Results of the Grid Friendly™ Appliance Project

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ABSTRACT

As part of the Pacific Northwest GridWise™ Testbed Demonstration funded by the U.S. Department of Energy (DOE) and others, Pacific Northwest National Laboratory (PNNL) collaborated with Whirlpool Corporation, Invensys Controls, the Bonneville Power Administration, PacifiCorp, Portland General Electric, and several smaller utilities to install 150 new Sears Kenmore clothes dryers and to retrofit 50 existing electric water heaters in homes in Washington and Oregon. Each dryer and water heater was configured to respond to the Grid Friendly™ appliance controller, a small electronic circuit that sensed underfrequency grid conditions and requested that electric load be shed by the appliances. These controllers and appliances were observed for over a year in residences spread over a wide geographic area.

The controllers were found to respond predictably and reliably despite their geographic separation. Over 350 minor underfrequency events were observed during the experiment. This paper presents the distributions of these events by season and by time of day. Based on measured load profiles for the dryers and water heaters, the average electrical load that can be shed by each of the two appliance types was estimated by time of day and by season.

Battelle, which operates PNNL for DOE, has been assembling a suite of grid-responsive functions and benefits that can be achieved through the control of relatively small, distributed loads and resources on a power grid. These controllers should eventually receive acceptance for the opportunities they offer for circuit protection, regulation services, facilitation of demand responsiveness, and even power quality.

The Grid Friendly Appliance (GFA) Controller

Electric power grid frequency is a grid-wide indicator of the instantaneous match between supply and demand on the power grid. If a large electric power generator unexpectedly halts supply to the power grid, the grid frequency decreases until supply and demand can be rebalanced. Presently, severe underfrequency excursions are corrected by substation underfrequency relays that can de-energize entire feeders at prescribed underfrequency thresholds.

The Grid Friendly appliance (GFA) controller used in this project accurately senses power-grid frequency and can be configured to alert its appliance when the frequency matches or exceeds an assigned threshold. Two hardware versions of the GFA controller are shown in Figure 1. The larger of these two was used in the project. The underfrequency threshold was set relatively high at 59.95 Hz to detect minor underfrequency excursions of the type that would be predicted to happen approximately once per day.

Experimental Methods

The GFA controller would ideally become closely integrated into an appliance. Integration was only partially accomplished during the Grid Friendly Appliance Project because of a tight schedule and safety concerns. Close collaboration between three business entities produced the clothes-dryer module shown in Figure 2(a). The module includes a load-control module from Invensys Controls, a communication processor from Whirlpool Corporation, and Pacific Northwest National Laboratory's (PNNL's) appliance controller. The module is shown installed on the wall behind a project dryer in Figure 2(b).

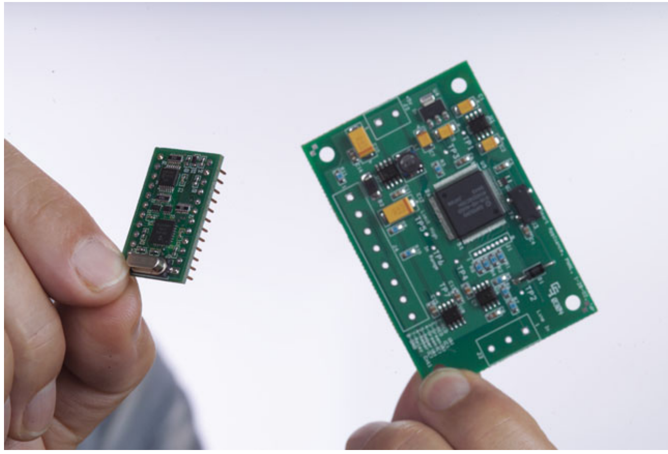


Figure 1. The Project's (Right) and a Newer Version of the GFA Controller

Upon recognizing an underfrequency event, the GFA controller changed the logic state of an output pin. That output signal was detected by both the load-control module and Whirlpool communication processor. The Whirlpool communication processor then converted the signal into the dryers' proprietary serial communication protocol that was then received by the dryers' embedded processors via a cable and port that had been made available for the project on the back panel of the dryers. The Invensys load-control module transmitted the occurrences of underfrequency events and major changes in sensed electrical loads along with a time stamp to home communication gateways. Communication between the gateway, dryer, and water heater was wireless, and the data were relayed from the gateway to a central location for the project via existing broadband Internet connections at the homes.

The water heater module was simpler. It required no Whirlpool communication processor, and the water heater was controlled by the power electronic switch resident in the load-control modules.

Upon receiving the underfrequency signal, the dryer rapidly shed electrical power to its heating elements, but the dryer drum continued to tumble. The dryer load was demonstrated to respond in less than one-half second after the onset of an underfrequency event. The dryer continued to reduce its load until either the GFA control became unasserted or until 10 minutes had elapsed, whichever occurred first. This response to the GFA controller and two additional responses were designed into the dryer's processor controls by dryer manufacturer Whirlpool Corporation. The three responses are summarized in Table 1.

While the underfrequency controller was only partially integrated, the project did achieve interoperability between dissimilar, proprietary protocols of two vendors. Project collaborators have consequently recognized the potential value of reducing energy-response requests to a limited set of Boolean signals at the interface between vendors' products (Eustis, Hammerstrom, and Horst 2007).

The water heaters responded similarly but shed their entire heating load. There was no limit placed by the water heaters on the duration of underfrequency events. The water heater load was shed by the operation of the existing switch in the vendor's load-control module.

The GFA controller allowed no events shorter than about 16 seconds. After becoming set at 59.95 Hz, the controller awaited recovery of the frequency to 59.96 Hz. Then it started a 16-second timer that must elapse before the underfrequency signal would be released. If the grid frequency happened to fall below 59.96 Hz again during that count, the counter restarted. This design was used to avoid rapid changes

Figure 2. (a) Dryer Control Module Components and (b) Dryer Module Installed with a Project Dryer

Table 1. Dryer Response Summary

Bit	Water Heater Response	Dryer Response
GFA	Underfrequency shed: 0—Curtail entire load 1—Release load	0—Immediately turn off heating elements for up to 10 minutes. Drum motor is not affected. 1—Release heating-element load.
Pr	High price response: 0—No action 1—No action	0—Display “Pr” on panel front. User must push start twice to override. 1—No action
En	Demand response: 0—No action (existing GoodWatts LCM response possible) 1—No action	0—Display “En” on panel front. Must push start twice to override. 1—No action

in the appliance load if the frequency were to hover near the threshold frequency. The minimum event duration also verified that the event would be long enough to be recognized and recorded by the load-control modules.

One-hundred-fifty clothes dryers were manufactured and installed, distributed evenly among three project sites—Gresham, Oregon; Yakima, Washington; and on the Olympic Peninsula (Port Angeles and Sequim), Washington. Twenty-five water heaters were retrofitted in Yakima and on the Olympic Peninsula. The local utilities facilitated recruitment from among their customers. Data were collected from these appliances for about 15 months from early 2006 through March 2007. Participating homeowners were given the modified project dryers as a participation incentive. Some participants also received monetary incentives for their participation in the Olympic Peninsula Project (Hammerstrom et al. 2007a) that shared some participants with this project. All project equipment, except the dryer, was removed at the end of the project. Additional details and discussion about the project may be found in the Grid Friendly Project final report (Hammerstrom et al. 2007b).

Defining the Underfrequency Events

PNNL has measured and recorded continuously since 2002 the electrical frequency of the Western U.S. power grid at Richland, Wash. Data points are collected there every 0.1 second. These historical data were used to design the experimental threshold frequency, as was described in Lu and Hammerstrom (2006). Underfrequency events were defined from these measured data each time the frequency data series should have triggered the GFA devices. Indeed, 358 such underfrequency events were defined. On average, an underfrequency event was recognized almost once per day during the project for the given frequency threshold.

Each defined event was further characterized by two parameters—its frequency depth and its duration. *Frequency depth* was defined as the minimum frequency measured during the event from the grid-frequency data series. *Event duration* was defined as the length of time frequency remained below the GFA threshold frequency based on the data series. The distributions of these two parameters are shown in Figure 3. As should be expected, the frequency-depth likelihood decreased rapidly below the threshold frequency. That is, most underfrequency events were shallow, and the frequency did not fall far below 59.95 Hz.

Most events were also relatively short. An interesting maximum (the mode) occurred in the interval representing 10 to 15 seconds. That is, if grid frequency fell below 59.95 Hz, it was most likely that it would remain below 59.95 Hz for only 10 to 15 seconds. Only eight events endured 3 minutes or longer. The longest event encountered during the project was 10 minutes long.

Field Observations

Data were collected from the experimental appliances, and these data were then compared with the occurrences of the defined underfrequency events. This collected data confirmed that the GFA controllers observed and responded to the same events that were observed within the Richland data stream. In Figure 4, the distribution of events recognized and responded to by each GFA controller are shown. Some variability is shown, but the appliances were shown to recognize approximately the same number of events. The average water heater observed 315 ± 82 events. The average dryer observed 322 ± 52 events. Two water heater extreme points were discarded. The standard deviations of these distributions might have been strongly affected (inflated) by several additional errant outliers, but the credibility of these outliers could not be fully discounted. Causes for the low outliers, for example, could have included unplugged or disconnected appliances and poorly communicating monitoring equipment.

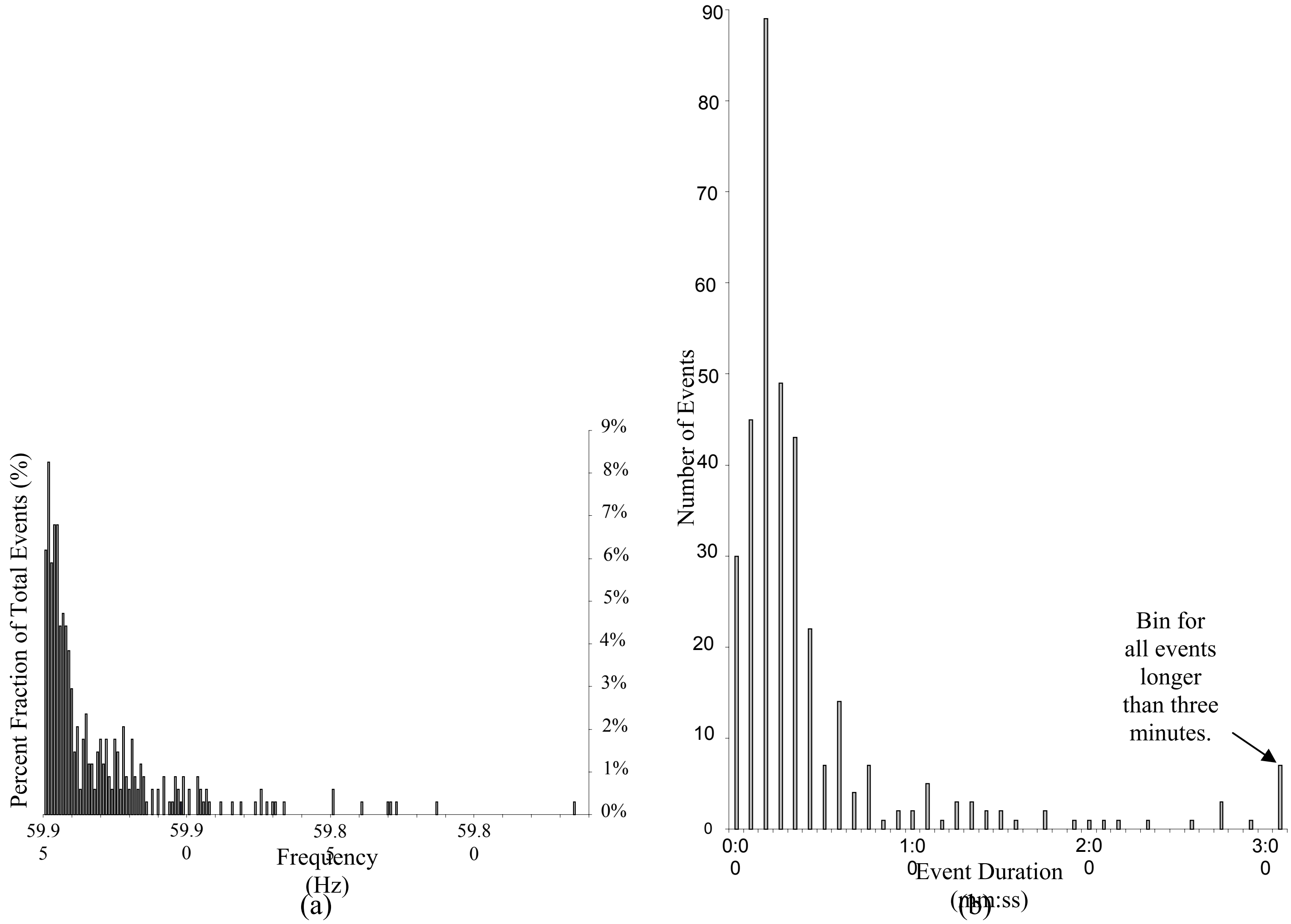


Figure 3. Distribution of (a) Event Frequency Depths and (b) Event Durations

The field data reveal vast anecdotal evidence that the controlled appliances shed load in response to the GFA signals that they received. Figure 5 shows one such time series. Before the GFA event, this project dryer cycled its heating element on and off as it maintained a high temperature within its drum. The power consumption cycled between about 6 kW and 0.5 kW as the appliance turned its heating element on and off. The lower power level was approximately the power needed by the motor that turned the appliance's drum. Upon recognizing an approximately 3-minute underfrequency event, the dryer shed its heating load. After the event concluded, the higher power level resumed, and it took a little longer to reheat the dryer drum.

The accuracy of the appliance power measurements taken by the load-control modules was not critical to the project. The measurements were taken only to confirm that appliance responses were occurring and to crudely estimate, if possible, the magnitude of load affected by the underfrequency responses. While useful and interesting for obtaining anecdotal observations like that shown in Figure 5, the observations of appliance load changes proved somewhat unreliable, and they were therefore not useful for assessing the value of aggregate load responses.

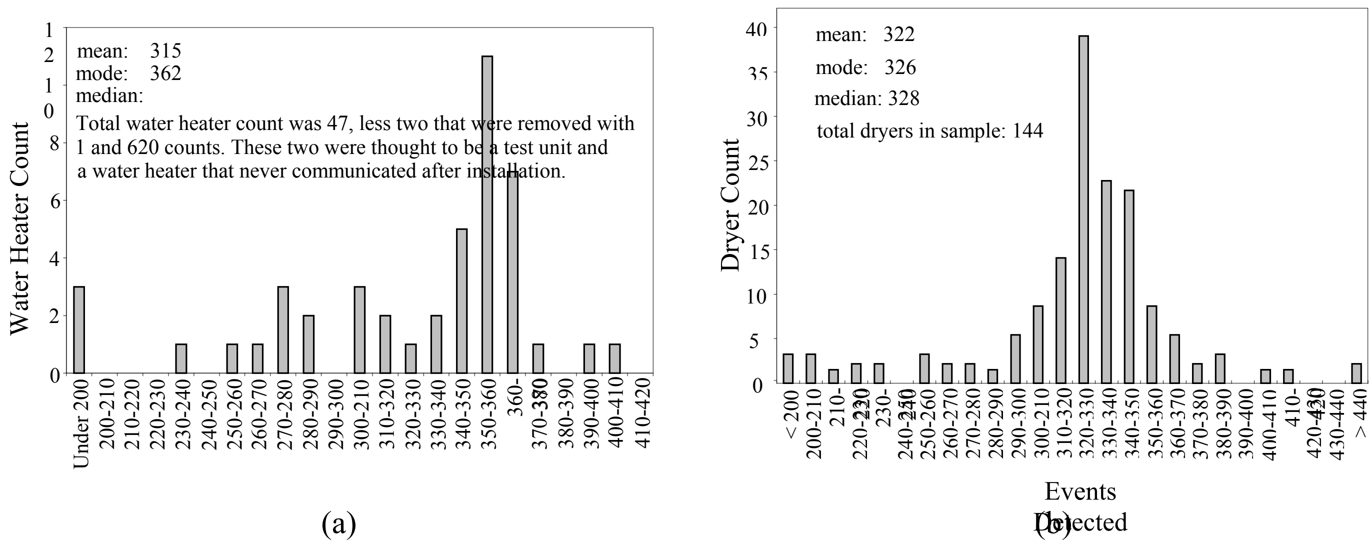


Figure 4. Distribution of Underfrequency Events Observed by Project (a) Water Heaters and (b) Dryers

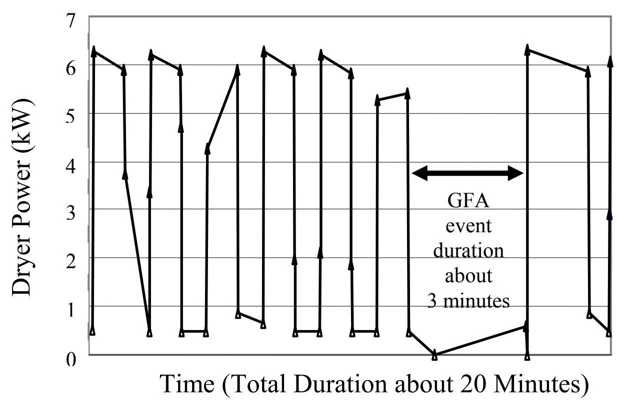


Figure 5. Response of a Single Project Clothes Dryer During a 3-Minute Underfrequency Event

The aggregate underfrequency responses of the appliances were observed in both the time domain and as a function of the event parameters (i.e., frequency depth and event duration).

Figure 6 shows a single, shallow underfrequency event and all the time stamps reported by the load control modules for the event in each of four city project locations. The continuous line shows a frequency history and underfrequency event. When the many GFA controllers sensed this event, time stamps were applied to the event by the load-control modules at the appliances. The discrete time-stamp points were spread out on the vertical axis for visibility purposes only. This spread on the vertical axis has no other meaning. Observe that the reported time stamps were similar across the multiple test sites. However, the measurements were reported to have occurred over almost a full minute, and time stamps were reported both before and after the event. That is unlikely. Furthermore, a 10-second periodicity appeared in the reported time stamps. While these event reports by the distributed appliance modules were useful for confirming whether the events were or were not sensed, these data-quality issues (data periodicity, inaccurate timing match with frequency data stream) limited any conclusions that could be made about response durations or about the rapidity or propagation of the responses in the field.

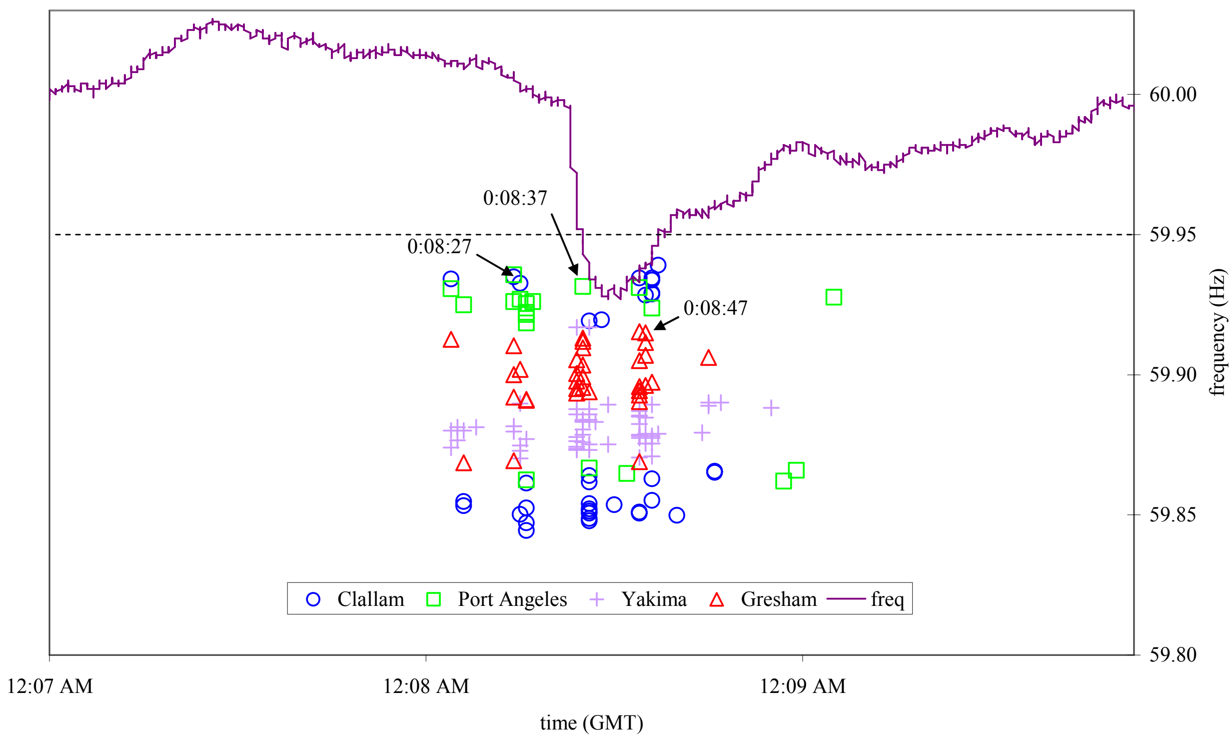


Figure 6. An Underfrequency Event and the Time Stamps Reported for the Event by Appliances

Figure 7 represents the aggregate responses of all the GFA controllers as a function of frequency depth, one of the two event parameters introduced earlier. The frequency depth increases from the left and the threshold frequency toward the right. There are two points shown for each defined underfrequency event—one for the project dryers and one for the project water heaters. Each point represents a pairing of the percentage of appliances that successfully recognized an event and the lowest frequency observed during the event (i.e., the event's *frequency depth* that was defined earlier).

It is apparent from Figure 7 that virtually all the GFA controllers successfully detected and responded to any underfrequency event that fell 0.003 Hz or more below their frequency threshold. Very shallow events showed less unanimous responses. This level of successful detection is remarkable given the geographical distribution over which the devices were spread and given that the responses were compared to a standard (the Richland frequency data stream) that was defined at a point still farther away from the GFA controllers.

Correlation of Events to Appliance Use

Having shown that a reliable and predictable underfrequency response can be achieved by the GFA controllers over a large geographic area, it remains to be shown how the responses of these appliances could affect the grid. For example, how many water heaters or dryers must be made frequency responsive to achieve a given aggregate load shed? Because the GFA controller approach relies on many distributed responsive loads, a statistical argument is offered. The occurrences of the project's underfrequency responses and the average power consumptions of the water heater and dryer appliances over time were correlated to address this question.

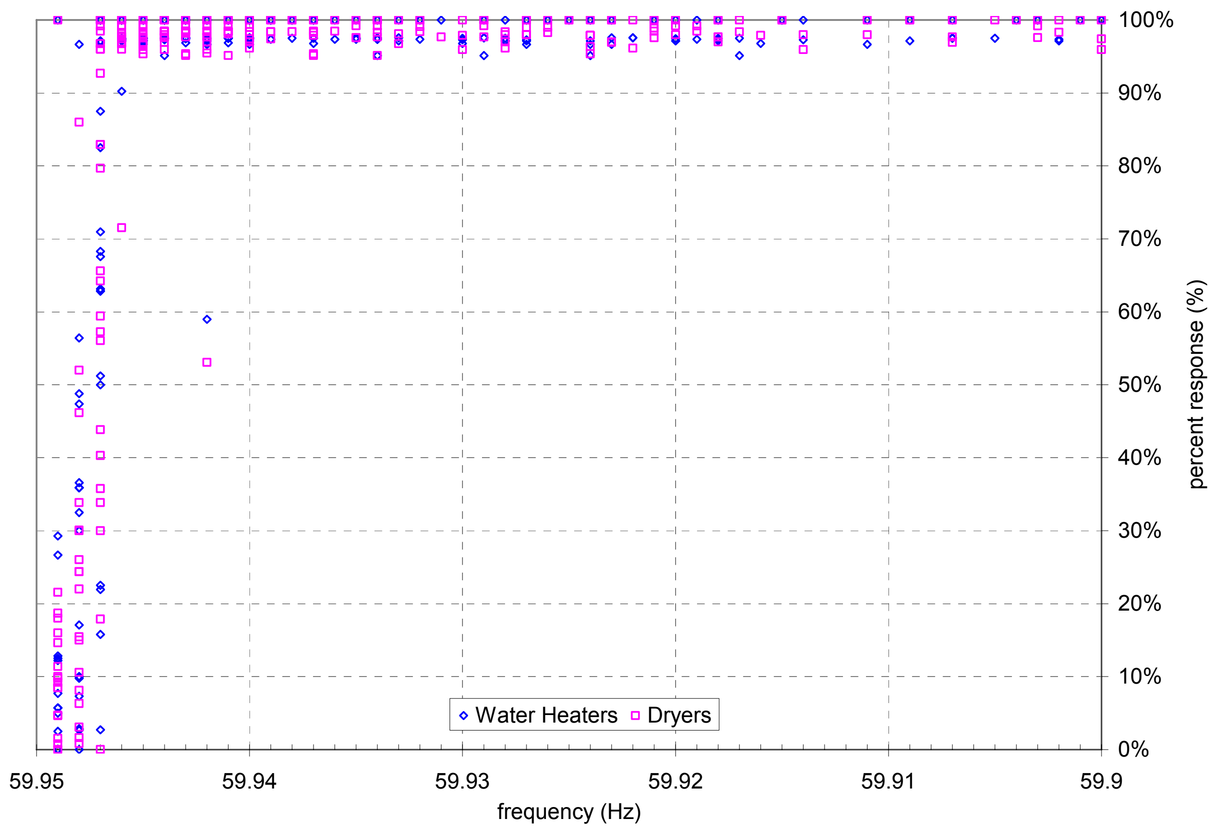
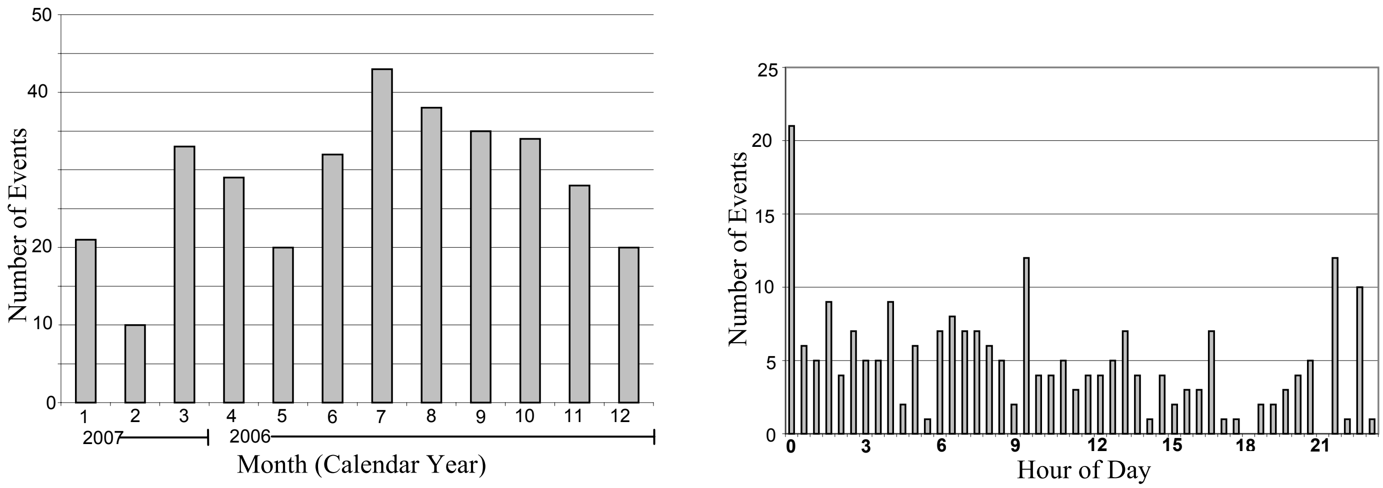


Figure 7. Percentage of GFA Controllers Successfully Detecting Events versus Event Frequency Depths

First, one should address whether there exists any discernable pattern or predictability for the occurrences of the underfrequency events. Figure 8 shows the distribution of project underfrequency events by month of year and by hour of day. In Figure 8(a), there appears to be a trend for more underfrequency events to occur in the warmth of summer (July 2006). Indeed, it is reasonable that frequency might be less stable while the power grid is stressed by air conditioning loads. But multiple years' data would be needed to confirm this trend, and some underfrequency events were observed during every project month.

In Figure 8(b), the occurrences of underfrequency events are shown by the hour on which they occurred. Each bar represents one-half hour. An unexpected concentration of events appeared during the first half hours of each day (12:00 to 12:30 AM) according to this figure. While the many occurrences at the beginnings of days were confirmed by collaborating utilities, no reason for the many early-morning events could be found, and the collaborating utilities thought that the many early-morning occurrences must be an anomaly. No other clear trend can be supported from the distribution.

The project next looked at the load curves for the water heaters and dryers. These data were available from energy services provided to the homeowners by Invensys Controls. Appliance usage data were available to the project at 15-minute intervals. Figures 9(a) and 9(b) show the average daily load profiles for the water heaters and dryers, respectively. Four curves are shown on each figure—one for each quarter of the year. The quarterly differences are interesting, but they probably do not differ enough to greatly affect the present argument. Also, these load curves were for Northwest appliance owners and may not be transferable to other regions.



(a) (b)

Figure 8. Total Underfrequency Events Recorded by the Project by (a) Month and (b) Hour

The water heater load shows a morning and an evening peak. The shape is similar to that of an entire residence in the Pacific Northwest. At most, about 700 W is available to be shed, on average, by each electric water heater between about 6 and 9 AM. The water heaters can shed only about 100 W each, on average, from midnight until about 4 AM.

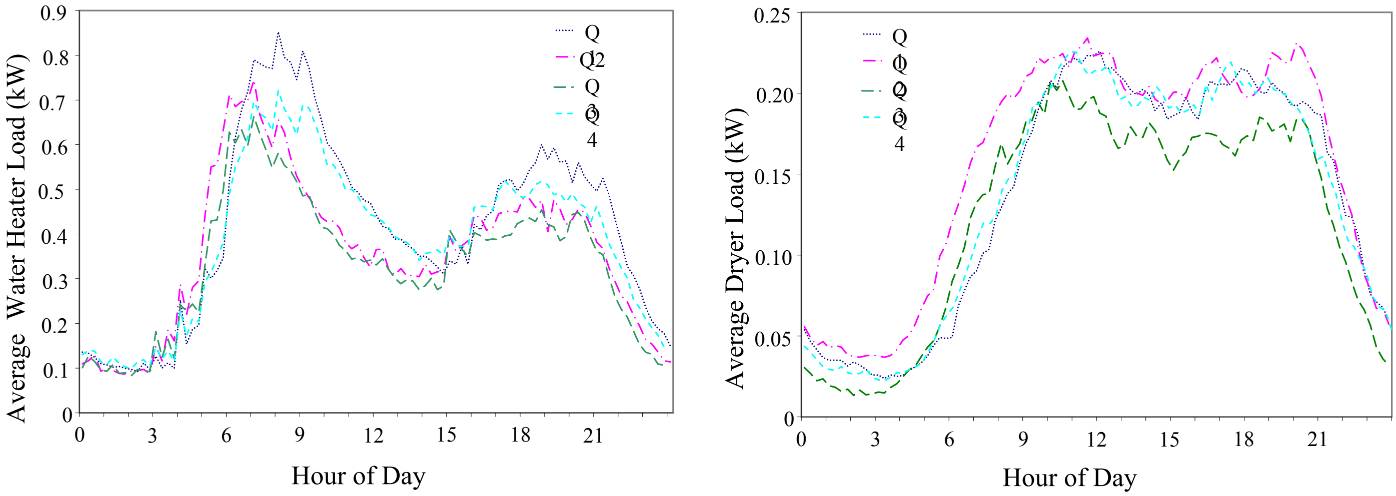
The dryer's average electrical load is somewhat smaller at about 200 W per appliance. However, the load value is very flat throughout the day. Only about 25 W are available, on average, for each dryer from midnight until about 4 AM.

These results should scale reasonably well in the Pacific Northwest. For example, given these load curves, it would take at least 1,400 and at most 10,000 electric water heaters fitted with the GFA controller to achieve 1 MW of underfrequency-responsive water heater load, depending on time of day. It would take about 5,000 dryers to achieve 1 MW of fast, underfrequency-responsive load throughout most of the day.

Future Opportunities for Autonomous Controllers

This project demonstrated that small loads like appliances can participate reliably in underfrequency responses from the demand side. Their participation could reduce the need for costly spinning reserves on the power grid. Service providers have perhaps begun to recognize this value, but the industry could hasten the adoption of these tools by providing commensurate incentives. Further efforts are also underway to reduce the costs of providing and installing such controllers, thus improving their ability to compete among other controllable resources available to grid operators.

The author understands too that while each appliance load is small, the simultaneous responses of multiple megawatts of appliance load done improperly could harm grid stability. Algorithms for the graduated shed and release of loads must be further developed and tested. Overall, this potential resource must be designed alongside and coordinated with other demand- and supply-side resources available to system operators.



(a) (b)

Figure 9. Average Daily Load Curves for the Project's (a) Water Heaters and (b) Clothes Dryers

While this paper addressed only underfrequency stability responses, autonomous devices also have the capability and opportunity to respond in the narrow frequency band around 60 Hz where they could help regulate grid frequency. This capability may prove especially valuable in micro-grids where supply-side regulation resources might be scarce. With exogenous communication, small loads could also participate in more traditional regional regulation services now accomplished through generation control.

The GFA also has access to and monitors system voltage. It can, therefore, in principle, contribute to system voltage stability on feeders. Early demonstrations have been completed at PNNL for the application of the GFA controller to induction motor loads that exacerbate fault-induced voltage sags. Appliance controllers should also provide delayed cold-load pickup of large loads to facilitate the re-energizing of the grid and individual feeders after outages.

And finally, an autonomous controller that can sense small voltage or frequency changes could receive these small changes themselves as communication signals, negating the need for additional external communications between utilities and the controlled loads. This is perhaps an opportunity for achieving very inexpensive demand response.

Conclusions and Recommendations

The GFA autonomous, underfrequency load-shed controller was applied to almost 200 water heaters and clothes dryers in homes widely distributed over the Pacific Northwest. Over 350 shallow underfrequency events were observed and responded to by these controllers during the project. The GFA controller reliably detected and responded to the underfrequency events on the electric power grid.

Few clear trends were observed for the times at which such underfrequency events might be predicted to occur. Their occurrences were quite random. Based on measured load curves, the average clothes dryer represents about 200 W of load that can be shed throughout most of the day. Each water heater represents up to 700 W of load, on average, available to shed. These controllable loads were much smaller during early morning hours.

No technology hurdles prevent the application of autonomous appliance controllers for underfrequency load shedding. More research will be needed to properly coordinate these resources with existing demand- and supply-side resources as these tools become adopted. The technology will be economically more attractive if standardization occurs, making future appliances delivered to consumers ready to respond to these and other devices.

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