



Adaptive Transmission and Distribution Modeling and Simulation Tools for Supporting Integration and Operation of High Penetration of DERs

Final Project Report

S-107

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



Adaptive Transmission and Distribution Modeling and Simulation Tools for Supporting Integration and Operation of High Penetration of DERs

Final Project Report

Project Team

Qihua Huang, Project Leader
Colorado School of Mines

Venkataramana Ajjarapu
Iowa State University

Meng Wu
Arizona State University

Graduate Students

Owen Cornmesser
Colorado School of Mines

Aditya Shankar Kar
Iowa State University

Zeming Zhou
Arizona State University

PSERC Publication 25-06

December 2025

For information about this project, contact:

Qihua Huang
Colorado School of Mines
Electrical Engineering Department
1500 Illinois St., Golden, CO 80401
Phone: 303-273-3960
Email: qihuahuang@mines.edu

Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: <http://www.pserc.org>.

For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
527 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-727-2052

Notice Concerning Copyright Material

PSERC members are given permission to copy without fee all or part of this publication for internal use if appropriate attribution is given to this document as the source material. This report is available for downloading from the PSERC website.

Acknowledgments

We acknowledge the technical feedback from project advisors.

Executive Summary

This project is motivated by the growing integration of utility-scale and distributed energy storage resources (DER) in both transmission and distribution (T&D) systems. As the implementation of FERC Order 2222 is coming and DER proliferate, it is imperative to adequately model and efficiently analyze the dynamic impacts of DER on T&D systems, capture and leverage full capabilities of DER to facilitate large-scale DER integration and T&D system operation. Integrated T&D modeling and co-simulation tools have been developed by reusing existing simulators. One fundamental issue is that existing transmission and distribution system simulation tools are modeling-fidelity-agnostic, i.e., they solve dynamic simulation problems with all the details in the input system models regardless of system conditions and contingencies. As a result, they are computationally inefficient and inadequate to deal with complex, large-scale T&D systems, and engineers must manually perform model reduction or simplification for almost every study, which is ad-hoc, time-consuming and error-prone. All these contribute to renewable integration queue backlog problems in many independent system operators (ISOs) and utilities.

Our project goals are 1) to help ISOs and utilities address these issues by transforming the model reduction and selection from a manual, ad-hoc and out-of-simulation-loop process into a systematic, automated, and AI-enhanced process within a suite of new T&D modeling and simulation tools; and 2) to help the industry tap into the var flexibility offered by DERs to enhance T&D system voltage stability as well as renewable integration.

To achieve the goals above, this project develops an adaptive, multi-fidelity and AI-accelerated T&D co-simulation tool to improve the computational efficiency of dynamic simulation for large-scale T&D systems, and make transient stability simulation and dynamic contingency analysis of large-scale T&D systems on laptops and servers feasible and practical. The research is presented in four chapters (Chapters 2-5).

Chapter 2 — Aggregate DER Reactive-Power Capability Curve: Develops a TSO–DSO framework that aggregates feeder-level inverter VAR flexibility via D-OPF, feeds it to a T-OPF during contingencies, then dispatches VAR setpoints back to effective DERs; in the 9-bus/37-node tests this keeps voltages within limits under generator and line outages and reduces feeder reactive losses from 3.94 to 3.69 MVar with sensitivity-aware dispatch.

Chapter 3 — Data-Driven and LLM-Assisted Distribution Modeling: Identifies reduced-order, globally linear dynamics from partial POI measurements using delay embeddings and DMD

(Koopman-style), accurately reconstructing responses even with FIDVR; also introduces a fine-tuned LLM assistant for PSCAD Python automation (mitigating hallucinated APIs) and a “Grid-Scout” field-to-model pipeline (Flutter app + AWS/MySQL) that updates OpenDSS models from QR/GPS-tagged equipment data.

Chapter 4 — Screening for T&D Multi-Fidelity Modeling: Shows that short-circuit analysis provides an accurate and generally conservative estimator of minimum voltage during three-phase faults—robust to aggregation, DER penetration, and dynamic loads—validated on IEEE-9 and -300 systems and in T&D co-simulation; this supports fast identification of where detailed distribution models are actually needed.

Chapter 5 — Automated & Adaptive Distribution Modeling for Contingency Analysis: Automates case building by thresholding short-circuit voltages to “high-impact” regions (disaggregate there, aggregate elsewhere), achieving more than 4 times lower runtime than fully disaggregated simulation while cutting average RMSE by 10 times and max voltage error by more than five times versus a fully aggregated model; it also analyzes accuracy–runtime tradeoffs as the voltage threshold varies.

Project Publications

- [1] A. Alkhonain, A. Singhal, A. K. Bharati, and V. Ajjarapu, “Sensitivity-aware reactive power dispatch of DERs to support transmission grid during emergency,” in 2023 North American Power Symposium (NAPS), 2023, pp. 1–6.
- [2] A. S. Kar, K. K. Challa, A. K. Bharati, A. Singhal, and V. Ajjarapu, “Robust VAR Capability curve of DER with Uncertain Renewable Generation,” accepted, IEEE Power and Energy Society General Meeting (PESGM), Seattle, 2024
- [3] O. Cornmesser and Q. Huang, “Identification of Impact Regions for Adaptive Distribution System Modeling in Transmission-Level Dynamic Contingency Analysis,” accepted and presented at CIGRE Grid of the Future Symposium, Raleigh, NC, Nov. 2024
- [4] Gareth Calkins, Carlos Desio, Musheer Gorani, J. Scott McCain, Seth Palkki, Jose Manuel G. Dolot, and Meng Wu, “Undergraduate Research on A Smart Field Data Collection and Model Updating Tool for Distribution Power Systems,” *57th North American Power Symposium (NAPS)*, Hartford, CT, USA, Oct 2025.
- [5] A. S. Kar, K. K. Challa, A. K. Bharati, and V. Ajjarapu, “Harnessing Flexibility of Distribution System With Uncertain Loads and DERs,” submitted to IEEE trans. on power system, Dec, 2024.

- [6] O. Cornmesser and Q. Huang, “Contingency-aware multi-fidelity modeling and simulation for dynamic contingency analysis under high penetration of distributed energy resources”, under preparation.

Student Theses:

- [1] Owen Cornmesser, “Adaptive transmission and distribution dynamic contingency analysis with high penetrations of distributed energy resources.” Master thesis, Colorado School of Mines, Golden, Colorado, May, 2025 .

Industry Advisors

Panitarn (Joseph) Chongfuangprinya	Hitachi America Ltd.
Bo Gong	Salt River Project
Mingguo Hong	ISO New England
Akshay Korad	Midcontinent Independent System Operator
Weijia Liu	National Renewable Energy Laboratory
Zhongxia Zhang	Dominion Energy
Parag Mitra	Electric Power Research Institute
Deepak Ramasubramanian	Electric Power Research Institute
Evangelos Farantatos	Electric Power Research Institute
Alberto Del Rosso	Electric Power Research Institute
Harvey Scribner	Southern Power Pool
Mohit Singh	ComEd
Sid Suryanarayanan	Eaton