Synthetic, Realistic Transmission and Distribution Co-Simulation for Voltage Control Benchmarking

Preprint

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Synthetic, Realistic Transmission and Distribution Co-Simulation for Voltage Control Benchmarking

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***Abstract*—As distributed energy resources (DERs) play an increasing role in generation and grid services, control and market paradigms will need to be tested with models that incorporate transmission and distribution systems. The test systems will need to be realistic and accessible for researchers to form conclusions about realistic behaviors and maintain comparability and repeatability of results. These test systems also must have high resolution models of sufficient size for realistic distribution and transmission interaction. This paper demonstrates the tightly coupled HELICS-based co-simulation of realistic synthetic distribution and transmission models for the Austin metropolitan area and how this framework can be used to analyze resultant behaviors from distributed resources and their controls. These results are compared to the same distribution system run without co-simulation using a fixed feed-in voltage. Results show that even without advanced voltage controls, the feed-in voltage response when coupled to the transmission system results in a lower level of voltage excursions, suggesting the importance of using this type of realistic, tightly coupled, transmission and distribution co-simulation when assessing DERs.**

Keywords—power system simulation, power distribution, power transmission, co-simulation

I. INTRODUCTION

Realistic, detailed, and tractable representations of distribution and transmission systems in co-simulation provide a way to explore control methods and system planning as distributed generation takes a more significant role in supply and system stability. This paper describes how the synthetic transmission and distribution grid (T&D) dataset for Austin, Texas [1] can be combined with the HELICS co-simulation framework [2] to produce a tractable, modular co-simulation of a realistic distribution and transmission system.

There have been several studies of distribution systems or transmission systems in isolated models or of co-simulations with reduced models of each. Decoupling the systems or reducing the order of co-simulated transmission and distribution systems maintains tractability and allows rapid analysis of results and is appropriate for many power system studies. However, as increased distributed generation is adopted and DERs play a larger role in ancillary services, the co-simulation of both transmission and distribution systems becomes more important. Co-simulation allows proven tools for each domain to be separately leveraged instead of requiring development of a new and untested integrated tool. It also allows for computation to be distributed across resources for computational tractability [3]. A demonstration of transmission and distribution models using the IGMS co-simulation platform revealed the necessity for replicable realistic transmission and distribution data set pairs given the difficulty aligning IEEE bus systems with real systems when only one is available [4]. Other co-simulation platforms used for this type of work include FNCS [5], which along with IGMS and other influences served as the motivation for developing the HELICS framework used here [2].

Some past studies have used loosely coupled co-simulations, which, unlike closely tied simulations, assume that loads and system responses change slower than each time step, limiting applicability of the setup or reducing accuracy when modeling systems with more rapid load changes [6], [7]. An iterative approach to assure convergence at the boundaries between the transmission and distribution system is required for systems with high penetrations of DER or rapidly changing loads. Iterative approaches which assure convergence before advancement are considered closely tied or tightly coupled and have been demonstrated for scaled down regions [8], [9] and for real systems [10]. Simplified transmission and distribution systems do not capture the complexity of real systems, while real system studies are difficult to benchmark against given the restricted nature of real system configuration data. A closely tied, synthetic, realistic system for the entire metropolitan region of Austin is provided here to allow benchmarking and facilitate sharing of controls development efforts.

In addition to simulation, a core challenge for these studies is access to data. A library of synthetic transmission systems for benchmarking AC-OPF algorithms was created to fill the need for modern transmission test systems [11]. The IEEE distribution test feeders are openly available and have been used for testing of a range of power flow solution and control algorithms, but are often applied past their intended purpose as they were not created to necessarily align with real feeder configurations but to test different powerflow algorithm aspects [12] and are also limited to single feeders rather than full-scale representations including multi-feeder substations [13]. Full-scale, synthetic, US-style distribution test feeders that are realistic but not real have also been developed to facilitate distribution system control algorithm testing including distributed energy resource (DER) control and response modeling of realistic feeders [14], but they still rely on the researcher to implement the interactions among the grid components and control systems under test.

This paper expands on previous work to demonstrate a framework for utilizing synthetic test systems within a co-simulation and then use it to study the convergence of realistic, but not real, synthetic distribution and transmission models in tightly coupled co-simulation for evaluation of varying control schema or network interactions. The novel contributions of this work are 1) the tight coupling of the co-simulation to assure convergence at each timestep 2) the use of much larger, realistically-scaled transmission and distribution models, and 3) capturing geographically relevant diversity in the distribution system. This work also highlights the need for tightly coupled transmission and distribution co-simulation for benchmarking and evaluation of voltage regulation methods.

Section II of this paper describes the pieces of the co-simulation and how they are integrated. Section III provides a brief description of the Austin, Texas use case. Section IV shows how the co-simulation enhances the realistic response of each system. While Section V summarizes findings and conclusions

II. METHODOLOGY

This co-simulation is a closely tied co-iteration of a detailed synthetic, realistic but not real, distribution system and a corresponding realistic but not real transmission system. The distribution system is simulated using many instances of OpenDSS and the transmission system is simulated using a single instance of PowerWorld. The interface between transmission and distribution and the co-iteration is facilitated via HELICS co-simulation platform. Fig. 1 shows the interaction between transmission and distribution models through the HELICS platform at iteration with each timestep to assure timestep convergence before model advancement.

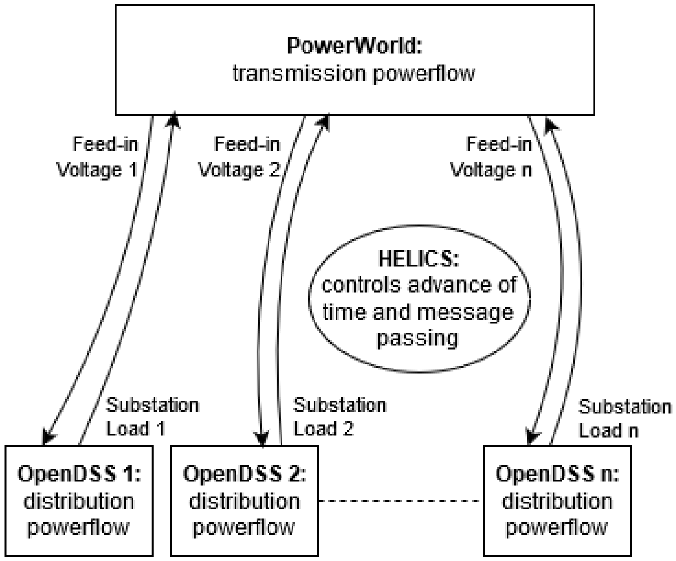

Figure 1: Transmission and distribution coupling through HELICS where voltage and load information are iterated at each timestep until convergence before simulation advancement

A. SMART-DS Implementation

The Austin dataset was generated using the same methodology used to generate the SMART-DS datasets [14]. Parcel information obtained for Austin was used to generate peak planning loads for each customer. The Reference Network Model for U.S. Style distribution (RNM-US) then built the electrical infrastructure to support these planning loads using a catalog of electrical equipment—including medium and low voltage lines, transformers, regulators capacitors and switching devices. Postprocessing was then applied to add substation and controller information and output the models in OpenDSS. Timeseries loads at 15 minute resolution were generated using residential and commercial building load models, ResStock [15] and ComStock [16], were then attached to each customer. The OpenDSS models, as seen in Fig. 2, are partitioned by substation for ease of integration with HELICS.

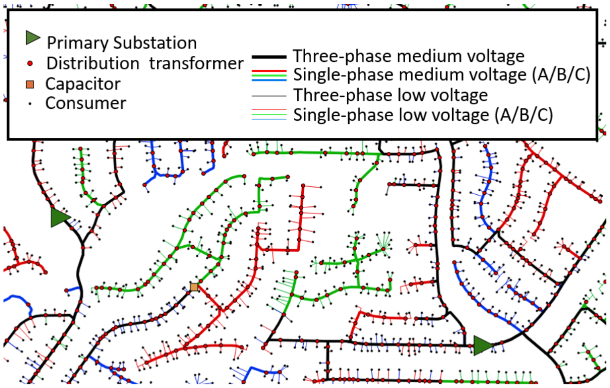

Figure 2: Distribution feeder map for a sample region of the SMART-DS datasets showing substations, distribution transformers, capacitors, load points, voltage levels, and phases

B. Transmission and Distribution Modeling

The powerflow solution and simulation of the distribution system is handled by OpenDSS, while the transmission powerflow solution and simulation is handled by PowerWorld. Since there are 120 interconnection points between the transmission and distribution systems for the Austin region as represented, the distribution model is split up into 120 different instances of OpenDSS that are spread across computational cores. The separation of distribution systems into different instances of OpenDSS aids with the scalability of the model and simulation. A single distribution feeder can be run for small scale testing on a single OpenDSS instance without loading the entire region's data. At the same time, increasing the region covered in the simulation is facilitated, because the increase only requires a new instance of OpenDSS for the new area and a new feed-in voltage connection, instead of requiring alteration of previously configured areas. The transmission model is simple enough to be contained on a single Windows workstation. The spread of the distribution system across many cores, and subsequently computational nodes, reduces computational time for simulation and allows for parallel computing of each feeder set. In this sense, the computational resources required scale linearly with the number of distribution system interconnections modeled, while the run time remains relatively constant.

Identify applicable funding agency here. If none, delete this text box.

C. HELICS Co-Simulation Setup

HELICS co-simulation platform is used to allow the distribution and transmission systems to communicate despite being simulated using different software across different cores on different machines and operating systems. Each instance of OpenDSS and the instance of PowerWorld included in this co-simulation is run as a HELICS federate which connects to a message bus where publications and subscriptions are passed to one another. The distribution federates pass circuit net load at the point of common coupling (PCC) to the transmission system. Likewise, the transmission system passes feed-in voltage at the PCC to each corresponding distribution system model.

HELICS also enables us to use tight coupling of the transmission and distribution systems through co-iteration. With this approach, the federates iterate powerflows at a single timestep until the average absolute value change in distribution load at each PCC is less than 10^{-4} kW and the change in feed-in voltage at each distribution system is less than 10^{-4} pu. Once the timestep has converged, then the distribution and transmission federates are allowed to advance. This tight coupling assures that the full system has converged to a consistent set of physical conditions before advancing to the next timestep. The tight coupling also allows for more accurate implementation of voltage control measures, because the models reach a converged response to the control signal at each timestep.

III. AUSTIN TEXAS USE CASE

Travis County is the fifth largest county in Texas, and includes the fourth largest city in Texas, Austin. The load for the synthetic system developed with ResStock and ComStock is designed be representative of Austin building designs and capture load responses to real historical weather from the year 2012. We use the syn-austin-TDgrid_v03 version of the data set [1], shown in Fig. 3, which is intentionally designed to be different from the actual electric grid that supplies power in Travis county today to avoid any sensitivity with infrastructure information.

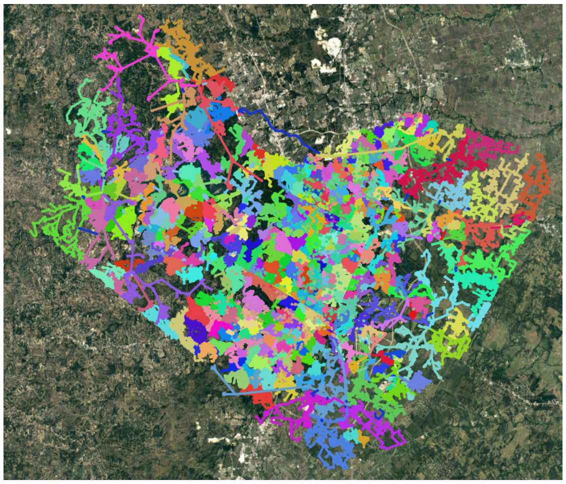

Figure 3: A map of the Travis County synthetic transmission and distribution grid [1]

The combined system serves a synthetic version of the geographic region of Travis County, Texas, including the city of Austin and surrounding areas in central Texas. The combined system has four voltage levels with 230kV and 69kV lines connecting the transmission system and 12.47kV lines connecting the distribution system.

The network has a total of 173 transmission buses, 128 of which are load substations connected to the distribution network. The system load is met by 39 generators on the transmission level.

The distribution network consists of a mix of 448 rural, suburban, and urban feeders that service 307,236 customers for the Travis County area, with a total system peak of 3,254 MW. The system contains 132,406 distribution transformers whose capacities range from 10-1500kVA with an average of 5.3 consumers per distribution transformer, which is typical when commercial loads are a part of the feeder network.

IV. SIMULATION AND RESULTS

The Austin, Texas models are used to simulate January 1st, 2012, a 24-hour day at 15-minute timesteps, in a tightly coupled co-simulation of transmission and distribution. Five high performance computing nodes, with 36 physical cores or 72 virtual cores are used to run the distribution system, which enables each OpenDSS instance to run on its own physical core with ample spare space on each node to handle background processes. A single core handles the HELICS broker which contains the message bus and assures that values are passed to the correct federates. It also coordinates time advancement of the simulations which each have different run times. A separate Windows machine hosts the PowerWorld simulation of the transmission system and is linked with the distribution federates through HELICS. Once the OpenDSS models are all loaded, each timestep takes less than two minutes to complete. Given the lack of advanced controls or distributed resources in this simulation, the closely tied co-simulation converges in 2 re-iterations or less for each timestep. Voltages, loads, and the number of iterations per timestep are exported from both the transmission and distribution systems for analysis.

The closely tied transmission and distribution co-simulation results in fewer voltage excursions than simulating the distribution system with a nominal feed-in voltage. In both scenarios the number of buses with voltage excursions outside ANSI Range A reached 25% and mainly occur during the middle of the day when loads are highest.

As seen in Fig. 4 the simulation of only the distribution system with nominal feed-in voltage has voltage excursions on around 25% of the buses, with a concentration around the middle of the day when we see peak loading, and tapering off in the evening with loads. High mid-day peaks of over 60MW are included for some loads in the current version of the dataset and are effective at inducing large overloads. These loads will be removed in future versions of the distribution dataset to better align with real load magnitudes. This shape is predictable given that the distribution only simulation does not have load response capabilities and relies solely on voltage regulators on the distribution feeders to maintain voltage levels.

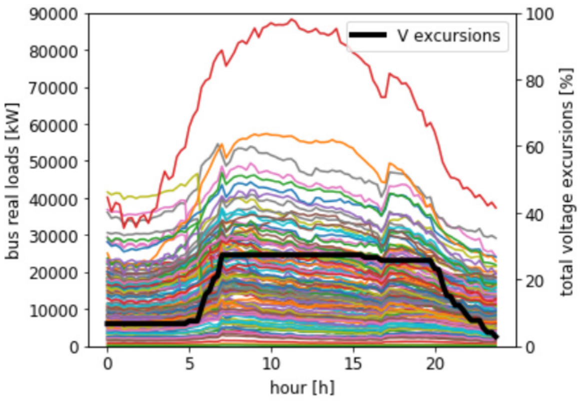

Figure 4: Real power loads on each of the 128 distribution feeders (left axis) and the percentage of distribution buses with voltage excursions (right axis) when run with nominal feed-in voltage.

As seen in Fig. 5 the co-simulation experienced voltage excursions at similar times but on fewer distribution buses. Excursions are close to zero in the early morning when load is low and are reduced from 7am to 8pm, during the of the middle of the day. The transmission system adjusts feed-in voltages and re-solves the power flow to support the varying loads throughout the day. This indicates that distribution system load response controls that aim to minimize voltage excursions should be benchmarked against a distribution system with responsive feed-in voltage to determine the actual benefit of advanced control.

The load profiles of the distribution-only simulation and transmission-distribution co-simulation are very similar with some deviations in the morning when the distribution-only simulation experiences a low number of violations and the transmission system is able to regulate the voltage and net loads are reduced on some feeders.

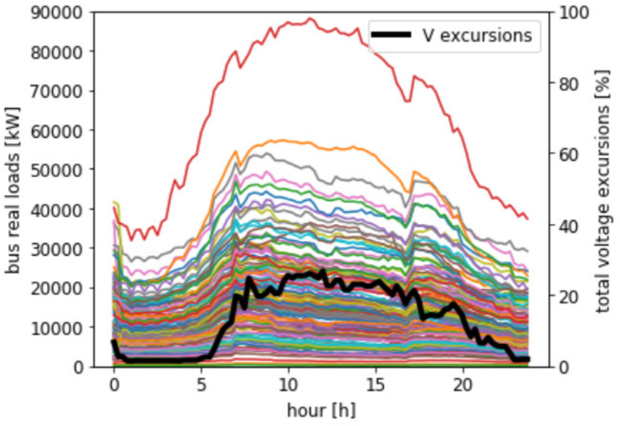

Figure 5: Real power loads on each of the 128 distribution feeders (left axis) and the percentage of distribution buses with voltage excursions (right axis) when run with closely tied transmission and distribution co-simulation.

When the voltage excursions are examined on an individual distribution feeder basis as seen in Fig. 6 the distribution-only system, as modeled with nominal feed-in voltage, shows voltage excursions start in the morning and taper off in the evening. Some distribution feeders experienced excursions on 100% of their buses meaning that a nominal feed-in voltage for those buses is not sufficient to meet the system loading. However, the transmission and distribution co-simulation voltage excursions on individual feeders, seen in Fig. 7, shows a flickering of excursions during the middle of the day. This indicates that the transmission voltage response is able to assist with voltage stability to some extent, but that there are feeders where the voltage is near the ANSI limits. As the transmission system responds to these highly loaded feeders, they alternate between being within ANSI limits, and having nodes with voltage excursions.

The high percentage of buses with excursions on some feeders in both simulation configurations shows that the overall excursions for the system are concentrated at specific feeders which need better voltage support.

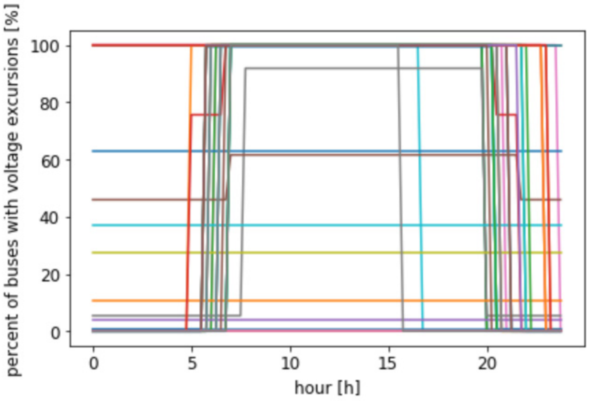

Figure 6: The percent of distribution buses per feeder substation connection for the distribution system run with fixed nominal feed-in voltage

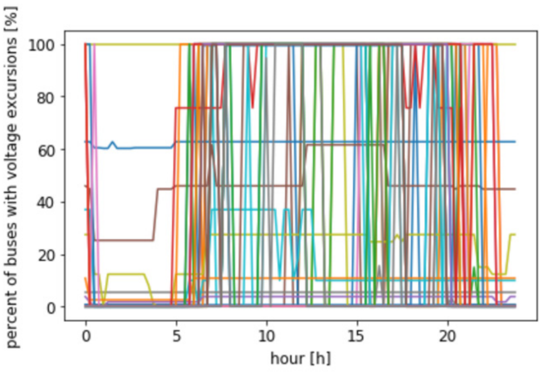

Figure 7:The percent of distribution buses per feeder substation connection for the distribution system run with transmission and distribution systems in closely tied co-simulation

Voltage excursions using distribution-only simulations occur for 18.97% of the total 39,872,952 bus-hour combinations over the 24-hour horizon simulation, while for the transmission-distribution co-simulation, voltage excursions occur for only 13.46% of bus hours. This is a 29% improvement in voltage support from allowing transmission feed-in voltage to help support distribution voltage challenges.

CONCLUSION

A closely tied distribution-transmission co-simulation of realistic synthetic distribution and transmission models was implemented for an Austin region test case and compared to the same distribution models simulated with fixed feed-in voltages. These feeder models provide a realistic, at-scale demonstration of the effects of transmission co-simulation on distribution system voltage and load profiles. The 29% reduction in voltage excursions by incorporating transmission responses to distribution feed-in voltage means that voltage control methods should be benchmarked on closely tied transmission and distribution co-simulation platforms to assure the voltage stability improvement is significant for real systems. The fact that the datasets are also geographically matched also opens up future research opportunities to consider geospatially accurate transportation patterns, building codes, renewable resource, and other location-specific studies.

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