Reduced Order WECC Modeling for Frequency Response and Energy Storage Integration

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Abstract—This paper presents a simple reduced order model of the western grid interconnect (WECC) that includes interconnect inertia, load frequency response, and generation primary frequency response. The model is validated against detailed power flow and transient response studies and recreates the WECC frequency response to a large generator outage to within 0.01 Hz RMSE, with the same frequency nadir and settling frequency. To properly capture the generation primary response, three classes of generation are used: slow, medium, and fast. The slow group responds with a time constant of 27 seconds, the medium group with a time constant of 19 seconds, and the fast group with a time constant of 0.5 seconds. The model is used to investigate the usage of domestic water heaters to assist in primary frequency response and reduce the impact of sudden load or generation changes. It is shown that even a very small-scale implementation of demand response via domestic hot water heaters – about 1% – can improve the frequency nadir by 10%, from 59.666 Hz to 59.697 Hz. The settling frequency is improved from 59.768 Hz to 59.789 Hz.

Index Terms—Energy storage, frequency response, power system stability.

I. INTRODUCTION

This paper presents two things: first, a simplified model of the WECC western interconnect that captures inertial response, load frequency response, and three classes of primary response generation; second, the usage of this simplified model to investigate the possible benefit of large-scale energy storage with domestic water heaters to WECC transient stability.

Domestic water heaters represent a huge potential form of energy storage, both in terms of energy capacity and power capacity. In this paper, only the time scale that covers primary response is considered. Generally, grid reserve generation can be classified into four timescales [1].

- Inertial response: inertial response is not dispatched, but instead is the manifestation of the physical property that rotating mass discharges energy when decelerated, and charges energy when accelerated.
- Primary control: the response of generators under the control of governors to increase generation when speed (i.e., frequency) decreases and decrease generation when speed increases. This is a closed loop local-level control and the typical response time is on the order of seconds. Primary response typically arrests, but does not correct, deviations in frequency. It is the first active layer of defense for grid stability.
- Secondary control: the next level of control is secondary control, in which additional generation setpoint operation is adjusted to correct for persistent frequency deviation (i.e., drive the frequency back towards 60 Hz.) Secondary control timescales are typically minutes.
- Tertiary control: the last level is tertiary control, which is loosely defined as additional dispatcher corrections and scheduling, which typically cover timescales from minutes to hours.

This paper describes the development of a reduced-order model of the WECC interconnection and the usage of the reduced-order model to estimate the benefit of domestic water participation in frequency response (i.e., primary control) to assist in grid stability and recovery to large generator outages. First, a simple high-level model of the WECC is developed that can recreate the WECC frequency response to a large generator outage with proper modeling of system inertia, load frequency response, and primary frequency response of generation. This simple model will then be used to estimate the benefit that large-scale water heater energy storage implementation can provide to transient response and system stability.

II. WECC BASE CASE OVERVIEW

Data for this study comes primarily from the 2011 California Independent System Operator frequency response study and the summary paper “Emergency Response” [2], [3], specifically the winter low-load high-wind case. This base case is for a total WECC load of 91,300 MW, with wind providing 14% of the generation. A loss of two Palo Verde units totaling 2,690 MW is simulated. This causes a transient drop in frequency, as shown in Fig. 1. The frequency nadir is 59.67 Hz at a time of 9.8 seconds after the loss of the Palo Verde units with a settling frequency of 59.78 Hz.

III. WECC REDUCED-ORDER MODEL

A simplified reduced-order model of the WECC has been developed. The model is shown in MATLAB/Simulink in Fig. 2.

This model includes system inertia, load frequency response, and primary response of three classes of generators: slow, medium, and fast. The basis for modeling generators of different response speeds is the result from the 2011 Miller, Shao, and Venkataraman report [2], which showed that primary
control responsive generators have a wide range of response times, from only seconds to well over a minute to respond to the Palo Verde unit loss. The model parameters were tuned by successive sweeps, until a frequency response fit of 0.01 Hz RMSE was found. The model parameters are given in Table I.

A comparison of the model transient response against the benchmark case is shown in Fig. 3. The responses of the load and the fast, medium, and slow generators are shown in Fig. 4.

IV. WATER HEATER MODELING

A. Power and Energy Capacity

Electric water heaters are a significant energy storage resource. Standard residential electric water heaters are 50 or 60 gallons capacity, with one heating element at the bottom of the tank, and another approximately two-thirds up the tank, as shown in Fig. 5.

The hot water outlet is at the top of the tank. The upper element has priority and heats the upper one-third of the tank to the desired temperature, usually around 120 degrees Fahrenheit or 130 degrees Fahrenheit. The lower element can be active when the upper element is off (i.e., the upper one-third of the tank is at the desired temperature) and heats the lower two-thirds of the tank to the desired temperature. Generally the water stays well stratified, and the lower two-thirds of the tank can be assumed to hold a temperature below that of the upper one-third of the tank. This structure allows for great opportunities for utilizing electric water heaters as energy storage. The temperature of the lower two-thirds of the tank can be manipulated in an intelligent way without greatly affecting the temperature of the water in the upper one-third of the tank, which is the water withdrawn by the user.

Assuming a standard residential electric water heater of 50 gallons capacity, an outlet temperature of 130 degrees Fahrenheit, and an inlet temperature of 60 degrees, the lower two-thirds of the tank requires approximately 5 kWh of energy to heat. Therefore, by controlling the lower two-thirds of the tank temperature to range from the inlet temperature as the lower bound, and the outlet temperature as the upper bound, a potential energy storage capacity of 5 kWh can be utilized. Typically each of the upper and lower elements are rated for 4.5 kW. Under the standard configuration, the upper element
Fig. 4. Responses of the load and the fast, medium, and slow generators to the simulated loss of generation. The fastest generator group (green trace) reaches its maximum response around 10 seconds, closely following the frequency of the system. The medium speed and slow speed generator groups (red and brown traces) reach their maximum generation in 40 seconds and 60 seconds after the disturbance, respectively. The total generation (light blue trace) is the sum of these three groups and very closely matches the base case generation response.

Fig. 5. Water heater diagram. The upper element has priority and heats the upper 1/3 of the tank where the hot water outlet is located. The lower element can operate when the upper element is off, and heats the lower 2/3 of tank where the cold water inlet is located.

has priority to heat the upper portion of the tank. If the upper element is off, the lower element is enabled. Therefore, the two elements operate exclusively, and the total water heater power capacity is 4.5 kW.

When referring to water heaters generating (i.e., discharging), it is not meant they literally push energy on the grid, but instead decrease their load by the amount they are effectively generating, as if some local generation source has come online to decrease the net load.

B. Aggregate Water Heater Modeling

A single water heater could be modeled very simply as a battery or capacitor. However, we are interested in modeling the aggregate of millions of water heaters. The aggregate system will have a power capacity, and a state of charge. Contrary to a simple single battery or capacitor, the power capacity of the aggregate system will be a function of the state of charge. For example, consider the state of charge of the entire aggregate system to be 0.5 (i.e., half full). In that case, some of the water heaters will be fully charged, some partly charged, and some fully discharged, such that the total state of charge is 0.5. However, the water heaters that are fully charged will not be able to contribute to total charging power capacity, and the water heaters that are fully discharged will not be able to contribute to total discharging power capacity. Consider the case of the total system state of charge at 0.9. In that case there are many water heaters that are fully charged, a few that are partly charged, and very few that are fully discharged. Thus the total charging power capacity will be small, and the total discharging capacity will be large. Therefore for the aggregate system of millions of water heaters, we expect the charging and discharging power capacity to be a function of the total aggregate state of charge. This is illustrated in Fig. 6.

We have assumed a linear relationship of power capacity to SOC. Research to refine the relationship is a good topic for future research.
V. WECC TRANSIENT RESPONSE WITH WATER HEATER ENERGY STORAGE

The simplified WECC model shown in Fig. 2 has been modified to include the water heater modeling, shown in Fig 7. The goal is to show the benefit to transient response that water heater loads can provide. The water heater power is to be controlled proportional to frequency, thus providing primary frequency response. When the frequency drops below 60 Hz due to the simulated loss of the Palo Verde units (2.69 GW = 0.029 PU), some of the water heater capacity will respond by decreasing load, thus helping to stabilize the system.

This paper does not focus on the exact hardware implementation of the water heater control system, but in practice it could be quite straightforward. For example, simply the bottom element of the water heater could be replaced by an augmented heating element that includes a simple circuit to detect frequency. As the frequency decreases, the effective element resistance – and therefore the element power – can be effectively changed by pulse width modulating the applied voltage. If the home resident is in need of hot water, the upper element will be on and the lower element is unpowered. If the upper tank is standing by with the desired water temperature, the lower element will be available, and thus with a simple augmentation of the thermostat to respond to frequency, will be silently increasing or decreasing the temperature in the lower tank according to frequency. By staying within this traditional water heater control framework, the upper tank and home resident comfort remains the priority. This simple modification would require no additional communication interface; it would effectively utilize frequency to detect the state of the generation-load balance. Under this scheme, the response of any one individual water heater cannot be guaranteed. However, the aggregate water heater behavior of millions of water heaters should be predictable.

It is estimated there are approximately 3 to 4 million residential water heaters in the Pacific Northwest [4]. Assuming each water heater to have a power capacity of 4.5 kW, there is a total residential water heater load capacity of approximately 15,000 MW. This research, we make a very conservative estimate of 3 % of that resource (500 MW) is available for demand response (i.e., primary frequency participation) for the entire WECC. Assuming each water heater to have a power capacity of 4.5 kW, that is a total of 111,000 water heaters. Assuming 5 kWh per water heater, there is a total energy storage resource of 555 MWh.

Two scenarios are simulated: the aggregate water heater load responding at the standard droop of 5 %, and a more aggressive scenario of the aggregate water heater load responding at a droop of 0.38 %. For the 5 % droop case – which is a standard setting for generation on primary frequency control – the generator governor is set to modify the generator power setpoint at a rate of \( P_{\text{rated}} \) per 3 Hz. For the 0.38 % case, the generation setpoint is modified at a rate of \( P_{\text{rated}} \) per 0.23 Hz. Generally,

\[
P(f) = P_{\text{setpoint}} + P_{\text{rated}} \frac{f}{k_{\text{Hz}}} \tag{1}
\]

For the water heater control \( P_{\text{setpoint}} \) is simply the current natural water heater load, which is treated as zero in the simulation. (Note that zero load in the simulation does not represent objectively zero Watts, but is instead the bias point of the simulation.) The parameter \( k_{\text{Hz}} \) is 3 Hz for the 5 % case, and 0.23 Hz for the 0.38 % case. A value of 0.23 Hz was chosen as that is the frequency nadir of the benchmark case. Thus when \( k_{\text{Hz}} \) is 3 Hz, approximately 0.23/3 = 7.7 % of the total aggregate water heater capacity will be utilized, whereas when \( k_{\text{Hz}} \) is 0.23 Hz, approximately 100 % will be utilized.

The aggregate water heater parameters are given in Table II.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{whTotCap}} )</td>
<td>total aggregate water heater power capacity</td>
<td>500</td>
<td>MW</td>
</tr>
<tr>
<td>( J_{\text{whTotCap}} )</td>
<td>total aggregate water heater energy capacity</td>
<td>555</td>
<td>MWh</td>
</tr>
<tr>
<td>( k_{\text{Hz}} )</td>
<td>water heater freq. response constant</td>
<td>{0.23, 3.00}</td>
<td>Hz</td>
</tr>
</tbody>
</table>

The simulation results are shown in Fig. 8 and Fig. 9. The initial aggregate water heater SOC is 0.5, and therefore 250 MW of the 500 MW is available for charging, and 250 MW available for discharging.

The results show that for the standard case of full water response per 3 Hz of frequency deviation, only about 1/5 (50 MW) of the available 250 MW is utilized. However, even with this modest response, there is a small but measurable benefit in the frequency nadir and settling frequency. For the more aggressive case of full water heater response per 0.23 Hz of frequency deviation, the full water heater capacity of 250 MW is utilized. The benefit is much greater in this case, with the frequency nadir increased from 59.666 Hz to 59.697 Hz over the base case, which is a 10 % improvement in the deviation from 60 Hz.

The cases are summarized in Table III.

<table>
<thead>
<tr>
<th>Case</th>
<th>Freq nadir</th>
<th>Settling freq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>59,666 Hz</td>
<td>59,768 Hz</td>
</tr>
<tr>
<td>( k_{\text{Hz}} = 3 ) Hz</td>
<td>59,673 Hz</td>
<td>59,771 Hz</td>
</tr>
<tr>
<td>( k_{\text{Hz}} = 0.23 ) Hz</td>
<td>59,697 Hz</td>
<td>59,789 Hz</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This paper demonstrates the calibration of a greatly reduced order model of the western interconnect, and the usage of that model to investigate the impact of large-scale integration of domestic hot water heaters for energy storage and frequency response. The simulations suggest that even a very modest penetration of water heaters (approx. 500 MW power capacity and 555 MWH energy capacity), can have a significant impact on reducing the frequency deviation nadir and the settling frequency deviation in response to a large generation outage.
Fig. 7. Simplified WECC model with aggregate water heater modeling. The water heater parameters are given in Table II. The blocks in the upper right model the water heater power limits, which are linear functions of SOC as illustrated in Fig. 6. The commanded water heater power \( P_{\text{wh.cmd}} \) is the desired water heater power above or below the nominal “natural” water heater load at that moment. The amount of increase or decrease in the water heater load is dictated by the control variable \( k_{\text{Hz}} \), which specifies the amount of commanded water heater power per deviation in frequency.

Fig. 8. Frequency response of the WECC to the Palo Verde outage (2.69 GW of lost generation) under three scenarios: the base case of no water heater energy storage, the standard case of all available water heaters responding for 3 Hz (5%) deviation, and the aggressive case of all available water heaters responding for a 0.23 Hz (0.38%) deviation. The frequency nadirs and settling times are summarized in Table III.

With hot water heaters responding at the standard of generation rated capacity per 3 Hz deviation, there is a small but measurable reduction in the 60 Hz deviation nadir, from 59.666 Hz to 59.673 Hz. If the water heaters are set to respond much more aggressively: full rated capacity per 0.23 Hz deviation, the water heaters can contribute their full 250 MW capacity (assuming 50% SOC) and the frequency nadir improved from 59.666 Hz to 96.697 Hz, which is a 10% improvement in the deviation from 60 Hz. We conclude that domestic hot heaters represent a very large, fast, and flexible resource that should be able to be utilized with a much lower implementation cost than new energy storage.

REFERENCES