



Framework to Analyze Interactions between Transmission and Distribution (T&D) Systems with High Distributed Energy Resource (DER) Penetrations

Final Project Report

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Power Systems Engineering Research Center
*Empowering Minds to Engineer
the Future Electric Energy System*



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Executive Summary

With the growing levels of DER deployment, it is imperative to analyze the interactions between electric power transmission and distribution (T&D) systems, especially the impacts of distribution system connected DERs on the transmission systems operations. This project develops an iteratively coupled T&D analysis framework through co-simulation approach to address the future requirements for modeling and analysis of the large-scale integrated T&D systems with high levels of DER penetrations. The impacts of DERs on T&D system may manifest as steady-state concerns (voltage regulation, variability, voltage unbalance), dynamic concerns (frequency regulation), or in its transient response (angle and voltage stability during faults). Depending upon the requirements for DER impact study, we present three types of co-simulation methods: *quasi-static co-simulation* to evaluate steady-state concerns; *hybrid co-simulation* to evaluate and mitigate frequency regulation concerns, and *dynamic co-simulation* to model T&D system response during transients/faults.

The proposed framework utilizes dedicated software modules to solve the decoupled T&D models. The T&D interactions are captured by exchanging network solutions at the point of common coupling (PCC). An iterative coupling approach is adopted for co-simulation that results in a co-simulation model that closely approximates the behavior of a stand-alone unified T&D simulation platform. The iterative vs. non-iterative coupling of T&D systems are thoroughly evaluated using rigorous simulation studies. It is observed that a non-iterative coupling for quasi-static T&D co-simulation study may lead to significant errors for cases with significant DER variability and unbalanced loading conditions. However, a non-iterative coupling may be able to accurately model hybrid co-simulation cases if simulation time is advanced in small steps. Finally, it is validated that a coupled T&D model with a three-sequence transmission system model and power flow solver is more accurate compared to a positive-sequence model, especially when DERs introduce significant phase unbalance.

Need for Co-Simulation

Several exploratory studies and field demonstrations have pointed out that the new and recent developments, including the integration of DERs, electric vehicle loads, and energy storage units are increasing the stress on power delivery systems. Unfortunately, most of the existing DER interconnection studies evaluate the integrational challenges of DERs either only at the distribution level or on a decoupled T&D system. The decoupled T&D system analysis models (1) distribution system as lumped loads and (2) transmission system as a constant power source. The potential impacts on the transmission grid are either ignored given low penetrations of DERs or are non-representative due to the decoupled T&D model. It is expected that the ongoing and future large-scale DER deployment projects can potentially affect the regional transmission grid operations. The situation worsens in rural areas where the distribution system is lightly loaded and covers an extended area with low load density. Specifically, in the lightly loaded areas, with the increase in DER penetrations, the distributed generation may exceed the local consumption needs, resulting in a reverse power flow condition from individual consumers through the feeders back to the distribution substation and possibly into the transmission system. Therefore, a decoupled analysis of T&D system is no longer adequate, calling for new tools capable of capturing the interactions between T&D systems with high-levels of DER penetrations.

Summary of the Research Contributions

As discussed before, in this project, three co-simulation models are developed to evaluate the impacts of DERs on the integrated T&D systems. These are quasi-static co-simulation (suitable for voltage regulation and power flow studies), hybrid co-simulation (to simulate frequency regulation concerns and AGC response from DERs), and dynamic co-simulation (to model system response during transients and faults).

In Chapter 1, we detail an iteratively coupled *quasi-static T&D co-simulation* framework where both the transmission and distribution systems are simulated in quasi-static mode. This part is the major emphasis of this project, and the work is jointly conducted by Washington State University and Colorado School of Mines. In Chapter 2, a *hybrid co-simulation* framework is developed to study DER variability and its effects on the bulk grid frequency and AGC response. In *hybrid co-simulation approach*, we model the transmission system in dynamic simulation mode while distribution system is modeled in a quasi-static mode; this part of the study is mainly conducted by Washington State University. In Chapter 3, a *dynamic T&D co-simulation* framework is introduced by Colorado School of Mines where both transmission and distribution systems are simulated in dynamic mode. The objective is to study the integrated system response during faults and transients with high-levels of DER penetrations.

Chapter 1 – Quasi-Static T&D Co-Simulation Framework

The focus of this chapter is the development of an iteratively coupled co-simulation framework for the quasi-static analysis of T&D systems. Therefore, the transmission and distribution systems are simulated in the quasi-static mode of operation. Recently, several T&D co-simulation frameworks for the quasi-static analysis have been proposed in the literature, including, but not limited to FNCS, IGMS, HELICS. The existing quasi-static T&D co-simulation frameworks, however, are limited in accurately modeling T&D interactions as these conduct transmission system analyses using a balanced positive sequence power flow approach that does not account for unbalanced load conditions. Furthermore, the existing co-simulation methods loosely couple T&D systems introducing errors in the solutions. To address these concerns, an approach to iteratively couple the T&D systems using a co-simulation approach is proposed. The proposed framework is comprised of three modules: a three-sequence ac power flow for the transmission system, a three-phase power flow solver for the distribution system, and an iterative coupling approach at the T&D interface. The co-simulation approach is implemented using MATLAB coupled with OpenDSS. The proposed framework is suitable for the integrated analysis of T&D systems subject to unbalanced load conditions and significant variations in load demand.

An analytical formulation for the boundary variable updates that represent the coupled T&D system with interface constraint equations is developed. This analytical model characterizes the convergence of the proposed iterative co-simulation framework as a function of T&D system conditions. The developed non-linear interface constraint equations are solved using the first-order and second-order convergent techniques based on Fixed-Point Iteration (FPI) and Quasi-Newton method, respectively. The proposed iteratively coupled quasi-static T&D co-simulation framework is used to evaluate the impacts of distribution-connected PVs on both transmission and distribution system voltages.

The developed framework is tested using IEEE 9-bus and IEEE 39-bus transmission system models coupled with multiple EPRI Ckt-24 distribution feeder model. The conditions for convergence by exchanging the boundary variables at the PCC are examined in detail using several

case studies with varying levels of distribution load unbalance and PV penetrations. The simulation results highlight the need for co-simulation when evaluating DER impacts for the cases with high levels of distributed PV deployment and their utility in supporting the grid via active voltage regulation methods. A case study in which multiple distribution systems coupled to the transmission load points is also presented to demonstrate the scalability of the approach. The results obtained using co-simulation approach are validated against a standalone T&D system simulated in OpenDSS. It is demonstrated that the iteratively coupled T&D model closely approximates the stand-alone T&D model for highly stressed system conditions.

The main take away here is that the iteratively coupled co-simulation framework provides accurate convergence characteristics at the T&D boundary when compared to the existing loosely coupled co-simulation models. It is also shown that the boundary variable update rules (also called co-iteration rules) using Quasi Newton method results in faster convergence than the FPI method; the improvements in the number of iterations and the time taken to converge are more pronounced for stressed system conditions.

Chapter 2– Hybrid T&D Co-Simulation Framework

The increasing penetrations of renewable resources such as solar and wind resources with high variability in generation patterns may result in increased uncertainty in the supply and demand unbalance. In the bulk grid, the frequency regulation services performed by automatic generation control (AGC) plays a critical role in maintaining the supply-demand balance. Traditionally, the majority of frequency regulation capability is provided by specially equipped generators. As technologies evolve, the participation of new types of flexible energy resources such as battery energy storage systems (BESS) and flywheels, with their significantly faster ramping capabilities, can reduce the need to procure additional regulation capacity for variable generation resources. In order to successfully integrate BESS technologies in the grid for frequency regulation services, they must be included in the distribution system planning process, and their impacts should be evaluated at both transmission and distribution levels.

Owing to these emerging concerns, there is a need for integrated modeling and analysis of transmission and distribution systems for the AGC simulation studies. A high-level of DER penetrations in the distribution system may lead to reverse power flow from distribution to transmission systems that may adversely affect the transmission system operations resulting in frequency regulation problems. Furthermore, with frequent load changes and BESS responding to RegD (fast responding AGC signals) from the ISO, an aggregate battery model at the T&D coupling point is no longer adequate to represent actual system response. The ISOs should be aware of the BESS availability at every connecting point in the distribution system to perform planning studies for AGC response from BESS requiring an integrated T&D system analysis. While a fully dynamic T&D model can capture these scenarios, it is unnecessarily complicated. This is because, although the transmission system needs to be modeled in a dynamic mode to fully study the bulk grid AGC response, for frequency regulation concerns, the effects of distribution-connected DER generation variability can be captured using quasi-static simulations for distribution systems. This calls for a hybrid co-simulation platform that can appropriately model the bulk grid frequency response due to variable DERs.

In this chapter, an iteratively coupled T&D hybrid co-simulation framework is developed to study the effects of distribution-connected DERs/PVs on AGC response and the utility of BESS in maintaining supply-demand balance for scenarios with highly variable DER/PV generation

profiles. The proposed hybrid co-simulation framework is demonstrated using IEEE 9-bus transmission system model coupled with multiple EPRI Ckt-24 distribution system models. The generator dynamic model for the IEEE 9-bus transmission system is available in PSAT MATLAB toolbox. The quasi-static model for distribution system is developed using OpenDSS. The interactions between transmission and distribution systems at the point of common coupling (PCC) are captured using a tightly-coupled co-simulation interface developed in MATLAB. The developed hybrid T&D co-simulation platform is used to understand the PV integration impacts at both transmission and distribution levels, specifically, the effects of PV generation variability on the AGC dispatch signals. The utility of distribution-connected BESS on improving the AGC response by providing frequency regulation services is also detailed.

Chapter 3 – Dynamic T&D Co-Simulation Framework

The existing dynamic co-simulation studies focus on studying the stability issues for the bulk grid when subjected to a transient event such as transmission line faults. The high-levels of DER penetrations can potentially aggravate or reduce the stability concerns during and post transient period. For example, the revised interconnection standard IEEE 1547-2018 allows the DERs to provide ride-through capabilities for dynamic voltage and frequency support that can help mitigate stability concerns for the bulk grid. The primary objective of this chapter is to develop a framework to understand the effects of high DER penetrations during faults on the bulk grid. Towards this goal, we present a loosely coupled T&D co-simulation framework for dynamic studies along with a model for DER ride-through requirements for distribution-connected DERs. The proposed framework leverages the stand-alone programs for dynamic simulation of T&D systems by coupling the solutions at the T&D interface. An integrated T&D dynamic model is developed using a positive-sequence simulation for the transmission system and a three-phase approach for the distribution systems. The T&D dynamic co-simulation is developed using PSAT & OpenDSS with MATLAB interface; transmission positive sequence dynamic model is developed in PSAT and distribution systems dynamics are simulated using the dynamic simulation mode in OpenDSS. The control of DER smart inverters is modeled using the IEEE 1547-2018 standard. Preliminary studies are presented to assess the impacts of DERs on the bulk grid system.

Project Publications:

- [1] Krishnamoorthy, Gayathri, and Anamika Dubey. "A framework to analyze interactions between transmission and distribution systems." In *2018 IEEE Power & Energy Society General Meeting (PESGM)*, pp. 1-5. IEEE, 2018.
- [2] Yaswanth Nag Velaga, Aoxia Chen, P. K. Sen, Gayathri Krishnamoorthy, and Anamika Dubey. "Transmission-Distribution Co-Simulation: Model Validation with Standalone Simulation." In *2018 North American Power Symposium (NAPS)*, pp. 1-6. IEEE, 2018. (second best paper)
- [3] G. Krishnamoorthy and A. Dubey, "Transmission–Distribution Cosimulation: Analytical Methods for Iterative Coupling," in *IEEE Systems Journal*.
- [4] Krishnamoorthy, Gayathri, and Anamika Dubey. "Iteratively-Coupled Co-simulation Framework for Unbalanced Transmission-Distribution System," *accepted for publication in IEEE PES PowerTech Milano 2019*.
- [5] Gayathri Krishnamoorthy, and Anamika Dubey. "Distributed PV Penetration Impact Analysis on Transmission System Voltages using Co-Simulation" *accepted for presentation in 2019 North American Power Symposium (NAPS)*.

- [6] Yaswanth Nag Velaga, Aoxia Chen, P.K. Sen, Gayathri Krishnamoorthy, and Anamika Dubey “Advancements in Co-Simulation Techniques in Combined Transmission & Distribution Systems Analysis,” *accepted for publication in The Journal of Engineering*.
- [7] Yaswanth Nag, Aoxia Chen, Gayathri Krishnamoorthy, Anamika Dubey, and P.K. Sen, “Trends and Future of Rural Electric Utilities: Challenges and Opportunities,” *accepted for publication in IEEE IAS REPC Conference (2019)*.
- [8] Rabayet Sadnan, Gayathri Krishnamoorthy, and Anamika Dubey “Comparison of different coupling method used in transmission and distribution (T&D) co-simulation’, *submitted to IET GT&D*.
- [9] Gayathri Krishnamoorthy, and Anamika Dubey, “Hybrid Transmission Distribution (T&D) Co-simulation Platform: Frequency Regulation Services using Battery Energy Storage Systems,” submitted to PSCC 2020.
- [10] Gayathri Krishnamoorthy, and Anamika Dubey, “Co-optimization of T&D system operations by optimal scheduling of Battery Energy Storage Systems (BESS),” (in preparation).

Student Thesis:

- [1] Gayathri Krishnamoorthy, “An Iterative Co-simulation Framework for the Integrated Transmission and Distribution System Analysis,” M.S. Thesis, Washington State University, May 2018.
- [2] Yaswanth Nag Velaga, “Co-simulation Framework for Integrated Transmission and Distribution (T&D) Analysis with High Distributed Energy Resource (DER) Penetrations” Ph.D. dissertation, Colorado School of Mines (in progress).