Transactive Control for Efficient Operation of Commercial Buildings

Sneharaj Ramdaspalli, Manisa Pipattanasomporn, Murat Kuzlu, Saifur Rahman.
Bradley Department of Electrical and Computer Engineering and Advanced Research Institute,
Virginia Tech, Arlington, VA 22203, US

Abstract — **This paper describes the model development of a commercial building and investigates benefits of transactive control for efficient operation of buildings. The model of a DOE standard small office building is developed in GridLAB-D (an agent-based distribution system simulation environment) and validated with the model simulated in EnergyPlus. A passive transactive control strategy has been applied to estimate the peak demand reduction potential and energy savings of a building in a transactive energy market. This analysis forms an outline for efficient operation of commercial buildings by adopting market-based control strategies and lays a corner-stone for studying building-to-grid integration in a transactive control based network. In addition, this paper also describes limitations of the model and discusses the scope for future improvements.**

Index Terms — **Agent-based platform, Commercial Buildings, Dynamic Pricing, HVAC (Heating, Ventilation and Air-Conditioning), Transactive Control.**

I. Introduction

In today's environment, with the penetration of distributed energy resources (DERs) in commercial buildings, bidirectional energy transactions with the grid are feasible. This paper models a commercial building in a transactive control network to study the impact of building-to-grid integration in a transactive energy market. The commercial buildings energy consumption survey (CBECS) results show that there were 5.6 million commercial buildings in the United States in 2012 [1]. Office spaces show the highest growth rate in the category of small and medium sized commercial buildings. Empowering these buildings with intelligence and employing load reduction techniques during peak periods provide a significant impact on the distribution grid [2]. Research shows that there can be significant reduction in peak demand and overall electrical energy consumption by the incorporation of price elasticity [3]. Towards this end, a transactive control strategy effectively serves the purpose of load reduction during the peak demand period. In the transactive control environment, buildings/appliances actively participate in an electricity market. While there are several pricing schemes like time-of-use (ToU), critical peak pricing (CPP), variable peak pricing (VPP), real-time pricing (RTP), in this paper we consider a transactive control strategy based on a RTP scheme in a stubauction market.

Several studies [4-8] have modeled commercial building operation with the main objective to improve the efficiency of HVAC systems using model predictive control (MPC) schemes. Among different simulation software currently available, EnergyPlus [9] offers the most comprehensive platform to model commercial buildings, taking into account external factors, such as occupancy and weather conditions, in addition to building parameters. On the other hand, GridLAB-D [10] offers a versatile platform that allows incorporation of transaction-based control to manage building operations. It provides an ideal environment to model the building-to-grid interaction and evaluate the impact of transactive control strategy on peak demand reduction and energy saving potential at the building level.

In a transactive control based approach, buildings are viewed as fundamental units connected to the power grid. The transactive energy vision enables buildings to transact with the grid and modify their electricity consumption profile in accordance with real-time grid conditions. While authors in [11] discuss about the importance of using transactive control for buildings, authors in [12,13] discuss how transactive control provides a means of coordinating the response of smart grid assets, the effect of a congestion market at the distribution feeder level and estimate its impact on customer bills. In [14] authors detail through theoretical and practical aspects of transactive control and provide analytical methods to operationalize such a design. Preliminary studies conducted in [15, 16] explore value streams and effects of a residential double-auction market with transactive controllers on the operation of electric power distribution system. In [17] the authors present a simulation model for the integration of DERs in the building and in [18], an energy scheduling algorithm supporting power quality management in commercial building micro grids is presented.

While GridLAB-D has in-built models for residential use, not much support is provided to model commercial buildings. Commercial buildings differ from residential models, especially in terms of HVAC requirements and usage of specific loads based on occupancy. This paper attempts to extend the application of transactive control to commercial buildings and estimate its benefits from the grid's and commercial building's standpoints. In this work, a DOE standard building model for a small commercial office space located in Maryland, USA is taken as reference [19]. This building is simulated in EnergyPlus and validated against real-life energy consumption profile. An equivalent office building model has been constructed in GridLAB-D and compared against the EnergyPlus model. A transactive controller has been developed in order to adjust the HVAC load in the modeled office building, hence making the building demand responsive to real-time electricity prices. This paper focusses on modeling a commercial office building in GridLAB-D, implementing a transactive control strategy and studying its impact on the building operation.

II. Model Description

A. Model of a Small Office Building in GridLAB-D

Details of a DOE standard building for a small commercial office space are provided in Table I. This building is located in Baltimore, Maryland, USA. It has five zones – one core zone and four surrounding zones. Schedule of operation and energy consumption details of each zone are obtained by simulating the building in EnergyPlus. Each zone has a rooftop unit (RTU) to address its heating and cooling requirements. Primary loads in this office building are cooling, heating, lighting and plug loads (equipment).

TABLE I. DETAILS OF SMALL OFFICE BUILDING

Attribute	Quantity	Units
No. of floors	1	-
Area	5,500	sq. ft.
No. of zones	5	-
Interior lighting capacity	5.5	kW
Exterior lighting capacity	6	kW
Installed HVAC capacity	12	kW
Equipment load	5	kW

Occupancy based hourly operating schedule of various loads on a typical weekday in the building, is shown in Figure 1.

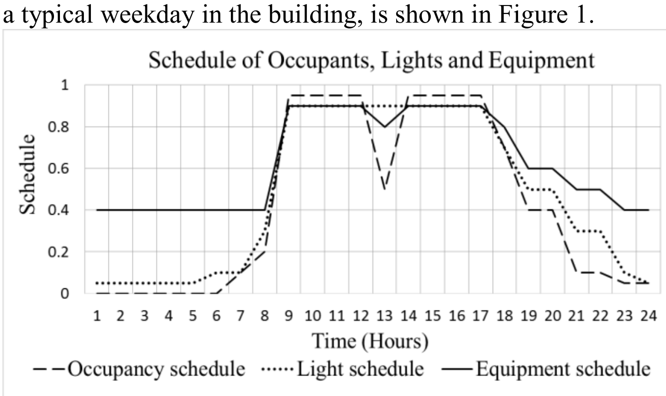

Figure 1. Hourly schedule of occupants, lights and equipment in the building

Occupancy details and schedules for lighting and equipment are provided as a number between 0 and 1. For example, a value of 0.5 means that during that hour, the power consumption of equipment is half of the maximum capacity. The maximum number of occupants in the building is 255. This varies across the day with an occupancy schedule shown in Figure 1.

The HVAC settings for the building are as follows:

- The HVAC system runs from 6:00 A.M. to 10:00 P.M.
- During weekdays, the cooling set point is maintained at 75ºF from 6:00 A.M. to 10:00 P.M. and at 80ºF for rest of the day.
- On Saturdays, the cooling set point is maintained at 75 ºF from 6:00 A.M. to 6:00 P.M. and at 80ºF for the rest of the day.
- On Sundays and holidays, the cooling set point is at 80ºF for the entire day.

B. Model Validation

The office building is modeled in GridLAB-D by extracting the information for load schedules, their ratings and necessary building parameters from EnergyPlus. The period of simulation is from 1st July 2012 to 7th July 2012, with a resolution of one minute. Loads are modeled by configuring their schedules appropriately in GridLAB-D, as per the details shown in Figure 1.

Lighting load: The lighting load has been modeled indoor as 'incandescent' type with an installed capacity of 5.5 kW. It must be noted that total lighting load for the building includes both interior and exterior lights. This detail is taken into account while configuring the schedule for lighting in GridLAB-D.

Plug load: The plug load model in GridLAB-D has an installed capacity of 5 kW, following EnergyPlus data.

HVAC load: The building with a footprint of 5,500 sq. ft is modeled in GridLAB-D. In case of both Energy Plus and GridLAB-D, outdoor temperature information is obtained from an appropriate climate file and HVAC power consumption is calculated based on outdoor temperature and indoor set points.

Following building data from EnergyPlus, the building is modeled in GridLAB-D to have five HVAC units, each of which is associated with each zone. Then, the overall power consumption of the building from GridLAB-D is scaled to match with that from EnergyPlus. This is shown in Figure 2.

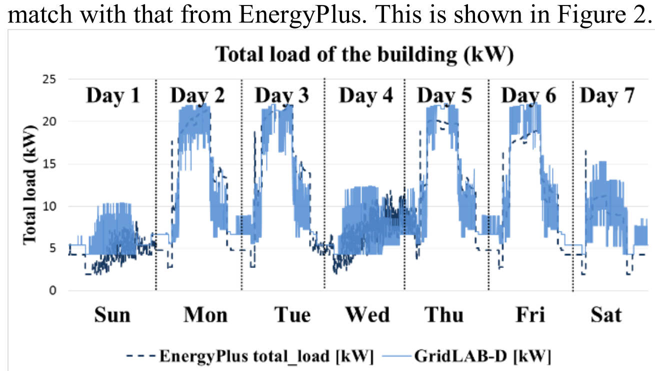

Figure 2. Comparison of total load profiles modeled in EnergyPlus and GridLAB-D

Note: Wednesday (Day 4) is a holiday (4th July, 2012) and hence the load profile resembles that of Sundays.

This figure clearly depicts the close correlation between office building modeled in EnergyPlus and GridLAB-D. The discrepancy in the peak load of the HVAC system in EnergyPlus and GridLAB-D is because EnergyPlus models the commercial building taking into account finer details regarding building envelope and position of doors and windows in the building. Also the maximum allowance in schedule value for safe operation of plug load is 0.9, as a result of which the power consumption of plugload in GridLAB-D is lower than that in EnergyPlus.

This justifies the commercial office space model built in GridLAB-D, taking into account an aggregate load behavior based on the building's net power consumption.

III. Passive Controller Design

In a real-world environment, majority of small office buildings have no building automation systems to control their operation. Empowering a building with intelligence implies the ability to automatically adjust its operating parameters to optimize building functionality, reduce peak demand and save energy [20]. As the first step, the impact of transactive control in an active system is studied. In an active system a price signal is sent from a utility to the end user. This method of control uses passive controllers that provide information to consumers (such as real-time market prices) so that the controllers' setting can be adjusted [21]. The model and scheme of operation of a passive controller in the electricity market is detailed below.

A. Operation/Model of a Passive Controller

In an active market, a passive controller adjusts the internal set point of selected building loads by responding to an external price signal. This work examines an HVAC system in a commercial building.

In GridLAB-D, the real-time market prices are fed to the passive controller through the auction object. This object is configured as a buyer-only market and hence cannot receive bids. The real-time market price information for this simulation is obtained from a utility company located in U.S. In addition to this information, a rolling 24-hour average of the price signal (P_{avg}) and a rolling 24-hour standard deviation of price σ_{actual} is fed to the passive controller in the form of an external player file in GridLAB-D.

The hourly profile of real-time market price from 1st July 2012 to 7th July 2012 used in this study is shown in figure 3.

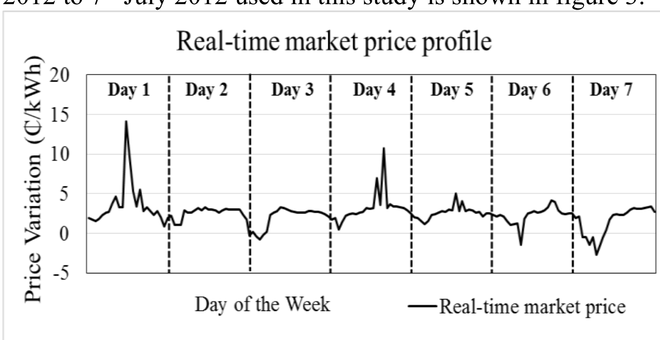

Figure 3. Real-time electricity market price profile

During the period of simulation, the real-time market price deviates between 14.1 c/kWh and -2.7 c/kWh.

<u>*Mode of Control:*</u> The above mentioned passive controller is configured in the *RAMP* mode of control (see Figure 4).

It uses a piece-wise linear function to adjust the set point as a function of a rolling average of the real-time electricity price and its standard deviation. From Figure 4, it can be seen that the rate of change of set-point temperature (i.e., slope) can have different values, indicating different end use preferences for heating and cooling response. Additionally, T_{min} (minimum acceptable temperature) and T_{max} (maximum acceptable temperature) need not be symmetric. ΔT is the difference between the desired temperature ($T_{desired}$) and new set point temperature (T_{set}), taking the current market price into account. T_{min} and T_{max} define the temperature set point limits; the slope of the ramp function determines the temperature sensitivity of the controller with respect to the varying market price. This can be configured as per the user comfort. σ_{actual} is the standard deviation of the real-time market price from the mean price (P_{avg}), which has the value between σ_{min} and σ_{max}.

When the current market-clearing price (P) is higher than P_{avg}, the new cooling set point temperature is raised. Conversely, when the current market price is lower than P_{avg}, the cooling set-point is adjusted lower. The constraints on the operation are subjected to the following inequality.

$$T_{min} - T_{desired} \leq \Delta T \leq T_{max} - T_{desired} \tag{1}$$

The configuration parameters of the designed passive controller object in GridLAB-D are shown in Table II.

TABLE II. PASSIVE CONTROLLER CONFIGURATION

Details	Parameter	Type
1	Control variable	Cooling set point
2	Control Mode	Ramp
3	Expectation property	P_{avg}
4	Observation property	σ_{actual}
5	Ramp high	1.5 c/ºF
6	Ramp low	3.5 c/ºF
7	Range high	10.0 ºF
8	Range low	0.0 ºF
9	T_{min}	75 ºF
10	T_{max}	83 ºF

Ramp high: Rate of increase of the cooling set point with market price;
Ramp low: Rate of decrease of the cooling set point with market price.
Range high and range low are the upper and lower limits to which the participant allows the temperature swing.

The control period of this controller is one minute; which means it updates the thermostat(s) with new information from the market on a one-minute interval. Figure 5 depicts a flow chart describing the working of passive controller in response to the market price signal.

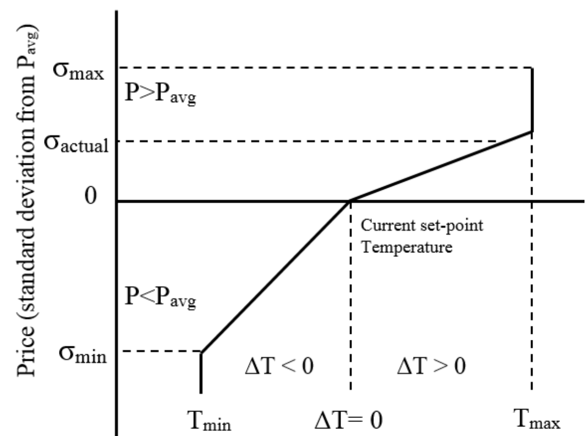

Figure 4. Ramp mode of control for a building's cooling system

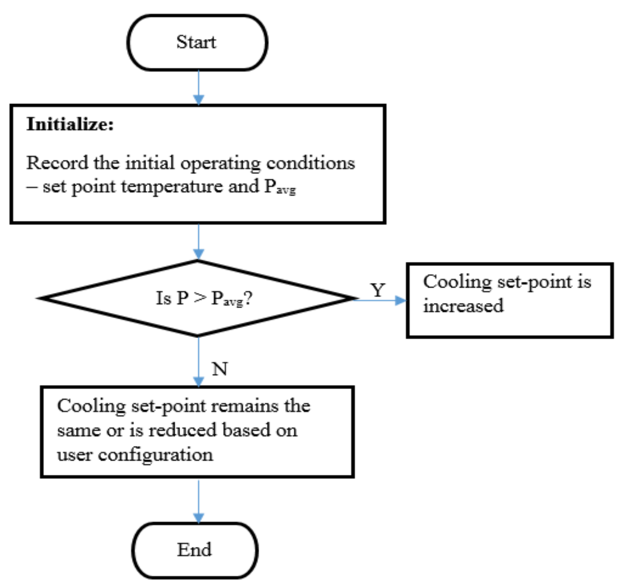

Figure 5. Flow chart showing the scheme of operation of a passive controller

Since the ‘range low’ is configured at zero in our passive controller model, when $P < P_{avg}$ the cooling set point will not be altered. In this paper, this method of transactive control is used for HVAC control, but it can also be extended to the lighting appliances and non-critical plug loads.

IV. Results and Discussions

The model of an office building described in Section II is simulated along with the developed passive controller (described in Section III) in GridLAB-D. The ramp mode of control has been adopted for the passive transactive controller. In this mode of control, the base set point of the HVAC system varies according to the mean market price, after the market is cleared. In this study, the market is cleared at one-minute intervals.

Figure 6 shows the behavior of the HVAC system with and without the passive transactive controller. It can be clearly seen that in the case with no control, the air temperature is fluctuated between 74°F and 76 °F during weekdays from 6:00 A.M. to 10:00 P.M, and between 79°F and 81°F during weekends/holidays (except during transitions of schedules and at night when indoor temperature decreases as outdoor temperature decreases). Upon imposing the real time price signal, the HVAC system now adjusts its cooling set point and power consumption for a wider bracket of air temperature (between 75°F – 86.9°F). This results in a significant reduction in power consumption, especially during peak demand periods.

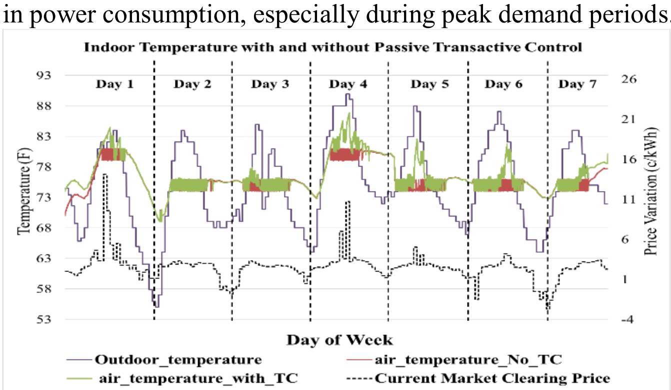

Figure 6. Profile of indoor air-temperature with and without control

Note: At the end of Day 1 and beginning of Day 2, the indoor temperature went down and reached the minimum of 69 °F. This is due to the drop in the outdoor temperature.

From Figure 6, the following points can be observed:

(i) Real time market price and indoor air temperature are in positive correlation, in the case with passive control.

(ii) Although the air temperature increases with the price signal, there is an upper limit which inhibits the violation of comfort to the customer.

(iii) After the control period, the AC turns on and there is a tendency to rebound. But the cooling set point temperature is clamped by the T_{min}, which is 75 °F in this case.

(iv) With passive control the cooling set-point is raised to 86.9 °F as against 80 °F (on Day 4).

From Figures 7 and 8, a decreasing trend in power consumption is observed, as the market price reaches a high. In particular, the power consumption of the HVAC system is reduced by an average of 0.668 kW on a typical weekday and 0.452 kW when averaged over a week.

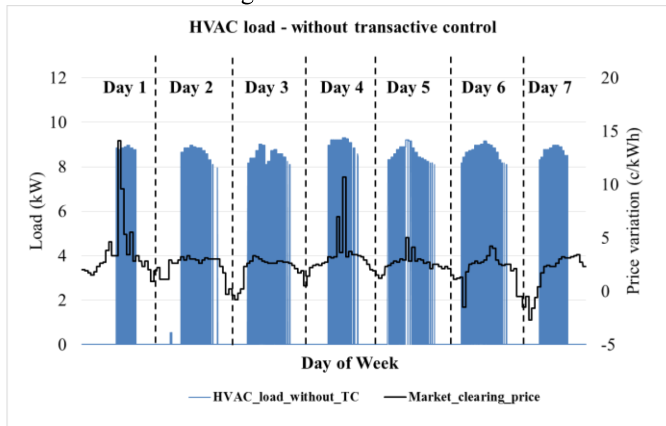

Figure 7. HVAC load profile without the transactive control

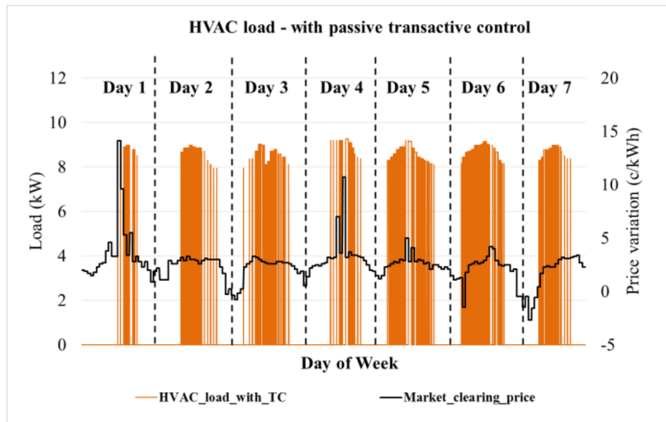

Figure 8. Operation of HVAC with the passive transactive control

The reduction in HVAC power consumption with respect to the variation in real-time electricity price can be clearly observed from one-day time sample shown in figure 9.

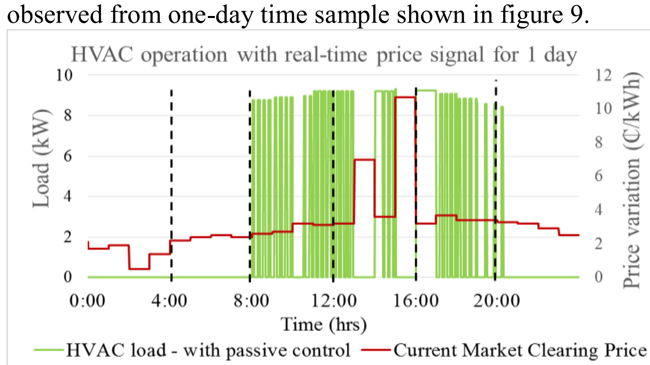

Figure 9. HVAC operating status with respect to real-time price for one day

When the electricity market price signal is relatively low, the HVAC system is active. As soon as the real time price reaches a peak, the HVAC system limits its consumption until a declining trend is observed in the price signal. In this way, by pricing the electricity high during the peak demand period, the occurrence of peak power consumption can be mitigated. It must be noted that although the peak load of the HVAC system remains the same, the occurrence of the peak load is now shifted to a low demand period.

V. CONCLUSION

A passive transactive control scheme makes the energy consumption profile of buildings price-responsive. In terms of electrical energy savings, simulation results indicate an average energy savings of 16.03 kWh over a typical weekday and 76 kWh over the simulated week, which can be translated to a savings of about 3952 kWh annually. The average cooling load is reduced and hence a significant reduction in aggregate energy consumption can be observed across a group of buildings. This control method can be further improved by modeling the office building in a double auction market, having two-way communication between building loads and the electricity market. Unlike a stubauction market, in a double auction market, market-clearing price is reached based on two-way negotiations between building loads and market. As a result, there is a dynamic equilibrium at all points of time.

This work can be further expanded to investigate the integration of an aggregate group of buildings into electric grid and study the overall behavior of the electric grid with a group of smart buildings in a transactive control network.

VI. REFERENCES

[1] 2012 CBECS Preliminary Results [Online]. Available: http://www.eia.gov/consumption/commercial/reports/2012/preliminary/ Retrieved: June 2016.

[2] Z. Zhou, F. Zhao, J. Wang, "Agent-based electricity market simulation with demand response from commercial buildings", in *Proc 2012 PES GM – Power and Energy Society, General Meeting*, San Diego CA, July 22-26, 2012, pp. 1-6.

[3] U.S. Energy information administration, "Price elasticities for energy use in buildings of the united states", Oct 2014 [Online]. Available: http://www.eia.gov/analysis/studies/buildings/energyuse/pdf/price_elasticities.pdf. Retrieved: June 2016.

[4] A. Sreedevi, A. Kaul, K. Radhika, "Modelling and simulation of hvac system for energy analysis and management of commercial buildings", in *Proc 2014 I4C – International conference on Circuits, Communication, Control and Computing*, Bangalore, India, Nov 21-22, 2014, pp. 186-191.

[5] H. Huang, L. Chen and E. Hu, "A hybrid model predictive control scheme for energy and cost savings in commercial buildings: simulation and experiment", in *Proc 2015 ACC – American Control Conference,* Chicago IL, July 1-3, 2015, pp. 256-261.

[6] M. Maasoumy, B. M. Sanandaji, A. Sangiovanni-Vincentelli and K. Poolla, "Model predictive control of regulation services from commercial buildings to the smart grid", in *Proc 2014 ACC – American Control Conference,* Portland OR, June 4-6, 2014, pp. 2226-2233.

[7] J. Zhao, K. P. Lam, B. E. Ydstie, "EnergyPlus model based predictive control (EPMPC) by using MATLAB/SIMULINK and MLE+", in *Proc 2013 BS – Conference of International Building Performance Simulation Association*, August 2013. [Online]. Available: http://www.ibpsa.org/proceedings/BS2013/p_1168.pdf. Retrieved: June 2016.

[8] M. Miletic, A. Schirrer, M. Kozek, "Load management in smart grids with utilization of load-shifting potential in building climate control", in *Proc. IEEE Smart Electric Distribution System and Technologies (EDST),* Vienna Sep 8-11, 2015, pp. 468-474.

[9] EnergyPlus Simulation software [Online]. Available: https://energyplus.net/ Retrieved: June 2016.

[10] GridLAB-D Simulation software [Online]. Available: http://www.gridlabd.org/ Retrieved: June 2016.

[11] S. Katipamula, "Smart buildings can help smart grid: Transactive controls", *in Proc 2012 ISGT – Innovative Smart Grid Technologies,* Washington DC, Jan 16-20, 2012, pp. 1.

[12] R.B. Melton, D.J. Hammerstrom, "Transactive control: A technique for widespread coordination of responsive smart grid assets", *in Proc 2012 ISGT – Innovative Smart Grid Technologies,* Washington DC, Jan 16-20, 2012, pp. 1.

[13] R Pratt, "Transactive control with real-time prices and a double-auction feeder market", *in Proc 2012 ISGT – Innovative Smart Grid Technologies,* Washington DC, Jan 16-20, 2012, pp. 1.

[14] P. Huang, J. Kalagnanam, R. Natarajan, M. Sharma, R. Ambrosio, D. Hammerstrom, et.al, "Analytics and transactive control design for the pacific northwest smart grid demonstration project", *in Proc 2010 SmartGridComm – First IEEE international Conference on Smart Grid Communications, Gaithersburg MD, Oct 4-6, 2010*, pp. 449-454.

[15] S. Widergren,, J. Fuller, C. Marinovici, and A. Somani,, "Residential transactive control demonstration", *in Proc 2014 ISGT – Innovative Smart Grid Technologies,* Washington DC, Feb 19-22, 2014, pp. 1-5.

[16] J.C. Fuller,, K.P. Schneider,, D. Chassin,, "Analysis of residential demand response and double-auction markets", *in Proc 2011 PES GM – Power and Energy Society, General Meeting,* San Diego CA, July 24-29, 2011, pp. 1-7.

[17] J.X. Serrano, G. Escriva, "Simulation Model for Energy Integration of Distributed Resources in Buildings", *IEEE Transactions Latin America*, vol. 13, issue 1, Jan 2015, pp 166-171.

[18] M. Hong, X. Yu, N-P Yu, K.A. Loparo, "An Energy Scheduling Algorithm Supporting Power Quality Management in Commercial Building Microgrids", *IEEE Transactions on Smart Grid*, vol.7, issue 2, Dec 2014, pp 1044 -1056.

[19] DOE Reference Commercial Building [Online]. Available: http://energy.gov/eere/buildings/commercial-reference-buildings Retrieved: June 2016.

[20] K. Karnatz, R. Knight, and R. Szcodronski, "Taking the first steps towards intelligent buildings", September 2014 [Online]. Available: http://www.facilitiesnet.com/buildingautomation/article/What-Does-8220Intelligent-Building8221-Mean-Today-Facilities-Management-Building-Automation-Feature--15283. Retrieved: June 2016.

[21] K.P. Schneider, J.C. Fuller, D. Chassin, "Analysis of distribution level residential demand response", *in Proc 2011 PSCE – Power Systems Conference and Exposition,* Phoenix AZ, March 20-23, 2011, pp 1-6.