Scalable Modeling Of Future-Grids Under High Penetration Of Distributed Energy Resources Through Multi-Timescale T&D Co-Simulation

**Abstract**

Power system is evolving with rapid changes in the transmission and distribution (T&D) systems. The distribution systems are experiencing significant integration of distributed grid-edge technologies often referred to as distributed energy resources (DERs) like solar photovoltaics (PV), battery storage, electric vehicles, demand response with flexible loads, utility scale renewables, etc. These changes in the power grid are challenging the assumptions usually made for bulk power system analysis, especially that the distribution systems are passive consumers leading to unforeseen and unexpected changes in the T&D interactions and grid operations.

It is important to capture these changes in the power grid for accurate power system analysis which can be effectively done through T&D co-simulation. We have developed a scalable T&D co-simulation platform using commercial solvers that enables detailed modeling of the transmission and distribution systems that can capture the true response of the system under multiple timescales (sec-min-hrs). The T&D co-simulation framework developed can perform steady state, quasi-steady state and dynamic T&D co-simulation using detailed phasor domain models along with the network models. The T&D co-simulation tool has been verified using large IEEE test systems and is shared to US national labs, independent system operators (ISOs), and utilities.

This research has presented the importance of modeling distribution systems along with the transmission system for long-term voltage stability margin assessment (VSM). A detailed analysis of net-load unbalance (NLU) impact on VSM was done that also demonstrates the need for T&D co-simulation, especially for cases with high unbalance and high DER penetration in the distribution system. The DERs are not guaranteed to proliferate in a balanced manner in the distribution system that can further aggravate the NLU and in turn aggravate the VSM of the system. These details of the distribution system cannot be captured effectively using aggregated models like the equivalent feeder impedance models. To use the aggregated models under changing operating conditions, frequent computation of the equivalent feeder parameters is necessary at each operating condition that further requires detailed distribution system analysis. Therefore, utilizing T&D co-simulation is an effective method to capture the T&D interactions accurately.

Based on the understanding developed about the impact of DER penetration and NLU on the long-term voltage stability margin of the system, for any DER coordination problem, the VSM of the system can be added as a constraint. Due to the highly non-linear behavior of the voltage instability phenomenon, it is difficult to formulate a VSM constraint. Therefore, a pseudo VSM constraint in the form of NLU constraint is designed as a part of an aggregator model for DER orchestration. A case study with co-simulation of IEEE 9-Bus transmission and modified IEEE 4-Bus distribution with the DER orchestration with the pseudo VSM constraint is used to demonstrate the impact of coordinating DER that resulted in the operating point with a 45% enhanced VSM.

The T&D interactions also play an important role in short-term grid behavior. With large amounts of DERs integrating into the system, the inertia of the grid is reducing due to the replacement of the large synchronous machines. Under these conditions, the short-term frequency stability of the system can be affected and can lead to a poor primary frequency response of the grid. To understand this phenomenon better, a systematic method for dynamic T&D co-simulation is developed that includes coordination of the T&D models for accurate initialization of the dynamics of the T&D systems. This research has demonstrated the role of distributed inverter-based-resources (D-IBRs) with grid following (GFL) and grid forming (GFM) controls in primary frequency response of the grid. The research has demonstrated the impact of GFM inverters on the primary frequency response on a large system with a total number of 286383 T&D buses and more than 10000 D-IBRs. This research has also demonstrated the scalability of the developed framework with parallel GridLAB-D instances running along with a comparison of the computation times for a simple test case and the large system test case.