Evaluating the Impact of Price-Responsive Load on Power Systems Using Integrated T&D Simulation

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National Renewable Energy Laboratory

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Evaluating the Impact of Price-Responsive Load on Power Systems Using Integrated T&D Simulation

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***Abstract*—This paper explores the differences between simulating price-responsive load (PRL) interactions with power systems using integrated transmission and distribution (T&D) models and transmission-only (T-only) models. This analysis uses the Integrated Grid Modeling System (IGMS) software to capture "ISO-to-appliance" simulations using a synthetic T&D model built on the PJM 5-Bus transmission network with multiple full-scale taxonomy feeders that include physics-based models of thousands of customers and PRLs. The results show important differences in the impacts of PRLs between integrated T&D and T-only models. Experiments with the synthetic integrated T&D dataset demonstrated that integrated T&D simulation revealed notably larger differences between the PRL and no-PRL cases for load, and prices compared to T-only simulation. Similarly, differences are observed between the price response of individual buildings and distribution feeders and the corresponding transmission bus in the integrated T&D simulations, which are difficult to capture in traditional T-only simulations.**

***Index Terms*—flexible demand, co-simulation, distributed power generation, high performance computing, integrated transmission-distribution simulation**

I. Introduction

In recent years, integrated Transmission (T) and Distribution (D) simulation has emerged as a new approach for power systems analysis [1]–[4]. These efforts are motivated by a blurring of the distinctions between T and D operations and markets driven by increasing penetration levels of distributed energy resources (DERs). Moreover, the deployment of smart metering infrastructure provides a technological framework that can enable consumers to directly respond to electricity markets by controlling load such as heating ventilation and air-conditioning (HVAC) in response to price. Using integrated T&D models, power systems stakeholders can simulate the interaction between price-responsive load (PRL) and modern power systems with more fidelity than is possible with T or D models alone.

Although several past studies have explored the impact of PRL on power systems, most used transmission only (T-only) models [5]–[7], and a few used distribution-only models [8], [9]. As described in [1], such separate models do not capture the closed loop interactions between T and D. Moreover, in these efforts the price-responsive end-use equipment was either not modeled in detail [5]–[8], or a simplified representation was used where the impact of changes in the state of the distribution network on their power consumption was neglected [10].

In this paper we show that using an integrated T&D model to simulate the impact of PRL on power systems can help overcome these limitations. We also show that the integrated T&D model provides a more accurate and high-resolution view of the behavior of each PRL than is possible with a T-only model that cannot model each PRL individually and must make an assumption regarding the aggregate price-responsive behavior of PRLs at each transmission bus.

The remainder of this paper is organized into four sections including this Introduction. Section II discusses the modeling methodology used to create integrated T&D and T-only models, with particular focus on the modeling of PRLs. Section III presents the results of the simulations, focusing on the differences observed between integrated T&D models and T-only models to study the impact of PRL on power systems. Section IV concludes and discusses ways to further improve the simulation of PRL using integrated T&D models.

II. Developing Integrated T&D and T-only Models

A. Integrated T&D Model

The synthetic integrated T&D model used in this study is referred to as the 5-Bus/11-Feeder System. The transmission topology in the system was modeled using the PJM 5-bus transmission system [11], where the lumped loads were replaced with taxonomy feeders developed by the Pacific Northwest National Laboratory [12]. To restrict the size of the resulting T&D system, 11 taxonomy feeders were used to replace the lumped load and a scaling factor of 15.70 was applied to the power flowing through the feeder head before it was sent to the transmission network. The integrated T&D model consisted of 27,000 distribution nodes, over 25,000 distribution lines and transformers, and more than 9,000 residential and commercial buildings. Detailed description of the 5-Bus/11-Feeder System can be found in [13].

The integrated T&D model is simulated in the Integrated Grid Modeling System (IGMS) software, which co-simulates GridLAB-D [14], MATPOWER [15] and the Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV) [16] to perform quasi steady-state simulations [1].

B. Load Modeling in the Integrated T&D Model

The integrated T&D model uses a bottom-up approach, in which the load at the transmission buses is obtained from detailed models of distribution feeder primary and secondary circuits complete with individual PRLs such as HVACs, dishwashers, and water-heaters, and additional ZIP loads. To overcome the challenge of modeling thousands of individual loads we use *glmgen* [17] to automate the distribution feeder creation process [1]. The bottom-up load modeling approach is

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particularly useful for studying the impact of PRLs on power systems as we can directly capture the physical state dependence of their response to prices, and the resulting impact on transmission and distribution networks. In this paper, the price-responsive behavior is modeled only for HVACs.

C. Load Modeling in the T-Only Model

The T-only model used the identical transmission network model as was used in the PJM 5-Bus/11-Feeder system. The load in the T-only model was aggregated at the three transmission buses (B2, B3, and B4) using the constant power load model. The time-varying load profiles at each of the three transmission buses (B2, B3, and B4) were obtained by first calculating the real and reactive power flows at the head of each of the feeders using separate off-line GridLAB-D simulations and then summing to compute the resulting total power flow at each transmission bus. These separate GridLAB-D simulations assume the transmission bus voltages of one per unit on the high-voltage side of the feeder-head transformer. The T-only model was simulated in FESTIV.

D. Price-responsive Controller for HVAC Loads in Integrated T&D Model

The Passive Controller of GridLAB-D was used to model the price-responsive behavior of HVAC loads in the integrated T&D model [18], [19]. The price passed on to the individual passive controllers was the LMP of the transmission bus to which the HVACs were connected via the distribution feeders.

The detailed description of the passive controller can be found in [18], and the operation of the controller can be understood from (1), which describes the *RAMP* control mode of the passive controller [18] to calculate the new temperature setpoint for the HVAC system. In (1), either the $\{R_{high}, \Delta T_H\}$ pair, or the $\{R_{low}, \Delta T_L\}$ pair is selected. $\{R_{high}, \Delta T_H\}$ is selected if Δp is positive; $\{R_{low}, \Delta T_L\}$ is selected if if Δp is negative.

$$T_{set}(t) = \begin{cases} T_{des}(t) + k\Delta p & \Delta T_H \leq k\Delta p \leq \Delta T_L; \sigma(t) \neq 0 \\ T_{des}(t) + \Delta T_H & k\Delta p > \Delta T_H; \sigma(t) \neq 0 \\ T_{des}(t) + \Delta T_L & k\Delta p < \Delta T_L; \sigma(t) \neq 0 \\ T_{des}(t) & \sigma(t) = 0 \end{cases} \quad (1)$$

Where,

$$\Delta p = \left(p(t) - p_{avg}(t)\right); \; k = \frac{|\Delta T_H \text{ or } \Delta T_L|}{\sigma(t) * |R_{high} \text{ or } R_{low}|}$$

$T_{set}(t)$=calculated HVAC setpoint temperature; $T_{des}(t)$=desired HVAC setpoint temperature if the passive controller were absent; $p(t)$= price that is passed onto all the passive controllers connected to feeders supplied by the transmission bus; $p_{avg}(t)$ =moving average of the price for the last X hours, X here is selected as 12 hours; $\sigma(t)$=standard deviation of the price calculated using the last X hours of prices and $p_{avg}(t)$; ΔT_H= maximum positive offset from $T_{des}(t)$, $\Delta T_H \geq 0$; ΔT_L= maximum negative offset from $T_{des}(t)$, $\Delta T_L \leq 0$; R_{high} and R_{low}=unitless constants, positive for cooling mode, and negative for heating mode.

Although (1) governs the setpoint that is applied by the passive controller to the HVAC thermostat, the time-interval at which the setpoint is applied can be varied for each customer. In the paper, the setpoint is applied either at 15, 30, 45 or 60-minute intervals to avoid too many, or too few HVAC setpoint changes, and reflect the diversity in setpoint update interval settings that consumers might have in a large power system. These intervals are assigned randomly to the passive controllers governing the HVACs at the start of the simulation, and they are not changed during the course of the simulation. The ΔT_H values for the controllers used in the paper are normally distributed with mean of 2.26 °F and standard deviation of 0.99 °F. The ΔT_L values are fixed at -0.005 °F for all the controllers, which assumes HVAC setpoints will not be lowered when the actual LMP is lower than the trend. The R_{high} values are also normally distributed with mean of 2.55 and standard deviation of 0.20. The R_{low} values are equal to R_{high} . To keep the peak load close to the maximum system load specified in the PJM 5-Bus system (1,000 MW), approximately 40% of the HVAC loads are disabled in the PJM 5-Bus/11-Feeder system.

E. Price-Responsive Behavior of Load in T-Only Model

Because the distribution network is not captured in detail within the T-only model, PRL is instead simulated by modeling the aggregate load response at the transmission bus level. This is done by applying *own* price elasticities (or simply price elasticities) to loads, which modify the loads as the price is changed [20]–[23].

The own price elasticity of demand is calculated as the ratio of the relative change in demand of a quantity, to the relative change in its price, provided that all other factors affecting the demand are held constant [24]. Mathematically, the own price elasticity can be written as (2):

$$e_{own} = \left(\frac{\Delta D}{D}\right) / \left(\frac{\Delta p}{p}\right) = \frac{\Delta D}{\Delta p} . \frac{p}{D} \quad (2)$$

where, e_{own} is the own price elasticity, D is the previous demand (load), p is the previous price, ΔD is the change in demand from D, and Δp is the change in price from p.

The literature suggests that the price elasticities for residential and commercial customers vary considerably, ranging from slightly less than zero to -0.4 in most cases [21]–[24]. Given this, it is important to model a similar level of responsiveness in the T&D and T-only simulations. This can be done by running a number of T-only simulations at different levels of demand elasticity that cover the range of interest [23], or by using the load and price data obtained from the integrated T&D simulation to calculate price elasticities. We opted for the latter approach to provide more comparable, model-specific values for price elasticity. Moreover, in the absence of data regarding the distribution network, the number of PRLs, and the controllers used in the PRLs, a transmission operator or a planner is restricted to using aggregate demand and real-time LMP data to estimate the demand elasticity. Price elasticity estimated using this approach, however, is an approximation because the conditions under which (2) is valid are difficult to fulfill. These conditions are (i) price should be the only independent variable, and (ii) price should change at the instant when the price elasticity is calculated.

To help isolate the effect of price in calculating the price elasticity, the change in load is calculated as the difference between the average load in the 5-minutes just preceding and succeeding the instant of the change in the LMP. The short time duration limits the impact of weather on the change in power demand, while allowing the impact of instantaneous change in HVAC power demand to be included as these are switched ON or OFF. Using the average load of the 5-minutes interval immediately after the change in real-time LMP also removes any short-term impact of PRLs on the LMP, because the new real-time LMP will not have been computed/applied until after the end of the 5-minute interval. However, the impact of time-varying non-price responsive load cannot be eliminated in this approach, as separate data regarding the distribution of load is lost when the load is aggregated at the transmission buses.

The real-time LMPs and aggregated loads at each of the three transmission buses obtained from the integrated T&D simulations are used for calculating the price elasticities. It is assumed the operator has no knowledge about the PRLs or their temperature update intervals.

The average price elasticities (averaged over the instants when real-time LMPs changed) calculated using the above approach for the three buses for the 24-hour simulation period were found to be -0.46 for bus B2; -0.25 for bus B3; and -0.11 for bus B4. These values are close to the typical range of price elasticities of loads reported in the literature.

III. Results and Discussion

For the T-only simulations, price elasticities obtained using the methodology described above were used to estimate demand for every 15-minute interval, corresponding to the smallest of the four intervals at which the HVAC thermostats were updated in the integrated T&D simulations. Specifically:

$$D_{new}(t) = D_{profile}(t) * \left(1 + e_{own}\left(\frac{p(t) - p(t-\Delta t)}{p(t-\Delta t)}\right)\right) \quad (3)$$

where, $D_{new}(t)$ is the load for a transmission bus that coincides with a 15-minite interval; $D_{profile}(t)$ is the load of the transmission bus in the absence of PRLs; e_{own} is the price elasticity for the transmission bus; $p(t)$ is the real-time LMP; Δt is the real-time economic dispatch time step (5 min).

1) Differences between Integrated T&D Simulations with and without PRL

Figures 1 and 2 compare the real power demand and the real-time LMPs at the transmission buses, obtained from integrated T&D simulations with and without PRL. Figure 3 shows the histogram of change in average power consumption of all the buildings modeled in the distribution feeders.

Tables I and II summarize the differences in operational impacts obtained from integrated T&D simulations performed in the presence and absence of PRLs. The parameters are calculated for all eleven feeders, and also at the three transmission buses. The "% Delta" column in tables I and II is calculated as $\% \, Delta = 100 \cdot (PRL - NO\_PRL)/NO\_PRL$; "NO_PRL" here and in all the figures and tables in the paper refers to the simulations performed in the absence of PRL.

TABLE I. Integrated T&D Simulations : Differences in Energy Consumed and Average Power over a Day

Feeder /Bus	Energy Consumed by Loads (MWh)			Average Power of the Loads (MW)		
	PRL	*NO_PRL*	*% Delta*	*PRL*	*NO_PRL*	*% Delta*
1	1149.66	1157.51	-0.68%	47.90	48.23	-0.68%
2	933.11	939.47	-0.68%	38.88	39.14	-0.68%
3	1018.63	1025.18	-0.64%	42.44	42.72	-0.64%
4	1094.01	1101.66	-0.69%	45.58	45.90	-0.69%
B2	4195.88	4223.49	-0.65%	174.83	176.03	-0.68%
5	1462.22	1472.14	-0.67%	60.93	61.34	-0.67%
6	1470.74	1481.07	-0.70%	61.28	61.71	-0.70%
7	1438.04	1447.27	-0.64%	59.92	60.30	-0.64%
8	1464.81	1474.53	-0.66%	61.03	61.44	-0.66%
B3	5836.15	5875.44	-0.67%	243.17	244.83	-0.68%
9	1222.82	1230.35	-0.61%	50.95	51.26	-0.61%
10	2935.41	2953.66	-0.62%	122.31	123.07	-0.62%
11	2726.20	2743.55	-0.63%	113.59	114.31	-0.63%
B4	6888.09	6928.29	-0.58%	287.00	288.75	-0.60%

TABLE II. Integrated T&D Simulations : Differences in Average Real-Time LMPs at Load Buses and Cost of Electricity over a Day

Feeder /Bus	Average LMP ($)			Cost of Electricity (thousand $)		
	PRL	*NO_PRL*	*% Delta*	*PRL*	*NO_PRL*	*% Delta*
1				27.82	28.42	-2.09%
2				22.44	22.88	-1.95%
3				24.60	25.10	-1.98%
4				26.46	27.01	-2.03%
B2	22.38	22.61	-1.02%	101.31	103.39	-2.01%
5				35.17	35.76	-1.65%
6				35.36	35.97	-1.68%
7				34.49	35.06	-1.62%
8				35.17	35.77	-1.66%
B3	23.07	23.35	-1.18%	140.21	142.57	-1.65%
9				34.16	35.10	-2.68%
10				79.53	81.54	-2.46%
11				74.01	75.88	-2.46%
B4	24.97	25.37	-1.57%	187.70	192.52	-2.50%

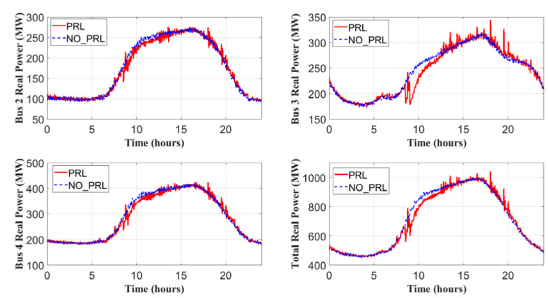

Figure 1. Real Power Demand at the Transmission Buses in Integrated T&D Simulations

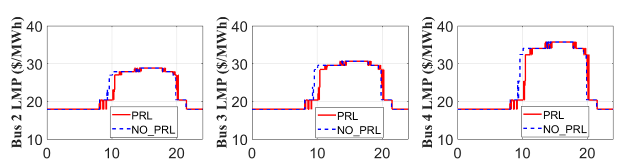

Figure 2. LMPs at the Buses B2, B3 and B4 in Integrated T&D Simulations

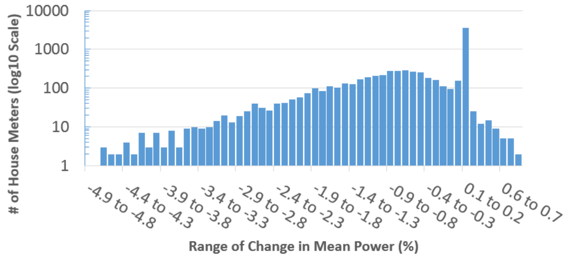

Figure 3. Histogram of Buildings where Average Power calculated over a day changed due to PRL in Integrated T&D Simulations

The key takeaways from the above tables and figures are:

- Figure 3 shows that the change in power consumption of individual buildings varied over a wide range (-5% to 0.7%). Interestingly, over 3,000 buildings witnessed a small increase in power consumption (between 0.1 to 0.2%) in the presence of PRLs.
- The addition of PRL reduced the demand during the morning load up-ramp (figure 1). As a result, the LMPs (figure 2) were also reduced. The increase in demand during the evening load down-ramp was minimal due to the very small ΔT_L (-0.005 °F) assigned to all the passive controllers. This prevented HVAC thermostat setpoints from being substantially reduced from their desired setpoints resulting in minimal increase in demand.
- A few spikes are seen in the load profile with PRLs. This can be attributed to the switching of states of a cluster of HVACs as they respond to the thermostat setpoints set by the passive controller, and the weather.
- Table I shows that at the transmission bus level, the average power and the energy consumed at all the three transmission buses reduce with the addition of PRL. Table II shows that the average LMPs, and the cost of electricity consumption (sum of product of LMP and energy) at the transmission buses are also reduced when price-responsive behavior of HVAC loads in enabled. There is a small variation in the magnitudes of changes in power, energy, and cost for the feeders when compared with the changes observed at the transmission buses.

2) Differences between T-only and Integrated T&D Simulations

Figures 4 and 5 show the real power demand and the real-time LMPs at the transmission buses obtained from T-only simulation with and without PRL.

In the T-only simulations, price-spikes were observed at a couple of instances during the evening load down-ramps when PRLs were present (figure 5). These occurred as price elasticity caused loads to increase in response to reduced real-time LMPs, and small amount of load was shed (4 MW at 5:30 p.m.) and reserves were deployed (at 8:00 p.m.) to meet the increased demand. Since the time of the price spikes did not coincide with the 15-minute PRL update interval, the load did not change as a consequence of the price-spikes. This can be seen in figure 4, where load spikes are not observed in the presence of PRLs. Tables III and IV summarize the results obtained from T-only simulations after neglecting the price-spikes. Since the T-only model does not include distribution feeders, only transmission bus level values are provided in tables III and IV.

The following key differences can be observed between the integrated T&D simulations and the T-only simulations:

- Figure 3 revealed wide variation in the change in average power at individual buildings between PRL and NO_PRL simulations using the integrated T&D model. A large number of buildings even witnessed a slight increase in the average power when PRLs were enabled in the integrated T&D model. Such observations cannot be made from the T-only model.
- Comparing tables I and II with tables III and IV reveals significant differences between PRL and NO_PRL simulations using integrated T&D and T-only models. E.g., while the maximum change in the cost of electricity between PRL and NO_PRL simulations using the integrated T&D model was 2.50% (table II), it was only 0.26% in the T-only simulations (table IV).
- As tables III and IV show, differences in the performance of each feeder in the presence and absence of PRLs can be obtained directly from integrated T&D simulations. However, the transmission bus is the finest level of resolution present in the T-only model .

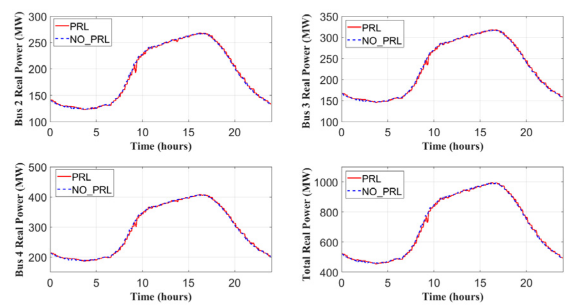

Figure 4. Real Power Demand at the Transmission Buses in T-only Simulations

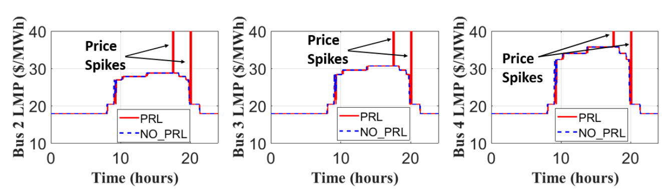

Figure 5. LMPs at the Transmission Buses B2, B3 and B4 in T-only Simulations

TABLE III. T-ONLY SIMULATIONS : DIFFERENCES IN ENERGY CONSUMED AND AVERAGE POWER OVER A DAY

Feeder /Bus	Energy Consumed by Loads (MWh)			Average Power of the Loads (MW)		
	PRL	*NO_PRL*	*% Delta*	*PRL*	*NO_PRL*	*% Delta*
B2	4583.69	4586.21	-0.05%	191.65	191.76	-0.05%
B3	5433.36	5435.51	-0.04%	227.18	227.27	-0.04%
B4	6962.24	6964.24	-0.03%	291.10	291.19	-0.03%

TABLE IV. T-ONLY SIMULATIONS : DIFFERENCES IN AVERAGE REAL-TIME LMPS AT LOAD BUSES AND COST OF ELECTRICITY OVER A DAY

Feeder /Bus	Average LMP ($)			Cost of Electricity (thousand $)		
	PRL	***NO_PRL***	***% Delta***	***PRL***	***NO_PRL***	***% Delta***
B2	20.728	20.747	-0.09%	110.27	110.52	-0.22%
B3	22.692	22.726	-0.15%	136.07	136.37	-0.22%
B4	23.446	23.486	-0.17%	193.20	193.7	-0.26%

IV. CONCLUSIONS AND FUTURE WORK

The results discussed in section III show that by using high resolution integrated T&D models that include detailed models of end use appliances and PRLs, the impact of PRLs on individual customers, distribution feeders, and the bulk power system can be calculated in one simulation. Such detailed analysis cannot be performed with T-only models that aggregate distribution network load to the transmission load buses. The detailed data generated from integrated T&D model-based simulations can be used by utilities and policy makers to design or adjust the real-time pricing tariffs such that the benefits of the tariffs for utilities and customers alike can be maximized.

While it is possible that with improved estimates of price elasticities T-only simulations may provide similar differences in loads and real-time LMPs between PRL and no-PRL cases as are obtained from integrated T&D simulations, obtaining such estimates under high penetration levels of PRLs that respond to real-time LMPs is difficult due to the following reasons:

- A wide range of price elasticities for residential, commercial and industrial loads have been reported in various studies. Selecting an appropriate price elasticity from the reported values is therefore difficult. Even if a value each is selected for residential, industrial, and commercial loads, it may not reflect the price-response of loads modeled in the study system as was seen in figure 3 where a large number of loads witnessed a slight increase in their power consumption when price-responsive behavior of loads was modeled.
- If load and price data generated from a simulation is used to calculate the price elasticities, the simulation should model the T and D networks, the electricity market, and the behavior of PRLs with reasonable accuracy. Therefore, some form of integrated T&D model is needed.
- Since price elasticity of load is a function of the "equilibrium point", i.e., the price and load at which it is calculated and price should be the only independent variable when calculating the price elasticity, it is not easy to extract correct price elasticities from integrated T&D simulations. Even if the price elasticities are obtained, they need to be recalculated when system operating conditions, such as demand, generation characteristics, network topology, and price-responsive controllers change.

If improved price elasticity estimates are obtained by overcoming the above challenges, T-only simulations may provide differences in the aggregate power system response between the PRL and no-PRL cases that are similar to those observed in integrated T&D simulations. However, variation in the responses of individual buildings, as seen in figure 3 cannot be obtained with T-only simulations.

Preliminary simulations have been performed to evaluate the interactions between PRL and high DER penetration levels using integrated T&D models. At present, the market simulations do not directly consider DER generation and PRLs while making the day-ahead and real-time unit commitment decisions. Work is in progress to include this capability in the modeling tools with a hope of identifying best practices for incorporating DERs and PRLs into the day-ahead and real-time unit commitment. Once included, this capability will allow better evaluation of the interactions between DERs and PRLs and the ability of PRLs to increase load during low LMPs to prevent/reduce events where minimum generation limits of conventional generation are reached.

V. REFERENCES

[1] B. Palmintier *et al.*, "IGMS: An Integrated ISO-to-Appliance Scale Grid Modeling System," *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1525–1534, May 2017.

[2] Peter Evans, "Regional Transmission and Distribution Network Impacts Assessment for Wholesale Photovoltaic Generation - Consultant Report," California Energy Commission, Consultant Report CEC-200-2014-004, Aug. 2014.

[3] H. Jain, A. Parchure, R. P. Broadwater, M. Dilek, and J. Woyak, "Three-Phase Dynamic Simulation of Power Systems Using Combined Transmission and Distribution System Models," *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4517–4524, Nov. 2016.

[4] Q. Huang and V. Vittal, "Integrated Transmission and Distribution System Power Flow and Dynamic Simulation Using Mixed Three-Sequence/Three-Phase Modeling," *IEEE Trans. Power Syst.*, vol. PP, no. 99, pp. 1–1, 2017.

[5] Z. Zhou, F. Zhao, and J. Wang, "Agent-based electricity market simulation with demand response from commercial buildings," in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–1.

[6] R. Fernández-Blanco, J. M. Arroyo, N. Alguacil, and X. Guan, "Incorporating Price-Responsive Demand in Energy Scheduling Based on Consumer Payment Minimization," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 817–826, Mar. 2016.

[7] K. Singh, N. P. Padhy, and J. Sharma, "Influence of Price Responsive Demand Shifting Bidding on Congestion and LMP in Pool-Based Day-Ahead Electricity Markets," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 886–896, May 2011.

[8] C. Cecati, C. Citro, and P. Siano, "Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 468–476, Oct. 2011.

[9] Mark Ruth, Annabelle Pratt, Monte Lunacek, Saurabh Mittal, Hongyu Wu, and Wesley Jones, "Effects of Home Energy Management Systems on Distribution Utilities and Feeders Under Various Market Structures: Preprint," presented at the 23rd International Conference on Electricity Distribution, Lyon, France, 2015.

[10] A. G. Thomas, C. Cai, D. C. Aliprantis, and L. Tesfatsion, "Effects of price-responsive residential demand on retail and wholesale power market operations," in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–8.

[11] F. Li and R. Bo, "Small test systems for power system economic studies," in *IEEE PES General Meeting*, 2010, pp. 1–4.

[12] K. P. Schneider, Y. Chen, D. P. Chassin, R. Pratt, D. Engel, and S. Thompson, "Modern grid initiative distribution taxonomy final report," *PNNL-18035 Pac. Northwest Natl. Lab. Richland Wash.*, 2008.

[13] Himanshu Jain, Bryan Palmintier, Ibrahim Krad, and Dheepak Krishnamurthy, "Studying the Impact of Distributed Solar PV on Power Systems using Integrated Transmission and Distribution Models," in *2018 IEEE PES T&D Conference and Exposition*, Denver, CO, USA, 2018.

[14] D. P. Chassin, J. C. Fuller, and N. Djilali, “GridLAB-D: An Agent-Based Simulation Framework for Smart Grids,” *J. Appl. Math.*, vol. 2014, pp. 1–12, 2014.
[15] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, “MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education,” *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 12–19, Feb. 2011.
[16] E. Ela and M. O’Malley, “Studying the Variability and Uncertainty Impacts of Variable Generation at Multiple Timescales,” *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1324–1333, Aug. 2012.
[17] E. Hale, T. Hansen, and B. Palmintier, “NREL/glmgen,” *GitHub*. [Online]. Available: https://github.com/NREL/glmgen. [Accessed: 07-Nov-2016].
[18] “Transactive controls - GridLAB-D Wiki.” [Online]. Available: http://gridlab-d.shoutwiki.com/wiki/Transactive_controls. [Accessed: 14-Sep-2017].
[19] D. J. Hammerstrom *et al.*, “Pacific Northwest GridWise™ Testbed Demonstration Projects; Part I. Olympic Peninsula Project,” Pacific Northwest National Laboratory, Richland, WA, PNNL-17167, Oct. 2007.
[20] B. Neenan and J. Eom, “Price Elasticity of Demand for Electricity: A Primer and Synthesis,” EPRI, Palo Alto, CA, White Paper 1016264, 2007.
[21] S. Fan and R. J. Hyndman, “The price elasticity of electricity demand in South Australia,” *Energy Policy*, vol. 39, no. 6, pp. 3709–3719, Jun. 2011.
[22] “Evaluation of the 2006 Energy-Smart Pricing PlanSM - Final Report,” Summit Blue Consulting, LLC, Boulder, Colorado, Nov. 2007.
[23] K. Spees, “Impacts of responsive load in PJM: Load shifting and real time pricing,” in *Developing & Delivering Affordable Energy in the 21st Century*, Houston, TX, USA, 2008.
[24] “Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them,” U.S. Department of Energy, Feb. 2006.