-loop feed-forward controller

Simulation results demonstrate:

- Active power control
- Independent reactive power control at primary and secondary ports
- Operation with arbitrary input/output voltage phase angles



Conclusion and Impact

- Year 1 Objectives and Outcomes
  - BDS Device Characterization – One BDS device type originally expected, **3x** completed
  - Development of Power Flow Model – Complete
  - Demonstration of Three-Port Circuit – Planned for end of FY, on schedule

- If successful, this project will demonstrate SST modules that **cost less, live longer, take up less space, and do more to support the grid**.
- Simpler module circuit—lower cost and better reliability
- Efficiency improvement reduces thermal management requirements
  - Loss reduction of 50% or more (half as many on-state resistances in power transfer pathway)
- Power density
  - 5-10x faster rise/fall times for GaN BDS devices (25ns vs 125-250ns for SiC MOSFET), increased switching frequency leads to magnetic component volume reduction
- Flexibility and scalability
  - Power flow control is the key to SST value

Acknowledgements

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- Special thanks to our industry partners:
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  - Infineon: Edward Jones, Sameh Khalil, Eric Faraci

U.S. DEPARTMENT of ENERGY

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Todd Marzec
Pitt



Brandon Grainger
Pitt



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Pitt

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