Demonstration of a home energy management system with smart thermostat control

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Demonstration of a Home Energy Management System with Smart Thermostat Control

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***Abstract*— A home energy management (HEM) system has the potential to enable demand response (DR) implementation for residential customers. This paper presents a detailed hardware architecture that allows control of an air conditioning (AC) unit by varying the thermostat set point. This can be accomplished by controlling a Wi-Fi enabled thermostat via an HEM system. The hardware demonstration of the proposed architecture is also discussed. This work showcases the applicability of the HEM system in managing an AC unit through a smart thermostat control. This approach can serve as an alternative to allowing an electric utility to perform remote disconnect to AC units. Controlling an AC unit by adjusting the thermostat set point can ensure lower average power consumption of the AC unit during a demand response period, along with better temperature control and improved equipment lifetime.**

***Index Terms*— Demand response (DR), home energy management (HEM) system, and smart thermostat.**

I. INTRODUCTION

IMPLEMENTATION of smart grid projects worldwide has resulted in increasing customer involvement and incorporation of demand response at customer premises. Demand response admittedly has the potential to maintain supply-demand balance even during unexpected supply-limit conditions by allowing selective load curtailments during peak demand periods [1]. This also reduces stress on transmission lines and overall improves system stability. In recent years, many demand response programs for different customer classes have been developed and implemented [2-11]. In the U.S., the commercial sector is already being served by a number of demand response (DR) programs by third-party providers and hence the technology is quite mature. On the other hand, residential demand response programs are sparse in comparison, but provide ample opportunity for load reduction, if implemented wide-scale. This creates the need for effective DR programs for residential customers, which take into account customer preferences while ensuring that load control requirements are met.

Demand response can be implemented on residential customers using automated DR approaches, which allow end-use load curtailment without homeowner intervention, based on either incentive-based or time-based DR programs [12]. Incentive-based programs include interruptible load, direct load control, etc., which shed loads based on some forms of load control signals sent by a utility. On the other hand, time-based programs include critical peak pricing, dynamic pricing or time-of-use programs and rely on some forms of time-varying tariff schemes.

According to FERC [12], more than 80% of the U.S. peak load reduction potential by residential customers comes from incentive-based programs. In our previous work [10], an automated DR program for residential customers was developed in the form of a Home Energy Management (HEM) system. The previously developed HEM system is an incentive-based automated algorithm that decides load curtailment based on a load-control signal from a service provider, according to a pre-set customer load priority. The hardware demonstration of the developed algorithm was presented in [11], which showed the applicability of a HEM system in residential load curtailment. This paper develops on the concept of these papers and adds a significant contribution by incorporating a smart thermostat in the existing HEM system. The smart thermostat is to replace the previous ON-OFF control for an AC unit with temperature set-point control. The proposed approach will improve the overall longevity of the equipment as opposed to directly cutting the AC power supply, which may result in potential damage and reduce equipment lifetime (i.e., in the case of cutting the AC power supply several times during a short duration).

This paper emphasizes on the hardware demonstration of the HEM system in a laboratory environment with the smart thermostat control, focusing on the overall system architecture, system setup, and communication between the HEM and the smart thermostat for AC control. A brief discussion on the HEM system and choices of smart thermostat are also provided in the paper.

II. AN OVERVIEW OF THE HEM SYSTEM

The authors have previously developed a set of HEM algorithms as presented in [10], and showcased the hardware demonstration of an equivalent system in a lab environment in [11]. A brief review of the previously developed HEM system is provided in this section for the reader to appreciate the present work. For an in-depth discussion, please refer to the above mentioned papers.

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A. *The HEM system*

In our previous work, the overall HEM system architecture comprises a gateway (i.e., smart meter), an HEM unit and several load controllers for appliance control. The proposed HEM system is programmed to automatically manage power-intensive residential loads to keep the total household load below a specified demand limit level. This system does not control loads like: refrigerator, coffee makers, lighting and other plug loads, because they do not contribute significantly to the overall household power consumption, but are of critical importance to the customer. These loads will be referred to as critical loads. They are only monitored by the HEM system. Only power-intensive loads like electric water heater (WH), AC unit, electric clothes dryer (CD) and electric vehicle (EV) are considered for control by the HEM system.

The HEM unit can be a computer with a set of demand response (DR) programs running, which can communicate with other units in the system. The HEM unit directly monitors power consumptions of selected loads and controls these loads with the help of load controllers. In our concept, a demand limit (kW) is imposed by a utility at the time during a DR event. A DR event is defined as a period during which load curtailment will be needed to ensure normal operation of an electric power system. Signals form a utility will be sent to the HEM unit through a gateway (i.e., a smart meter). This signal may consist of a DR limit amount (in kW) and its associated duration of a DR event (in minutes or hours). The HEM unit also receives input from homeowners about their load priority and comfort settings for selected appliances. Based on these settings and the demand limit, the HEM algorithm constantly decides which power-intensive loads to shed during the DR event to meet the demand limit. This intelligence of the algorithm ensures that during a DR event, even within a specified limit, critical loads are always served; and power-intensive loads are served in the order of their priorities set by the customer. The decision of the HEM unit is then communicated to selected load controllers, which in turn, directly switch associated appliance(s) ON/OFF. This communication between the HEM unit and load controllers can be realized by one or a combination of communication technologies, like Wi-Fi, Bluetooth, ZigBee, Z-Wave or Power line communication (PLC).

B. *The HEM algorithm*

As mentioned earlier, household appliances to be controlled by our HEM system are: water heater (WH), AC unit, clothes dryer (CV), and electric vehicles (EV). Each can have a comfort setting from the customer, for instance, the minimum temperature for water in WH can be set to 110ºF, the comfortable set-point temperature for AC unit can be 76ºF (±2ºF), and job completion time can be specified for CD and EV charging. A homeowner can also set their priority, i.e., customers may choose WH to be more necessary than the AC unit and may have similar priority order for the other appliances. The HEM algorithm starts by gathering current state information about all appliances, demand limit and duration and customer priority and preferences. It then constantly checks for demand limit violations and comfort setting violations. Demand limit violations are prevented by cutting OFF power to lower priority appliances. Comfort setting violations are prevented by turning ON appliances (in order of priority) keeping total consumption under a specified demand limit. This way, the algorithm seeks to meet both the DR limit requirement and the homeowner's comfort preference setting.

III. INCORPORATION OF A WI-FI ENABLED THERMOSTAT IN THE HEM SYSTEM

An AC unit is one of the most power-intensive loads in a house. It is also a very crucial load for residential customers, because room temperature has to be maintained within an acceptable range of customer comfort. For this reason, room temperature has to be continuously monitored by the HEM system. Direct ON-OFF control of the AC unit by the HEM system is effective for maintaining demand limit, but might not be effective in maintaining room temperature. Also, direct ON-OFF control may impose risk of permanent equipment damage or may reduce lifetime of the unit. Inclusion of a smart thermostat in the HEM system to control AC gives the flexibility of temperature set-point control in the HEM algorithm without the need of additional hardware. Also, its constant monitoring of room temperature dismisses the necessity of additional temperature sensors for the HEM system. The overall HEM architecture with the smart thermostat is shown in Fig. 1.

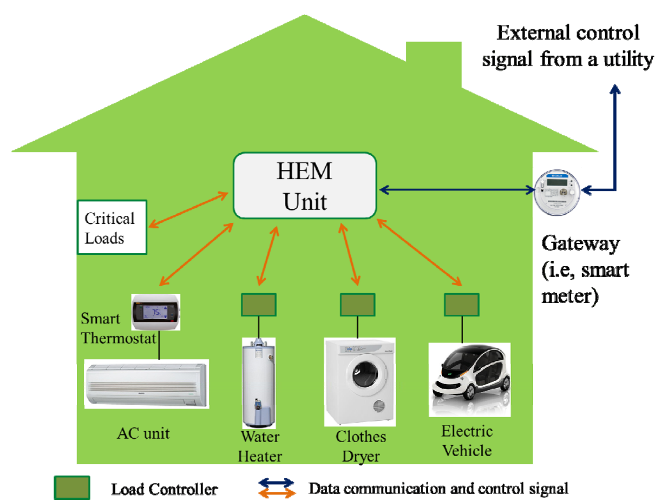


Fig. 1. Overall HEM system architecture with smart thermostat.

The HEM unit can communicate with the smart thermostat to a) constantly monitor the current temperature, and b) change the temperature set-point based on algorithm decision. The smart thermostat then controls the AC directly based on room temperature and set-point, and thus implements the HEM decision, and no additional load controller is necessary for AC control. Thus the HEM system is equipped with the capability of temperature set-point control, which can be very useful in implementing the comfort temperature zone of the customer in the algorithm. Also, the thermostat can control cooling and fan of the AC independently, thereby can maintain temperature more efficiently. It also helps to improve the overall lifetime of the equipment. In short, the inclusion of the smart thermostat in the system is definitely a very useful addition to the capability and longevity of the system.

IV. Selection of Smart Thermostat

A good number of smart thermostat products are commercially available. They vary in terms of features, size, communication technology used and price. For this work, it is imperative that the smart thermostat can provide two-way communication with the HEM unit. The communication technology used in the smart thermostat can be ZigBee, Z-Wave or Wi-Fi. Table I lists some of the smart thermostats currently available on the market that are capable of providing two-way communications.

TABLE I. Selected Commercially Available Smart Thermostats

Thermostat Name	Manufacturer	Communication Technology
EB-STAT-02 [13]	Ecobee	ZigBee
CCZ-T1-W [14]	Control4	ZigBee
TH8320ZW1000 [15]	Honeywell	Z-Wave
RCS TZ43 [16]	RCS	Z-Wave
Filtrete 3M-50 [17]	Radio Thermostat	Wi-Fi

The Filtrete 3M-50 smart thermostat [17] is selected for implementation in this work. The reason behind choosing this thermostat was: a) it can be communicated by Wi-Fi using the USNAP protocol, which provides easy but robust communication through internet (or LAN), b) the features of the thermostat are sufficient for this work, and c) proper documentation with the thermostat facilitates ease of installation and usage.

V. Hardware Demonstration of HEM System with Smart Thermostat

A. The Filtrete 3M-50 thermostat & its Connection with AC

The Filtrete 3M-50 thermostat has the capability to control a Heating, Ventilation and Air-Conditioning (HVAC) system. Appropriate external terminals can be connected with corresponding HVAC system terminals for the thermostat to control the HVAC system. Fig. 2 shows the thermostat's connections for a 4-wire heat/cool system.

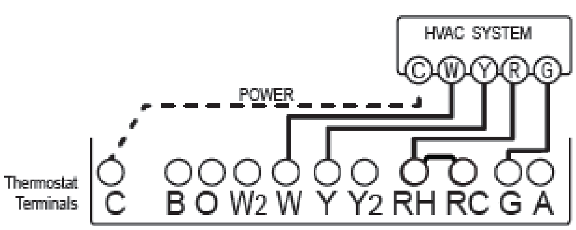


Fig. 2. Filtrete 3M-50 connection with a 4-wire HVAC system [17].

The 'C' terminal is the common terminal for power. The 'RH' and 'RC' terminals are shorted to make the other power terminal 'R'. 'Y', 'W' and 'G' are the terminals to provide signals for controlling the cooling, heating and fan respectively. In our laboratory setup, we have used a portable AC unit, and so we only needed 'C' and 'Y' terminals for providing signal for cooling.

B. Control Circuit for AC

As mentioned earlier, in the laboratory setup we used a portable AC unit to be controlled by the thermostat. As the control circuit of the AC was difficult to access, we built an external control circuit to control the AC, as shown in Fig. 3. Note that the control interface is needed for controlling the portable AC in our laboratory experiment. When the system is implemented in a real-world environment, a thermostat can be used to switch the HVAC systems ON/OFF directly.

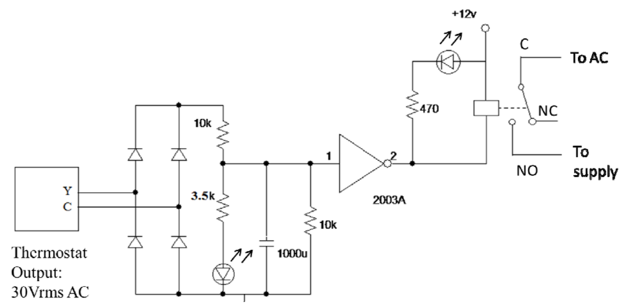


Fig. 3. Control circuit for portable AC unit.

The smart thermostat provides an AC signal of 24V rms value between 'Y' and 'C' terminals when it requires the cooling to turn ON, otherwise it provides zero voltage. The relay circuit we used is controlled by a DC voltage. Hence a full-wave rectifier circuit with capacitor was used to convert the AC signal to a DC signal. A voltage divider was used to adjust the DC voltage. Finally the obtained DC voltage was around 3.2V which was sufficient to trigger the inverted logic of ULN2003A, and it drew current from the DC supply through the relay, which connected the power supply to AC. When the thermostat sent a zero signal, relay was OFF, and hence AC was disconnected from the power supply. In the laboratory, we used a +12V DC supply to bias the relay circuit. We used the commercially available relay circuit board from DIY Electronics [18]. The LEDs in the circuit are only for display when the AC is ON.

C. Communication between the HEM and the Smart Thermostat

The HEM program can communicate with the thermostat using the Radio Thermostat Application Programming Interface (API) [19], which is a HTTP API. In this case, the thermostat acts as a server which takes requests from clients to query the thermostat state or control the thermostat operation. Clients can send HTTP GET requests to the thermostat to acquire current state of operation and temperature, and can send HTTP POST requests to the thermostat to change the set-point temperature or thermostat operation. Codes were included in the HEM program to send HTTP GET requests to the thermostat every 30 seconds (this sampling interval is adjustable) to monitor the room temperature. Based on decisions from the HEM algorithm, the HEM program sends

HTTP POST requests to change current set-point of the thermostat. The format of these requests was obtained from [19]. The round-trip communication time from sending a GET request and getting feedback from the thermostat was measured and it averaged around 0.5 seconds. This time can largely vary due to the speed of the Internet/Wi-Fi connection, distance between the HEM and the thermostat, and processing time of the smart thermostat to change its temperature set point and control AC status according to the HTTP request.

D. *HEM algorithm*

The HEM algorithm as discussed in Section II was modified to incorporate the use of temperature set-point control that has been enabled by the inclusion of smart thermostat in the system. In the changed algorithm, the temperature set-point for the AC unit control was set to 76ºF (±2ºF) by default (This value can be adjusted by the customer). If the demand limit of the DR event and the priority of the AC with respect to other appliances forces the HEM algorithm to decide to cut-off AC unit to provide power for a higher priority load, instead of directly turning the AC OFF, the HEM unit changes the set-point temperature of the thermostat to a higher temperature, i.e., 80ºF (±2ºF) (this value can also be adjusted by the customer). This causes the thermostat to turn OFF the AC unit. Thus the AC unit is shed to provide power to higher priority loads. However, if the temperature rises above the new acceptable range (i.e., 82 ºF in this case), the AC unit is served by shedding other appliances of lower priority if necessary to meet the demand limit requested.

When the AC unit is of the highest priority, the temperature set point is sent back to the default set point (i.e., 76 ºF). This way, the room temperature can be capped by a highest acceptable temperature (i.e., 82 ºF in this case) even when the AC unit is not the highest priority load in the household. In all cases, the AC unit is turned OFF by the thermostat when the room temperature goes below the acceptable range. Hence, the HEM algorithm only controls the temperature set point of the thermostat, and thermostat directly controls the AC unit to implement the HEM decision.

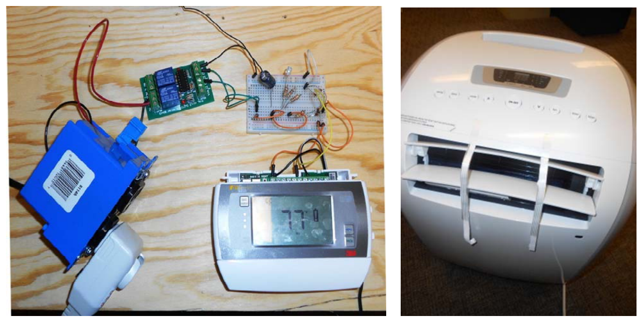
Algorithms for other appliances in the system (WH, CD and EV) remain the same as discussed in [11]. That is, the WH was turned ON if the water temperature fell below a specified temperature (i.e., 110 ºF) and turned OFF if it went above another specified temperature (120ºF). The CD has specified minimum ON-time and OFF-time for operation. Also, the job has to be completed within a specified time frame (i.e., by 12 am). The EV also has a specified completion time, by which the job has to be completed.

VI. DEMONSTRATION CASE STUDIES

This section presents the hardware demonstration case studies of the HEM system with smart thermostat to showcase the applicability of the system to address demand limit and customer preference.

A. *HEM System Setup*

Fig. 4 shows the smart thermostat setup in our laboratory environment. We used a portable AC unit to be controlled by the thermostat. A USNAP module was used with the thermostat for Wi-Fi connectivity. The thermostat was configured to be connected to the wireless local area network of the lab environment. In an actual household implementation, a router can be used instead to provide Wi-Fi connectivity to the thermostat. The HEM unit consisted of a laptop with internet connectivity that runs the HEM program. The HEM unit could communicate with the thermostat through the Internet. A local area network implementation is also possible if the Internet is unavailable for a certain household.



(a) (b)

Fig. 4. The HEM system setup in our laboratory: (a) the smart thermostat with its control circuit, (b) the portable AC unit controlled by the thermostat.

B. *Assumptions*

1) *House & Load*

The case studies are based on the parameters of a hypothetical average single family house with a size of 2500 sq. ft. [20]. The parameters are given in [11]. Only four power-intensive loads are controlled by the HEM system: a water heater, an AC unit, a clothes dryer and an electric vehicle. Critical loads are not controlled and their power consumptions are taken from the RELOAD database [21]. In the laboratory environment, due to unavailability of the actual loads of WH, CD and EV, representative loads were used. WH and EV were replaced by baseboard heaters and CD was represented by a hair dryer, due to similar load characteristics. The power consumption of these representative loads used in the laboratory are multiplied by corresponding scale factors to match the power consumption of actual loads. This scale factors are given in [11].

2) *Load priority*

The customer priorities for loads are assumed to be as follows: WH has a higher priority than AC, AC has a higher priority than CD and CD has a higher priority than EV.

3) *Comfort level setting*

The comfort settings are assumed to be as follows: hot water temperature has to be maintained between 110^{o}F-120^{o}F. Room temperature has to be maintained within ±2^{o}F of the set-point temperature, which initially by default is 76 ºF (can be changed to 80 ºF by the HEM algorithm as discussed in Section V). Both the minimum ON time limit and OFF time limit for the heating coils of the clothes dryer are set to be 15 minutes, and CD must finish its job by midnight. For EV, minimum 15 minutes EV charging time is specified before it can be shed, and it has to finish its job by 8am in the morning.

4) Variation in temperature

The laboratory environment for this experiment was a controlled-temperature environment, i.e., the temperature of the room was centrally controlled to be fixed at a certain set-point temperature (i.e., 74^{o}F). This limitation was overcome by using a space heater with constant heating in the room. The distance of the heater from the thermostat and the speed of the fan of the heater were adjusted to represent temperature rising profile similar to the real profile for the hypothetical household on a hot summer day.

C. Actual AC Measurement Data during a no-DR event

The AC unit was controlled by the HEM system with the smart thermostat for 3 hours from 5pm to 8pm without any DR event to see the actual power consumption of the AC and the room temperature profile. Fig. 5 shows these results.

As we can see from the figure, the portable AC unit consumed power in two steps when it was ON. This is because, when the AC was turned ON by the thermostat, first the fan of the AC unit was ON, which consumes low power, and then after some minutes the cooling compressor was ON, increasing the power consumption. The maximum power consumption of the AC was around 585 W. We used the scale factor to scale-up this value to match the actual power consumption of the AC unit for the hypothetical household. Also, we can see in Fig. 5 that the temperature increased in steps. This is due to the limitation of the thermostat, which could monitor and provide temperature data in 0.5 ºF steps.

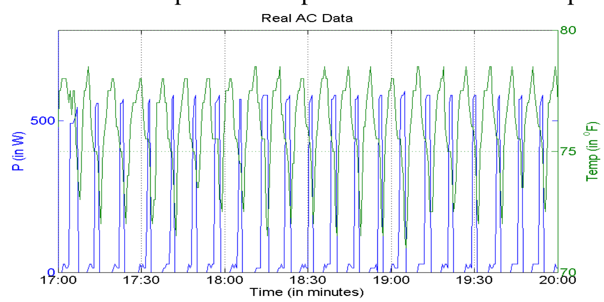
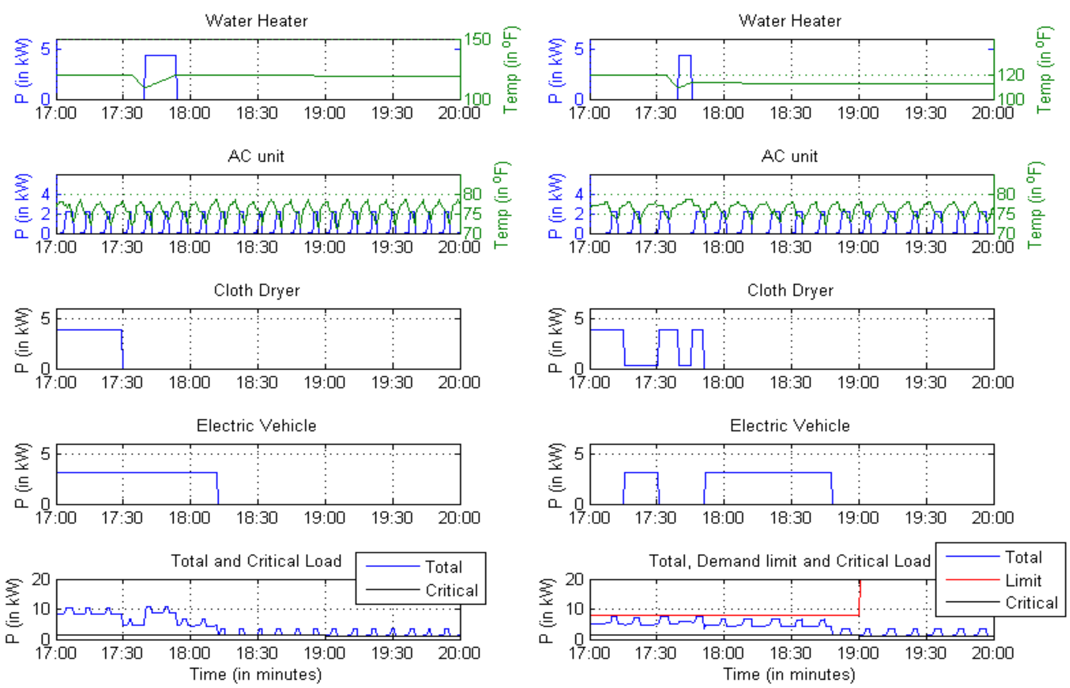


Fig. 5. Actual AC unit measurement data.

D. Case scenarios

To see the effect of demand response in household load control by the HEM system, the DR event was considered to be scheduled for 2 hours from 5pm to 7pm. A demand limit of 8kW was considered within the DR event period. This is the limit that the total household consumption should not exceed. We run the HEM program in real time for 3 hours from 5 pm to 8pm for two different cases. Case 1 considered no DR event. Case 2 was with the DR event as mentioned earlier. Fig. 6 shows the comparison between temperature profiles and power consumption of different appliances for the two case scenarios.

Case 1: No DR event: Fig 6(a) shows the power consumptions of different appliances along with temperature profiles from 5pm to 8pm without any DR event. As there is no demand limit, the HEM system does not have to shed any



(a) (b)

Fig. 6. Demand response demonstration results for a hypothetical 2,500 sqft home with scaled-up power consumption: (a) without a DR event; (b) with a DR event between 5pm and 7pm.

load. Thus all appliances are turned ON and OFF based only on their preset comfort level specified by a homeowner. This causes the peak consumption at 5:40pm to 5:48pm, when all the appliances were ON. The thermostat operates at the set-point temperature of 76 ºF and this set-point temperature is maintained throughout the 3-hour period of the experiment, as no demand limit existed during that time.

Case 2: With DR event: As we can see in Fig 6(b), the DR event was imposed between 5pm and 7pm with a demand limit of 8kW. During the DR event, from 5:40 pm to 5:48 pm, the WH was ON to bring the water temperature back to the specified limit. This caused the HEM to change the set-point temperature of thermostat to 80 ºF. This is why during the time WH is ON, AC was kept OFF by the thermostat, even though room temperature increased up to 80 ºF. The set-point was brought back to 76 ºF when the WH turned OFF and AC was next in priority. Hence thermostat turned the AC ON at 5:48 pm and brought the room temperature back to the comfort limit. The total power consumption was always within the specified demand limit of 8kW. This shows that the temperature set-point control of thermostat can be used to cap the highest allowable room temperature and thus further address customer preference while keeping the total household power consumption within a specified limit.

VII. CONCLUSION

This paper demonstrates the inclusion of a smart thermostat into the HEM system for residential DR implementation. This approach allows flexibility in room temperature control, and preventing room temperature rising above a certain acceptable range. The paper presents the hardware implementation of the HEM system with smart thermostat control in details and provides case studies to demonstrate its application. The proposed approach is expected to benefit the real world implementation of an automated HEM system for DR applications, and help reduce power system stress conditions while ensuring residential customers' comfort preferences.

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IX. BIOGRAPHIES

Avijit Saha (S'06 – IEEE) received his B.Sc. degree in Electrical and Electronic Engineering (EEE) from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, in 2009. He served as a Lecturer at the department of EEE in Ahsanullah University of Science and Technology, Dhaka, Bangladesh from March 2010 to July 2011. Currently he is working towards his Ph.D. degree in Electrical Engineering in Virginia Tech. His research interests include the areas of smart grid, demand response, home energy management systems and embedded systems.

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Manisa Pipattanasomporn (SM'11 – IEEE) joined Virginia Tech's Department of Electrical and Computer Engineering as an assistant professor in 2006. She serves as one of the principal investigators (PIs) of multiple research grants from the U.S. National Science Foundation, the U.S. Department of Defense and the U.S. Department of Energy, on research topics related to smart grid, microgrid, energy efficiency, load control, renewable energy and electric vehicles. Her research interests include renewable energy systems, energy efficiency, distributed energy resources, and the smart grid.