Development of an Agent-Based Distribution Test Feeder with Smart-Grid Functionality

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***Abstract*—This paper reports on the development of an agent-based distribution test feeder with smart-grid functionality. The test feeder is based on an actual distribution feeder with various additional features incorporated, including rooftop photovoltaic generation and price-responsive loads (e.g., plug-in electric vehicles and intelligent air-conditioning systems). This work aims to enable the integrated study of wholesale electric power markets coupled with detailed representations of the retail-side distribution systems.**

***Index Terms*—Air conditioning, electric vehicles, multi-agent systems, photovoltaic systems, power distribution, smart grid.**

I. Introduction

TODAY most consumers of electric power face fixed retail rates, hence their demands are independent of day-to-day variations in wholesale power prices. Consequently, for many purposes, wholesale power market researchers can treat demands for power as fixed inputs, avoiding the need for any detailed modeling of distribution systems. Nevertheless, the validity of conducting decoupled studies of wholesale and retail power system operations could be dramatically reduced in the near future with the development of smart-grid features such as demand response, dynamic-price retail contracting, distributed generation, and energy storage systems. These developments will lead to increased feedbacks between retail and wholesale power system operations that must be captured if empirical verisimilitude is to be attained. Realizing this need, an agent-based test bed has been developed for the integrated study of retail and wholesale power markets operating over transmission and distribution networks with smart-grid functionality [1], [2]. The current study reports on one aspect of this ongoing research: the development of an agent-based distribution test feeder (ABDTF) for evaluating the impacts of smart-grid market designs on distribution feeders.

The ABDTF will implement a detailed model of a distribution feeder with smart-grid functionality, including rooftop photovoltaic (PV) generation and price-responsive loads such as plug-in electric vehicles (PEV) and intelligent air-conditioning (A/C). The ABDTF will thus facilitate the study of the impacts of smart-grid technologies on distribution feeders. More broadly, however, the ABDTF will permit the performance evaluation of smart-grid market designs at both wholesale and retail levels.

The IEEE Distribution Test Feeder Working Group and the CIGRE Task Force C6.04.02 have developed several test feeders and network benchmarks [3]–[6]. However, the high-fidelity modeling of load is beyond the scope of these studies, whose purpose has been to provide common data sets to test and validate new algorithms for the analysis of distribution systems. For example, typically only load values or generic profiles are provided, but the load's dependence on the time of day or the weather is not accurately modeled. Environmental (e.g., temperature) and house parameters (e.g., ceiling height and area) are not accessible either. In consequence, these test feeders are not detailed enough for the evaluation of smart-grid market designs.

Researchers at the Pacific Northwest National Laboratory (PNNL) have developed a taxonomy of 24 prototypical feeder models that contain the fundamental characteristics of radial distribution feeders found in the U.S., based on 575 distribution feeders from 151 separate substations from different utilities across the U.S. [7], [8]. Each prototypical feeder is characterized by climate region, primary distribution voltage level, and other features. The feeder information is provided in a form that can be directly used in GridLAB-D [9], which is an open-source software platform developed by DOE at PNNL for the simulation of electric power distribution systems. Nevertheless, smart-grid technologies such as intelligent A/C systems, PEV and PV generation (with a consideration of cloud-passing effects) are still under development for the PNNL feeder models and are not yet available. Moreover, the PNNL feeder models are missing geographical coordinates of the feeder components important for the realistic rendering of dispersed PV generation units with a consideration of cloud patterns.

The ABDTF uses GridLAB-D to simulate a distribution feeder that incorporates various smart-grid technologies. It is based on an actual feeder from an electric utility in Iowa, with detailed specifications for distribution feeder equipment (such as fuses, switches, overhead and underground conductors, and service transformers) as well as for residential and/or commercial customers. Houses are virtually equipped with various smart-grid enabled technologies, such as rooftop PV generation and price-responsive demands in the form of PEVs and intelligently controlled A/C systems. Effects of cloud-passing on PV generation output are also considered. Realistic travel pattern data obtained from a 2009 National Household Travel Survey [10] are used to model PEV load.

This material is based upon work supported in part by the Electric Power Research Center of Iowa State University and the National Science Foundation under Grant No. 0835989.

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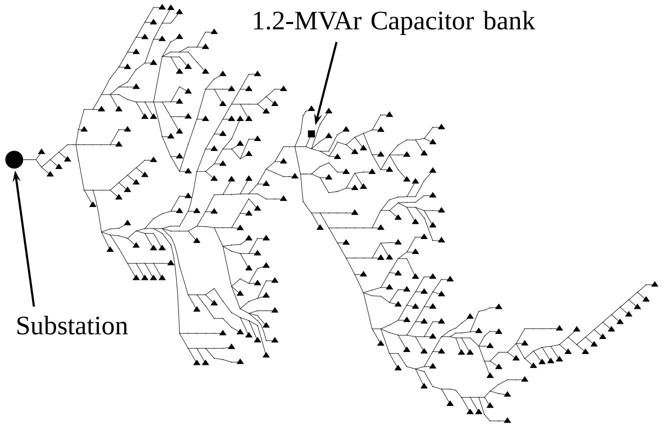

Fig. 1. Schematic of the feeder topology (this is not an accurate geographic representation). The triangles at the leaves of this tree represent distribution transformers.

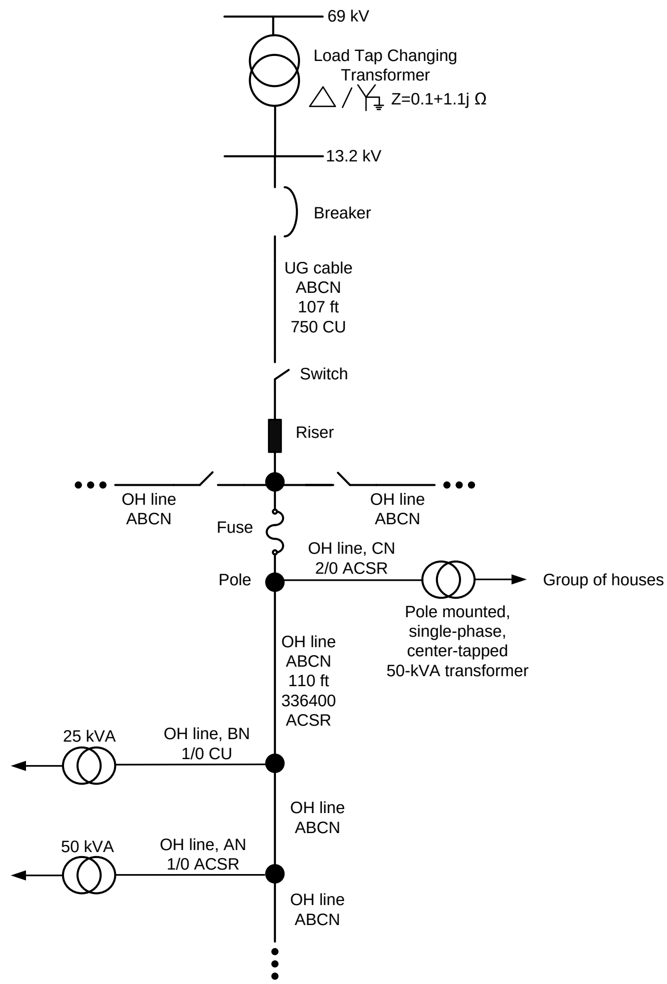

Fig. 2. One-line diagram of a small representative section of the feeder.

The ABDTF is agent-based in the sense that some of the distribution feeder components are modeled as interacting agents whose actions are determined by individually specified objectives or purposes subject to financial and/or physical constraints. For example, the actions of a household resident agent might involve the determination of optimal intertemporal comfort/cost trade-offs conditional on retail energy prices, environmental conditions, and equipment limitations. The actions of a PEV agent might involve the minimization of energy costs subject to feasible travel routes, time constraints, and charger rating. The actions of a PV agent might involve the maximization of harvested solar power subject to panel surface area and weather conditions (e.g., cloud cover).

The remainder of this paper is organized as follows. Section II describes the ABDTF topology and its main characteristics. Section III provides more details about the agents of the test feeder. In Section IV, an example is provided to illustrate how the developed test feeder can be used in a market analysis, with emphasis on the distribution system variables. Section V concludes the paper.

II. Distribution Feeder Description

The distribution feeder is providing electricity to a residential neighborhood in the state of Iowa. Its technical data were obtained from the electric utility that operates it. Fig. 1 depicts a schematic of the feeder's topology that includes all branches at the medium voltage level. Exact geographic coordinates of its components are also known, but are not reflected in the figure. Fig. 2 shows a small representative section of the feeder, including part of the substation. The other branches have similar characteristics. Therefore, the feeder is modeled with as much accuracy as possible, including asymmetry in the lines and the loads. The feeder's electrical component data are entered into a GLM file for use by GridLAB-D, which solves a sequence of three-phase power flows throughout the simulated time period at a user-defined time step.

The feeder's peak power at the substation is reported by the utility to be approximately 14 MVA. It consists of 316 medium voltage (13.2 kV) lines; 301 are overhead and 15 are underground. In terms of overhead lines, the feeder contains 7 different types of conductors, and has 98 three-phase plus neutral (ABCN) lines, 2 two-phase (ACN) lines, and 73 AN, 60 BN, and 68 CN single-phase lines. In terms of underground cables, there are 2 different conductor types, and 13 ABCN, 1 AN, and 1 CN cable. The main parameters of the overhead lines and underground cables are listed in Table I. The length of the lines varies between 5 and 522 feet. There are 175 single-phase center-tapped transformers rated 7621/240 V and 25 to 75 KVA, mounted on utility poles or concrete pads, with parameters listed in Table II. (Some of these parameters were obtained from [11].) Finally, the end-load consists of 1370 houses. For the modeling of the PV and A/C systems, it is necessary to know the floor area and number of stories for each house, as well as the area of the south-facing part of the roof of each house (where PV panels are typically installed). To this end, these parameters were estimated using Google earth [12] based on the geographic coordinates of the distribution transformers.

TABLE I
PARAMETERS OF OVERHEAD LINES AND UNDERGROUND CABLES

ID	Type	AWG/kcmil	Rating (A)
1	OH-ACSR	336.4	639
2	OH-AL	336.4	585
3	OH-CU	1/0	291
4	OH-ACSR	1/0	285
5	OH-ACSR	2	215
6	OH-CU	4	155
7	OH-CU	6	116
8	UG-CU	750	550
9	UG-AL	1/0	200

TABLE II
PARAMETERS OF SINGLE-PHASE CENTER-TAPPED TRANSFORMERS

Type	Rating (kVA)	Z_{series}(pu)	Z_{shunt}(pu)
Pole mounted	25	0.016+0.023j	339.6+331.8j
Pole mounted	50	0.014+0.024j	391.8+428.1j
Pole mounted	75	0.0135+0.030j	470.0+454.6j
Pad mounted	25	0.016+0.023j	339.6+295.5j

III. DESCRIPTION OF AGENTS

The end-use loads of the households are divided into two groups. The first group includes loads such as conventional thermostatically controlled A/C, water heaters, TV sets, fans, lights, ovens, and other common electric devices. These constitute a background non-price-responsive load, which is determined automatically by GridLAB-D's internal load modeling algorithms. The second group contains two kinds of "intelligent" loads, namely: (i) a new class of A/C controller that operates based on a varying retail price signal and the household resident's cost-comfort tradeoff preferences, and (ii) PEVs whose charging is performed overnight based on the same retail price signal as the A/C. The feeder also has a large penetration of distributed generation in the form of rooftop PV panels. It should be noted that the electric power and energy consumption of A/C systems and PEVs accounts for a substantial portion of the total feeder load. If installation costs continue to decline, it is also possible that rooftop solar will become much more prevalent in the near future in the United States. Each one of these technologies on its own merit has potential to impact distribution feeder reliability to a significant degree due, for example, to transformer overloading or unacceptable voltage deviations. In particular, the test feeder described herein allows us to study the behavior of such systems when responding to market-based price signals, and hence to evaluate the impact of market policies at the distribution level. Additional details about these smart-grid agents are provided in the following subsections.

A. Intelligent Air-Conditioning Systems

Households are equipped with a recently proposed intelligent A/C system with smart-grid functionality [13]. The qualifier "intelligent" means that the A/C controller has advanced computational capabilities and uses an array of environmental and occupancy parameters in order to provide optimal intertemporal comfort/cost trade-offs for the household residents, conditional on retail energy prices and environmental conditions. The term "smart-grid functionality" means that retail energy prices are allowed to vary throughout the day. They are transmitted to the A/C controller each day (say, at 6pm daily), thus allowing the controller to schedule its energy consumption for 24 hours in advance (starting at midnight). It should be noted that the entity (e..g, utility or A/C aggregator) that is responsible for providing the retail prices to the A/C systems (different from the fixed retail price that conventional uncontrollable loads pay) is another (profit-maximizing) agent which could be modeled within the wholesale power market simulation software.

B. Plug-in Electric Vehicles

Plug-in electric vehicles can help reduce dependence on petroleum and transportation costs. In addition, they can be aggregated to provide an array of ancillary services to the power grid with appropriate control [14]. Therefore, they could be an important ingredient in tomorrow's smart distribution systems, but they represent a substantial additional load to the system. In the ABDTF, PEV load is estimated using a stochastic formulation that takes into account spatial and temporal diversity [15]. When developing the PEV power consumption, various factors are modeled, for example, PEV fleet characteristics such as charge-depleting range and fraction of tractive energy from electricity in charge-depleting mode [16], [17], charging circuits [18], travel patterns [10], [17], and PEV load control and management strategies [19]–[21]. Similar to the A/C system, the PEV aggregator entity (or entities) could be modeled as a separate agent (or agents) in the wholesale market simulation.

C. Rooftop Solar Generation

Each house can have installed rooftop PV panels. The maximum amount of PV capacity is determined by the house's southern roof area. Each PV installation is represented as a separate agent with its own attributes and methods (rules of operation). The attributes include power rating and installation parameters such as tilt angle, cover area, and efficiency rating. The inverter is assumed to be operating in a quasi steady-state, under maximum power point tracking control [22]. In response to environmental inputs, such as solar radiation and ambient temperature, the PV panel reacts by generating different amounts of real power. The solar radiation pattern for each house is generated by moving over the feeder area a synthesized cloud pattern similar to the one shown in Fig. 3. Also, the PV inverter has the capability to supply or absorb reactive power from the grid in order to improve the local distribution system voltage profile. The design of algorithms for determining the appropriate reactive power compensation by the PV inverters is the subject of ongoing work.

IV. ILLUSTRATIVE EXAMPLE

The ABDTF is seamed with AMES [23], an open-source agent-based platform previously developed by a team of researchers at Iowa State University for the study of strategic trading in restructured wholesale power markets with congestion managed by locational marginal prices (LMPs). The

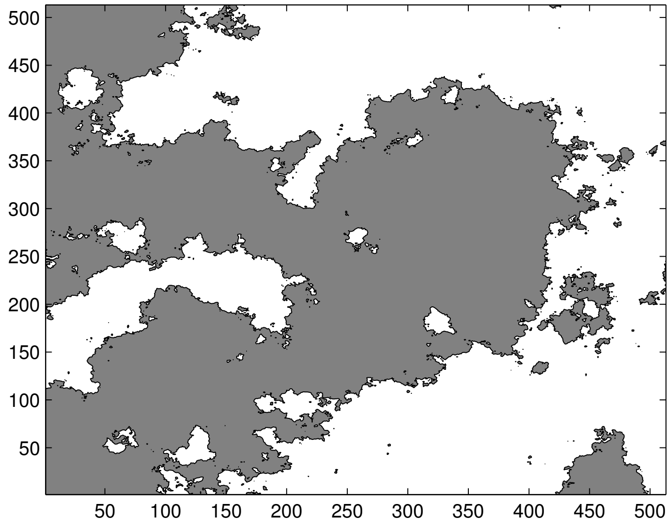

Fig. 3. Example of synthetic cloud cover used in the simulation, which moves over the distribution feeder area at constant velocity. The axes units are pixels, and one pixel represents 7 meters. Hence, this square area has a 3.5-km side. The cloud is represented by the gray area.

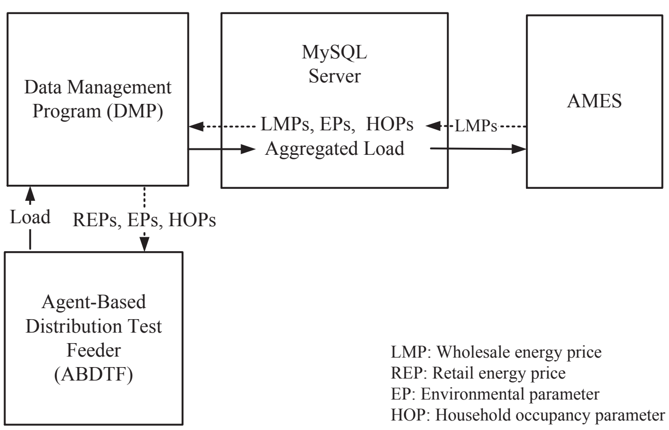

Fig. 4. Illustration of data flow for the integrated study of retail and wholesale power market operations.

resulting seamed platform will be used to conduct controlled computational experiments to investigate a number of important issues relating to smart-grid developments, such as how the penetration of price-responsive demand, PEVs, and distributed generation (e.g., PV) affects load profiles at the wholesale level.

Here a simple example that illustrates how the resulting seamed platform might be used to study feedback effects between retail and wholesale power system operations is presented. As shown in Fig. 4, the current implementation of such a study involves four main components, namely, the ABDTF running in GridLAB-D, a Data Management Program (DMP), a MySQL database server, and AMES running in Java.

The DMP has the following three tasks: (i) to receive environmental parameters (weather data and cloud pattern), household occupancy parameters, and 24-hour day-ahead wholesale energy prices (LMPs), and to map this data into retail energy prices (REPs); (ii) to send all information obtained in (i) to the ABDTF in comma-separated values (CSV) format; and (iii) to collect simulation results (aggregated load data) from the ABDTF output and transmit these results to the MySQL database server. The functionality of the DMP basically represents the communication between distribution-level components (e.g., advanced meters) and entities that exist at a higher level (e.g., transmission/distribution utilities, load serving entities, aggregators of demand response, or aggregators of plug-in electric vehicles). The MySQL database server maintains two repeatedly-updated information storage tables, one for storage of the LMPs obtained from AMES, and one for storage of the load data obtained from the ABDTF.

In what follows, simulation results are presented for a hot and cloudy summer day. The variation of environmental parameters used for day-ahead scheduling and real-time simulations is depicted in Fig. 5. A crudely predetermined schedule of appliances is used to construct the internal heat flow rate for the day-ahead scheduling of the A/C systems. A finer variation of appliances and occupant activity is assumed to occur in real-time. The retail price for this day, which is communicated to the smart A/C systems and the PEVs, is the day-ahead LMP (this could be obtained from AMES) plus a mark-up of 5 cents/kWh, shown in Fig. 6.

Figs. 7(a) and 7(b) depict the total real and reactive power load at the substation. The reversal of real power flow at the substation during the daytime is due to the high penetration of PV units in this case. For this example, a 100% penetration level was assumed for the rooftop PV units, where penetration level is defined as the total PV panel area divided by the total available south roof area. Figs. 7(c) and 7(d) show the total real power consumption from the smart A/C systems and the PEVs, respectively. The penetration level of PEVs in this case is 25%, i.e., one out of four vehicles is randomly selected to be a PEV. Half are charged at off-peak hours with a minimum-cost control algorithm, whereas the other half start charging at the time when they return home paying the usual flat electricity price. Fig. 7(e) presents the total real power generated from the PV units. Finally, Fig. 8 shows the real power losses on the various types of feeder components.

Fig. 9 illustrates maximum, minimum and average voltages at the meters of the residential loads. As can be seen, the maximum voltages become significantly higher than 126 V for some residential customers due to the reverse power flow caused by the PV units. The ANSI Standard C84.1 [24] requires that the voltage at residential loads remains within five percent (114–126 V) from its nominal value (120 V).

V. Conclusion

Ideally, smart-grid technologies should be thoroughly evaluated prior to their deployment. The primary goal of this project is to supply researchers with an agent-based implementation of a distribution test feeder that provides a high-fidelity representation of electrical topology, environmental parameters, and loads arising from households equipped with smart appliances and dispersed generation units. The availability of such realistically rendered distribution test feeders should facilitate the study of market design at the retail level. Moreover, as discussed in previous sections, the agent-based distribution test feeder can be seamed with agent-based

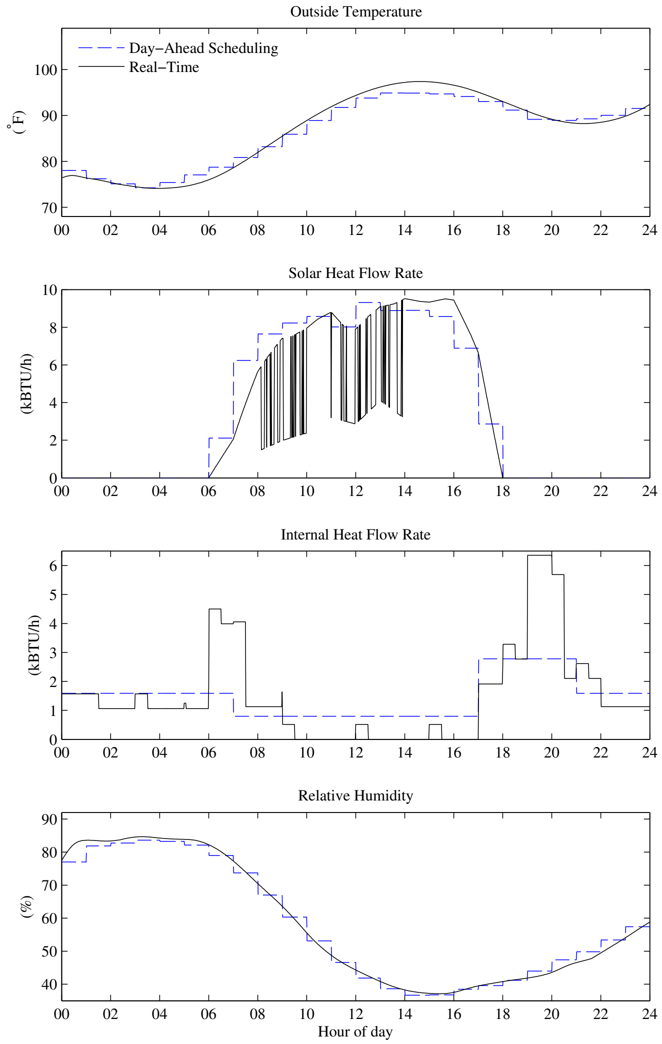

Fig. 5. Variation of environmental parameters for day-ahead scheduling and real-time simulation. The solar irradiation and internal heat flow rates differ for each house.

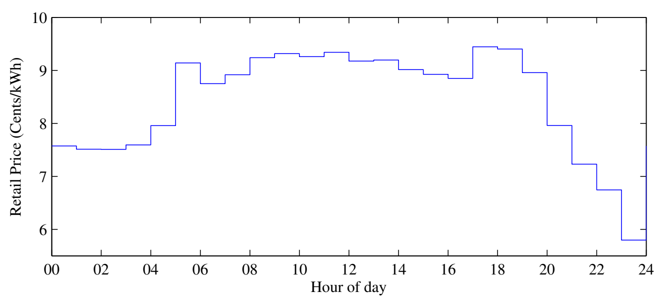

Fig. 6. Retail price variation.

platforms implementing wholesale power market operations, such as the AMES platform [23], thus permitting the integrated study of retail and wholesale power market operations.

ACKNOWLEDGMENT

The authors thank Colin Christy, Chengrui Cai, and Auswin George Thomas of Iowa State University for their assistance in obtaining the data and running the simulations.

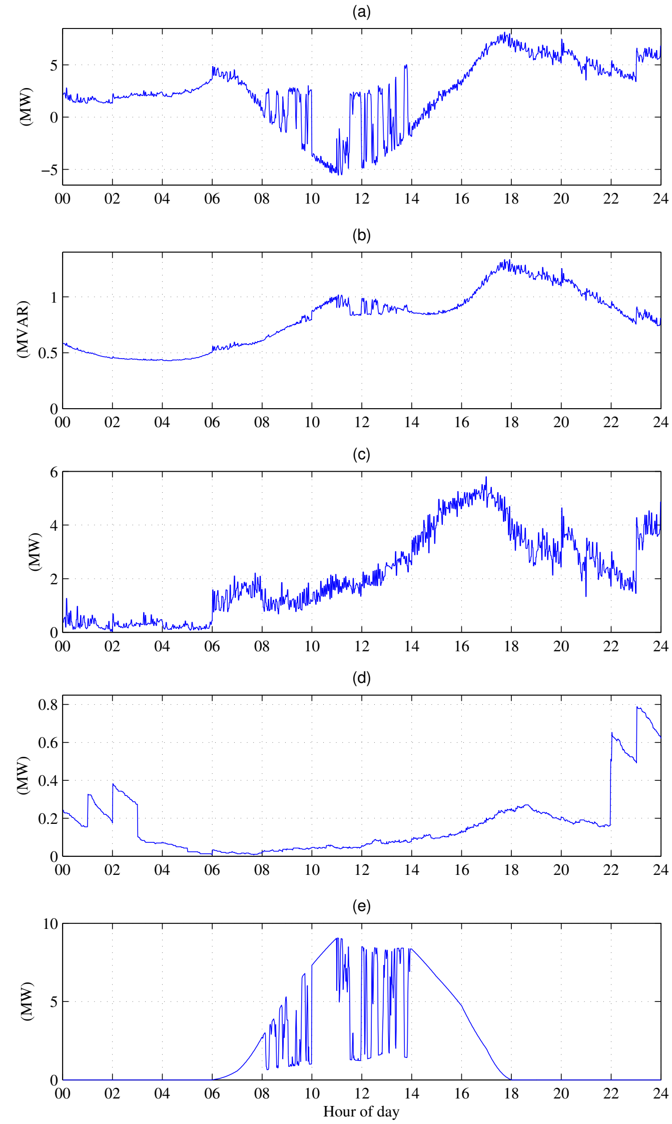

Fig. 7. (a) Real power at the substation, (b) Reactive power at the substation, (c) Real power consumption from all smart A/C systems, (d) Real power consumption from all PEVs, (e) Real power generation from all PV units.

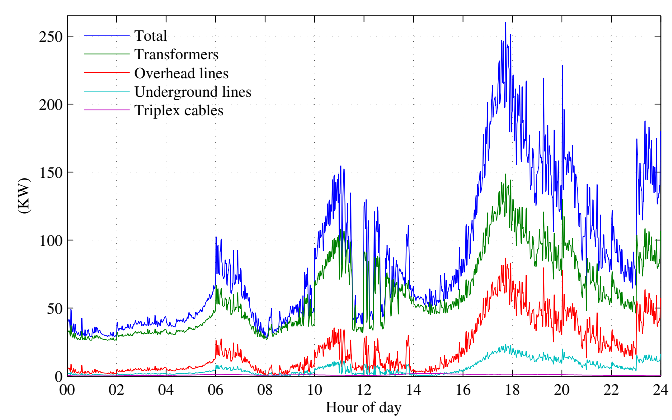

Fig. 8. Real power losses.

REFERENCES

[1] Integrated retail/wholesale power system operations with smart grid functionality: Project homepage. [Online]. Available: http:

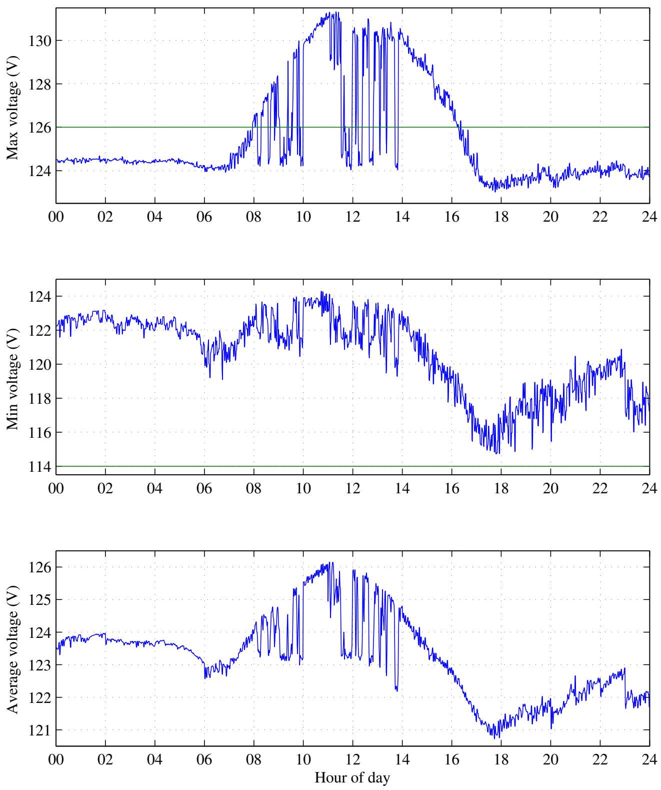

Fig. 9. Maximum, minimum, and average voltages of residential loads.

//www.econ.iastate.edu/tesfatsi/IRWProjectHome.htm
[2] D. Aliprantis, S. Penick, L. Tesfatsion, and H. Zhao, "Integrated retail and wholesale power system operation with smart-grid functionality," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, Minneapolis, MN, Jul. 2010.
[3] W. H. Kersting, "Radial distribution test feeders," in *Proc. IEEE Power Eng. Soc. Winter Meet.*, vol. 2, Columbus, OH, Jan. 2001, pp. 908–912.
[4] Distribution test feeders. IEEE PES Distribution System Analysis Subcommittee. [Online]. Available: http://www.ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html
[5] K. Strunz, R. H. Fletcher, R. Campbell, and F. Gao, "Developing benchmark models for low-voltage distribution feeders," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, Calgary, AB, Jul. 2009.
[6] K. Rudion, Z. A. Styczynski, N. Hatziargyriou, S. Papathanassiou, K. Strunz, O. Ruhle, A. Orths, and B. Rozel, "Development of benchmarks for low and medium voltage distribution networks with high penetration of dispersed generation," *CIGRE Report*, 2006.
[7] K. P. Schneider, Y. Chen, D. P. Chassin, R. Pratt, D. Engel, and S. Thompson, "Modern grid initiative distribution taxonomy final report," Pacific Northwest National Laboratory, Tech. Rep., Nov. 2008.
[8] K. P. Schneider, Y. Chen, D. Engle, and D. Chassin, "A taxonomy of North American radial distribution feeders," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, Calgary, AB, Jul. 2009.
[9] GridLAB-D. Pacific Northwest National Laboratory (PNNL). [Online]. Available: http://www.gridlabd.org/
[10] U.S. Dept. of Transportation, Federal Highway Administration. National household travel survey (NHTS). [Online]. Available: http://nhts.ornl.gov/download.shtml
[11] T. Gönen, *Electric power distribution system engineering*, 2nd ed. CRC Press, 2007.
[12] Google earth. [Online]. Available: http://www.google.com/earth/index.html
[13] A. G. Thomas, P. Jahangiri, D. Wu, C. Cai, H. Zhao, D. C. Aliprantis, and L. Tesfatsion, "Intelligent residential air-conditioning system with smart-grid functionality," *under journal submission*.
[14] K. Fell *et al.* (2010, Mar.) Assessment of plug-in electric vehicle integration with ISO/RTO systems. KEMA, Inc. and ISO/RTO Council. [Online]. Available: http://www.isorto.org/
[15] D. Wu, C. Cai, and D. C. Aliprantis, "Potential impacts of aggregator-controlled plug-in electric vehicles on distribution systems," in *Proc. 4th IEEE workshop Comput. Adv. Multi-Sensor Adap. Process. (CAMSAP)*, San Juan, PR, Dec. 2011.
[16] M. Duoba, R. Carlson, and D. Bocci, "Calculating results and performance parameters for PHEVs," presented at the SAE World Congr. Exhibit., Detroit, MI, Apr. 2009.
[17] D. Wu, D. C. Aliprantis, and K. Gkritza, "Electric energy and power consumption by light-duty plug-in electric vehicles," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 738–746, May 2011.
[18] *SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler*, Society of Automotive Engineers (SAE) Std. J1772, Jan. 2010.
[19] K. Parks, P. Denholm, and T. Markel, "Costs and emissions associated with plug-in hybrid electric vehicle charging in the Xcel Energy Colorado service territory," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-640-41410, May 2007.
[20] A. Brooks, E. Lu, D. Reicher, C. Spirakis, and B. Weihl, "Demand dispatch," *IEEE Power Energy Mag.*, vol. 8, no. 3, pp. 20–29, May/Jun. 2010.
[21] D. Wu, D. C. Aliprantis, and L. Ying, "Load scheduling and dispatch for aggregators of plug-in electric vehicles," *IEEE Trans. Smart Grid (Special Issue on Transportation Electrification and Vehicle-to-Grid Applications)*, to appear.
[22] C. Cai, P. Jahangiri, A. G. Thomas, H. Zhao, D. C. Aliprantis, and L. Tesfatsion, "Agent-based simulation of distribution systems with high penetration of photovoltaic generation," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, Detroit, MI, July 2011.
[23] AMES wholesale power market test bed homepage. [Online]. Available: http://www.econ.iastate.edu/tesfatsi/AMESMarketHome.htm
[24] *American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz), ANSI C84.1-2011*, American National Standards Institute (ANSI) Std.

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