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A Field Test of Direct Load Control of Water Heaters and its Implications for Consumers

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***Abstract*—Utilities and customers are now operating more closely than ever. The prevailing numbers of grid-interactive Distributed Energy Resources are being integrated to provide grid reliability and stability. Different methods of control have been implemented to utilize these Distributed Energy Resources, such as Service-Oriented Load Control and Direct Load Control. This paper investigates the issues associated with the latter. A Direct Load Control method is applied to two Distributed Energy Resources, Electric Water Heater and Heat Pump Water Heater. A load shifting scenario is created where each water heater turns off during water draw events that coincide with peak demand periods. The results of the tests indicated a significant decrease in the temperature of the water in the tank. This implies that using Direct Load Control to control water heaters adversely impacts customer comfort which might lead to unenrollment from Demand Response programs.**

***Index Terms*—Load Management, Direct Load Control, Service-Oriented Load Control, Distributed Energy Resources, Demand Response.**

I. Introduction

Advancements in communications technologies and smart energy protocols are enabling new ways of interaction between utilities and end-users. Electricity consumers are becoming active participants by providing utilities with means to ensure grid reliability and stability. With these advancements, the deployment of Distributed Energy Resources (DERs) has become economically feasible and, therefore, widely used. For instance, grid-interactive inverters provide functions such as frequency-Watt and Volt-VAr curve control [1], [2]. These curves can be updated by a utility using the Smart Energy Protocol (SEP) 2.0, also known as IEEE 2030.5 [3].

In general, DERs are grid-interactive customer-owned generation, storage, and load assets, which typically provide power and energy on the kW/kWh scale. Dispatched in large aggregations, however, DERs can provide meaningful, multi-MW scale impact within a balancing area [4]. Battery-Inverter Systems (BISs) are another example of DERs that are finding market share and are being aggregated to provide grid services. As well, though a more nascent trend, utility customers are purchasing grid-interactive consumer appliances. These appliances use other smart energy protocols such as CTA-2045, EcoNet, or SunSpec to facilitate information exchange between the appliance and a utility [5], [6].

DERs may be controlled using Service-Oriented Load

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Control (SOLC) or Direct Load Control (DLC). In the latter, a utility has direct control of a customer's DER. DLC has been used for decades. Florida Power Corporation developed a large-scale DLC program, starting in 1979, which aggregates a diversity of DERs, including Electric Water Heaters (EWHs), central air-conditioners, and pool pumps [7]. DLC has enabled deployment of multiple utility programs that use large aggregations of customer appliances to provide Demand Response (DR) service [8]–[10]. However, customers participating in a DLC-based DR program do not have control over their DERs, beyond initially enrolling in a program. The utility may disconnect the customers' DERs at any time for a duration of its choosing, regardless of customer preference.

DLC DR programs that use Thermostatically Controlled Loads (TCLs), such as water heaters, have been shown to cause customer discomfort [11]. Therefore, various DLC algorithms have been proposed that provide grid services and maintain end-users comfort levels [12], [13]. For instance, Hashem et al. demonstrate a voltage control method that reduces peak load demand. Though the simulation results showed a drop in the peak load when less voltage is applied to EWHs heating elements, customers may experience excessive hot water in practice, so customer comfort is not guaranteed.

SOLC is a modern approach to load management. It is based on Service-Oriented Architecture (SOA), which is the principal architecture for providing services within the internet, as well as among devices within IoT networks [14], [15]. SOA has been proposed for information exchange between networked consumer appliances using a platform-independent protocol [16], [17]. SOLC is SOA applied to utility load management. By adopting a service-oriented framework, SOLC ensures the customer remains in control of their DER [18]. For SOLC, a service provider, the utility, provides a list of services to a service registry. A service requester, the DER controller, identifies services from within the service registry. The service requester then binds to the service provider to invoke a service [19]. The DER owner may interface with the controller to authorize or override a service request. By adopting SOLC, customers retain the choice to participate in services, thereby leaving them in control of their DER.

In this work, we explore the implications associated with DLC. We created automated load control and peak-load shifting scenarios to investigate DLC implications. The test station used for this study features two CTA-2045-equipped water heater units [20]. CTA-2045 enables residential devices to provide energy management and control services [21]. However, for this work we use the CTA-2045 capabilities strictly to control the conditions of our DLC tests and record test data. Each water heater unit is equipped with a Distributed Control System (DCS), which translates instructions from the test operator to CTA-2045-equivalent commands. The DCS also records test data, including thermal energy stored within the tank, power consumption, and the volume of water draw events.

The baseline case for this study shows the water heater behavior without the load shifting scenarios. The results obtained from the cases where the load shifting scenarios are applied then compared with the baseline case. Thus, the implications of DLC are studied and analyzed.

This paper is organized as follows: In Section II, we describe the CTA-2045 commands used for this work, the DCS, the aspects of the load-shifting scenarios, and the water heaters' *EnergyTake* characteristics. Section III discusses and analyzes the results of two presented case studies. Finally, this paper is concluded in Section IV.

II. Testing Methods

A. Water Heater Messaging

In this work, we use the CTA-2045 protocol to read the water heaters' properties and send basic control commands. The control commands in the CTA-2045 standard are, by design, not able to switch off the water heaters completely. Instead, control commands have windows of operation relative to the thermal energy stored within the tank. These windows of operation are defined by the DER manufacturer. For example, a frequently used command in this work is the *load up* command. This command instructs the water heater to heat the water in the tank until the *EnergyTake* is zero, which occurs when an internally-measured tank temperature reaches a customer-specified set point.

The *EnergyTake* is the amount of electrical energy that a water heater would need to consume to heat the water in its tank to the temperature set point. As the *EnergyTake* increases, the tank water temperature decreases. Generally, when a water heater is in idle mode, it tends to slowly lose energy. This is known as "idle losses," and results in a gradual increase in *EnergyTake*. *EnergyTake* increases rapidly when a water draw occurs, wherein hot water is removed from the tank and replaced with cold water from the household water supply. *EnergyTake* decreases when the water heater energy source turns on, and it is zero when the tank temperature equals the temperature set point.

Through observations, we have found that the EWH and Heat Pump Water Heater (HPWH) windows of operation for this command are $120°F$ - $117°F$ and $120°F$ - $118°F$, respectively, when the set points of both units are $120°F$ [22]. We use the *load up* command to preheating the water heaters prior to a DR event, thereby ensuring consistency between test cases. Fully-charged water heaters present "best case" scenarios before the onset of DR events. The water heaters retain more hot water during DR events and experience lower power ”bounce back” consumption at the conclusion of DR events, thereby defining an upper bound on performance.

B. Distributed Control System

Both water heaters in our test bed are equipped with a Distributed Control System (DCS), which manages control commands and reads the units' states [22]. As mentioned previously, the DCS translates instructions from the test operator into equivalent CTA-2045 commands. The DCS also sends a CTA-2045 commodity read query to the water heaters once per minute. This query is used to report the water heater power consumption in Watts (W) and *EnergyTake* in Watts-hour (Wh). The DCS also records water draw volumes via flow meters.

C. Direct Load Control Actuation

This work explores the implications of using DLC to manage water heaters. Our water heater station includes two water heater units, each energized through a Remotely-Controlled Circuit Breaker (RCCB). The RCCBs are used to actuate DLC events (This is not advisable for compressor-based DER, such as HPWH). The water heater units are a dual-heating element EWH and a hybrid (heat-pump & heating element) HPWH. Each water heater unit is set to draw water multiple times per day, simulating a household water draw routine. By using the RCCBs to provide DLC, load control scenarios can be initiated during select periods.

D. Load Control and Water Draw Events

The goal of a DR program is to shift power consumption to low demand periods, which correlate with off-peak loading periods. For example, water draws that occur during a peak demand period would not immediately trigger a recharge; power consumption would be shifted to an off-peak period. This is achieved via

TABLE I

AUTOMATED WATER DRAW SCHEDULE

Event	**Time**	**Amount** (gpm)	**Duration** (Minutes)
Morning Shower	6:45 a.m.	20	9
Dish Washer	7:00 p.m.	5	2
Evening Shower	8:00 p.m.	10	5

DLC by opening the RCCBs at the onset of a peak demand period, then closing them afterwards. However, as stated previously, the objective of this work is to explore DLC management of water heaters and the implications for customers, rather than evaluating peak demand mitigation during peak demand periods.

E. Water Heater EnergyTake Characteristics

As stated in Section II-B, the DCS reports the *EnergyTake* of the water heaters once per minute. The *EnergyTake* is the amount of electrical energy that the water heaters would need to consume to heat the water to the temperature set point. The *EnergyTake* thermostat dead-band and set points are defined by the manufacturer. During normal operations, the thermostat dead-band for the EWH ranges between 0 Wh and 900 Wh. Once the *EnergyTake* reaches 900 Wh, the heating element turns on and heats the water to the specified set points.

The HPWH, however, has two heating sources: a compressor and a resistive heating element. The compressor turns on when the *EnergyTake* reaches 675 Wh. The compressor then gradually heats the water to the specified set point. The heating element, on the other hand, only triggers if the *EnergyTake* reaches 2000 Wh, indicating an excessive water draw. It then rapidly heats the water, though not to the specified set point. Once the *EnergyTake* reaches 1000 Wh, the heating element switches off and the compressor turns on to heat the water to the specified set point. This HPWH control logic causes a delay when responding to CTA-2045 commands.

III. CASE STUDY ANALYSIS

Prior to demonstrating water heaters behavior while using DLC, we first ran a baseline case to determine the real power and *EnergyTake* trends when CTA-2045 *load up* commands are sent to the water heaters units. All tests were conducted over a full day period. The water heaters are set to automatically run three water draw events. Each water draw event is distributed over a time period, which is monitored by a flow meter. The starting time, amount, and duration of each water draw event are shown in Table I. The DCS collects data throughout the day to record the EnergyTake of each unit, in Watts-hour, and the power consumption, in Watts. The baseline case results are contrasted against the DLC load-shifting cases, which are presented in Section III-B. To implement DLC, each water heaters is switched off at the onset of a DR period by opening the RCCBs. Later, each water heaters is switched back on after the DR period ends by closing the RCCBs.

A. Baseline Test Cases

*1) **HPWH Behavior**:* Figure 1 shows the *EnergyTake* (top) and the power consumption (bottom) trends for the HPWH when a *load up* command sent. The HPWH reports the *EnergyTake* in 150 Wh increments. A *load up* command is sent to the HPWH 50 minutes prior to the first water draw event, taking into consideration the time it needs to heat the water. Once the *load up* command is received, the HPWH fan turns on for one minute, then the compressor turns on. For the first water draw, at 06:45 a.m., the *EnergyTake* reached 1425 Wh. This *EnergyTake* value is equivalent to a water temperature of approximately 109°F. This large temperature drop is attributed to the 20 gallon water draw event.

The HPWH takes 107 minutes to recover and heat the water to 120°F. The HPWH reports a 150 Wh increase in *EnergyTake* at 04:00 p.m., which is in response to

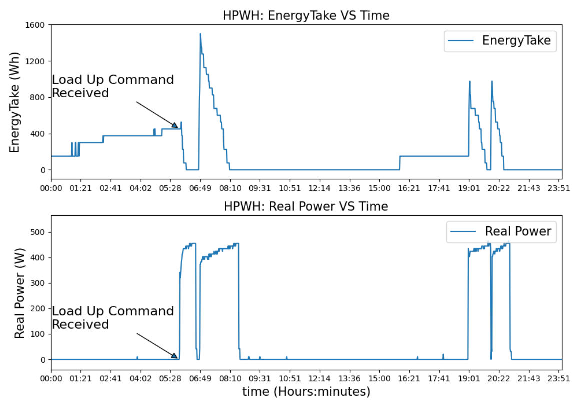

Fig. 1. HPWH Baseline Case: *EnergyTake* (top) and Power Consumption (bottom) with ONLY *load up*

idle losses. The next scheduled water draw event occurs at 7:00 p.m., which is five gallons. The HPWH takes 50 minutes to recover. Lastly, a ten gallon water draw event occurs at 8:00 p.m. The recovery time for this event is 60 minutes. The reported *EnergyTake* for the evening water draw events is 975 Wh. Note that for the water draw events at 07:00 p.m. and 08:00 p.m., the DCS did not send a *load up* command to the HPWH. The *load up* command minimum threshold is 200 Wh. Since the *EnergyTake* had not exceeded 200 Wh, the *load up* command would have been ignored by the HPWH.

The HPWH power consumption behavior is shown in Figure 1, bottom plot. The first power surge, at 05:55 a.m., occurs because of the *load up* command that was sent to preheat the HPWH to $120°F$. The second surge, at 06:50 a.m., was caused by the morning water draw event at 06:45 a.m. Note that these water draw events triggered the compressor; the heating element remained OFF for the full day period of this case study. Therefore, the peak power consumption of the HPWH is approximately 450 W, attributed to the compressor.

*2) **EWH Behavior**:* The *EnergyTake* and the power consumption of the EWH are shown in Figure 2. Unlike the HPWH, the EWH reports *EnergyTake* in 75 Wh increments. Two *load up* commands were sent to the EWH, one prior to the morning draw and one prior to the evening draws. The EWH responded to the *load up* commands in less than 20 seconds. Since the EWH takes significantly less time to heat the water, a *load up* command was sent 10 minutes before each water draw event, which was sufficient to heat the water up to the specified set point prior to the water draw events.

Figure 2 shows that the EWH *EnergyTake* due to the 20 gallon water draw event at 6:45 a.m. is 1325 Wh. This *EnergyTake* value is nearly equal to the recorded *EnergyTake* in the HPWH case, which was 1425 Wh, as would be expected since the water draws were of the same volume. However, in the EWH case, the heating element triggers less than one minute ($\approx$ 56 seconds) after the start of the water draw. This occurs when the temperature threshold is reached (corresponding to an *EnergyTake* of around 900 Wh). This is a fast response compared to the HPWH, which requires approximately two minutes for the compressor to turn on. Therefore, the recovery time is greatly decreased, by 90 minutes, in the EWH case. The next water draw event starts at 07:00 p.m., followed by a third at 08:00 p.m. The recorded *EnergyTake* values for both events are 975 Wh and 1200 Wh, respectively.

B. Load Shifting Test Cases

In Section III-A, we demonstrated the water heaters behavior when running the water draw schedule shown in Table I with a *load up* command sent prior to each water draw event. In this section, however, a DLC scenario is simulated by sending a command to the RCCBs, which switches the water heaters off five minutes prior to each water draw event. The impact of the DLC scenarios on the *EnergyTake* and power consumption are discussed in the following sections.

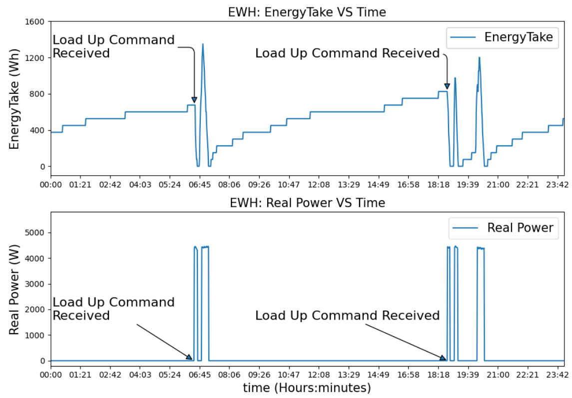

Fig. 2. EWH Baseline Case: *EnergyTake* (top) and Power Consumption (bottom) with ONLY *load up*

*1) **HPWH Behavior**:* Figure 3 shows the HPWH *EnergyTake* (top) and power consumption (bottom) over a 24 hour period. A *load up* command was sent at 05:30 a.m. to heat the water in the tank to the set point, $120°F$. Since the *EnergyTake* was less than the heating element threshold ($\approx$ 2000 Wh), only the compressor triggered and remained on for approximately 60 minutes. At 06:40 a.m., five minutes prior to the 20 gallon water draw event, a command was sent to open the RCCB, thereby turning the HPWH off. 30 minutes later, at 07:10 a.m., the RCCB was instructed to close, thereby switching the HPWH back on. As a result of switching the HPWH off, the communications with the DCS are also interrupted. Therefore, the EnergyTake is not reported during the DLC period. Since the HPWH did not turn on during this period in response to the water draw event, the *EnergyTake* reached 3400 Wh ($\approx 92°F$). Due to the opening of the HPWH RCCB, the effect of the *load up* command was diminished and, therefore, it neither reduced the recovery time nor mitigated the peak power consumption, as shown in Figure 3.

Note that in this case, the *EnergyTake* is recorded to be well in excess of its normal maximum compared to the baseline case. For the same water draw event in the baseline case, Figure 1, the recorded *EnergyTake* was 1425 Wh ($\approx 108°F$). Furthermore, in the baseline case, the heating element of the HPWH did not trigger during the 20 gallon and ten gallon water draw events. Only the compressor turned on and heated the water to the specified set point. In this case, however, the heating element of the HPWH triggered, indicating an excessive drop in the tank water temperature. This immoderate *EnergyTake* indicated that the tank temperature is well below the temperature set point, $\approx 92°F$, which could very well result in customers not having sufficient hot water.

Another RCCB command was sent at 6:55 p.m., five minutes prior to the five gallon water draw event. Normally, the HPWH takes 50 minutes to recover from such a water draw event. However, the HPWH switched back on at 07:25 p.m., which reduced its recovery time window. Therefore, the compressor triggered for only 25 minutes before it was interrupted by another RCCB command at 07:55 p.m. At 08:25 p.m., the end of the DLC period, the HPWH came back online. Since the HPWH did not heat the water completely after the five gallon water draw event at 07:00 p.m., the *EnergyTake* built up and reached 3075 Wh ($\approx 95°F$). These high *EnergyTake* values are likely enough to result in customers discomfort.

Note that the power consumption plot in Figure 3 shows three very brief power surges after each DLC period ends. The reason for these surges is that when the HPWH comes back online, the heating element automatically turns on for a minute and then turns off. These brief surges occur during the boot sequence that initiates after the HPWH becomes energized, regardless of the *EnergyTake*.

*2) **EWH Behavior**:* Figure 4 (top plot) shows the *EnergyTake* behavior of the EWH during the DLC test. A *load up* command was received at 06:16 a.m. to pre-

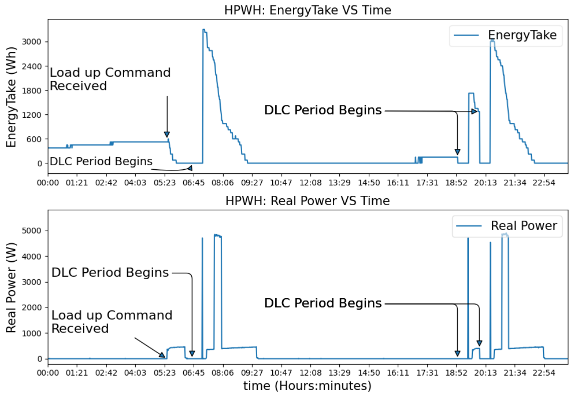

Fig. 3. HPWH Load-Shifting Case: *EnergyTake* (top) and Power Consumption (bottom) with *load up* and DLC commands

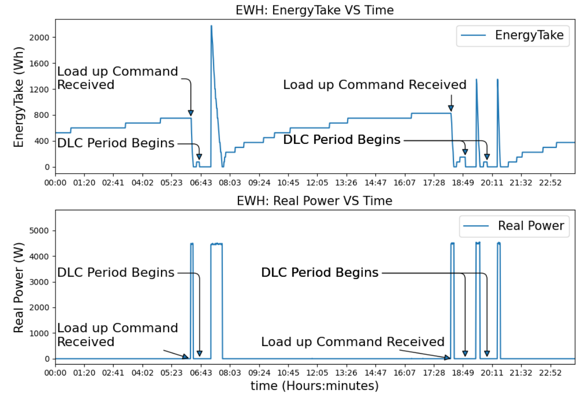

Fig. 4. EWH Load-Shifting Case: *EnergyTake* (top) and Power Consumption (bottom) with *load up* and DLC commands

heat the water in the tank. The heating element brought the water to the set point in seven minutes. An RCCB command was sent at 06:40 a.m., de-energizing the EWH five minutes prior to the 20 gallon water draw event. The EWH came back online 30 minutes later, after the DLC period ended. As the EWH was offline during the water draw event, the heating element did not trigger and the *EnergyTake* reached 2200 Wh ($\approx 100°F$). For the same water draw event in the baseline case, Figure 2, the *EnergyTake* reached only 1325 Wh ($\approx 107°F$). The difference in *EnergyTake* between the EWH baseline case and the DLC case is 875 Wh. As such, the water temperature in the tank is $7°F$ lower in the DLC case. The *EnergyTake* then gradually increased after the first water draw event until it reached 825 Wh by 06:30 p.m., due to ambient losses. A *load up* command was sent to heat the water in the tank before the second water draw event at 07:00 p.m. The RCCB was opened at 06:55 p.m. to switch the EWH OFF for a 30 minute DLC period. The EWH came back online at 07:25 p.m. Unlike the HPWH, the EWH recovery time period was short enough to heat the water to the specified set point, $120°F$, before the next DLC period started at 07:55 p.m. While the EWH was offline, a ten gallon water draw event occurred at 08:00 p.m.

IV. Conclusion

As communication technologies advance, deployment of customer-owned loads to provide grid reliability is becoming feasible. Different methods of control have been implemented to use such loads. DLC, particularly has been widely used by utilities to integrate customer-owned appliances to provide DR services. This paper investigates the issues associated with DLC using grid-enabled EWHs and HPWHs.

Our results show that *EnergyTake* can rise significantly if water heaters are de-energized during DLC periods, particularly if water draw events occur during those periods. These very high *EnergyTake* values indicate the water temperature is well below the tank temperature setpoint, and therefore, much less hot water is available for the customer. Customer dissatisfaction has been shown to result in complaints and unenrollment from DR programs [11]. DLC of water heaters is likely to adversely impact customer comfort, which could result in lower customer participation.

Alternatively, rather than de-energizing an appliance using an RCCB, DR can be realized using a protocol that abstracts the load reduction as a function. For instance, a function could be used that instructs a grid-interactive appliance to remain off unless a manufacturer-defined comfort threshold is crossed, for example, by lowering a temperature set point just a couple of degrees below the customer's set point. Each water heater would contribute less to the DR response, but customer program retention would likely be higher.

Alternatively, service providers could use DR programs that employ Service-Oriented Load Control. For a SOLC DR program, the service provider posts a list of DR services, to which DER controllers have access. The DER controllers select DR services that they are capable of providing. This process may even involve the DER owner to authorize or override this service selection. Thus SOLC ensures customers remain the final arbiters of service participation, which should improve customer satisfaction, and result in higher levels of customer participation to the benefit of the service provider.

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