Electric Water Heater Modeling and Control Strategies for Demand Response

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***Abstract*— Demand response (DR) has a great potential to provide balancing services at normal operating conditions and emergency support when a power system is subject to large disturbances. Effective DR control strategies can help relieve balancing and frequency response burdens on conventional generators in addition to reducing generation and transmission investments needed to meet peak demands. This paper discusses modeling residential electric water heaters (EWH) in households and tests their responses with various control strategies implementing DR. The open-loop response of EWH to a centralized control signal is studied by adjusting temperature settings to provide balancing services; and two types of decentralized controllers are tested to provide frequency support following generator trips. EWH models are included in a simulation platform capable of performing electromechanical simulations, which contains 147 households in a distribution feeder. Simulation results show the effectiveness of EWH responses and its dependence on hot water usage. These results provide insight and suggest the need for control strategies to achieve better performance in demand response implementations.**

***Index Terms*— Centralized control, decentralized control, demand response, electrical water heater, smart grid**

I. Introduction

THE fast deployment of smart grid technology and growing renewable energy penetration bring about many advantages as well as challenges to operate modern power grids in a reliable and economic way. On one hand, the increasing penetration of renewable resources like wind and solar can help reduce carbon emissions, pollutants and energy dependency on fossil fuels; on the other hand, such variable resources increase power system uncertainty, which result in additional balancing requirements for ancillary services (frequency response, regulation and load following). Recent renewable integration studies have demonstrated a strong correlation between ancillary service requirements and installed capacity of renewable energy [1-3] and consequently the integration cost. An increase in the capacity of renewable energy usually requires additional balancing capability from conventional generation units, due to increased level of forecast errors and intra-hour variance. Also, the displacement of conventional generation by renewables reduces the frequency response capability of the power system, because less number of online generators will be able to increase their outputs after a forced generation outage. Generation (and transmission) capacity is also required to increase over time to satisfy peak load demand. Typical load curves in the U.S. show that the annual peak load only occurs for a very short period throughout a year. This phenomenon causes large amounts of investment in expanding generation and transmission unutilized most of the time.

For the above reasons, reducing system peak load, emergency response, and balancing service obligations on conventional generation units will help greatly in building a more economic and secure future power grid. Among different smart grid technologies, demand response control provides a promising way to shave load peak, fill valley, reduce balancing requirements and provide emergency support. Designed and implemented properly, DR will be capable of providing all the above benefits at a potentially lower cost than any other alternative. It is essential to understand the characteristics and potential issues of each candidate of DR controls for the purpose of fully realizing their benefits. This paper focuses on understanding the effects of DR control on electric water heaters (EWH). As an important type of load, EWH contributes a large portion of household loads in the U.S. and has the following advantages to implement demand response control:

(1) There is a large population of EWHs in the U.S., and each water heater has a relatively high power consumption compared to other home appliances such as clothes washer, dryer and refrigerator. In certain areas, EWHs can consume up to 30% of a household load and contribute significantly to the peak load [4].

(2) The heating element in an EWH is actually a resistor, which does not require reactive power support from the power grid. This feature makes it very convenient and flexible to control the switching action of an EWH, compared to air conditioners (A/C). There is no lockout time when turning on/off EWHs, which makes it possible to implement a high frequency control signal to EWHs to meet certain power system needs.

(3) EWHs can be used as an energy storage device by heating water to a higher than normal temperature range so that no energy is wasted in providing balancing services. This feature can help reduce peak load and also relieve system ramping-down capacity for regulation.

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The idea of using EWHs for providing balancing services has been introduced by previous research efforts [5]-[7]. Reference [5] proposes an EWH control using an additional heating element for DR purposes; it is shown that DR with EWHs can follow a frequency regulation signal. However, few publications have looked into the detailed dynamic performance of a large population of EWHs that are connected to a power grid, in providing ancillary services and emergency support. Various factors including voltage magnitudes, load models used in a simulation and the coupling between EWHs and other elements in a power grid, which can significantly affect DR performance, are usually ignored in simplified or aggregated models.

To overcome the above issues and provide a more realistic evaluation, this paper models the heat transfer process of an EWH in details and incorporates this model into a simulation platform with other home appliances. A micro-grid with power sources and a distribution feeder is built to examine the dynamic performance of EWHs under different control strategies. The effect of frequency response from EWHs can be more conveniently observed in this micro-grid setting and the knowledge gained can be generalized to grid-connected systems. No additional DR dedicated heating device is added to the EWH, as was done in [5]. Instead, the response capabilities of standard EWHs are analyzed with the assumption that it can be turned on/off by adjusting its temperature set point. A centralized control approach by adjusting EWH temperature settings to follow a balancing signal (also applicable to peak reduction and valley filling) is tested. Two types of decentralized control (or autonomous control) are developed to provide emergency support in response to loss of generation. Through a few study scenarios, this effort has shown that EWHs can be very effective in providing frequency support and balancing services, with dependence on hot water usage. Benefits and limiting conditions regarding each control method are discussed to facilitate the best use of demand response and to avoid adverse effects.

This paper is organized as follows. In Section II, a detailed EWH model is introduced, which includes a one-node model and a two-node model representing two different operation modes. Switching logics between the two models are also described. Section III presents the principles and characteristics of centralized and decentralized controls for grid support. In Section IV, a simulation platform is described to represent a distribution feeder with 147 household load models. Detailed settings of parameters are also provided. Section V discusses the simulation results regarding each type of control and their characteristics. Section VI concludes the paper and provides recommendations for further work.

II. Modeling of Electric Water Heater

We use a comprehensive model for the heat transfer process in an EWH, which switches between a one-node model and a two-node model depending on the situation. It was developed the state-of-art software for distribution network simulation, GridLAB-D [8]. This thermal model is used to control the on/off state of a heating device (resistor) that is connected to an electromechanical model of the power system, as described in Section IV.

A. One-node Model

By definition, the one-node model assumes that the water tank has a uniform temperature. This model is valid when the EWH has a full tank or empty tank of hot water ("all hot" or "all cold"). The heat transfer process is modeled as a first order differential equation:

$$Q_{elec} - \dot{m}C_p(T_w - T_{inlet}) + UA_{wh}(T_{amb} - T_w) = C_w\frac{dT_w}{dt} \quad (1)$$

where Q_{elec} is the heating capacity of the resistor in the water heater, in BTU/hour; $\dot{m}$ is the hot water flow rate, in lb/hour; C_p is the thermal capacitance, in BTU/(lb*°F); T_w is the water temperature, in °F; T_{inlet} is the temperature of inlet water, in degree F; UA_{wh} represents the thermal conductance of the tank shell, in BTU/°F /hour; T_{amb} is the room temperature, in °F; and C_w is thermal capacitance, in BTU/°F. This model calculates the actual water temperature at any given time, which is used to control the switching action of the water heater. For a desired temperature, T_{set}, the switching logic can be designed as follows:

(a) If $T_w>=T_{w\,set} + T_{w\,deadband}$, turn off the water heater.
(b) If $T_w<=T_{w\,set} - T_{w\,deadband}$, turn on the water heater.

Typically, the temperature setting can range from 110 °F to 130 °F. In this study, the deadband of the water heater controller is set to 2 °F.

B. Two-node Model

In contrast with the one-node model, the two-node model is valid when the EWH is in a partial depletion stage, indicating that both hot water and cold water are inside the tank. Thus, the two-node model assumes two compartments of water: (1) The upper compartment of water has a uniform temperature close to temperature setting (hot); and (2) the lower compartment of water has another uniform temperature close to inlet water temperature (cold). The concept of this model is shown in Fig.1. This model is used to calculate the height of the hot water compartment inside the water tank, using the following equations:

$$dh/dt = a - b*h \quad (2)$$

$$a = \frac{Q_{elec} + UA_{WH}*(T_{amb} - T_{lower})}{C_w*(T_{upper} - T_{lower})} * H - \frac{\dot{m}*C_p}{C_w} * H \quad (3)$$

$$b = UA_{WH}/C_W \quad (4)$$

where H is the maximum height of the water tank, in feet; T_{lower} is set to inlet water temperature; T_{upper} is set to T_w in the one-node model and h is the height of hot water slug, as a state variable.

C. Switching Logics between One and Two-Node Models

Because each model represents a certain condition of the EWH a switching function needs to be carefully defined to model it correctly. A flag is used as an indicator. If flag =1, one-node model is used; if flag=2, two-node model is used. The following model switching logic is used to determine when to switch to the one-node model from the two-node model, and vice versa.

<u>Switching from two-node to one-node:</u>

If flag=2

if h=H and dh/dt >= 0

flag is set to 1 and h is set to H

end

When the EWH is at a recovery stage and the height of hot water is increasing, the two-node model applies. When h reaches the maximum tank height H and it continues to grow as hot water usage is zero, the one-node model is enabled with the temeprature set to a previously known value. Note that a similar switching action when h=0 and dh/dt<0 is ignored because this process does not affect the power consumption characteristic of EWH.

<u>Switching from one-node to two-node:</u>

If flag=1

if $\dot{m} > \dot{m}_{min}$

flag=2 and T_w is held constant with the current value

end

where $\dot{m}_{min}$ is a tolerance value that can trigger a change in h so that dh/dt<0. This switching action means that whenever there is a sufficiently large hot water consumption, EWH is at a depletion stage and the two-node model is applied.

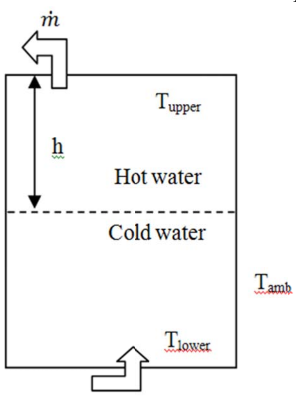

Fig. 1. Two-node model of EWH.

D. Behavior of a single EWH

Fig. 2 shows the behavior of a single EWH at normal operating conditions, with nominal voltage magnitude. Starting from one-node model with zero water flow rate, hot water temperature drops slowly because of heat loss (see top left plot), but it is still within the deadband of temperature setting so the heating element remains off. At the 5th hour, a large water flow rate occurs that triggers the two-node model. As a result, h drops very fast until it reaches 0 (top right plot). After water flow rate goes back to zero, h recovers to the maximum when the one-node model is triggered again. At this moment, the EWH does not stop heating until the hot water temperate reaches the upper deadband, $T_{w\ set} + T_{w\ deadband}$. Similar performance can be found when there is another hot water usage event occurring at around the 11th hour. From these curves, it can be found that the EWH behavior can be largely affected by the water flow rate. Therefore, it is very important to understand people's behavior in using hot water to better design DR controllers for EWHs.

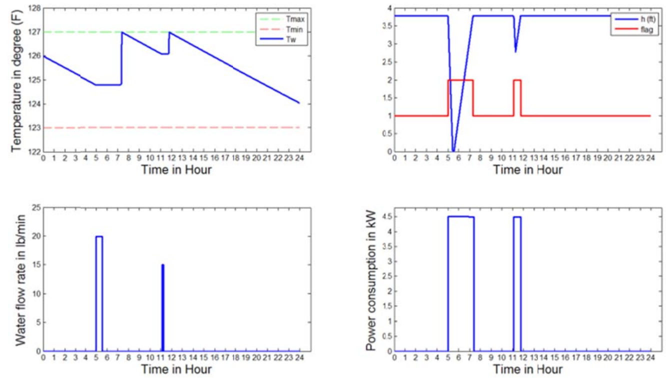

Fig.2. Behavior of a single EWH.

III. EWH Controller Design for Demand Response

In this section, a few control strategies are described for testing the performance of EWHs in providing frequency regulation and emergency support.

A. Centralized Control for Frequency Regulation

In this control scheme, it is assumed that each EWH is capable of receiving signals from the control center. The centralized signal is applied to the temperature setting of each EWH device instead of simply turning EWH on or off. It can ensure customer's comfort level to a certain extent by enforcing upper and lower temperature setting limits. The centralized signals in the form of either sinusoidal wave or step change with different frequencies and magnitudes are tested to observe the corresponding amplitudes and time delay. No communication delay is modeled when applying the centralized signal to EWHs. This procedure helps identify predictability, nonlinearities, and possible limitations of DR to provide ancillary services. It also helps identify response time and availability of EWH to follow a realistic regulation signal with various frequency components.

It is important to note that when applying a change in the temperature setting of EWH, the reference value of h is also adjusted, with the magnitude proportional to that of temperature change. This feature allows for a control action to the EWH when it is working in a two-node mode.

B. Decentralized Control for Emergency Support

Two types of decentralized controllers are described in this section for EWH response to frequency deviations.

<u>*Type I: Randomized threshold and reconnection delay*</u>

A Type I controller on an EWH is developed to provide frequency support by tripping water heaters (if they are turned on at the moment) in case of generation deficiency, with random tripping threshold and random reconnection delay [9]. The control actions are described as follows:

(i) For an EWH unit i, if its local bus frequency drops below a threshold, *FreqThrs(i)*, for at least 100 ms, this EWH unit is turned off.

(ii) The same EWH unit is turned back on only when its frequency recovers back to a threshold, *FreqThrs(i)+0.03* Hz, for more than 30 seconds.

The selected threshold for each EWH is randomized to avoid all EWHs turning off at the same time in case of a sudden frequency drop. It is assumed that *FreqThrs(i)* is evenly distributed from 58.8 Hz to 59.94 Hz. To avoid the occurrence of cold load pick up, a random delay, $T_{delay}(i)$, is added to a Type I controller to allow the EWH to be turned back on following a turning off action. That is, after an EWH is turned off by the frequency controller, it will stay out of service for a time of $T_{delay}(i)$ before it is permitted to be turned back on. $T_{delay}(i)$ is also randomized, which is evenly distributed from 2 to 4.25 minutes.

Type II: Frequency-temperature setting Droop

This controller consists of a proportional droop loop that acts on the local temperature setting of electric water heater. The control structure is shown in Fig. 3. The temperature setting is reduced in the water heater when the frequency is lower than the nominal value. The temperature change signal can also be obtained from the centralized controller. The temperature settings in this case are modified by both the decentralized and centralized controllers.

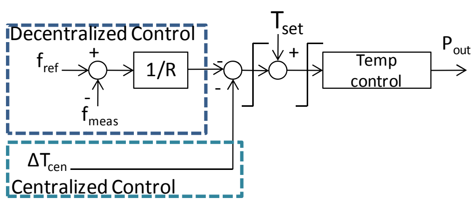

Fig. 3. Decentralized frequency control for demand response.

IV. Simulation Platform

The simulation platform for the performance of EWH with demand response is developed in a commercial power system simulation package, Digital Simulation and Electrical Network Calculation Program (DIgSILENT), developed by DIgSILENT PowerFactory [11].

A. A micro-grid model

A modified IEEE 34 bus distribution system is used in this study with system topology shown in Fig. 4, where bus 800 is connected to four diesel generators as power sources. To observe the impact of DR responding to frequency events, the majority of the lumped loads are replaced by the detailed household loads. Each household model is equipped with an EWH, an A/C unit and an aggregate load representing all other electric appliances including lighting, clothes washer and dryer, dish washer and electric oven. A load factor of 40% is assumed for each lumped load to determine the number of households to be placed at each node. Thus, a total of 147 households were built in this test platform. More details regarding this distribution feeder can be found in Lu, et al. [10]. Wind turbines and photovoltaic generation models are disabled in this study.

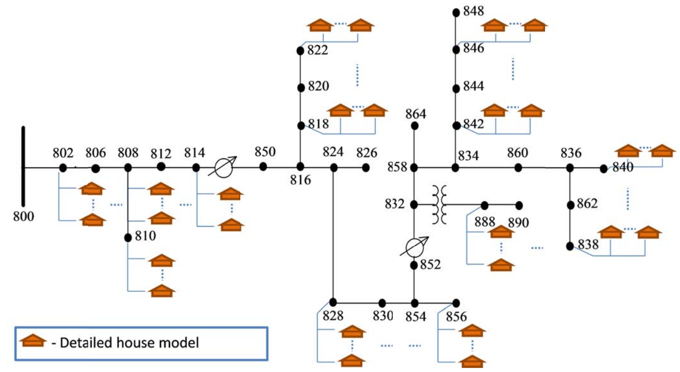

Fig. 4. Topology of the IEEE 34 bus test feeder.

Similar to the EWH model, differential equations are used to describe the heat transfer process of an A/C unit. However, this paper only focuses on the DR implementation on EWHs. DR controllers are not functioning for A/C units. A parallel effort is undergoing that focuses on the impact of DR implementation on both A/C units and EWHs [12]. The miscellaneous load model aggregates the relatively small appliances compared to A/C and EWH. These small appliances have no DR controllers. During transient simulation, typical load curves, including active and reactive power, are used to mimic the actual electric power consumption over time. In each household model, the capacity of A/C is assumed to be 3.7 kW, while the capacity of EWH is 4.5 kW. Fig. 5 provides a detailed diagram of the household load model developed in DIgSILENT. This model has the flexibility of simulating both decentralized control and centralized control schemes.

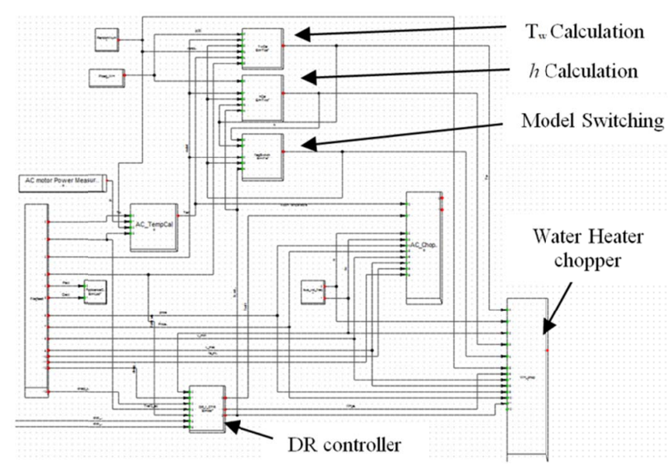

Fig. 5. Household load model developed in DIgSILENT.

B. Diversity of EWH

In this study, the same physical parameters of EWH are used with the detailed parameters listed in Table I. To ensure sufficient diversity in the 147 EWHs, random initial temperature values, temperature settings and hot water flow rates are used.

TABLE I
DETAILED PARAMETERS OF EWH IN THE SIMULATION PLATFORM

Parameter	Value	Units
Qelec	15360	BTU/hour
UA_{wh}	2	BTU/degree/hour
T_{inlet}	60	degree
C_p	1	BTU/lb/degree
C_w	417.11	BTU/degree
H	3.78	feet

Random Temperature Setting

It is assumed that the temperature setting of each water heater, $T_{setting}(i)$, ranges from 110 °F to 130 °F. The temperature setting follows a uniform distribution.

Random Initial Value

The initial value of each water heater is also randomized following a uniform distribution, ranging from $T_{setting}(i)$-1 to $T_{setting}(i)$+1 degree. The initial status of all water heaters is set to off position.

Generation of Water Flow Rate

Ten hot water flow rate curves are generated to mimic people's behavior during a typical day with 5-minute resolution. Each data point indicates a 5-minute constant water flow rate. One morning peak and one event peak are included in these curves. For each of the 147 water heaters, one typical curve is randomly selected where magnitude and time of occurrence of non-zero points are randomly shifted.

V. SIMULATION STUDIES AND DISCUSSION

This section describes the study scenarios created to implement demand response using EWHs. Simulation results and important findings regarding the advantages and disadvantages of each type of control are discussed in detail. Constant impedance model is used to represent EWHs in all the following study scenarios.

A. Base Case Scenario

As discussed in Section II.D, the power consumption of EWH is largely affected by people's behavior in hot water usage. Thus, it is necessary that we investigate DR implementation at different water usage conditions. In this study, we designed a base case scenario to represent a morning peak of hot water usage, starting from 5:00 am and lasting for 8200 seconds (approximately 2.28 hours). The total water flow rate from the 147 houses and the total power consumption from all 147 EWHs are shown in Fig. 6. Starting from zero water usage, the EWH power consumption is zero. As water flow rate increases, the strong correlation between the total power consumption and the total water usage can be observed.

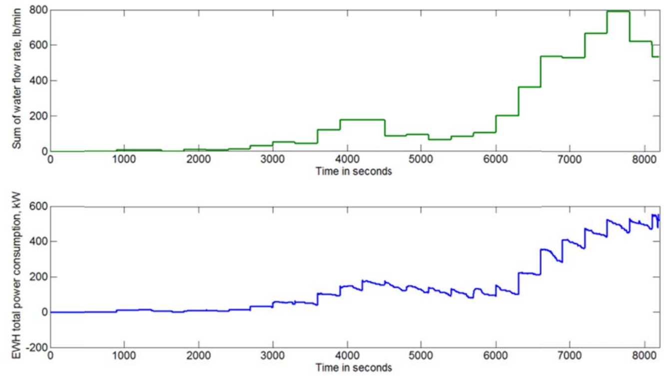

Fig. 6. EWH power consumption and water usage for base case.

B. Centralized Control for Balancing Services

Different types of balancing services require responses in different time horizons to balance the system. For example, load following signal requires a system response with a response time in the range of minutes; while regulation requires a faster time response in the range of seconds. This section tests the EWH performance to follow a step change signal (up/down) and a sinusoidal signal from the control center.

1) Step response

In this test, a step change in temperature settings of EWH is simulated at two different levels of water consumption. It can be expected that EWHs can respond well to a ramping-up signal when most of them are turned off, e.g. at night time with little water consumption. In contrast, a good response to a ramping-down signal can be expected when most of the EWHs are turned on, e.g. during morning peak hours with high hot water consumption. Fig. 7 shows the total power consumption change responding to different ramping-up signals. The EWH temperature setting changes range from 1 °F to 5 °F. The step-up signal is applied at 1400 seconds when the total hot water consumption is at a very low level.

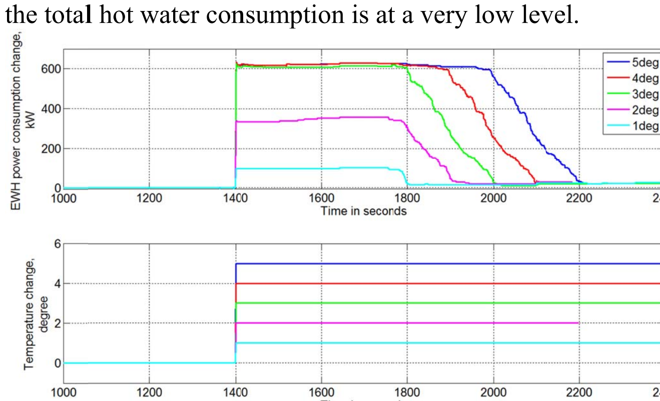

Fig. 7. EWH power responding to step change signals.

Fig. 7 clearly shows the impact of temperature setting change on the total power consumption. A higher change in temperature setting can cause more power consumption that last for a longer time. Since a +/- 2 °F dead band is used in all EWHs to control water temperature, a 3 °F change will cause all EWHs to be turned on at the same time. Further increasing temperature setting cannot further increase the ramping-up capacity because the 3 °F signal already exhausts all EWHs, but a longer duration in providing a ramping-up service can be expected as it takes longer for EWHs to reach a higher temperature setting. This feature can provide important information to system operators to better implement the demand response by adjusting temperature setting of EWHs. Linear relations between the energy consumption and temperature setting change can be derived from Fig. 8, for cases before and after saturation. A higher slope is observed for cases with temperature changes from 1 °F to 3 °F; while a slightly lower slope representing the saturation impact is observed for cases with temperature changes from 3 °F to 5 °F.

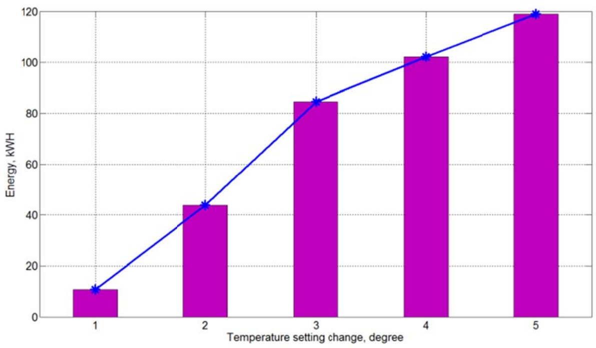

Fig. 8. Energy consumption with regard to temperature setting change for ramping-up.

A second simulation case is created to evaluate the performance of EWHs to follow a step-down signal at 7600 seconds, when total water consumption is at a high level (see Fig. 6). Signals with a temperature change ranging from -5 °F to -1 °F are tested. The maximum ramping-down capacities of EWHs with regard to the temperature changes are shown in Fig. 9. Linear relations between ramping-down capacity and temperature setting change are observed for cases before and after saturation, which are similar to the ones observed for the energy vs. temperature setting change in Fig.8.

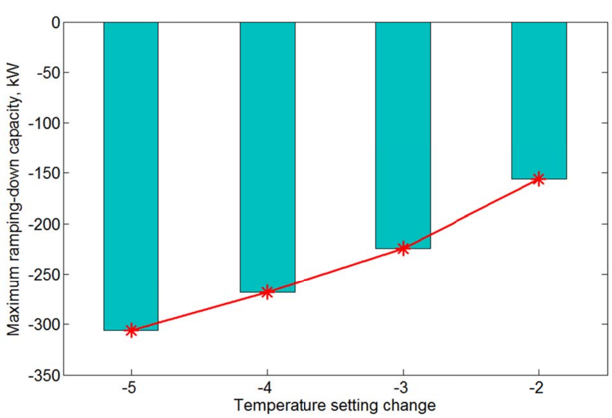

Fig. 9. Maximum ramping-down capacity with respect to temperature setting change.

2) Sinusoidal signal test

A centralized signal with a frequency of 0.001 Hz is used to adjust the temperature settings of all 147 EWHs. The total power consumption change (defined as $P_{response}$-$P_{basecase}$) that responds to the centralized signal is shown in Fig. 10. It shows that EWHs respond very well to the first ramping-up signal which is similar to the step-up response. However, following the first ramping-up action, all EWHs get saturated. This is caused by their low duty cycle when hot water consumption is zero. The water temperature is raised to a higher level within a short time but the temperature decline due to heat loss takes a much longer time to trigger the temperature controller to turn on the EWH again. To further explain the saturation phenomenon, the response of a single EWH is shown in Fig. 11. EWHs do not respond well to the next ramping-down and the following ramping-up/down signals until water usage occurs. After 3,000 seconds of simulation, the power consumption change starts to follow the sinusoidal signal as water consumption starts to increase. Although nonlinearity and distortion are observed in the power consumption curve, there is still a certain pattern of EWHs that can be followed. Firstly, the cycling frequency of total power consumption change follows the centralized signal well after 3000 seconds. Secondly, the ramping-down capacity is highly correlated to the water consumption rate. Higher water consumption indicates that more water heaters are turned on to heat water at the moment; therefore, there is more room for the total power consumption to ramp down by turning EWHs off. Thirdly, the ramping-up capacity cannot be further increased as water consumption rises to a very high level, because fewer EWHs are available to be turned on.

These observations are plotted in Fig. 12, where the numerical numbers 1 to 4 indicating the 4 cycles selected from Fig. 10. The "spikes" on the power consumption curve caused by transient voltage deviation were removed when the maximum ramping capacity, both up and down, were calculated. Similar to the step response in previous section, a linear relation is observed in the ramping-down capacity with regard to the total water consumption, as shown in the bottom plot of Fig. 12.

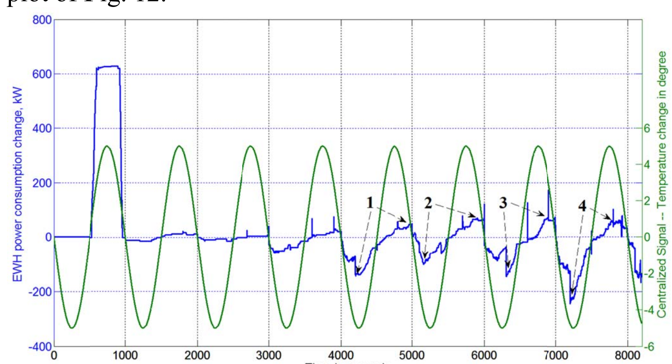

Fig. 10. Power consumption change responding to a 0.001 Hz signal.

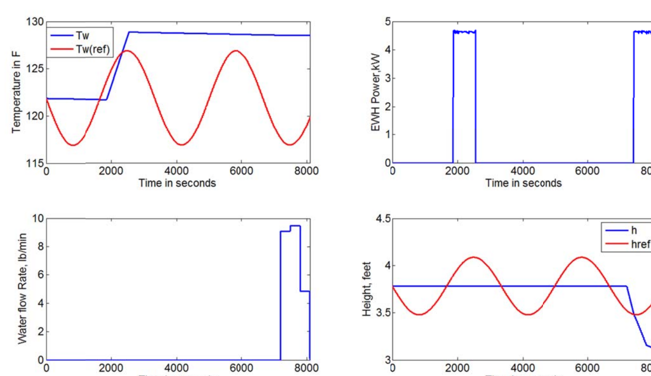

Fig. 11. Response of a single EWH to a 0.001 Hz sinusoid signal.

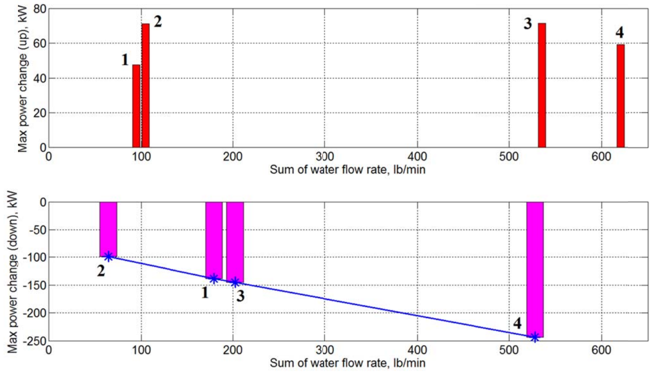

Fig. 12. EWH ramping capacity (up and down) with regard to total water consumption.

C. Decentralized control for emergency support

The two types of decentralized controllers described in Section III.B are tested by simulating a generator outage event in the micro-grid model. Considering the fact that no or little frequency support can be expected from EWHs when most of them are turned off due to low water consumption, this test simulates a generator outage at 7600s, which has an active power output of 600 kW. With most of EWHs turning on at 7600 s, the two types of decentralized controllers can be very effective in helping recover system frequency by tripping EWHs. The EWH total power consumption and the frequency profile at the main feeder are shown in Fig. 13. Both Type I and Type II controllers can help restore the system frequency profile very quickly in case of a frequency drop event. Less oscillation is observed in the frequency profile using Type I controller, but its maximum frequency deviation is slightly higher than that of Type II controller. Water heater load also recovers faster with Type II controller, as system frequency comes back to the normal range. The total amount of power reduction and the maximum frequency deviation in response to the generator tripping event is listed in Table II. By carefully tuning the parameters of Type I controller (e.g., the range of low frequency tripping threshold and the delay time) and Type II controller (e.g. the droop characteristic and proportion coefficient), it is expected to achieve better frequency support performance. The task of tuning parameters of controllers is beyond the scope of this paper and will be addressed in future work.

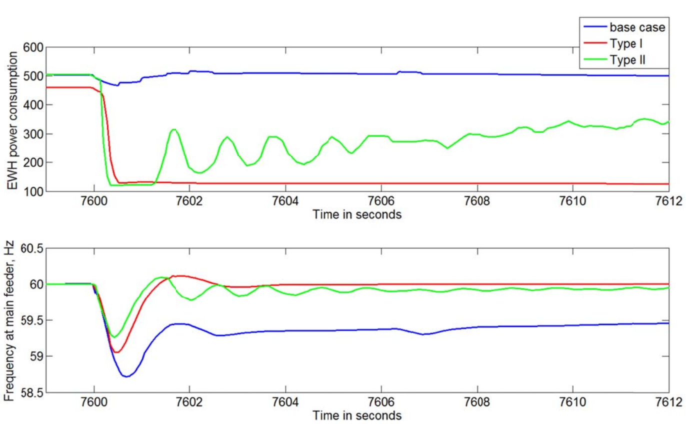

Fig. 13. EWH power consumption and frequency profile responding to a generator tripping event at 7600 s.

TABLE II
PERFORMANCE OF TYPE I & II CONTROLLERS RESPONDING TO A GENERATOR TRIPPING EVENT

	Max frequency deviation	Max power reduction
Type I	0.95 Hz	331.1 kW
Type II	0.74 Hz	384 kW

D. General Guidelines for DR Implementation via EWH

The above simulations and their analyses provide much important information in designing controllers for EWH to better implement demand response. General guidelines are summarized as follows:

1) EWH power consumption is highly dependent on hot water consumption. It is very important for system operators or the DR tools assisting operators in decision making to understand people's behavior in using hot water in order to achieve a satisfactory performance. As an example, at night time in the Bonneville Power Administration (BPA) area, there is usually a surplus of generation from wind farms, because of the strong wind at night time. Currently, ramping-down is required from conventional generators to maintain system balance, which is sometimes very difficult due to the already-low operation point. With DR implementation, a step up signal can be sent to all EWHs for absorbing the extra renewable generation. Since most EWHs have no water flows in the night, the power and energy that can be absorbed by EWHs is relatively simple to predict.

2) Applying step changes in temperature settings of EWHs is a very effective method to follow a centralized signal, and the response has little time delay. The expected response in terms of capacity and duration can be highly dependent on the availability of EWHs.

3) Sinusoidal type of signal for centralized control may cause EWHs to saturate. In other words, the response from EWHs is not expected to be fast in changing directions. Both the magnitude and ramp rate of EWH response are limited by hot water usage. Nonetheless, it can follow slow-changing balancing signals and relive some balancing burden on conventional generators. It is necessary to carefully tune the magnitude and frequency of the signal based on the availability of EWH to achieve desired performance.

4) Both types of decentralized controllers for emergency support are effective when there are many EWHs in on state. Parameters in the controllers shall be carefully tuned to avoid oscillations of power consumption in EWHs or big load rebound effect.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, a simulation platform capable of performing electromechanical simulations was introduced to model electric water heaters and test demand response implementations via EWH. Several demand response control strategies were simulated. Centralized signals in the form of sinusoidal curve and step change were applied to 147 EWHs simulated in the platform; two types of decentralized controllers for supporting system frequency were designed and tested. The effectiveness of performing balancing services and emergency frequency support and its dependence on hot water usage of these controllers were demonstrated through simulation results.

In future work, analytical methods should be developed to estimate the capacity of balancing services from EWHs at predicted hot water usage. The parameters in the above controllers will be fine-tuned for EWHs to effectively follow a realistic balancing signal. More diversity in the parameters of 147 EWHs such as tank sizes and nominal power will be added to the simulation platform to reflect a more realistic study scenario.

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IX. Biographies

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