Analysis of Active and Transactive Demand Response Strategies for Smart Residential Buildings

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Abstract—Dynamic pricing and demand response programs are playing key roles in the modern smart grid environment to manage peak loads. With the current advent of communication systems, more user-friendly price driven schemes started emerging at the residential level. In the United States, heating and air-conditioning loads are major contributors to total electricity consumption in residential buildings. In some areas, cooling loads during summer months are the highest of the whole year due to high outdoor air temperature and the wholesale electricity prices also increase as a consequence. In this paper, two demand response strategies i.e., active control and transactive control for a residential building are analyzed. Heating, Ventilation and Air Conditioning (HVAC) is considered as a responsive load and its set-point change to real-time prices and total power consumption in each method are analyzed. Modelling of single-family residential building and simulation are done in GridLAB-D.

Index Terms—Demand response, active control, transactive control, GridLAB-D.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Pi$</td>
<td>Current price signal ($/\text{kWh}$)</td>
</tr>
<tr>
<td>$\Pi_{\text{average}}$</td>
<td>24-hour average price ($/\text{kWh}$)</td>
</tr>
<tr>
<td>$\Pi_{\text{bid}}$</td>
<td>Controller’s price bid ($/\text{kWh}$)</td>
</tr>
<tr>
<td>$\Pi_{\text{cleared}}$</td>
<td>Cleared market price ($/\text{kWh}$)</td>
</tr>
<tr>
<td>$\sigma_{\text{actual}}$</td>
<td>24-hour standard deviation</td>
</tr>
<tr>
<td>$k_{\text{high}}$</td>
<td>Standard deviation from mean price at $T_{\text{max}}$</td>
</tr>
<tr>
<td>$k_{\text{low}}$</td>
<td>Standard deviation from mean price at $T_{\text{min}}$</td>
</tr>
<tr>
<td>$T_{\text{adjusted}}$</td>
<td>The actual temperature set point ($^\circ\text{F}$)</td>
</tr>
<tr>
<td>$T_{\text{current}}$</td>
<td>The current inside air temperature ($^\circ\text{F}$)</td>
</tr>
<tr>
<td>$T_{\text{desired}}$</td>
<td>The desired temperature set point ($^\circ\text{F}$)</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>Maximum acceptable temperature ($^\circ\text{F}$)</td>
</tr>
<tr>
<td>$T_{\text{min}}$</td>
<td>Minimum acceptable temperature ($^\circ\text{F}$)</td>
</tr>
</tbody>
</table>

1. INTRODUCTION

Global electricity demand increased by 3.1% in 2017 [1]. Supply-demand balance of electricity can be met by increasing the generation or optimizing the demand. Increase in the percentage of variable and intermittent renewable energy sources makes the control of the ”generation side” more challenging and hence controlling the ”demand side” is gaining more attention. Demand-side management (DSM) uses different strategies that motivate the consumers to shift their load in order to optimize their energy usage. Various DSM strategies have been explained in [2]. Authors in [3] have used differential evolution technique for DSM. DSM strategies for various end-use loads have been explained in [4]. Demand Response (DR) is a part of DSM. A detailed theory on definition and types of DR has been explained in [5]. DR strategies can be generally classified into two types: 1) Incentive based; 2) Price based. According to [6], Price based DR programs include

1) Time of use (TOU):  
   - TOU is static price schedule. Higher rates during peak consumption hours and lower rates during partial peak and off-peak hours

2) Critical Peak Pricing (CPP):  
   - Pre-specified higher price during a limited number of hours or days per year

3) Extreme Day pricing (EDP):  
   - Higher price for the whole 24 hours which is known only day-ahead

4) Real-time pricing (RTP):  
   - Market prices are forwarded to end-use customers.

DR is used for large industrial and commercial customers. Commercial building DR programs have been explained in [7] and [8]. Three control strategies that can be established between the utility and the customer [9].

1) Passive control:  
   - No real time transfer of price signal.

2) Active control:  
   - Real-time price signals are sent from utility to end-use appliances which then responds based on their comfort.

3) Transactive control:  
   - This control involves two-way communication in which end-use loads can bid for their demand and price is determined based on the bids from buyers and sellers.

In [10], HVAC operates only on indoor air temperature tolerance and not on retail price which is the passive control method of demand response. In [11], HVAC load changes when the retail price varies. The set-point temperature for cooling is changed when the 24-hour average price is sufficiently different from the current price. However, the price tolerance cannot be chosen. Authors in [12] proposed a dynamic demand response controller for the residential building which changes the thermostat set-point depending on the 15 minutes retail electricity price and set-point temperature preference to control HVAC loads. First field demonstration project of transactive
control "Olympic Peninsula Project" took place in the US with an objective of reducing congestion on the distribution network[13]. Authors in [14] used transactive control method for demand response of the commercial building. Network constrained transactive control in distribution side has been explained in [15]. Authors in [9] have applied active market control strategy to 1247 single family residence and analyze the peak power demand in various market clearing intervals. Detailed modelling and simulation of Double-Auction Markets have been done in [16]. The main contributions of this paper are, detailed modelling of the residential building is done by taking into consideration the thermal characteristics of construction materials because it significantly influences building energy consumption and the analysis of suitable DR strategy for residential buildings based on the nature of electricity market, consumer behaviour and from the utility perspective. The remainder of this paper is organized as follows: Section II presents the modelling of a single-family house in GridLAB-D. Section III explains the theory behind the active market and transactive market operations. Results are discussed in Section VI and finally Conclusions are made in Section V.

II. MODELLING OF A RESIDENTIAL BUILDING

A single-family residential building is modelled in GridLAB-D. Table I shows the details of a residential building model. The solar heat gain coefficient is taken as 0.64. Thermal resistance of materials and insulation of the residential building are considered to be high. The building is assumed to be smart with advanced communication systems and computing resources. For the purpose of simulation, residential building located in New York, USA has been considered. The Temperature in winter varies from \(-3^\circ{\text{C}}\) to \(4^\circ{\text{C}}\) and in summer varies from \(22^\circ{\text{C}}\) to \(30^\circ{\text{C}}\) approximately. Primary loads in the house are heating, cooling, lighting and plug loads. Hourly

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Quantity &amp; Units</th>
</tr>
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<tbody>
<tr>
<td>Floor Area</td>
<td>2000 sq.ft</td>
</tr>
<tr>
<td>No.of.Floors</td>
<td>1</td>
</tr>
<tr>
<td>Window to wall ratio</td>
<td>7%</td>
</tr>
<tr>
<td>Occupant</td>
<td>3 Residents</td>
</tr>
<tr>
<td>Lighting</td>
<td>2 kW</td>
</tr>
<tr>
<td>Plug loads</td>
<td>4 kW</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heat pump-Heating Electrical-Cooling</td>
</tr>
<tr>
<td>Weather and Location</td>
<td>Central New York, USA</td>
</tr>
</tbody>
</table>

In our study, lights and plug loads are considered as unresponsive loads and HVAC is considered to be a responsive load. Following sections discusses the market structure and controllers implemented in this paper.

1) Active market operations: In the active market, there are no bids from end-user side. As shown in Figure 2, Distribution Side Operator (DSO) sends a real-time price signal to the controllers of responsive loads. In addition to the current price signal, \(\Pi_{\text{average}}\) and \(\sigma_{\text{actual}}\) is communicated to the controllers. The active controller operates by responding to a combination of price signal and user set point. The controller can be connected to the end-use loads like water heater, refrigerator, freezer etc but the residential cooling system is considered in this paper. \(T_{\text{min}}\) and \(T_{\text{max}}\) define the user-defined temperature set-point limits. When \(\Pi\) is equal to \(\Pi_{\text{average}}\), the controller will set \(T_{\text{actual}} = T_{\text{desired}}\). \(\Delta T\) is the difference between the temperature set points.

\[
\Delta T = T_{\text{actual}} - T_{\text{desired}}
\]
If the 24-hour average price is higher than the real time price signal, then the controller will move the $T_{\text{actual}}$ lower than the $T_{\text{desired}}$ but it will be within minimum limit and if the 24-hour average price is lower than the real time price signal, the controller will move $T_{\text{actual}}$ higher than $T_{\text{desired}}$ but within the maximum limit. For a controller operating on HVAC cooling system, $\Delta T > 0$ indicates that $\Pi$ is higher than $\Pi_{\text{avg}}$. Similarly, $\Delta T < 0$ indicates that $\Pi$ is lower than $\Pi_{\text{avg}}$. In active market operations, the user can define their comfort set-point ranges and limits. But from the utility perspective, the active market does not play an active role in managing congestion. But in transactive control, it is two-way bidding from both suppliers and consumers (Double auction bidding) by taking into account distribution feeder level congestion.

### A. Transactive market operations

In transactive system, market clears based on the bids from sellers and buyers of energy. It is a typical two-sided bidding market. As shown in Figure 3, transactive controllers transform the customer’s need for heating and cooling into a value, express it as a price bid and once the market is cleared, translate the cleared price signal into set-point change. For end-use loads to participate in the transactive market, it must be able to

1. Decide the cost it is ready to pay for electricity
2. Bid its desired demand
3. Change the demand based on $\Pi_{\text{cleared}}$

The consumers have to set desired temperature and temperature limits ($T_{\text{max}}$ and $T_{\text{min}}$). Standard deviations $k_{\text{high}}$ and $k_{\text{low}}$ from the mean price are automatically assigned from the $T_{\text{max}}$ and $T_{\text{min}}$ values. $T_{\text{max}}$ and $T_{\text{min}}$ need not be identical. If the standard deviations ($k$) from the mean are infinitely large, then it will function like normal thermostat unaffected by market behaviour. In the cooling mode, a high value of $k_{\text{high}}$ will lead to relatively high bids when the current temperature exceeds the desired temperature and high bid prices will try to make corresponding bid win. Like in an active market, here also $\Pi_{\text{average}}$ and $\sigma_{\text{actual}}$ are sent along with market cleared price. Market clearing interval may be 5 minutes, 15 minutes or 1 hour. For each market clearing interval, controller’s bid price is determined by current internal air temperature and desired temperature. The bid value is determined by,

$$\Pi_{\text{bid}} = \Pi_{\text{average}} + \frac{(T_{\text{current}} - T_{\text{desired}}) * k * \sigma_{\text{actual}}}{|T_{\text{limit}} - T_{\text{desired}}|} \quad (1)$$

Then the controller reset the current set point to new adjusted set point. $T_{\text{adjusted}}$ can be higher or lower than the $T_{\text{desired}}$ based on the market clearing price. In cooling mode operation, lowering the adjusted set point below than the desired set point will increase the energy consumption as the controller takes advantage of low price. Figure 4 shows the thermostatic response for transactive control in cooling mode.

### IV. RESULTS AND DISCUSSION

Test cases are simulated using Typical Meteorological Year (TMY) weather data for Central New York from August 1st, 2017 to August 7th, 2017. Desired HVAC set-points are given in Table II. Total load of the building without any response to real-time price signal is shown in Figure 5 and the peak demand of the week is 9.2 kW. Figure 6 shows how the passive controller is responding to the user desired set points. Total load of the building including responsive and unresponsive loads is also shown for one particular day of interest. By examining figure 6, it can be observed that residential building has a peak load of approximately 8.5 kW and the peak occurs at hour 9 and between 18 and 20. A sudden spike in load at hour 9 might be because of HVAC consumption which
depends on outside weather condition and many other external parameters. Evening peak is because of increased lighting and plug loads which result from the increased occupants during that period. For all the hours, inside air temperature is following the $T_{\text{desired}}$ with the variation of about of ±1 °F. The real-time prices considered in this paper for active control is assumed for the analysis purpose. Market clearing price varies at every hour. From the utility perspective, all the consumers will respond during low price period and there will be new peak load during that period. This rebound effect can be eliminated by reducing the time period to 15 minutes or 5 minutes. The average price is considered to be 1 $/kWh. Figure 7 shows 24-hour active control based demand response. From Figure 7 it is clear that inside air temperature is in correlation with the real-time price for most of the time. At hour 11, the real-time price is less than the average price and the active controllers shift desired set point to the lower temperature. During 17-19 hours increased real-time price results in higher set point temperature. At hour 11, due to less real-time price, controller sets the actual set point as 73 °F whereas desired controller. From the current temperature, desired temperature and temperature limits, the controller will calculate the bid price according to equation 1 and adjust the inside temperature based on cleared market price according to 2. It is observed that during the transactive mode of operation, the residential building has a peak demand of 10.5 kW. The same residential building experiences different load pattern and peak demand for different control strategy.
This paper has analyzed the passive control and the real-time price based active and transactive control DR strategies on the operation of the single-family residential building. From the analysis, it is clear that the load pattern and peak demand of residential building are different for each control strategy and price signal plays an important role in distribution system operation. Compared to passive control, the active and transactive method requires robust communication to transfer information. Consumers willingness in participating in the market plays a major role in successful implementation of transactive control. From the utility perspective, price-based demand response strategies may result in new peak period which must be taken care of in order to avoid congestion. Future work will focus on the implementation of the transactive control strategy for a distribution network with congestion management.

V. CONCLUSION

REFERENCES


