Studying the Impact of Distributed Solar PV on Power Systems using Integrated Transmission and Distribution Models

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Himanshu Jain, Bryan Palmintier, Ibrahim Krad, and Dheepak Krishnamurthy
National Renewable Energy Laboratory

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Studying the Impact of Distributed Solar PV on Power Systems using Integrated Transmission and Distribution Models

Himanshu Jain, Bryan Palmintier, Ibrahim Krad, Dheepak Krishnamurthy
National Renewable Energy Laboratory (NREL)
Golden, CO, USA

Abstract—**Rapid growth of distributed energy resources has prompted increasing interest in integrated Transmission (T) and Distribution (D) modeling. This paper presents the results of a distributed generation from solar photovoltaics (DGPV) impact assessment study that was performed using a synthetic T&D model. The primary objective of the study was to present a new approach for DGPV impact assessment, where along with detailed models of transmission and distribution networks, consumer loads were modeled using the physics of end-use equipment, and DGPV was geographically dispersed and connected to the secondary distribution networks. The study highlights (i) how a lack of DGPV forecasting can increase the Area Control Error (ACE) at the transmission level for high penetration levels; and (ii) how capturing transmission voltage changes using integrated T&D can change simulated distribution voltage profiles and voltage regulator operations between integrated T&D and distribution-only simulations.**

Index Terms—**Solar Power Generation, Power Systems Analysis, Integrated Transmission and Distribution, High-performance Computing, Co-Simulation**

I. Introduction

The rapid growth of distributed generation from solar photovoltaics (DGPV) [1], [2] among other distributed energy resources has prompted increasing interest and multiple development efforts in the area of integrated transmission (T) and distribution (D) modeling [3]–[5]. Over half of current U.S. installations are connected to the distribution system, and this trend is expected to continue through at least 2020 [6]–[8]. This creates a challenge for transmission operations and wholesale electricity markets, since bulk system operators typically have very limited visibility into the quantities and amount of DGPV [9], [10]. At the same time, transmission network dynamics, such as voltage variations over the course of a day, can cause impacts on distribution system operations with high DGPV penetrations.

This paper presents study results that explicitly capture such T-D interactions at various penetration levels of DGPV. Unlike traditional approaches of evaluating the impact of solar PV on power systems using either transmission or distribution separately [11]–[14], the study presented uses a synthetic integrated T&D model to simulate the interactions between transmission and distribution networks and wholesale electricity markets at various penetration levels of DGPV in a single simulation. The Integrated Grid Modeling System (IGMS) [4] is used as the platform to co-simulate (1) the transmission power flow using MATPOWER [15]; (2) distribution network using GridLAB-D [16]; and (3) wholesale market operations using FESTIV [17].

The rest of the paper is organized as follows. In Section II, the synthetic integrated T&D model used for the study is discussed, along with a brief discussion about the approach used in IGMS to perform power systems simulations. Section III presents the results of the study, focusing on interactions between the transmission, distribution, and electricity markets operations at various DGPV penetration levels. Section IV summarizes the key takeaways of the study and the research being done to further improve integrated T&D simulations.

II. Synthetic Integrated T&D Model

A. Network Topology

The synthetic T&D model used in this study will be referred to as the *5 Bus/11 Feeder System.* The transmission topology in the system is modeled using the PJM 5 bus transmission system [18]. The lumped loads of the PJM 5 bus transmission system are replaced with taxonomy feeders developed by the Pacific Northwest National Laboratory [19]. Since the taxonomy feeders are designed to supply a limited load, replacing more than 1,000 MW of transmission load with the taxonomy feeders would have required several hundred feeders. To restrict the size of the resulting T&D system, eleven taxonomy feeders were used to replace the lumped load and a scaling factor of 16.67 was applied to the power flowing through the feeder head before it was sent to the transmission network. Table I shows the number and types of taxonomy feeders that were used to replace the lumped load at the three load buses in the transmission system. Bus # 5 in the transmission system was selected as the swing bus, as the largest generator in the system was connected at this bus. The topology of the resulting integrated T&D system, including the bus numbers and generator names (which correspond to

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those given in [18]) are shown in Figure 1. A complete description of the test system can be found in [20].

Table 1: Number and Type of Taxonomy Feeders at each Transmission Load Bus

Feeder Type	B2	B3	B4
R3-12.47-1	-	-	2
R3-12.47-2	3	-	-
R3-12.47-3	-	4	-
GC-12.47-1	1	-	1

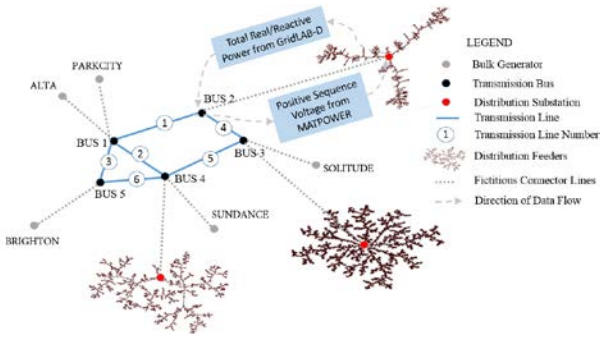

Fig. 1. Topology of the 5 Bus/11 Feeder System

The process for automatically adding residential and commercial buildings in feeders with end-use equipment, and providing enough diversity in equipment characteristics such that realistic transmission level load profiles are generated, is automated in IGMS using *glmgen* [4]. All the end-use loads are connected to the secondary distribution network.

B. DGPV Model

Similar to the addition of end-use loads in the distribution feeders, DGPVs were added to the feeders using *glmgen*. By specifying the percentage penetration level of DGPVs (as a fraction of annual energy consumption of a feeder, which is obtained as a product of the annual energy intensities of buildings [W/sq. ft] and their floor areas [sq. ft]), *glmgen* automatically added DGPVs to the feeders. Three scenarios with DGPV penetration levels of 20% (low), 30% (medium), and 50% (high) were created. Note that these are annual energy-based percentages as is commonly used in transmission analysis. The % peak load penetrations—as is common in distribution analysis—are much higher. The power factor of the DGPV inverters was fixed at unity.

C. Power Systems Simulation in IGMS

The wholesale electricity market model used in the 5 Bus/11 Feeder System simulates day-ahead, intra-daily, and real-time market operations. The day-ahead unit commitment (UC) market clears once a day, 12 hours before the start of the operating day, and looks ahead for the next 24 hours using the generation bid curves and load forecast provided to FESTIV. The intra-daily UC is repeated every 15 minutes, with 15 minutes resolution, for the next 3 hours. The real-time market clears every 5 minutes with a one hour look-ahead horizon based on a persistence-based real-time load forecast. In other words, the load at each bus calculated by GridLAB-D at the beginning of the current 5-minute interval is assumed to be the load forecast for the next real-time market interval.

FESTIV [17] has the unique capability to model the impact of automatic generation control (AGC) on the power generated by bulk generators. In order to use this capability of FESTIV, GridLAB-D is solved every four seconds, and the system-wide load obtained at each four-second interval is provided to FESTIV, which compares it against the total system generation to calculate the Area Control Error (ACE). The ACE is used to adjust the output of each generator between the 5-minute real-time market clearing intervals.

Since FESTIV uses DC optimal power flow, it does not calculate the voltages at the transmission buses. The transmission bus voltages are used by GridLAB-D as the feeder head voltages for solving the distribution power flow. Therefore, the generation schedules determined by FESTIV at each 4-second interval, and the load calculated by GridLAB-D at the 4-second interval are supplied to MATPOWER to obtain the transmission bus voltages. Reference [4] discusses the interface between the balanced transmission system model and the unbalanced distribution system model. Table II summarizes the key components of the 5 Bus/11 Feeder System along with the number of such components.

Table II: Type and Number of Key Components in the 5 Bus/11 Feeder System

Type of Component	**Quantity**	**Type of Component**	**Quantity**
Transmission Buses	5	Residential Buildings	6,900
Distribution Nodes	27,225	Commercial Buildings	2,702
Transmission Lines	6	# of Solar PV Inverters (low)	1,481
Distribution Lines	17,988	# of Solar PV Inverters (medium)	2,244
Distribution Transformers	8,187	# of Solar PV Inverters (high)	3,711
Synchronous Generators	5		

III. Simulation Results

The simulation results presented in this section are for a weekday in the month of August. Since the distribution feeders correspond to climate region 3 [19], the Typical Meteorological Year (TMY2) from Phoenix, Arizona, provides the weather and irradiance for load and DGPV. The simulations were performed on the National Renewable Energy Laboratory (NREL) High Performance Computing system, Peregrine, located in the NREL/DOE Energy Systems Integration Facility (ESIF). One 32-GB computation node of Peregrine with 16 cores was used for the simulations.

Even for the modest 5 Bus/11 Feeder System, the 4-second simulation time step (for AGC response, transmission, and distribution power flows) generated a large amount of data, particularly for the distribution network. So this discussion focuses on representative results showing interactions between transmission, distribution, and real-time market operations. Results for the case with no DGPV are referred to as "base."

A. *Transmission System Performance*

Figures 2 and 3 show the real-time load profiles of the real and reactive powers at the system level, and at each transmission load bus for the base and the three DGPV scenarios. The following observations can be made from the figures:

a. The load modeling approach used in IGMS, as discussed in the previous section, creates realistic load profiles, thereby providing an alternative to using static load profiles.

b. The duck-shaped load curves (Figure 2) that are seen at the transmission buses for all the DGPV penetration levels suggest that modeling a large number of DGPV, connecting them at the secondary distribution networks, and making their power output a function of incident solar insolation can generate accurate net-load profiles that could be used for simulating electricity markets.

c. Although the DGPV are operated at unity power factor, the reactive power demand at the transmission buses decreases slightly as the penetration levels of DGPV increase (Figure 3). This can be explained by the increased proximity of power generation to the load, which reduces real power flows through the distribution network, thereby also lowering reactive power losses and hence the reactive power demand from the transmission system.

B. *Electricity Markets Operations and AGC Performance*

Figure 4 shows the real power outputs of all the bulk generators for the base and the three DGPV scenarios, which are determined based on the net-load of Figures 2 and 3, the real-time economic dispatch set-points, and the modification of the set-points by the AGC to minimize the ACE. The ACE is shown in Figure 5. The key observations that can be made from Figures 4 and 5 are:

a. The total energy generated by the bulk generators decreases as the penetration levels of DGPV increase. However, in the "high" case, excessive solar power generation between 10 a.m. and 3 p.m. causes the generators to hit their minimum limits.

b. When the generators hit their minimum limit in the *high* case, the generators could not be shut down, as the operator, FESTIV, does not have visibility into the distribution network. Turning generators off without knowing the net load forecast could jeopardize the system reliability. As a result, the mismatch between load and generation, or the ACE magnitude, increased significantly from 10:00 a.m. to 3:00 p.m. (Figure 5). In all other cases, the net-load was above the system's minimum generation and the ACE remained close to zero.

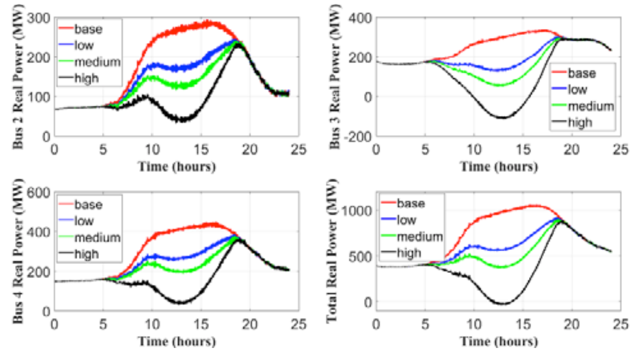

Fig. 2. Load (Real Power) in the PJM 5 Bus Transmission System

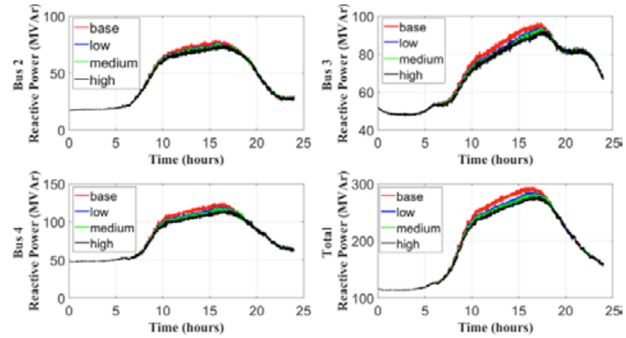

Fig. 3. Load (Reactive Power) in the PJM 5 Bus Transmission System

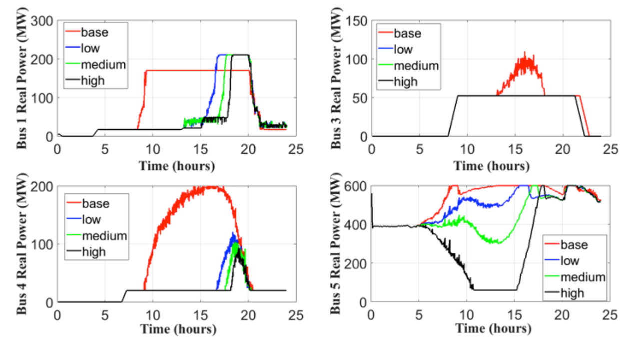

Fig. 4. Real power generation in the PJM 5 Bus Transmission System

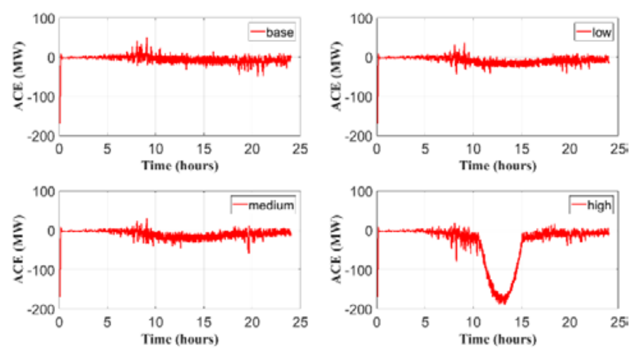

Fig. 5. ACE in the Base and the Three DGPV Scenarios

C. *Distribution System Performance*

Since bus 2 is the only load bus without transmission-connected generation to control the voltage, its voltage magnitude can change. Therefore, the performance of one of the distribution feeders connected to the bus, R3-12.47-1, is discussed in this section. The feeder is connected to bus 2 through a Wye-Wye-ground, 230/12.47 kV transformer. A three phase, gang operated voltage regulator is connected at the secondary of the transformer, with a reference voltage of 7,500 V (line-neutral (L-N)) and dead-band of 120 V.

Figures 6-9 compare the performance of feeder R3-12.47-1 between integrated T&D, and standalone-distribution-only (D-only) simulations performed in GridLAB-D under the assumption of fixed 1.0 p.u. voltage of the transmission bus. This assumption is typically made in distribution power flow analysis. Figure 6 shows the transmission bus voltages (L-N) at bus 2 under the base and three DGPV penetration scenarios. Only one line is plotted for the D-only simulations in Figure 6 as the transmission bus voltages are fixed at 1.pu. in all the scenarios. The voltage regulator output voltages (L-N) are shown in Figure 7, where the same color is used for all the scenarios in D-only simulations as the voltages are within 1 V of each other. Figure 8 shows the voltage regulator tap positions, while Figure 9 shows the voltages at one of the single-phase secondary nodes of the feeder under the base and the three DGPV scenarios. The following observations can be made from the figures:

a. It can be seen from Figure 6 that while the daytime transmission voltages vary during the day and increase with the increase in DGPV penetration levels in integrated T&D simulations, such differences are not visible in D-only simulations, as the transmission bus voltage is assumed to be fixed at 1.0 p.u.

b. Observations similar to those made above from figure 6 can be made for figure 7, which shows the voltages at the output of the voltage regulator. However, an interesting phenomenon that is not observed for the transmission bus voltages in Figure 6, are the almost instantaneous jumps in voltages obtained from integrated T&D simulations. These jumps occur when the voltage regulator's output voltage breaches the lower limit of the voltage regulator dead-band, which is 7,440 volts. No such jumps occur in D-only simulations, as the voltage regulator output voltages (overlapping dashed lines around 7,480 V) stay between 7,440 V and 7,560 V in all the scenarios.

c. Figure 8 shows the reason for the jumps in the voltages obtained from integrated T&D simulations, which is the movement of voltage regulator taps from 6 to 7 to prevent the voltage regulator output voltage from violating the 7,440 V threshold. However, in D-only simulations the voltage regulator taps stay at 6 throughout the simulation as the voltage regulator output voltages (overlapping dashed lines in Figure 7) stay within the dead-band.

d. The impact of variation in transmission bus voltage and the regulator tap movement is propagated into the secondary distribution network, as can be seen from Figure 9 where the voltages obtained from integrated T&D and D-only simulations at one of the secondary nodes are also plotted. While the daytime voltages at the secondary node increase with an increase in DGPV penetration levels for both integrated T&D and D-only simulations, the instantaneous voltage jumps are absent for the D-only simulations. Moreover, the timing of the jumps coincides with that of the voltage regulator taps in the integrated T&D simulations (Figure 8).

These results show one value of performing integrated T&D simulations for studying the impact of DGPV on distribution systems. Forgoing the actual transmission voltage profile, and assuming the transmission system serves as an infinite bus can result in erroneous distribution system response, which in the presented study was observed for the voltage profiles and the movement of voltage regulator taps. At low DER penetration levels, similar results may also be obtained using a time varying feeder-head voltage in D-only simulations; however, as the quantity of DERs increases, they can impact the transmission voltages. Such interactions—particularly reactive power shifts from inverter volt/VAR, or price-responsive load changes—would not be captured when assuming static transmission conditions, but can be captured with integrated T&D analysis.

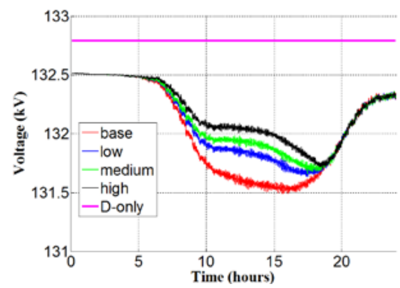

Fig. 6. L-N Transmisison Bus Voltages for Feeder R3-12.47-1 with D-only (T voltage=1.0 p.u.) and Integrated T&D Simulations at 7,200 V base

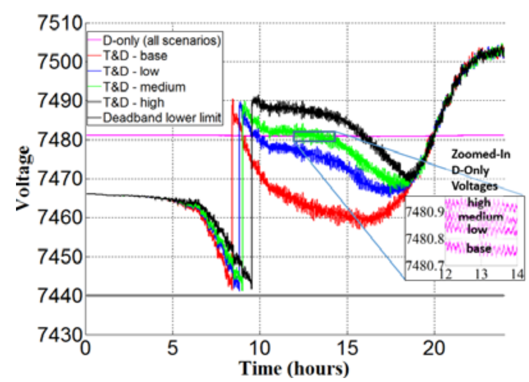

Fig. 7. L-N Regulator Output Voltages in Feeder R3-12.47-1 with D-only (T voltage=1.0 p.u.) and Integrated T&D Simulations

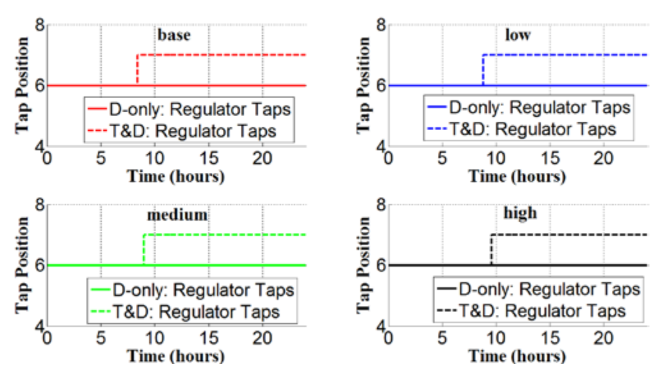

Fig. 8. Regulator Tap Positions in Feeder R3-12.47-1 with D-only (T voltage=1.0 p.u.) and Integrated T&D Simulations

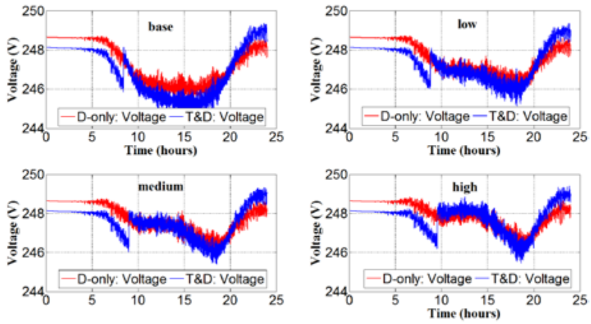

Fig. 9. Single-Phase Voltages at a Secondary Distribution Node in Feeder R3-12.47-1 with D-only (T voltage=1.0 p.u.) and Integrated T&D Simulations

IV. Conclusion

This paper presented a new approach for studying the impact of DGPV on power systems using integrated T&D models. It was shown that by using diverse, physical models of end-use equipment and by siting DGPV at the secondary distribution networks, realistic net load profiles can be obtained. The impact of using these net load profiles at various DGPV penetration levels on power systems operations was discussed, and it was observed that without adequate operator visibility in the distribution network and corresponding DER-aware net load forecasts, minimum generation events may occur at high DGPV penetration levels. The differences in distribution system response that are obtained when realistic representation of transmission system is used in integrated T&D simulations and when the transmission network is assumed to be an infinite bus in distribution-only simulations were also highlighted.

Research is in progress to further improve the integrated T&D simulations performed using IGMS. Future research directions include integrating the DGPV forecast into market/AGC simulations to prevent large ACE under high DGPV penetration scenarios; and more detailed models of transmission-distribution substations. In addition, further studies on the value of T&D co-simulation with high penetrations of advanced DGPV inverters using volt/VAR controls, and of load-price interactions from price-responsive load controls may further highlight the value of explicitly capturing the coupling between transmission and distribution systems.

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