PRESENTATION SUBMISSION INFORMATION

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- **Author(s):** Feng Qiu, Xiaonan Lu, and Alex Q. Huang
- **Organization(s):** Argonne National Laboratory (prime); Purdue University; University of Texas at Austin

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DOE OE TRAC PEER REVIEW 2026

PRESENTATION 1.5 | SEPTEMBER 21, 2026

CHARACTERIZATION OF SOLID-STATE TRANSFORMERS

FENG QIU, XIAONAN LU, ALEX Q. HUANG
Argonne National Laboratory | Purdue University | University of Texas at Austin

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PROJECT OVERVIEW

Project Description:
Characterizing solid-state transformers (SSTs), emphasizing dynamic models, grid service functions, cost-benefit evaluation, supply chain analysis, and standardization

Technology Area: Advanced Transformers; Advanced Power Electronics

TRL Start: TRL 2 **TRL End:** TRL 4

Funding Profile: Federal Share $500,000; Cost Share $46,755

Period of Performance: 10/1/2025 to 9/30/2027

Prime National Lab: Argonne National Laboratory

Principal Investigator: Feng Qiu, Ph.D., Principal Engineer and Section Manager

Major Team Participants: Purdue University, West Lafayette; University of Texas, Austin

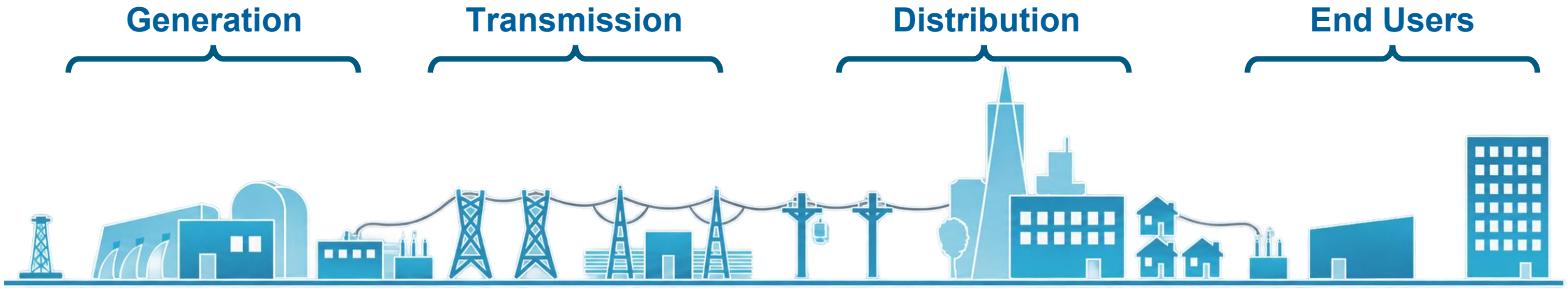
Industry Advisory Board: GE Vernova; Southern California Edison

Alignment with DOE OE goals:

- **Stabilize** the grid: dynamic models and ride through characterization of SSTs
- **Optimize** the grid: grid service functions and long-term cost-benefit insights
- **Grow** the grid: standardization enabling SST adoption for next-generation electrical systems

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PROBLEM STATEMENT

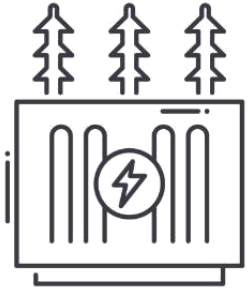


- Dispatchable resources
- Storage resources

- FACTS devices
- HVDC transmission systems

- Microgrids
- MVDC distribution systems

- Building-integrated generation resources
- Residential nano-grids



Transformers

(+) widespread deployment

(-) bulk size and high weight

(+) flexible access points

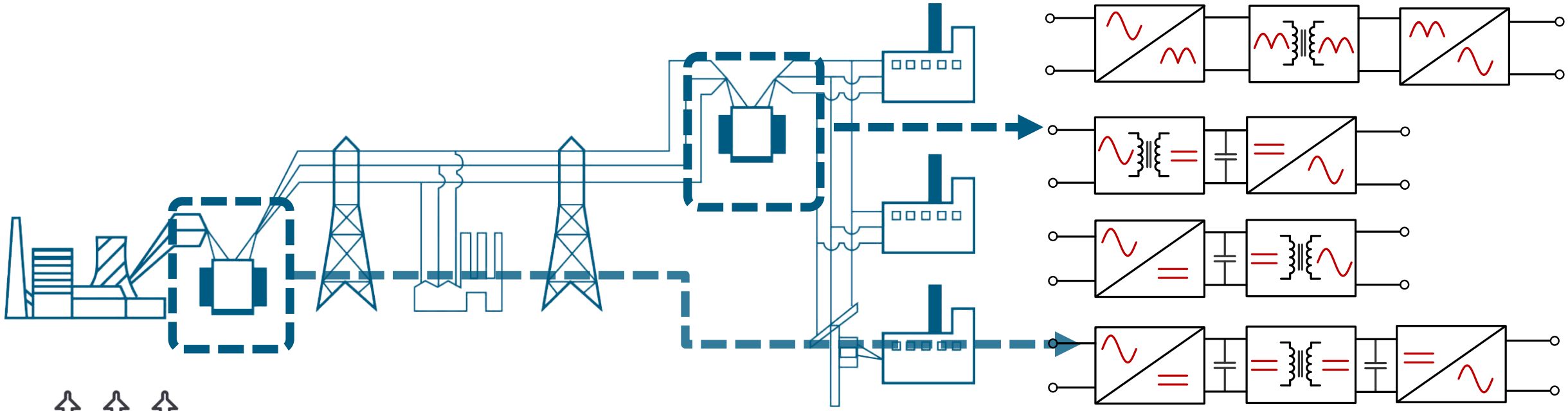
(-) maintenance challenges

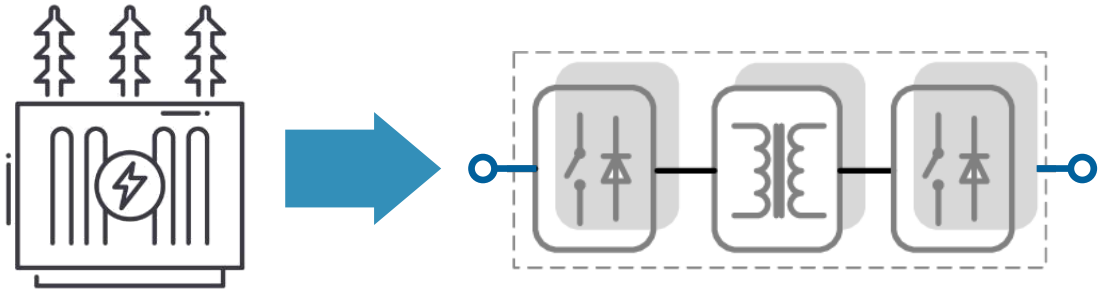
(+) mature technologies

(-) limited functionalities

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PROBLEM STATEMENT





conventional transformer

solid-state transformer

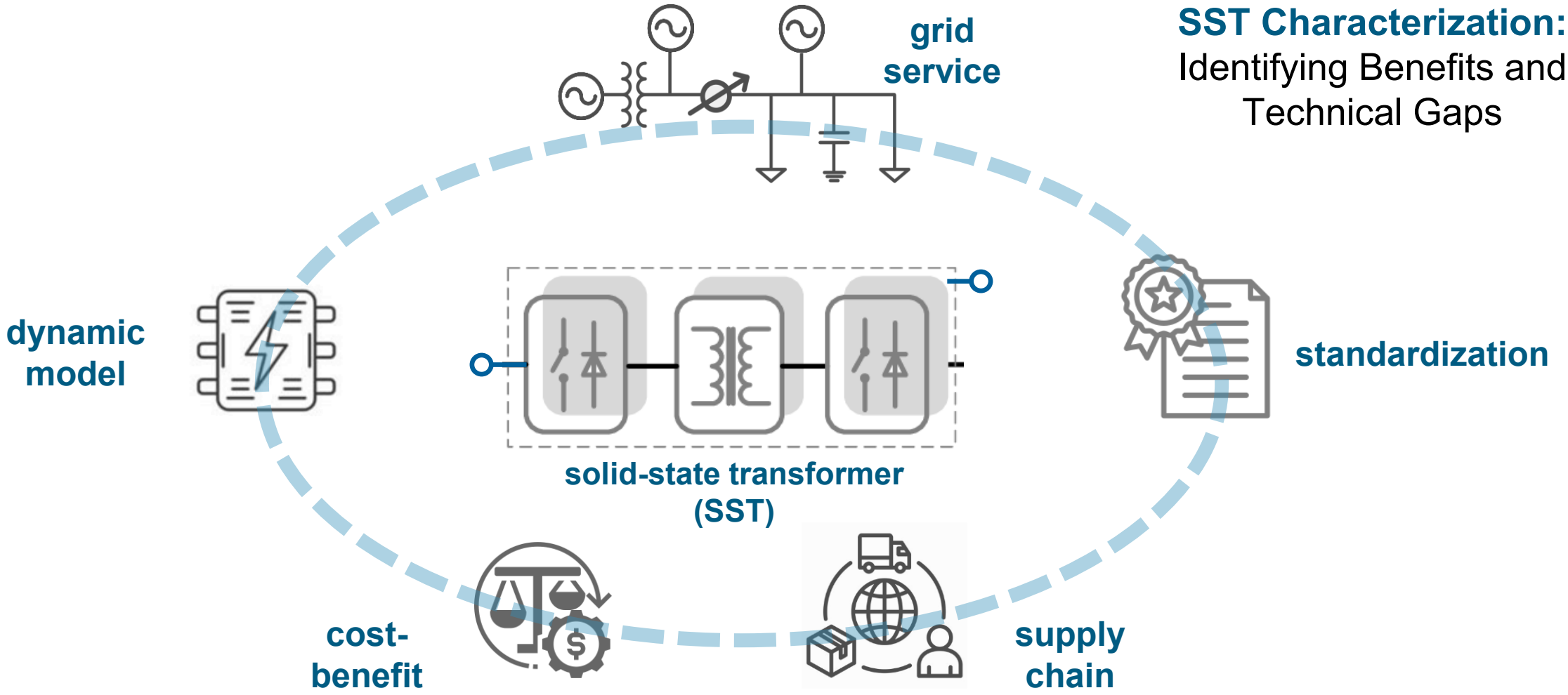
(+) light weight
(+) high power density
(+) versatile control functions
(+) various operation modes

Holistic characterization is still needed to quantify the benefits of widespread grid utilization of SSTs

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TECHNICAL APPROACH / INNOVATIONS

SST Characterization:
Identifying Benefits and Technical Gaps



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TECHNICAL APPROACH / INNOVATIONS

Thrust 1: SST Dynamic Phasor Modeling and Emerging Grid Functions

- Mixed-frequency **SST Modeling Framework**
  - Combined line-frequency and high-frequency **full-spectrum dynamics**
  - Balanced model **fidelity** and model **complexity**
  - A comprehensive framework covering EMT, phasor, and data-driven sections.
- **Grid services** with emerging control functions (e.g., **grid-forming**) and conventional control functions (e.g., **grid-following**)
  - **Normal operation:** frequency and voltage regulation, active and reactive power regulation
  - **Fault operation:** low/high-voltage ride through, low/high-frequency ride through
- **Large-scale simulation** with SSTs considering various grid scenarios
  - **Leveraging existing work** on dynamic inverter modeling (GFM, GFL)

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TECHNICAL APPROACH / INNOVATIONS

Thrust 2: SST Cost-Benefit Analysis and Supply Chain Risk Identification

- Identification of **"Long-Term" "Hidden"** costs and revenue streams
  - **LCOE** (levelized cost of energy) incorporating long-term costs (e.g., maintenance) and long-term revenue streams (e.g., grid services)
  - Sample revenue stream: **fast frequency response services** translated into revenue to offset capital and maintenance costs over time
- **Component-level supply chain risk analysis**
  - Supply chain risks: **magnetic components and semiconductor devices**
  - Leveraging past and ongoing efforts: SST LCOE analysis, Purdue semiconductor program

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TECHNICAL APPROACH / INNOVATIONS

Thrust 3: Industrial Standardization for SST Grid Integration

- **Insufficient industrial standardization** efforts on SST grid integration
  - Potential differences in standards and requirements **across regions** and **in different grid scenarios**
- **Evolving standard development** alongside the progress of grid modernization
  - Existing standard development efforts with active participation from the project team: Institute of Electrical and Electronics Engineers (IEEE) **P3105 Recommended Practice for Design and Integration of Solid-State Transformers in Electric Grid**
  - Leveraging existing **team participation** in the SST standard development working group

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TEAM AND RESOURCES

- **Argonne National Laboratory**
  - ✓ Dynamic modeling and simulation
  - ✓ Grid support functions
- **Purdue University**
  - ✓ SST modeling and control
  - ✓ Cost-benefit and supply chain risk analysis
- **University of Texas Austin**
  - ✓ SST implementation and optimization
  - ✓ SST industrial standardization
- **GE Vernova**
  - ✓ Global energy OEM for generation and transmission
  - ✓ HVDC and power electronics manufacturing
- **Southern California Edison (SCE)**
  - ✓ Major utility modernizing distribution grids
  - ✓ Interconnection standards and operations

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TASK BREAKDOWN

BP1

Task 1: project management

Task 2: industry advisory board

Task 3: data library building

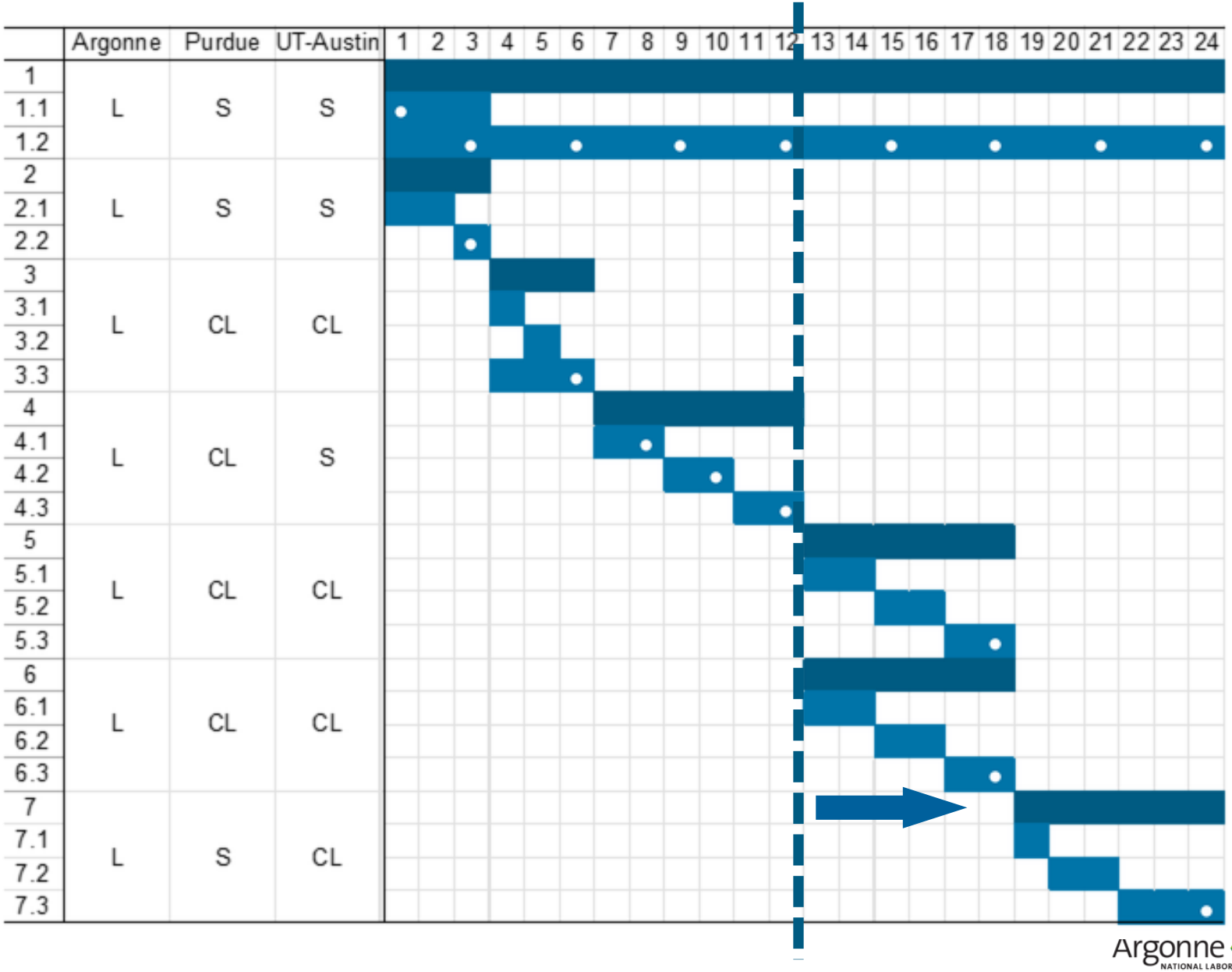
Task 4: dynamic modeling and sim

Task 5: cost-revenue

BP2

Task 6: supply chain

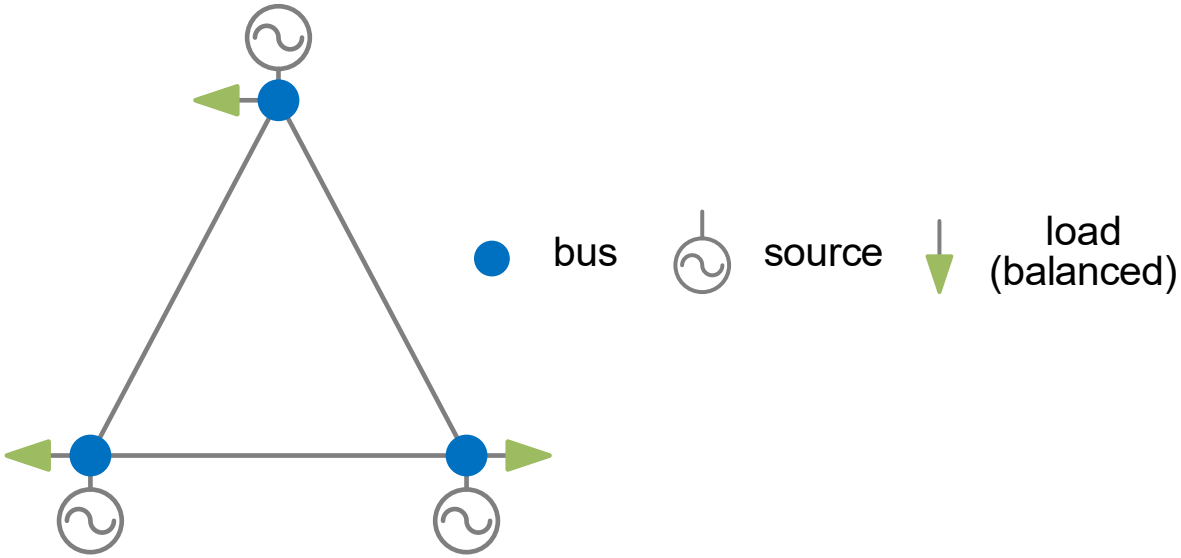
Task 7: standardization



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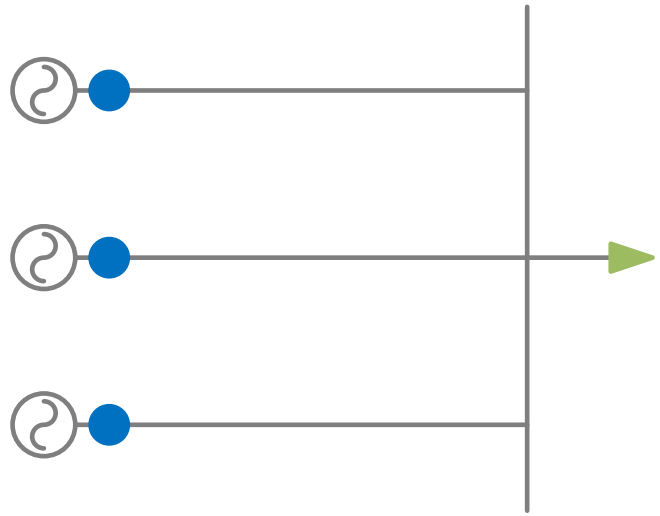
RESULTS: TEST SYSTEM DEVELOPMENT

Test System 1: 3-Bus, Meshed



- Meshed, 3-bus system with generators and inverter-based resources, such as energy storage
- **Features:** balanced, normal/fault conditions
- **SST access points:** generation buses for voltage conversion and line compensation

Test System 2: 3-Bus, Radial

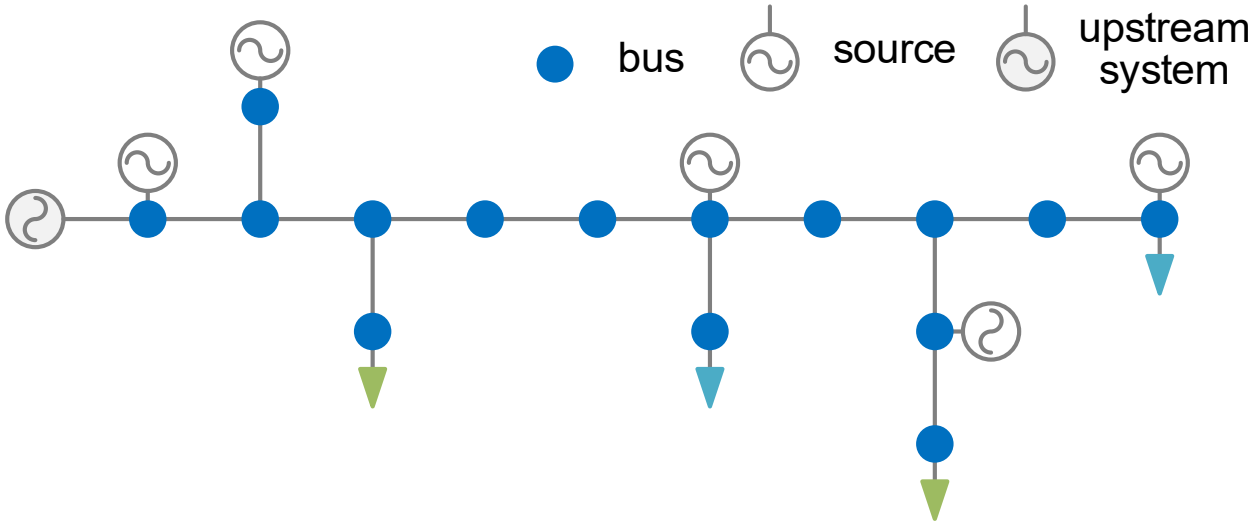


- Radial, 3-bus system with combined generators and inverter-based resources
- **Features:** balanced, normal/fault conditions
- **SST access points:** generation bus connection, point-of-interconnection (POI) interfaces

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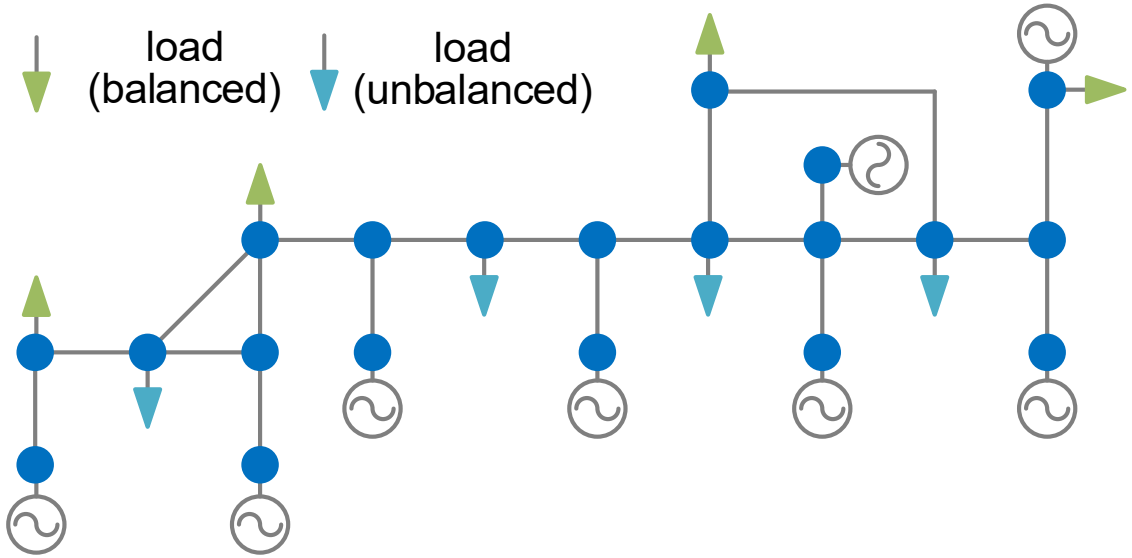
RESULTS: TEST SYSTEM DEVELOPMENT

Test System 3: 15-Bus, Radial



- Radial, 15-bus system with generators and inverter-based resources, in the context of unbalanced feeder scenarios
- **Features:** unbalanced, normal/fault conditions
- **SST access points:** substation interface; cross-branch soft open points; unbalance operating scenarios

Test System 4: 21-Bus, Hybrid Meshed/Radial



- Hybrid meshed/radial island grid with generators and inverter-based resources
- **Features:** mixed meshed and radial configuration, normal/fault conditions, unbalanced
- **SST access points:** generator step-up; meshed-loop nodes; radial branch decoupling

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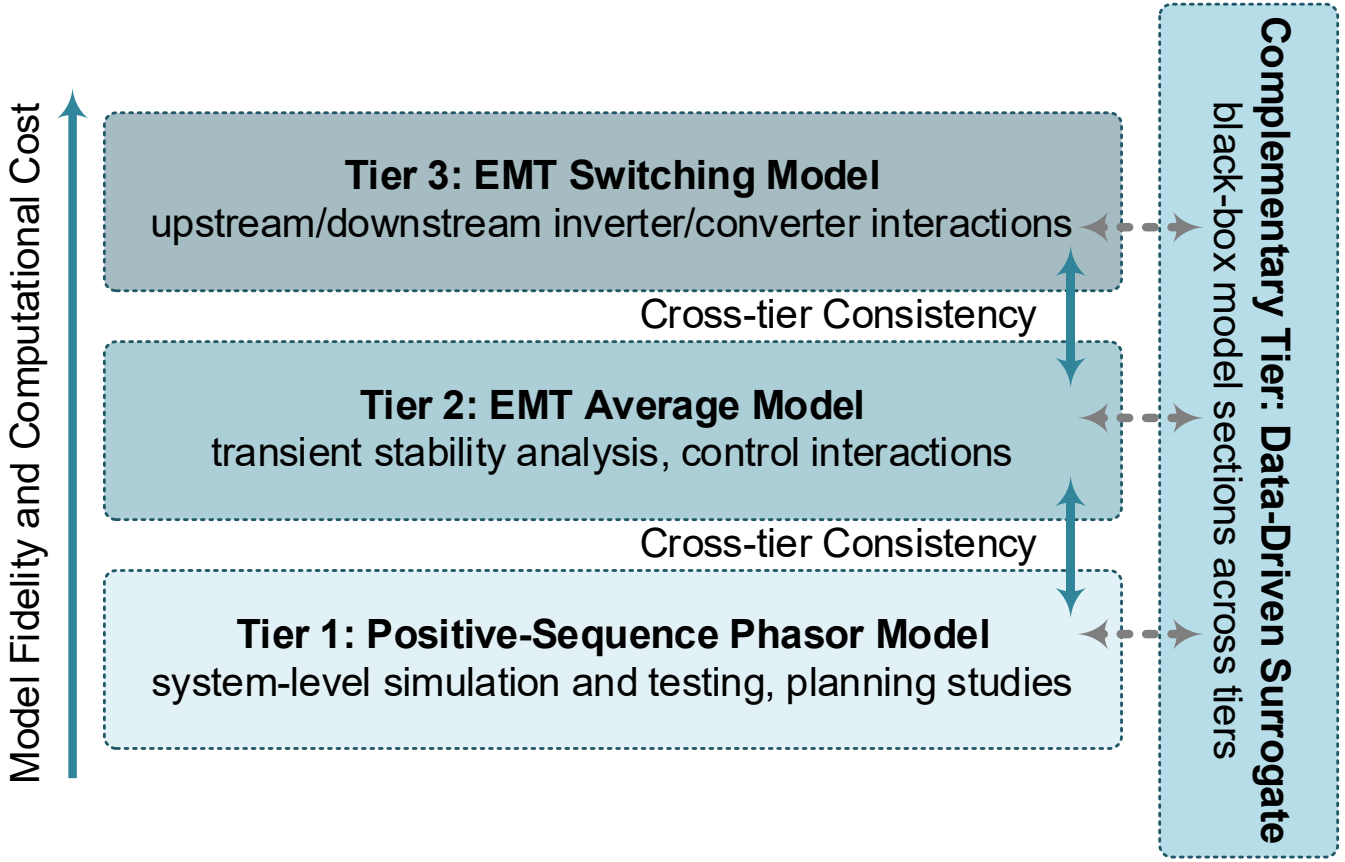
RESULTS: LITERATURE SURVEY ON SST MODELING

- **Comprehensive Literature Survey to Guide SST Model Development**
  - SST models cluster into three fidelity tiers: **EMT switching**, **EMT average**, and **positive-sequence phasor**.
  - **Data-driven and neural network surrogates** emerging as a complementary modeling tier.
  - SSTs positioned as the medium-voltage interface in emerging **data center power architectures.**
- **Key Gaps Shaping the Modeling Framework**
  - **Fragmented Practice:** cross-tier accuracy comparisons are comprehensively done; no generic SST model for transient stability analysis.
  - **A Varying-Fidelity SST Modeling Framework** is a vital intermediate tier bridging phasor and EMT domains, supporting various applications (e.g., data center dynamic modeling).

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RESULTS: VARYING-FIDELITY SST MODELING FRAMEWORK

- **Three Physics-Based Tiers** from positive-sequence phasor to switching EMT, plus a data-driven surrogate complementary layer
- **Cross-tier Consistency:** shared parameters and operating points, with quantifiable accuracy
- **Scenario-Driven Selection:** model representation with an appropriate fidelity is selected for given scenarios



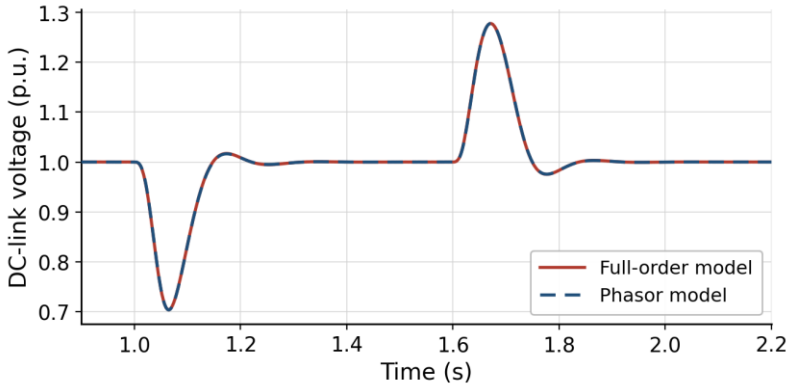
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RESULTS: PHASOR MODEL IMPLEMENTATION

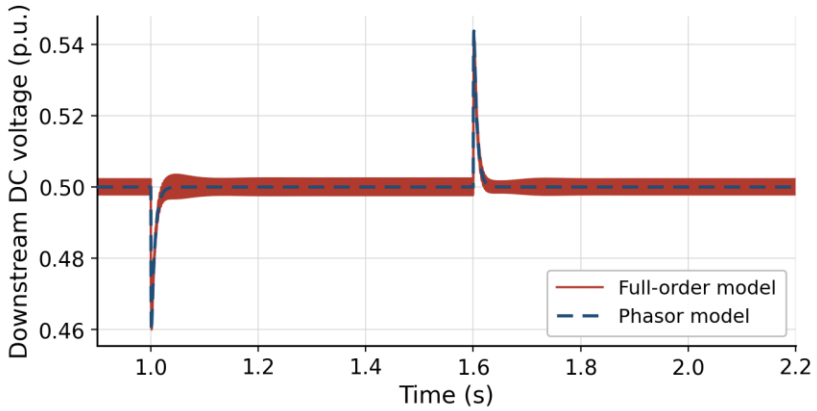
- **Phasor Models** emphasizing low-frequency dynamics have been implemented
  - **Energy Conversion Chain:** active front-end rectifier with PLL and DC-link control; dual-active-bridge (DAB) for DC-DC conversion, downstream loads.
  - **Positive-Sequence Phasor Model Formulation** targeting SST primary side modeling.
  - **Application Context:** mirroring the critical data center power architecture with SST-enabled configuration (controlled AC/DC, regulated DC-link, downstream POL converters, among others).
- **Verification Protocol**
  - Disturbance: 20% load power increase at t = 1 s, and 20% load power decrease at t = 1.6 s.
  - Requirement: relative error below 5% for all monitored electrical quantities.

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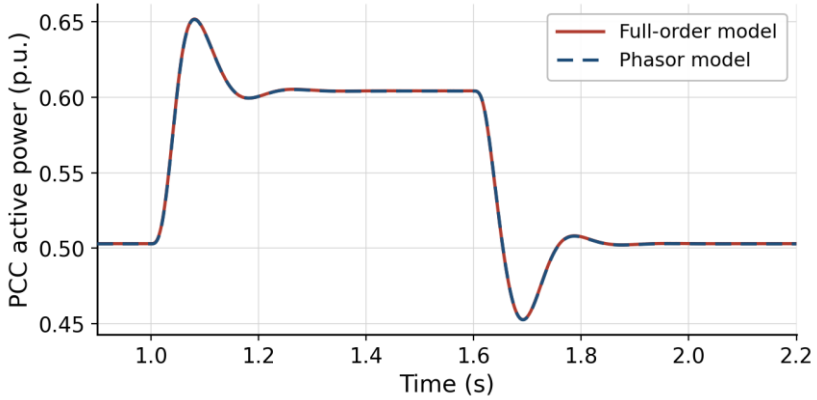
RESULTS: PHASOR MODEL VERIFICATION



DC-link Voltage



Downstream DC-link Voltage



PCC active power

- Developed phasor model tracks DC-voltage and power trajectories through the load step change transients
- Results compared against full-order switching models
- Maximum instantaneous error: ~0.9% (downstream DC voltage with step changes)

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CONCLUSION AND IMPACT

- **Conclusions to Date**
  - Data library and four SST test systems completed, with identified features and SST access points.
  - First-step dynamic phasor model completed and verified emphasizing SST primary-side dynamics.
  - Varying-fidelity modeling framework established with various model tiers for different applications.
- **Impacts and Next Steps**
  - Dynamic models provide clearer SST grid-impact assessment with balanced fidelity and computational efficiency.
  - Continue the project tasks on cost-benefit analysis, supply chain risk identification, standardization, among others.
  - **Adapt and extend the SST models with varying fidelity for data center power architecture dynamic modeling.**

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ACKNOWLEDGEMENTS

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[1] X. She, A. Q. Huang, and R. Burgos, “Review of solid-state transformer technologies and their application in power distribution systems,” IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 1, no. 3, 2013.

[2] S. R. Sanders, J. M. Noworolski, X. Z. Liu, and G. C. Verghese, “Generalized averaging method for power conversion circuits,” IEEE Transactions on Power Electronics, vol. 6, no. 2, 1991.

[3] H. Qin and J. W. Kimball, “Generalized average modeling of dual active bridge DC-DC converter,” IEEE Transactions on Power Electronics, vol. 27, no. 4, 2012.

[4] A. M. Stankovic and T. Aydin, “Analysis of asymmetrical faults in power systems using dynamic phasors,” IEEE Transactions on Power Systems, vol. 15, no. 3, 2000.

[5] Q. Huang and V. Vittal, “Advanced EMT and phasor-domain hybrid simulation with simulation mode switching capability for transmission and distribution systems,” IEEE Transactions on Power Systems, vol. 33, no. 6, 2018.

[6] X. Zhao and J. Zhao, “Dynamic modeling of data-center power delivery for power system resonance analysis,” arXiv:2604.06624, 2026.

[7] IEEE P3105, Recommended Practice for the Design and Integration of Solid-State Transformers in the Electric Grid (standard under development).

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Thank You!

Questions?

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