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Impact of Price-Responsive Load and Volt-VAr on Power Quality, Losses, and Customer Economics: A Distribution Grid Case Study

David Holmberg
Thomas Roth

NIST | NATIONAL INSTITUTE OF
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U.S. DEPARTMENT OF COMMERCE

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David Holmberg
Building Energy and Environment Division
Engineering Laboratory

Thomas Roth
Communications Technology Laboratory

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NIST Author ORCID iDs
David Holmberg: 0000-0002-1738-8190
Thomas Roth: 0000-0002-9986-7784

Abstract
This report presents insights into the impact of distributed energy resources (DER) price-responsive behavior on voltage for a distribution grid with significant customer-owned solar photovoltaics (PV) and batteries in addition to price-responsive heat pumps and water heaters. Price responsive loads result in more variable power flows and voltages. While peak load is reduced, significant amount of flexibility (load response) in this distribution grid increases the total power flow and voltage variation across the day while reducing hosting capacity. That is, while the loads on the grid provide significant flexibility to the bulk grid, this flexibility comes at the expense of voltage variability and significant power flow changes and even reverse power flows at the substation.

The model R4-12.47-1 (R4-1) distribution grid, with 523 houses representing most of the load, and each house with PV, batteries and price-responsive loads, was modeled in GridLAB-D. Simulations were run with GridLAB-D in a co-simulation environment using a NIST-developed device controller. Voltages, power flows, transformer loading, and losses are examined at different points on the grid. Simulations include price-response as well as Volt-VAr control to see how Volt-VAr can support the voltage impacts of price-responsive devices.

Devices responded primarily to day-ahead market hourly prices (DAP). In addition, response to 5-minute real-time market prices (RTP) was examined. Load controllers seek to maximize economic benefit for the customer, reducing consumption (or discharging storage) during high prices and shifting load to low price times. In addition to load response, Volt-VAr control of PV and battery inverters was used to demonstrate the amount of voltage support that could be provided and was shown to successfully pull the mean grid voltage down to within ANSI Range A limits.

The grid flexibility (amount of load that can be shifted) using battery charge/discharge plus setpoint temperature adjustment on the heat pump and water heater equals as much as twice the baseline peak grid load. The peak load for these experiments was 3 MW. The flexibility on this R4-1 grid moved demand up and down with a swing range of 6 MW when all responsive loads are turning on and off together due to rapid price changes. This behavior, in turn, can move average house voltage by 4 V. However, this amount of movement was only seen for the more volatile RTP signal, not for response to the DAP signal where the voltage range increased 25 % over the baseline 2 V range.

The observed decrease in hosting capacity is primarily a function of the mismatch of the flexibility response on this distribution grid compared to the grid as a whole. The results here provide a glimpse of challenges that could be encountered with price signals and price-responsive devices when too many devices respond to strong price signals. Recommendations are made for how a utility might craft a price signal that better supports voltage control.

Customers' payment for electricity depended greatly on the tariff (price signal) with average electricity charges across two days ranging from \$2 up to \$10.

Keywords

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1. Introduction

The current focus on using solar photovoltaics (PV) and wind generation moves us toward more intermittent power supply and, in turn, requires more storage in the system to balance out supply and demand. While additional utility-scale battery storage is one solution to the storage challenge, another is access to the electrical and thermal storage behind the customer meter. For residential customers, this storage is primarily contained in the thermal mass of the building and is made accessible via the heating, ventilation, and air conditioning (HVAC) system, electric domestic hot water (DHW) tanks, and battery systems that are often paired with rooftop solar [1]. Additionally, attention is being given to the flexibility provided by electric vehicle batteries that may serve to charge when the sun is shining and perhaps support voltage and capacity needs [2].

Variable supply must be paired with dispatchable generation and reserves (including storage) such that actual customer load can be reliably served. Utilities have traditionally accessed customer demand response (DR) when the grid is stressed. Electricity wholesale markets have also allowed aggregated DR to bid into the markets on the supply side. This approach to reducing load has proven successful [3]. Nonetheless, the grid is moving into new territory as more PV is added to the distribution system itself. Distributed PV provides power generation closer to where it is needed (*i.e.,* the load), which reduces losses, but also creates voltage challenges. Voltage is impacted on a congested distribution grid by PV over-generation during the midday and by loss of generation as the sun sets and load increases to an early evening peak.

One promising option is to pair distributed renewables with distributed customer flexibility. If PV arrays are over-producing, or causing voltage fluctuations, then the best place to compensate for these effects is at or close to the generation source. That is, to use local customer distributed energy resources (DER), including batteries and flexible load, to stabilize the voltage. Flexible loads and storage can consume more electricity when voltage is high while reducing consumption when voltage is low. Additionally, customers' inverters can raise and lower voltage [4–6] via reactive power support.

Flexibility is the capability of DER, including generation, storage, and loads, to adjust a building's demand profile across different timescales in response to grid needs [7, 8]. Grid needs are communicated by DR event signals, price signals, or automatic sensing (e.g., voltage and frequency). Customers may receive payments or other incentives via a market or DR program for being responsive.

While traditional event-based DR has been used sparingly, dynamic price tariffs can enable 24/7 DER flexibility as intelligent devices respond to price signals [9]. Dynamic tariffs include time-of-use (TOU) as well as retail price signals based on wholesale energy market clearing prices (whether real-time or day-ahead). The day-ahead price (DAP) is useful for planning storage charging and discharging to minimize cost [10]. The real-time market price (RTP) is valuable for engaging customer DER response to current (unforeseen) grid conditions. However, RTP is a marginal price and more volatile. Response to this price signal can result in strong variability in the power flow and voltage on the distribution grid and is less suitable for a more-congested grid, at least without smoothing or otherwise modifying it to serve as a retail price signal [11].

PV solar peak typically precedes the peak demand in homes that is driven by air-conditioning loads by about 6 hours, leading to voltage rise on solar peak. Volt-VAr reactive power support by smart inverters can reduce this voltage rise as well as reduce variability due to cloud-passing and load variation. This capability, in turn, can increase hosting capacity. Hosting capacity is the amount of DERs that the electric distribution system can reliably accommodate without significant grid upgrades [12]. Hosting capacity is defined here as the amount of distributed PV that can be accommodated while maintaining voltage levels within ANSI C84.1 Range A limits [13].

Earlier work on price-responsive controllers [10, 11] has shown the potential impact of price-response on voltage when heat pump controllers respond to either DAP or RTP. In [11] the studied DAP signal has only a single peak in early evening and the heat pump controllers seek to precool before the peak and then allow house temperatures to rise during the peak in order to limit energy use at the times when electricity is most expensive. This approach makes sense from a customer economics point of view but has a negative impact on grid power flows. In essence, price changes lead to synchronized power changes which produce voltage changes. This behavior was seen at hourly price changes as heat pumps reacted in unison[1] to a raised or lowered price. This synchronized response was even more pronounced for the RTP signal. The RTP is a volatile price signal, and the heat pump controllers react in turn by turning on or off at significant price moves up or down. These switches result in a significant volatility in power flow and voltage leading potentially to voltage violations as well as increased wear and tear on voltage regulators. Comparing RTP to baseline (no price response) showed an 800 % increase in power flow volatility (time step to time step average change in power flow) and 300 % increase in voltage standard deviation across the day (data from Table 1 in [11]).

The research in [11] demonstrated that heat pump price response can successfully shift energy off peak, but the result is an impact on voltage. Response to wholesale energy market clearing prices may shift power usage in response to grid needs, but it may also create problems on the distribution grid due to local congestion. This congestion will be more evident for grids with more price-responsive DER which in turn demands that price signals be less volatile and also that prices may need to be tuned to local voltage.

The current research had multiple goals to build on the research in [11]. The first was to develop a price-responsive water heater controller and battery controller in addition to heat pumps, responding to DAP and/or RTP. The second was to develop a function to implement Volt-VAr control in the battery inverters. Overall, the goal is to understand the impact of price-response and efficacy of price-response and Volt-VAr for increasing hosting capacity.

Volt-VAr injects reactive power (capacitive) when voltage is low up to some maximum percentage of the rated maximum real power delivery. At higher voltages, reactive power is consumed (inductive) to lower the voltage. The simulated Volt-VAr operates according to the IEEE 1547-2018 Category B standard profile [14].

A number of reports [4–6] have established the value of Volt-VAr control at inverters for voltage control. In [6], citing numerous utility pilots, researchers found Volt-VAr can increase hosting capacity with Volt-Watt as a backstop and serves well to minimize voltage variability and flatten

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[1] Each heat pump in the research had the same control logic. One may expect that with different controller implementations and a selection of different tariffs to choose from, the amount of synchronized response to price changes will be reduced. See [25].

voltage profiles on residential grids with significant PV. The Volt-VAr control was found to minimize curtailment and to inject or absorb significantly less reactive power compared to a fixed power factor setting. The EPRI report [5] examined different Volt-VAr curves and found that the IEEE 1547 category B default curve to be among the best, but that "best" depends on grid layout, line size, PV locations and other local conditions. None of these studies examined DER price-responsive voltage variations and interactions with Volt-VAr control.

Other reports [15–17] have noted the need to incorporate demand flexibility as a resource for balancing the grid along with the challenge of fairly compensating customer provision of demand response. As noted in [11], numerous utilities are now considering dynamic price tariffs to encourage customer flexibility.

This report presents the impact of DER price-response on voltage variation and the ability of inverter Volt-VAr control to minimize voltage excursion and volatility. This work looks at a single distribution grid with the majority of load in residential homes, with PV on all homes, along with price-responsive heat pumps, electric water heaters and batteries.

Compared to the grid simulated in [11], the grid simulated in this study is a less congested grid with fewer voltage problems, where price response is found to have less impact on voltage. Nonetheless, PV generation leads to areas of high voltage on the grid, and price-response does lead to voltage variability that causes voltage deviation outside ANSI Range A.

2. Experiment

2.1. Distribution Grid Model

The R4-12.47-1 test grid (R4-1) [10, 18], Fig. 1, with peak load around 3 MW (4 MW without PV generation), contains 523 residential homes, both single family as well as several multi-family dwellings. Approximately 30 % of the load on the grid can be attributed to small commercial and industrial facilities spread across the feeder. All homes on the grid have rooftop PV, batteries, heat pumps and 50 % have electric resistance water heaters.
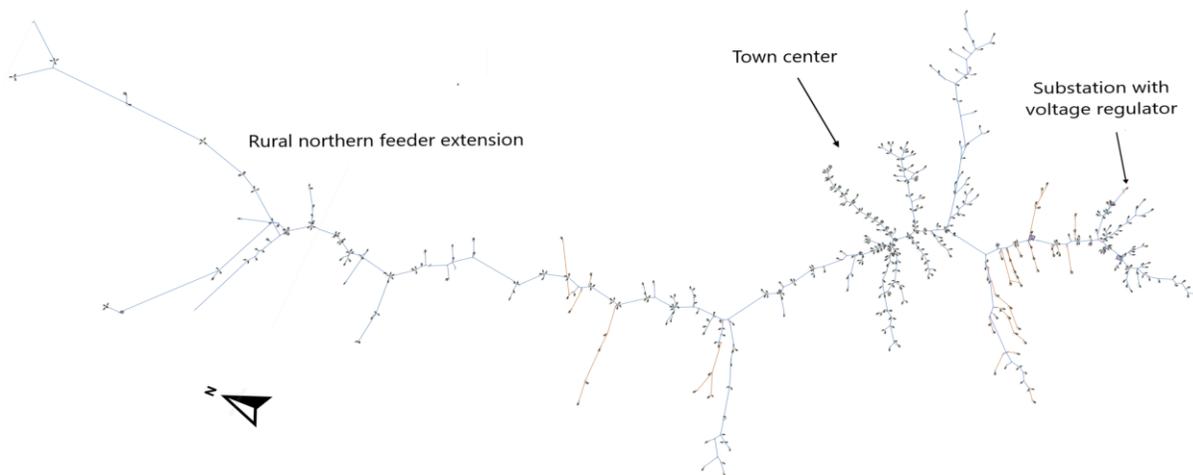
Fig. 1 R4-12.47-1 reference grid [18–20] schematic.

The R4-1 grid has a single voltage regulator at the substation and six capacitor banks at different locations around the feeder with total generation of 800 kVAr capacitive. Many of the houses on the grid (28 %) are served by dedicated pole-top transformers with 10 kW or 15 kW capacity ratings. This grid has only minor congestion issues. However, simulations were run in the original grid configuration (corresponding to the real-life distribution grid condition), where the substation voltage is set high, delivering an average 124.5 V to homes and above 126 V in many locations at some times of day, depending on load and solar generation.

2.2. Flexible Resource Controller

The NIST Flexible Resource Controller (FRC) [21] was developed for GridLAB-D to enable customer flexible loads to respond to price for cost savings as well as to implement Volt-VAr control in customer battery inverters. Simple algorithmic control based on daily peak prices and night minimum prices (assuming DAP is published day ahead) enables intelligent charging of storage at minimum price times and discharging of storage on the price peak.

The FRC manages electric heat pumps (HP), domestic hot water (DHW), and battery operation based on prices. The FRC receives both wholesale market hourly DAP and 5-min RTP. The FRC manages load based on DAP, reducing load or discharging when the price is high, and charging when price is low. The FRC also implements standard IEEE 1547 Category B Volt-VAr control to inject or consume reactive power based on local voltage to move voltage closer to nominal.

More specifically, for the HP, the FRC estimates the thermal storage in the house structure to find a thermal time constant and uses this information to precool the house ahead of the price peak. The house setpoint temperature is then raised during the peak price hours with the amount of temperature increase based on the comfort settings of the homeowner. For the DHW, the setpoint temperature is raised at night and reduced in the afternoon prior to the high prices. The FRC adds randomization to when the setpoint temperature is raised. Batteries are charged at night with a ramp up and back down, with peak charge at 3:00 a.m. Batteries discharge across the high-price period from 6:00 p.m. to 9:00 p.m. also with ramp up and down. More details on the controls are available in [21].

The FRC has a configuration file that allows enabling or disabling controls for different devices so that the flexibility of that device in its different forms can be examined independently or in combination with other forms of flexibility. The operation of the FRC is shown in Fig. 1.
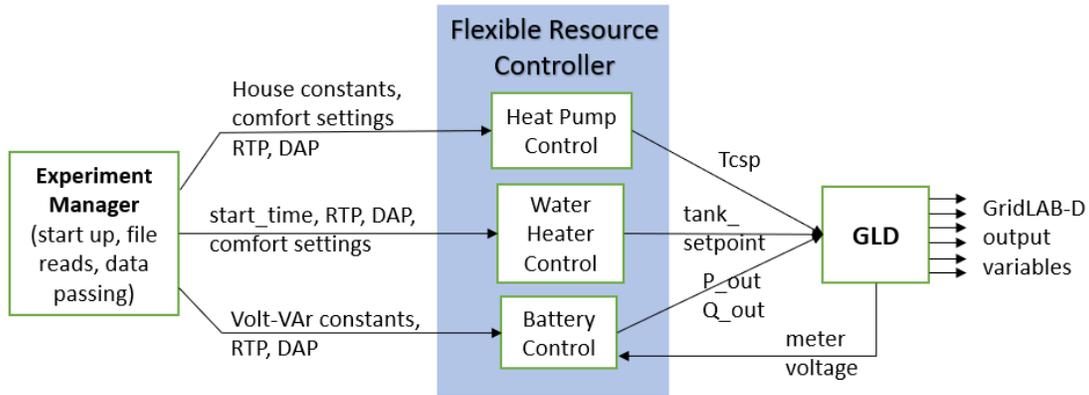
Fig. 2 Flexible Resource Controller architecture including its data exchange with the Experiment Manager and GridLAB-D (GLD).

The FRC was implemented as a Java federate in a High Level Architecture (HLA) [22] co-simulation. It interacts with other federates including the GridLAB-D (GLD) distribution grid simulation and an Experiment Manager that provides price data and configuration options. This co-simulation was developed using the NIST Universal Cyber Physical System Environment for Federation (UCEF) [23]. One instance of the FRC controls all 523 houses in the distribution grid to reduce the number of processes and corresponding messages required to run the co-simulation. Separate configuration files define house-specific control parameters such as comfort settings, and houses are independently controlled by the FRC.

As shown in Fig. 2, the FRC uses price, inverter Volt-VAr constants, house thermal constants and occupant comfort parameters, and configuration options (i.e., which control options to use for each device). The HP controller uses the DAP to generate house temperature cooling setpoints ($Tcsp$) to drive HP operation. The DHW tank setpoints are set based on DAP to optimize water heating with a lower tank temperature during the daily price peak. DAP is also used to guide discharge of the battery on price peak while charging at night when price is lowest. Additionally, the FRC reads in the local voltage measured at each house meter at each time step to determine the reactive power setting ($Qout$) and real power setting ($Pout$) to pass to the battery inverters for Volt-VAr control.

In addition to DAP-based controls mentioned above, there is also an option for an RTP-adjust functionality. The RTP-adjust monitors RTP for any excursion above the DAP peak price. The device controllers will then react to a price spike by raising house $Tcsp$, lowering the water heater setpoint, and discharging batteries. Details of the individual controllers are presented in detail in [21].

It is important to note that the FRC was not designed to manage loads in response to voltage. The HP, DHW and battery charge and discharge schedules are based only on price. This approach is advantageous to the customer for cost savings on electricity but may result in voltage problems for the utilities.

2.3. Prices and Weather

The FRC responds primarily to day-ahead prices, but also optionally to RTP spikes. The prices

are taken from CAISO July 6 and 7, 2017 market prices for Tucson, AZ, as shown in Fig. 3. The simulation uses Tucson temperature and solar insolation for those dates.
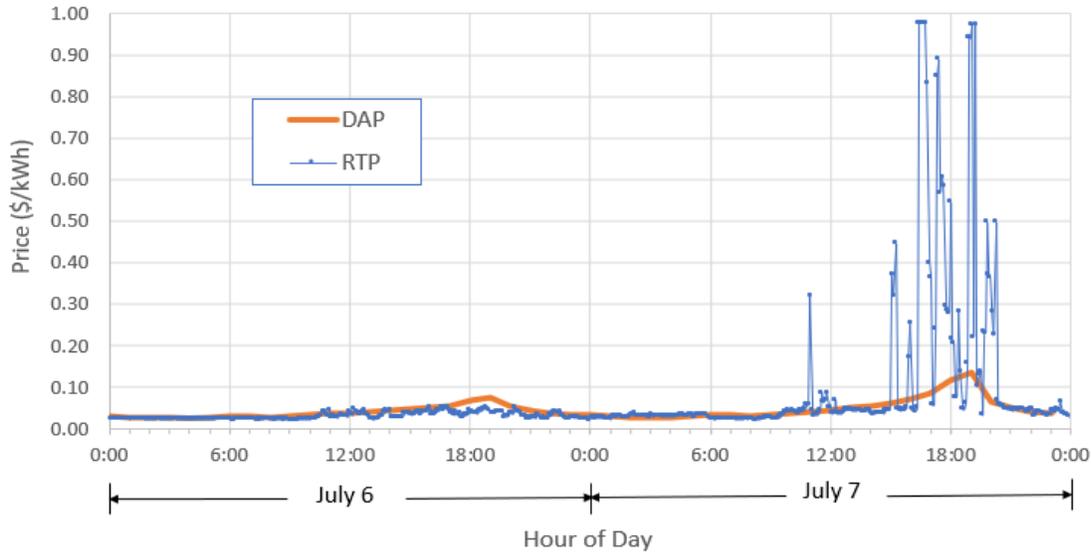
Fig. 3 Day-ahead and real-time prices for test days. The FRC controls storage based on DAP peaks and valleys, but also allows response to price spikes as seen on July 7.

2.4. Metrics and Test Sequence

The goal is to understand the impact of residential price-responsive behavior on customers (voltage variation, comfort and cost). GridLAB-D allows monitoring voltages and real and reactive power flows at grid nodes, metered values at homes, home device loads and temperatures, electrical losses, etc. These parameters were monitored at a few specific grid nodes (substation, transformer to a set of homes, and house meters themselves). In addition, the customer economics were evaluated.

Output data were written to files at a 5-minute rate, although much of the data are averages of the 5 one-minute simulation step values. Simulations were run to examine the impact of price-response and Volt-VAr on grid parameters.

The data presented in the results are limited to the following:

1. Baseline: no price-response. Customer energy consumption is paid based on DAP or RTP.
2. DAP: price-responsive devices (HP, DHW, battery) respond to DAP, with customer energy consumption paid based on DAP.
3. RTP: devices respond to DAP and additionally use the RTP-adjust functionality. RTP-adjust functionality responds to high RTP (overriding the DAP response). Customer energy consumption is paid based on DAP or RTP.
4. Volt-VAr: solar and battery inverter-based Volt-VAr control is added to the DAP response case (or RTP-adjust).

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Two sets of tests were run, first with the substation voltage regulator output voltage set to 125 V on a 120 V basis (this is the original setting, called reg125 in this paper), and a lowered grid voltage with the output of the voltage regulator set to 120.5 V (reg120.5).

3.   Results

3.1.   Baseline Simulations

3.1.1.   Baseline Original Model

The baseline model configuration includes the voltage regulator set to 125 V on a 120 V basis, with PV operational (set to unity power factor) and no price response. This configuration is identified hereafter as "reg125". The simulation takes place over the 48-hour period spanning July 6 through July 7, with hour 0 in the results corresponding to midnight on July 6. Fig. **4** shows a 3 MW real power load peak at approximately hour 18 (July 6, 6:00 p.m.). Without PV, the load peak is 4 MW around 4:00 p.m. This plot shows the classic duck curve, with a steep ramp up to the late afternoon peak. The reactive power, sourced from six capacitor banks on the distribution grid, is flowing out to the bulk grid most of the day except on peak when the inductive HPs are drawing more reactive power. Real power losses (right axis) follow the real power flow, with a minimum of 75 kW in the morning and a maximum above 100 kW at the evening load peaks. These losses include standby transformer losses as well as power flow resistance losses.

The resulting power factor remains close to 1 except in the morning when real power dips while reactive power is still significant. Power factor dips to 0.9 in the 7:00 a.m. to 9:00 a.m. window.
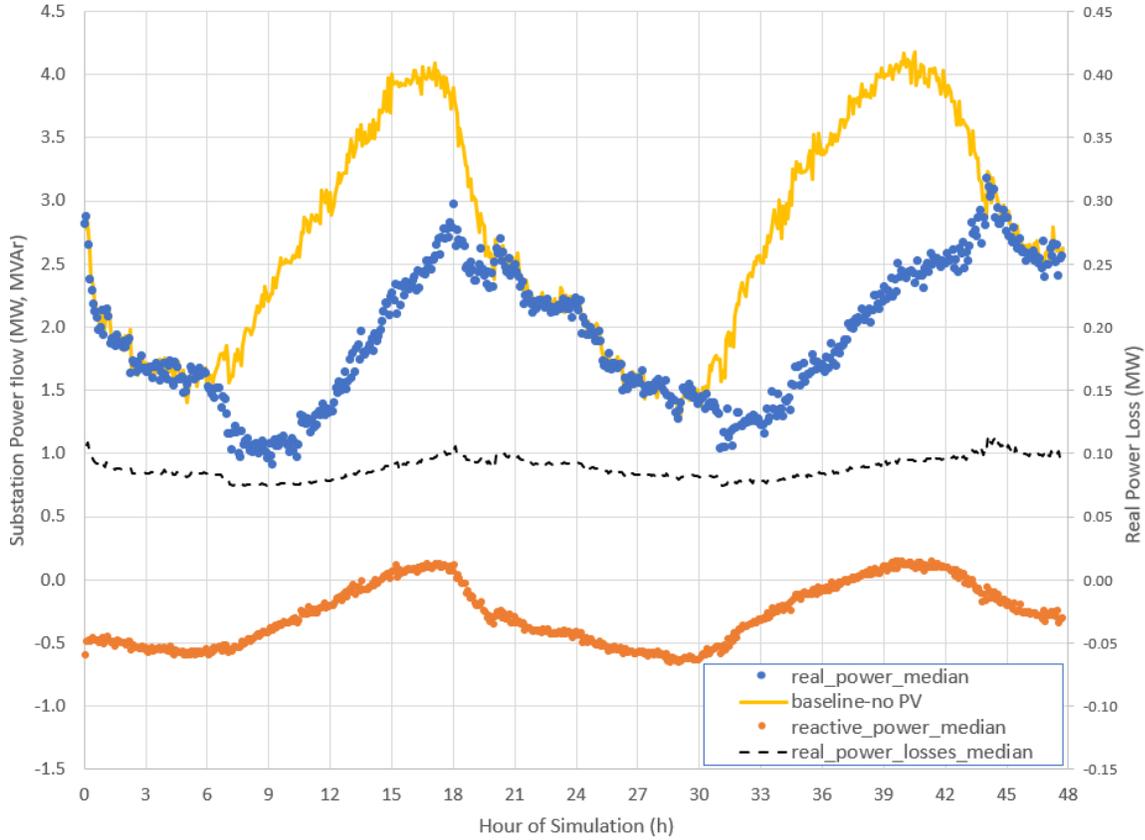
Fig. 4 Substation baseline (reg125) real and reactive power flows plus losses. The top trace is the real power flow with no PV generation showing the true load peak earlier in the afternoon and a total PV output close to 1.5 MW. Losses (right axis) and reactive power both track with the HP load.

Baseline average transformer loading (see 3.4 Transformer Loading and Losses) is only 16.9 % of rating with average peak loading of 50.5 %. However, for the single-house transformers that are rated at 10 kW, the average peak loading is 88 % due to load spikes with concurrent DHW and HP operation. The substation transformer is rated at 12 MW and there are 552 transformers in the circuit.

The average loads per house averaged across all houses are shown in Fig. 5. HP loads peak around 4:00 p.m. to 5:00 p.m., with minimum HP load at 6:00 a.m. The average DHW has a 6:00 a.m. peak, and plug loads peak in the late evening. The average house has a 4 kW ± 2 kW load for this Tucson summer simulation.
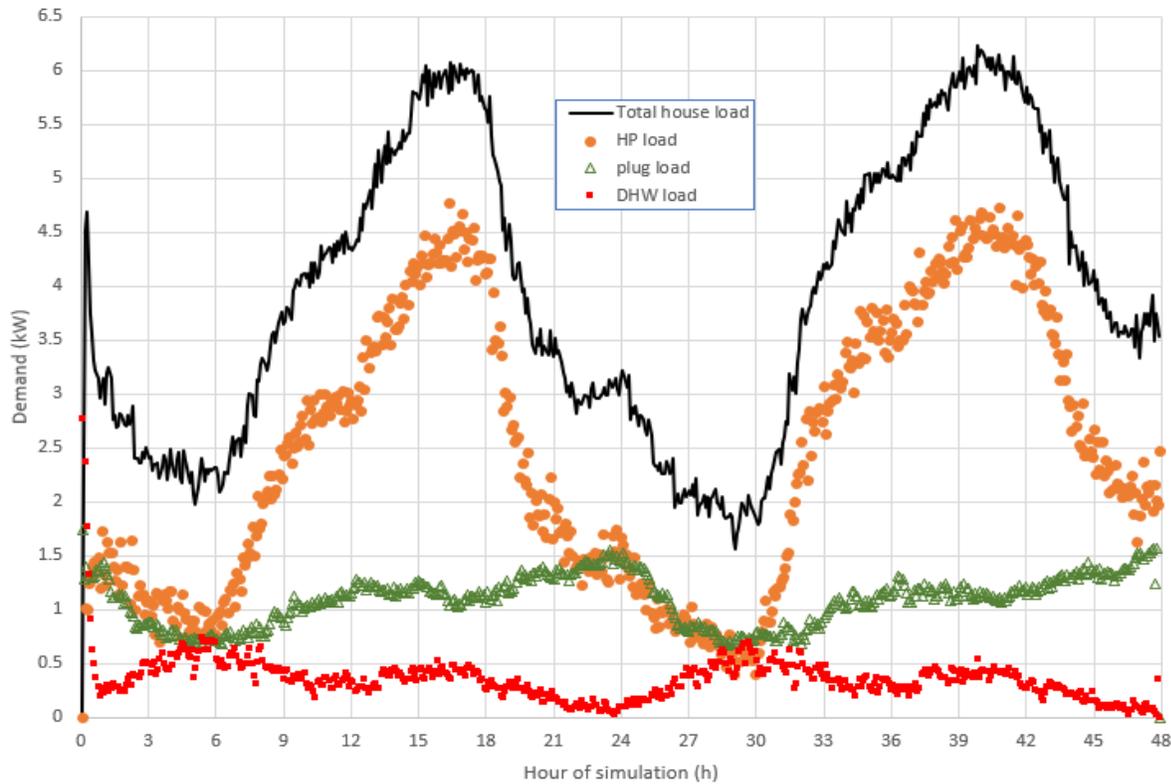
Fig. 5 Total house and device loads averaged across all houses. HP plus DHW plus plug loads add up to total load. Batteries are not operating in the baseline case.

Fig. **6** shows the baseline average house meter voltage corresponding to the above data. **Error! Reference source not found.** presents a box plot of house meter voltages based on data from all houses. Voltage is highest in the morning when load is low, even before the PV generation comes on. While PV generation is ramping up from 6:00 a.m. to noon, the load is ramping up faster such that voltage is dropping (for this summer scenario). The lowest voltage is at the 6:00 p.m. load peak (hours 18 and 42 in Fig. 6). The average voltage remains within a 2 V range across the 48-hour simulation and there is only one substation voltage regulator step change action at 3:00 p.m. on July 6 (hour 15 of simulation) which is the cause of the jump in voltage seen at that time on Fig. 6.
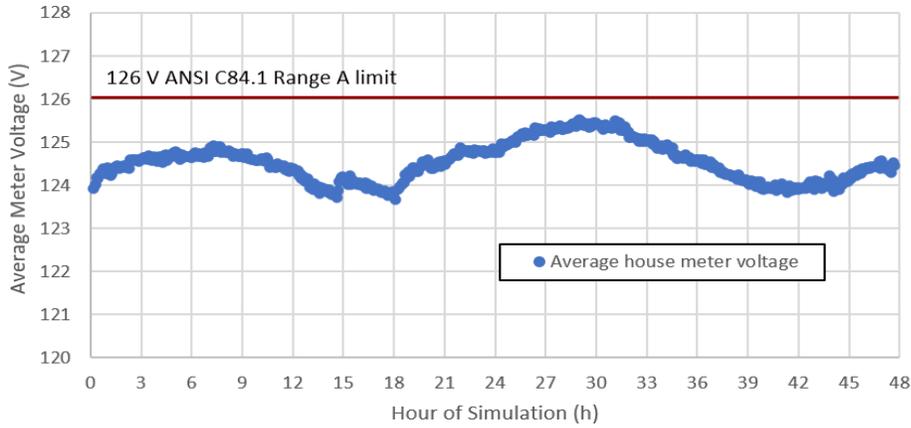
Fig. 6 Baseline average house meter voltage.
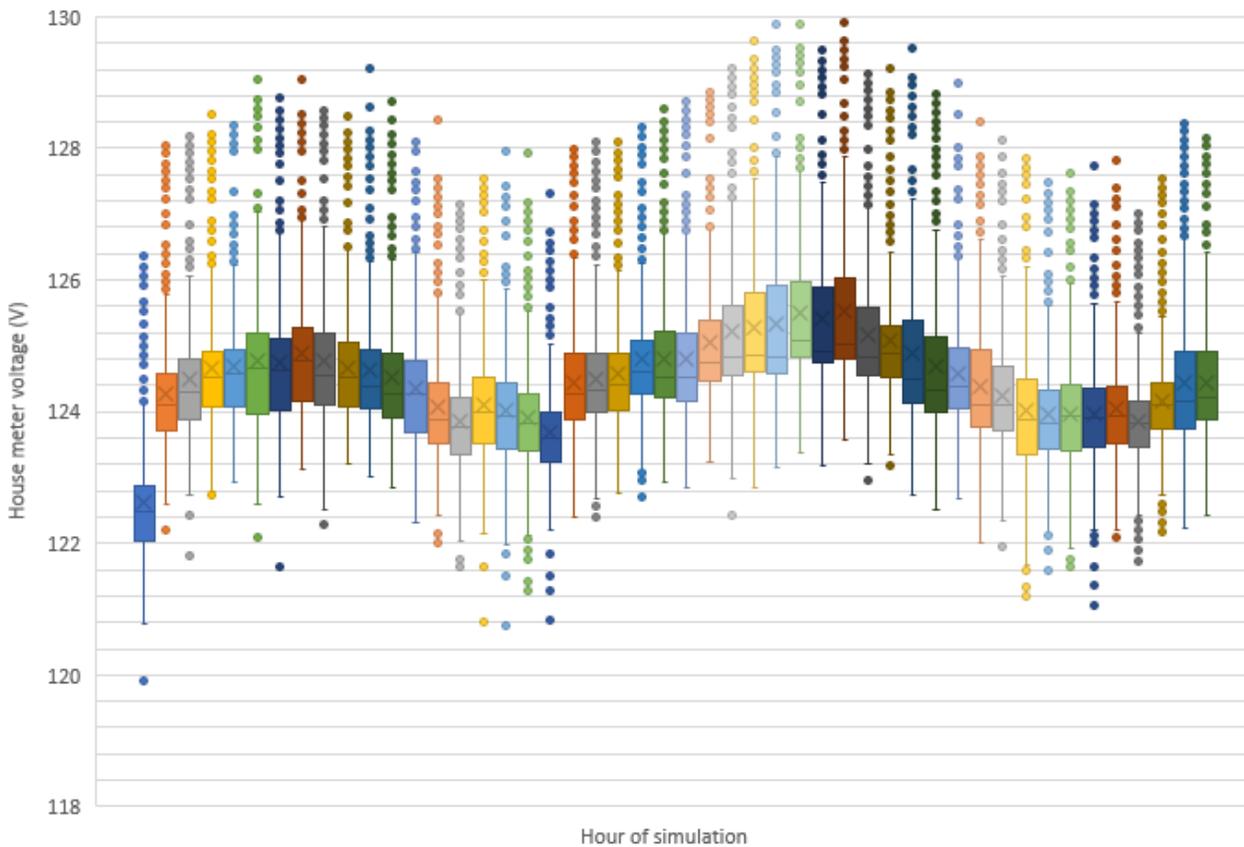
Fig. 7 Voltage levels across all houses at beginning of each hour, hours 1 to 48. Each box represents the voltages of the middle 50 % of the meters. Whiskers up are the top quartile; whiskers down are the first quartile. The dots show the voltage of "outlier" meters above and below the distribution. The lines across the middle of the box show the median and the "X" shows the average voltage (equal to Fig. 6).

While it is clear from Fig. 6 that the average house does not see voltages above 126 V, it is also clear from **Error! Reference source not found.** that some houses have voltages above 126 V (whiskers extend above 126 V) and a number of house meters (seen as dots in Fig. 7) are always

above 126 V. Fig. **8** shows approximately 100 houses at 126 V or above during the July 6 morning voltage peaks, and double that on July 7.
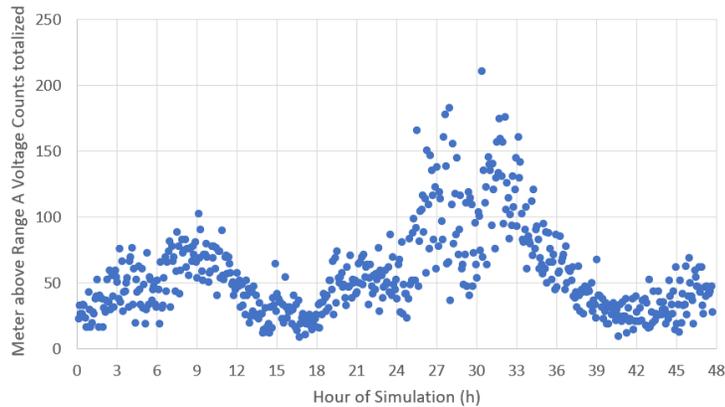
Fig. 8 Count of meters (out of 523 houses) above the 126 V limit during each 5-minute time window.

3.1.2. Additional Baseline Simulations

The original configuration was rerun with the substation voltage regulator adjusted down to 120.5 V on a 120 V basis (termed reg120.5), with the following changes. The average house meter voltages are reduced from 124.5 V down to 120 V. This adjustment then reduces the power flow proportionately by 4 %. Line losses are also reduced slightly. The highest voltage house meter of **Error! Reference source not found.** has peak voltage reduced to 126 V and v oltage violations are removed.

In addition to the above tests, this lower voltage grid was simulated with cooler weather conditions. The outdoor temperature was uniformly reduced by 14 °C (25 °F) in order to examine the impact on voltage of cooler Spring weather due to reduced cooling load on the houses. Note that solar insolation was not corrected. In fact, Tucson average solar insolation is 22 % higher in March compared to July[2] [24] and this adjustment would result in even greater PV generation and backflow to the bulk grid than recorded here.

Fig. **9** shows the baseline power flows for the reg120.5 real and reactive power flows for both the summer and cooler spring weather. Real power peak of spring simulation is reduced by 1.5 MW due to reduced cooling demands. The entire difference in real load is due to the HP load increase from spring to summer, with zero load in spring from 9:00 p.m. until 9:00 a.m. The substation spring load minimum is reduced to -0.4 MW (flowing out to the bulk grid) at 10:00 a.m. when the sun is shining, and HP load is low. Reactive power is more strongly capacitive with the minimum dropping by about 0.2 MVAr down to -0.75 MVAr on the morning load minimum[3]. Whereas the reactive power on load peak was above zero in the July simulation, now the reactive power peak is at -0.3 MVAr due to reduced HP real and reactive power demand. Losses are likewise reduced as seen in Fig. 10. The low power flows and reversing flows from bulk grid to

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[2] The total daily energy production is increased by 22 %, but that would not be the same as a 22 % insolation power increase across all hours or across all sunny hours.

[3] The 6 capacitor banks on the grid generate 0.8 MVAr reactive power that flows out if not consumed by HPs.

local distribution grid results in low and negative substation power factors as seen in Fig. 11. Voltages, as shown in Fig. 12, are raised by approximately 1 V across the day due to the lower power delivery from the bulk grid.
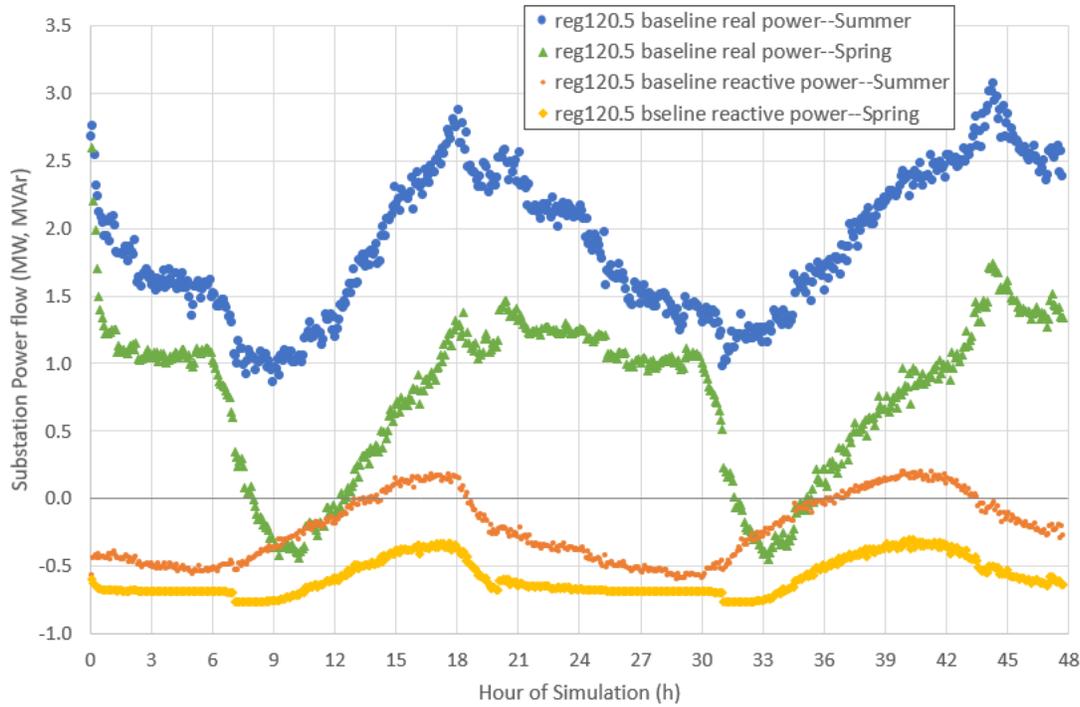
Fig. 9 Real and reactive power flows at the substation comparing reg120.5 summer data to the Spring baseline. Outdoor temperature was reduced 14 °C (25 °F) resulting in reduced HP load and backflow to the grid throughout the morning sunshine.
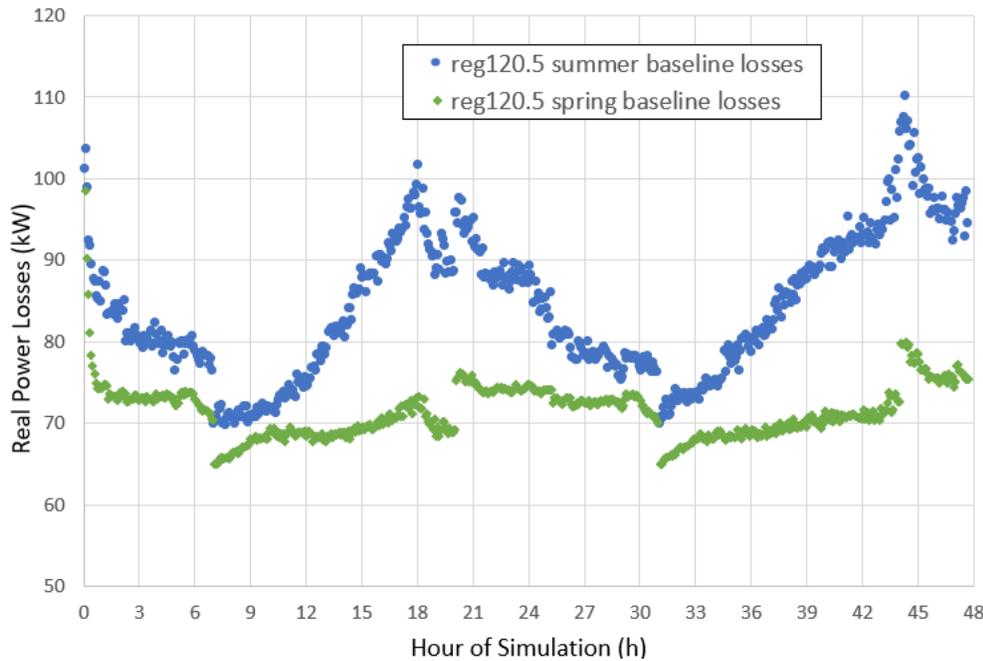
Fig. 10 Real power losses for springtime (reduced load) vs. reg120.5 summer baseline.
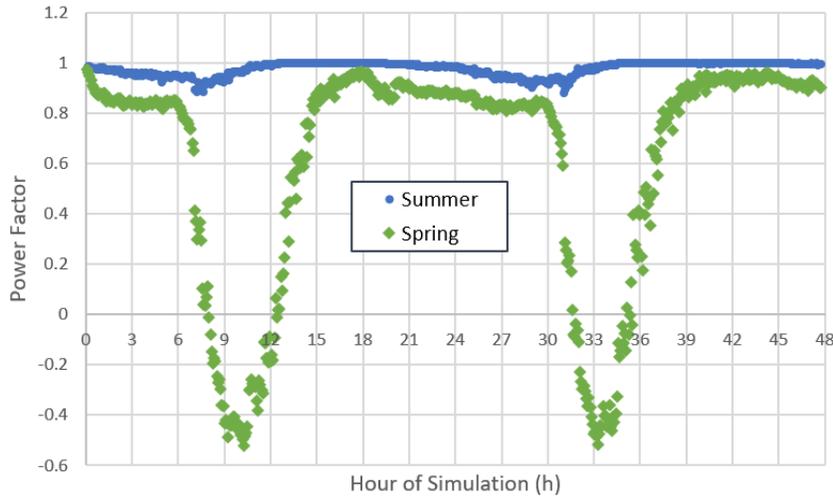
Fig. 11 Substation reg120.5 baseline power factor for summer and springtime.
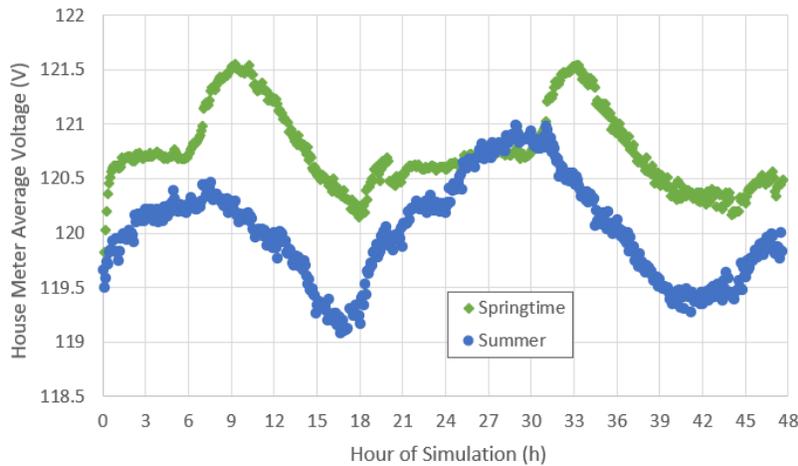
Fig. 12 Comparing average house meter voltages for baseline reg120.5 springtime reduced HP load case to summer case.

3.2. FRC Performance and Volt-VAr Operation

The FRC works to reduce energy consumption during the high price time of the day, based on DAP, and optionally in response to very high RTP. Results of energy consumption for HP, DHW and battery are presented first, and then the effects of adding the RTP adjustment, and then a look at battery reactive power flows when Volt-VAr is implemented. Following sections will look at the impact of these load modifications on the voltage aspect of power quality and other metrics.

Fig. **13** shows the comparison of baseline HP average energy consumption versus the FRC DAP response. The FRC estimates the optimal precooling window and precools the house ahead of the peak prices. This control approach is seen with the additional energy consumption in the noon to 5:00 p.m. window. Around 6:00 p.m. the energy consumption drops when the house setpoint temperature is raised (the amount that it is raised for each house depends on customer comfort

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parameter). Around 9:00 p.m. (hours 21, 45) there is some rebound cooling load to lower the house temperatures after the price peak.
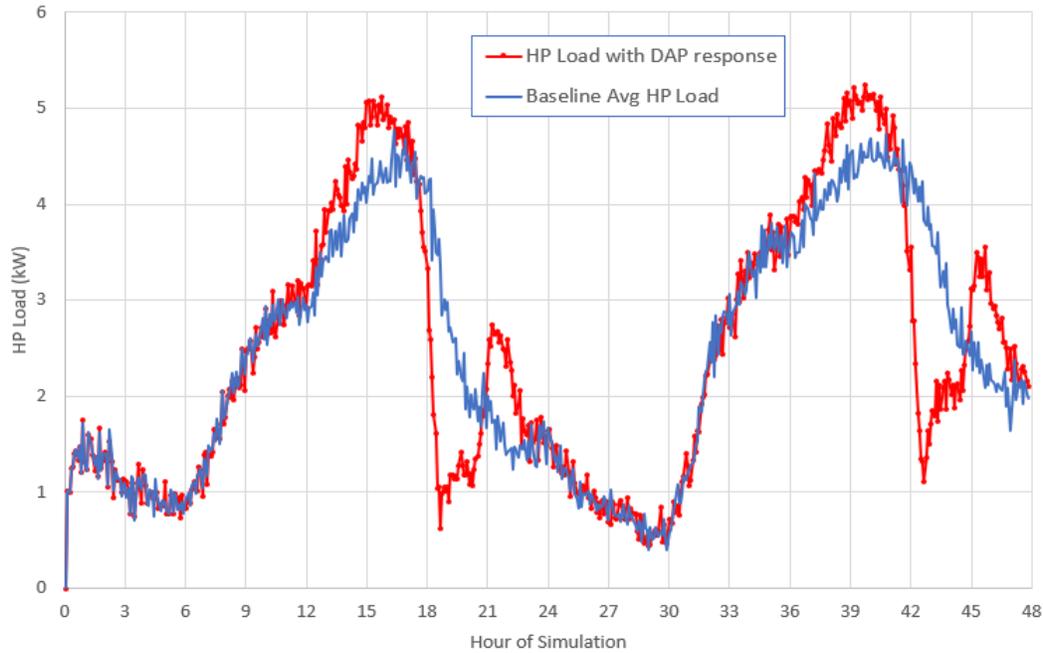
Fig. 13 Heat pump baseline and DAP-response energy consumption, average across houses.

Fig. **14** shows the water heater response to DAP, compared to baseline. The FRC raises the DHW setpoint temperature around 3:00 a.m. (with some FRC randomization) and the energy consumption increases above baseline for a few hours to raise the temperature. At noon, the setpoint is reduced in response to rising prices. The average consumption is also reduced until after midnight. Energy consumption is reduced approximately 20 % during the peak time compared to a 40 % reduction early in the afternoon indicating that it would be better to delay raising the setpoint to have more impact during the highest DAP prices.
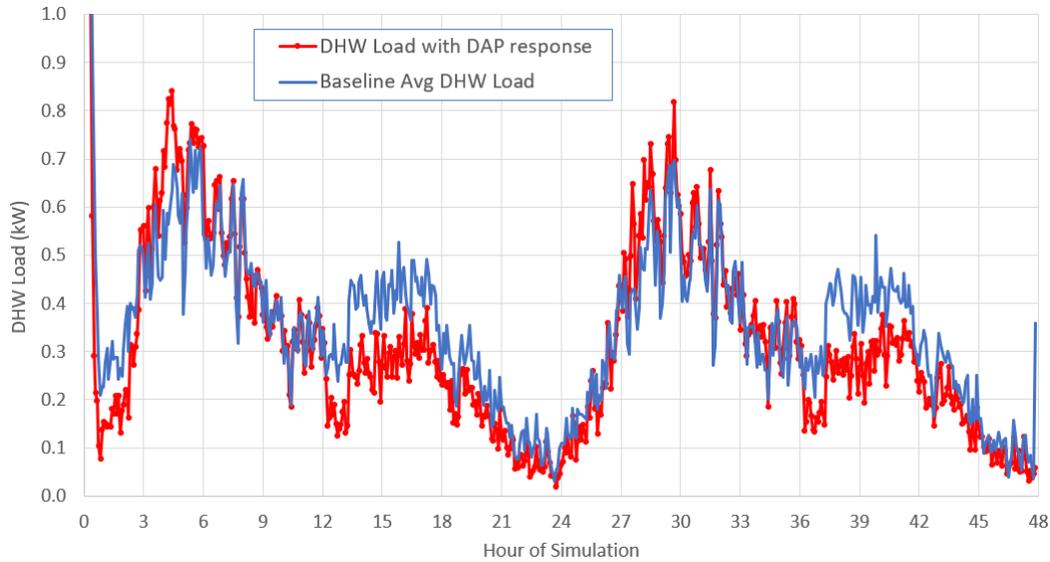
Fig. 14 Water heater load baseline and DAP response, average across houses.

The battery charges at night and discharges on the DAP peak according to a predetermined schedule. The FRC can also operate the battery in Volt-VAr mode. Fig. **15** shows the combined response. The battery charges in the early morning (*Preal* negative), and discharges during the price peak in the evening. Reactive power is inductive, with reactive power flowing from the transmission grid to the battery inverter, more when the voltage is high (when battery is discharging on peak) and less when the voltage is low (when load increases during charging). Note that these data are based on the original baseline simulation voltage levels (reg125). The reg120.5 simulation had very little Volt-VAr reactive power response due to the lower voltages on the system.

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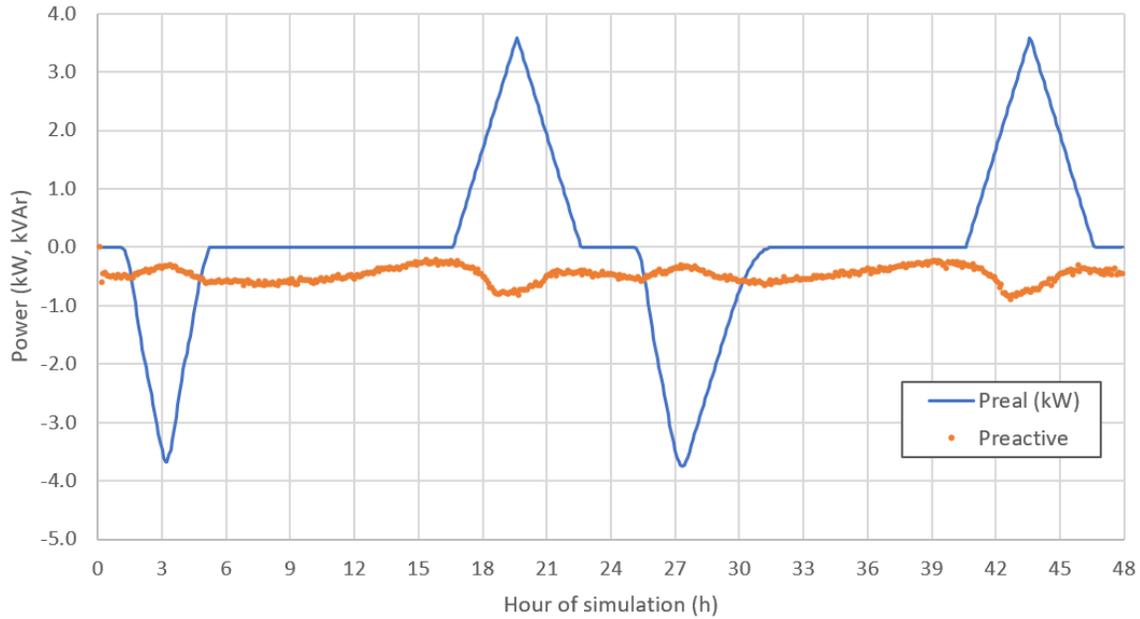
Fig. 15 Battery real and reactive power flows with FRC control. Charging and discharging are determined based on minimum and peak DAP. Reactive power is due to Volt-VAr response to generally high voltages.

The RTP-adjust function of the FRC changes the response above, since RTP response has priority. That is, if the RTP spikes, the response is to raise the HP setpoint and lower the DHW setpoint as well as to discharge the battery at max power output.

Fig. **16** shows the average HP energy consumption when the HP temperature setpoint is raised up (reduced cooling) during a price spike. One can see an initial drop in consumption down close to zero, and then a following rebound as HPs increase consumption (on average across 523 homes) to recover the original setpoint. The 6 kW jumps in the load seen here correspond to aggregate 3 MW jumps in the grid load, as will be seen in following sections.

Fig. 16 Heat pump with FRC RTP adjust function showing response of HP (average across all HPs) on July 7, raising the temperature setpoint during RTP spikes.

Fig. **17** shows the average DHW response. The RTP spikes result in an average 300 W change in DHW power consumption, corresponding to 80 kW change on the grid load.
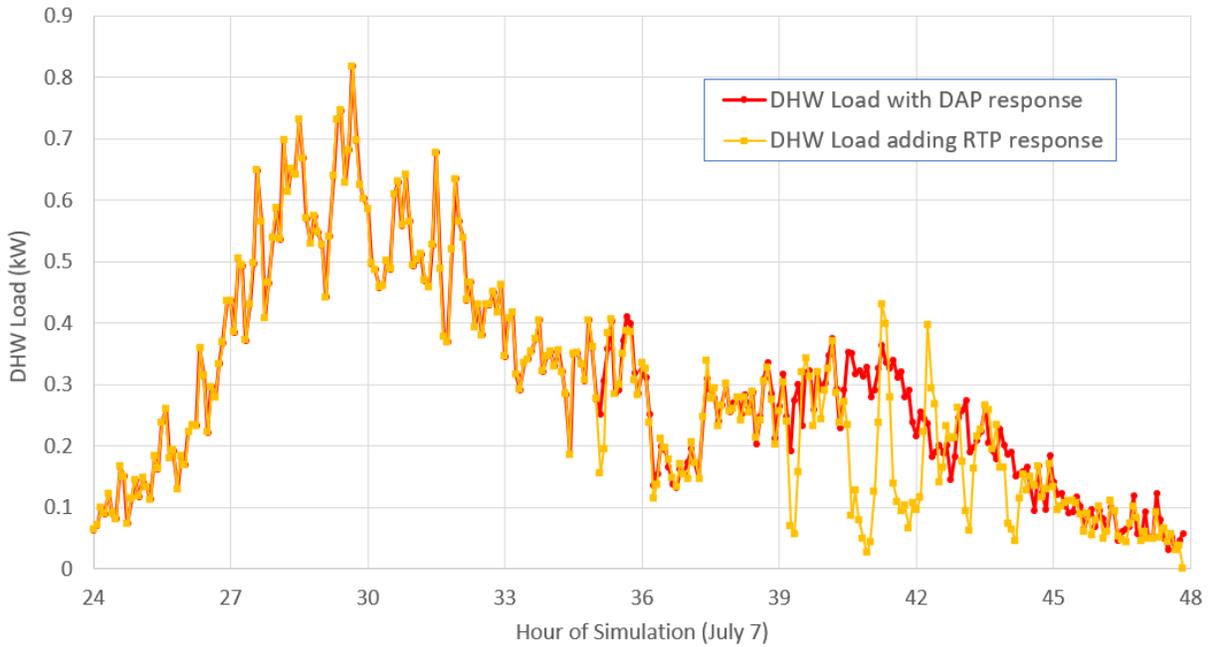
Fig. 17 Water heater with FRC RTP adjust function showing response of DHW (average across all DHW) on July 7, raising the temperature setpoint during RTP spikes.

17
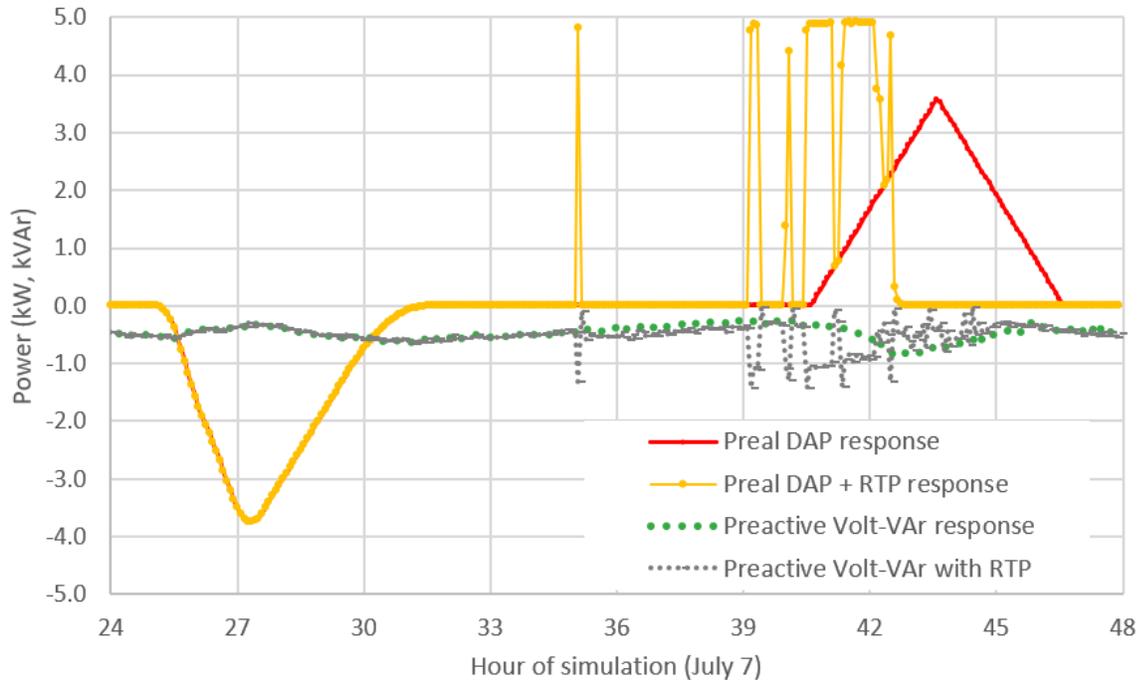
Fig. 18 Battery response to FRC RTP adjust function compared to real power DAP response and reactive power Volt-VAr response.

Fig. **18** shows the impact of the FRC RTP-adjust function on the battery operation, both real power and reactive. The regular DAP responsive battery discharge on July 7 evening is disrupted by the strong response to RTP. When a price spike arrives, the battery goes to full discharge (5 kW). The impact of this is to reduce the state of charge such that there is no additional capacity to discharge during the 7:00 p.m. peak hour. The reactive power Volt-VAr response, which for the DAP-only response was a smooth response to a slowly rising or falling voltage, now is rapidly changing up and down due to the voltage jerking up and down.

In addition to the FRC control, the GridLAB-D model allows configuring PV inverters for Volt-VAr provision. Fig. **19** shows the PV average system output with 4 kW peak output at 1:00 p.m., and power dropping rapidly after 6:00 p.m. Reactive power consumption (Volt-VAr response to voltage) looks similar to the battery inverter consumption (Fig. 15). The actual amount of reactive power consumed at the inverters is a function of the voltage which itself varies with selected FRC controls. For these figures, DAP control is implemented for all HP, DHW and batteries.
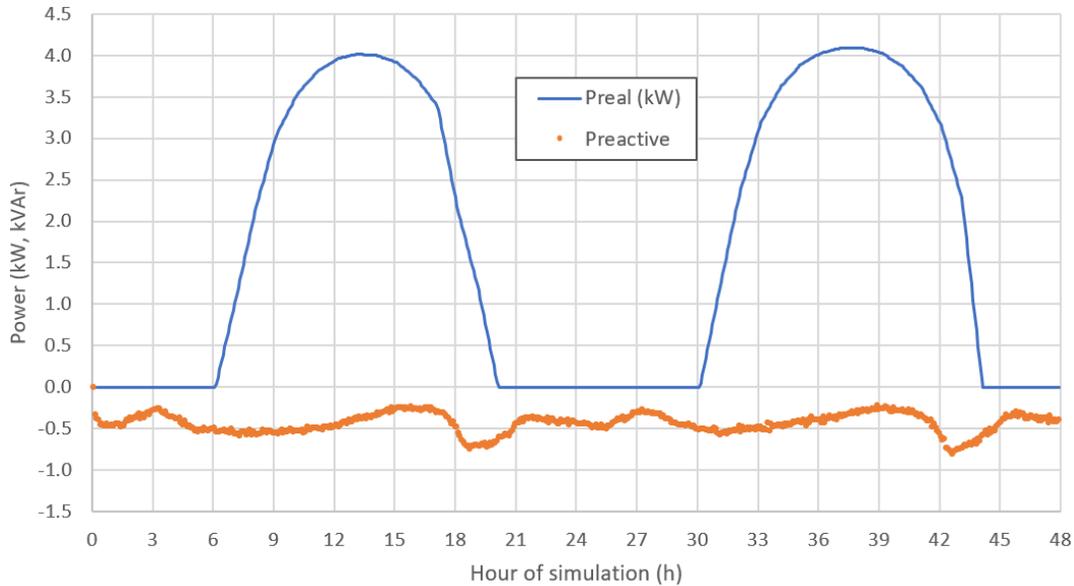
Fig. 19 Average Solar PV real and reactive power production with inverter Volt-VAr enabled.

3.3.   Power Quality

GridLAB-D is a quasi-steady state solver and was set to a resolution of 1 minute for these simulations. The results provide no insights on sub-minute voltage instabilities or other dynamic power quality phenomena. However, the results do show settled voltages, losses, power flows and device consumption for each node on the grid, given different setpoint and battery power configurations, along with Volt-VAr response to those voltages.

The power flow through the substation when FRC price response is implemented (DAP response for HP, DHW and battery) is shown in Fig. 20. One can see the battery charging peak at 3 a.m. and the drop in load from 6:00 p.m. to 8:00 p.m. that results from adjusting temperature setpoints up as well as discharging the batteries. The 7:00 p.m. load peak of Fig. 4 (baseline) has become the load minimum and well below the 1 MW minimum of Fig. 4, even with some backflow to the bulk grid. The new load peak at 3:00 a.m. is higher than the previous evening load peak (although this result is a correctable artefact of the batteries all charging at the same time). The reactive power primarily tracks with the HP inductive load (Fig. 13).

Adding Volt-VAr response at the battery inverters and at PV inverters results in no change to the real power flow, but a significant increase in reactive power requirement, also Fig. 20. The now inductive PV and battery inverters call for more reactive power drawn from the bulk grid. The greatest increase is during the price peak around 7:00 p.m. where the voltage is now the highest (due to low load) and reactive flow has increased by approximately 700 kVAr. The second most increase in reactive power demand is in the low load 6:00 a.m. to 9:00 a.m. time window. The resulting power factor stays close to 1 until 6:00 p.m. and then drops to below zero due to the negative real power flow (flowing out to the bulk grid).
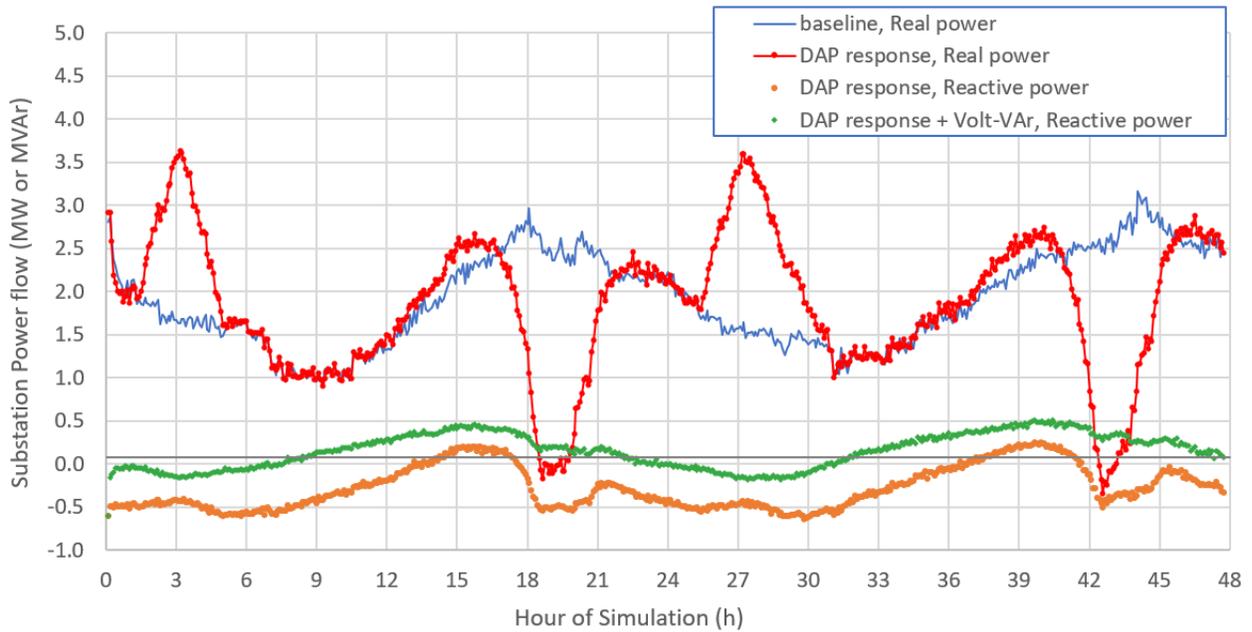
Fig. 20 Substation power flows with DAP response and additionally with reactive power flows when Volt-VAr control is added (for regulator set to 125 V).

The resulting average customer meter voltages (for DAP and additionally with Volt-VAr) are shown in Fig. 21. The range of voltage has increased higher and lower with the price response compared to baseline. The house voltages on average are high relative to the Range A 126 V limit. During the (now low load) peak price period, the average voltage exceeds 126 V. The Volt-VAr response significantly reduces this excess voltage, reducing the average peak voltage by 1 V. The significantly higher voltage, comparing DAP response to Volt-VAr on July 7 vs. July 6 (compare hours 21 to 39 to hours 0 to 15), is due in part to a voltage regulator step change up around hour 15 for both baseline and DAP response that does not occur for the Volt-VAr simulation.
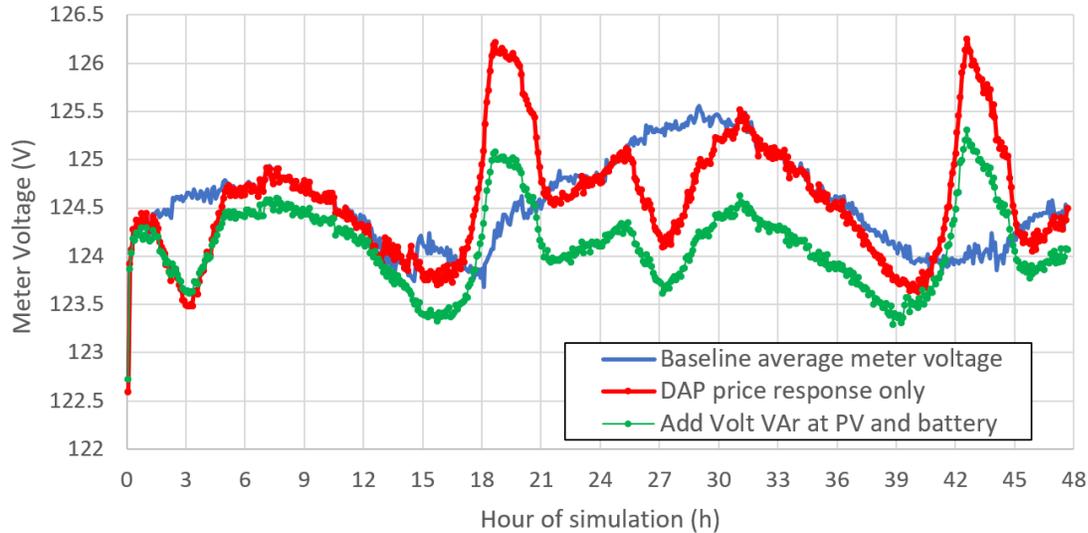
Fig. 21 Average customer meter voltage corresponding to Fig. 20.

Fig. **22** shows the substation power flows for July 7 when the RTP adjust function is turned on. This causes batteries to discharge and temperature setpoints to be adjusted when the RTP spikes up as seen in Fig. 3. The power flow actually reverses through the substation due to the output of the batteries in addition to PV generation. The result is large jumps in the power flow, both real and reactive. Fig. **23** shows the resulting voltage jumping 4 V up and down in response to the 6 MW power fluctuations. Average meter voltages reach as high as 127.6 V. Adding Volt-VAr control (batteries plus PV) successfully brings the average meter peak voltage to 126 V, although the maximum observed meter voltage is still at 130.2 V with Volt-VAr control, down from 134.4 without Volt-VAr. The voltage regulator also has significant step changes during these power and voltage shifts. Whereas under other tests there is one or two step changes across the 2 days of test, when RTP adjust is used there are a total of 10 additional step changes.
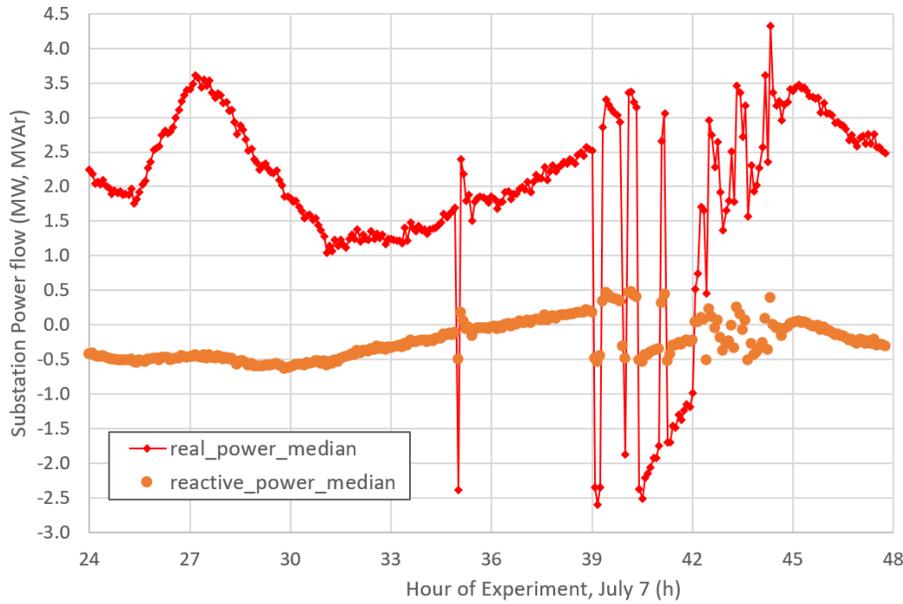
Fig. 22 Substation power flows with DAP and RTP response, with no Volt-VAr, only looking at July 7 (starting at hour 24 of 2-day simulation). July 6 has no price spikes and thus no RTP response.
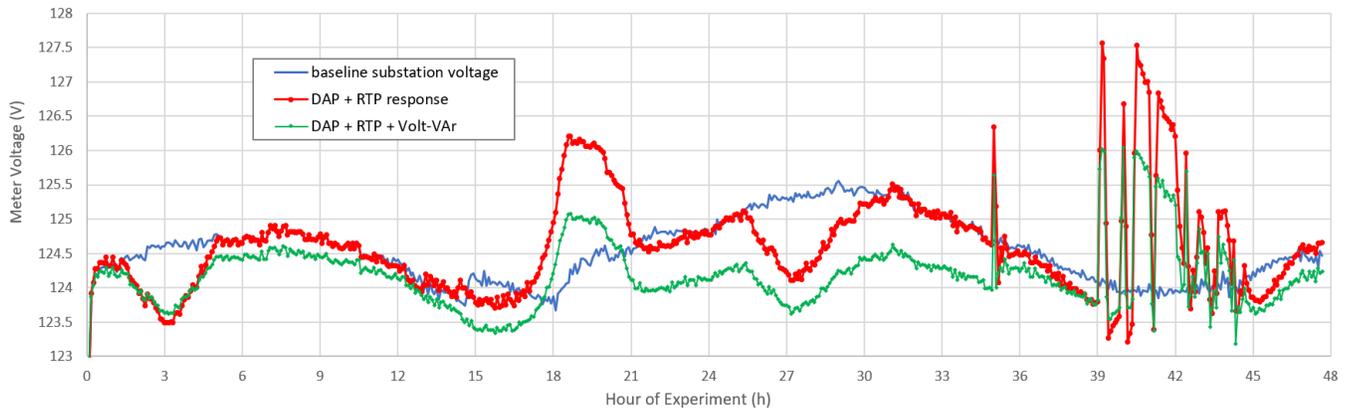
Fig. 23 Average customer meter voltage baseline and DAP plus RTP and also additional Volt-VAr response on top of DAP + RTP.

One might observe that the strong movement in voltage and the strong over-voltage is not a good result. Note that GridLAB-D PV inverters do not automatically curtail at high voltage. There is also no Volt-Watt control implemented that would serve to reduce the out-of-bound voltages. As noted in our earlier work [11], it is not advised to have this kind of volatile RTP signal passed to device controllers, at least for a grid with a significant percentage of price-responsive load, and especially if the grid is congested. Likewise, having the baseline voltage levels set so high may not be the best approach for a distribution grid with significant generation (PV and battery included).

As noted earlier, additional tests were run with the substation voltage regulator reset to achieve an average house meter voltage of 120 V. For those data runs, all voltages were reduced by 4.5

V, Volt-VAr had almost no application, and even with RTP-adjust there were only a few meters that went above 126 V.

3.4.   Transformer Loading and Losses

In general, R4-1 transformers are not heavily loaded. The average and peak loadings (% of load rating) for grid transformers are shown in Table 1. The "Percent of Xfmrs overloaded" column shows that 10.1 % of transformers have some instance of overloading during the baseline simulation. The degree of overloading is provided in the column to the right ("During Overload"), which provides the average amount of overload (% above rating) and duration of that overload. Volt-VAr response increases the load on a subset of transformers (such that percentage of transformers with overloading increases) while decreasing load on others (such that average is basically unchanged). Inverter Volt-VAr response to high voltage consumes more reactive power (flowing through the transformer) resulting in a lower power factor.

Table 1 Average real power load on all grid transformers and specific loading on Transformer 123 (Xfmr_123) that feeds four homes.

Test (reg125)	Average Xfmr Mean Loading (%)	Average Xfmr Peak Loading (%)	Percent of Xfmrs Overloaded (%)	During Overload* [average overload magnitude above rating (%), average duration (min)]	Xfmr 123 Mean Loading (%)	Xfmr 123 Peak Loading (%)
Baseline	18.8	68.5	10.1	[10.4, 53]	12.0	46.2
DAP response	18.2	76.5	11.3	[13.2, 42]	11.1	59.3
DAP + Volt-VAr	18.1	76.4	15.3	[15.3, 35]	10.9	59.5

* applies only to transformers with some overloading.

The right two columns provide loading for a representative single transformer (Xfmr_123) with a 50 kVA load rating serving four residential single-family homes, each with PV. The baseline power flows through that transformer are shown in Fig. 24, DAP response in Fig. 25 and additionally with Volt-VAr control (of PV and battery inverters) in Fig. 26. The clear difference between baseline and DAP response is the addition of battery charging in the 1:00 a.m. to 5:00 a.m. range, and the discharge of the batteries in the 6:00 p.m. to 9:00 p.m. (hours 18 to 21) range.

Adding Volt-VAr has essentially no impact on real power flows; however, the reactive power generally increases due to the overall high voltage on the grid (compare to Fig. 20).

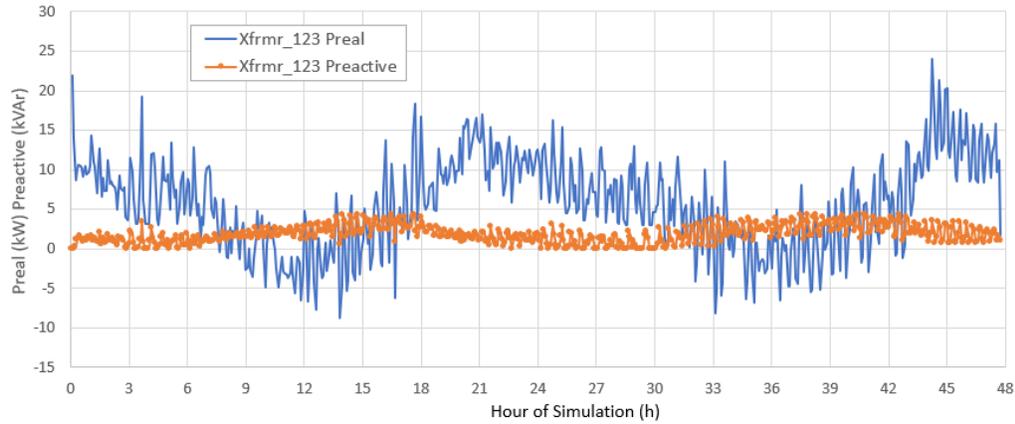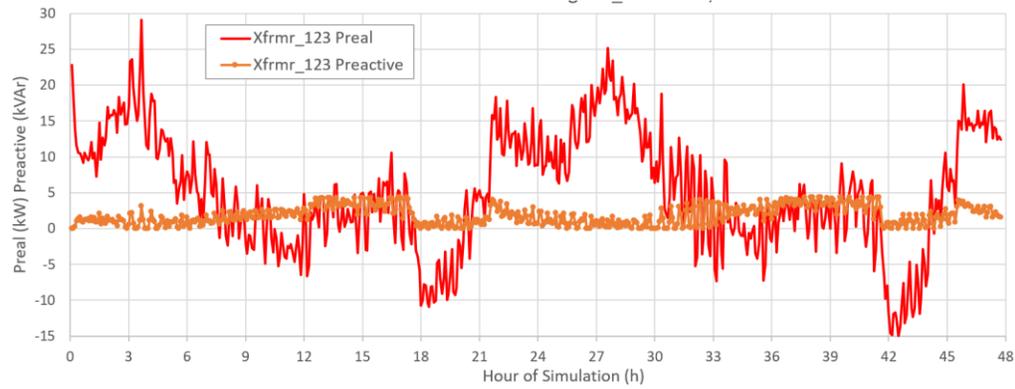**Fig. 24** Transformer 123 baseline real and reactive power flows.

Fig. 25 Transformer 123 DAP response real and reactive power flows.
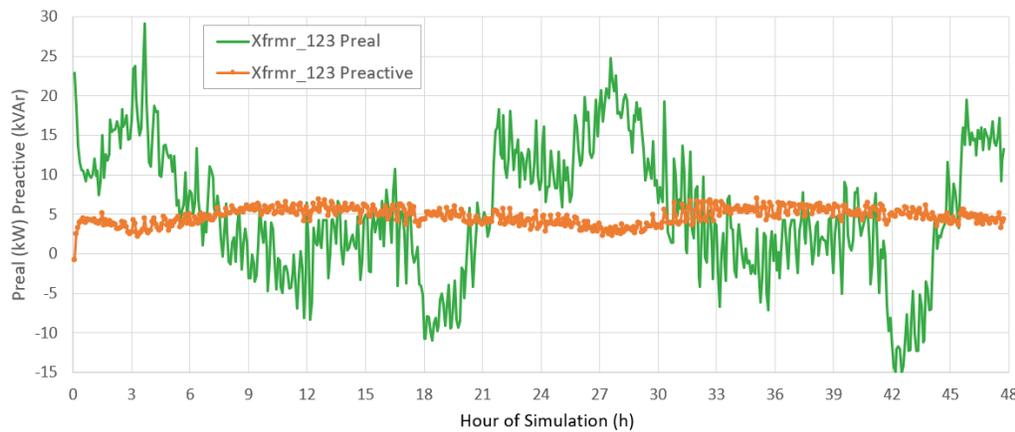
Fig. 26 Transformer 123 DAP response plus Volt-VAr real and reactive power flows.

Table 2 summarizes average grid loading and losses as well as loading and losses at transformer 123 (Xfmr_123) for the above three experiments. Small differences are observed. Adding DAP

response to the baseline results in a 2.4 % drop in power flow at the substation, but a 7.6 % drop in real power flow at Xfmr_123 (from 5.70 kW down to 5.265 kW). This larger drop percentagewise at Xfmr_123 is due to the higher percentage of PV behind the transformer compared to the full grid. In contrast, losses increase with DAP on the full grid, and even more for Xfmr_123, despite power flow decreasing. Losses increase due to the night battery charging while for Xfmr_123 the battery discharge provides very little reduction due to a high standby loss representing approximately 90 % of the losses. Volt-VAr reduces the substation losses slightly due to reduced voltage and resulting reduced power flow with less resistance losses. Xfmr_123 sees a slight increase in losses with Volt-VAr, perhaps due to the higher percentage of inverters behind it (relative to total power flow), where the inverters increase current to compensate for reduced voltage in order to deliver constant power. Increased current then results in increased wire resistance losses.

Table 2 Distribution grid average power and losses plus transformer 123 power and losses.

Run	Substation Pavg (MW)	Grid Real Losses (kW)	Substn Loss %	X123 Pavg (kW)	X123 Real Loss (W)	X123 Loss %
Baseline	1.912	88.37	4.62	5.70	260.8	4.58
DAP	1.866	89.75	4.81	5.265	267.1	5.07
DAP + Volt-VAr	1.861	87.86	4.70	5.247	270.7	5.16

Fig. **27** shows the distribution grid losses for baseline, DAP response and additionally with Volt-VAr (corresponding to Table 2 Grid Real Losses column). One can see that the Volt-VAr reduces the overall losses primarily in the morning and during the evening high-price period, which correspond to the high voltages on the grid (see Fig. 21).
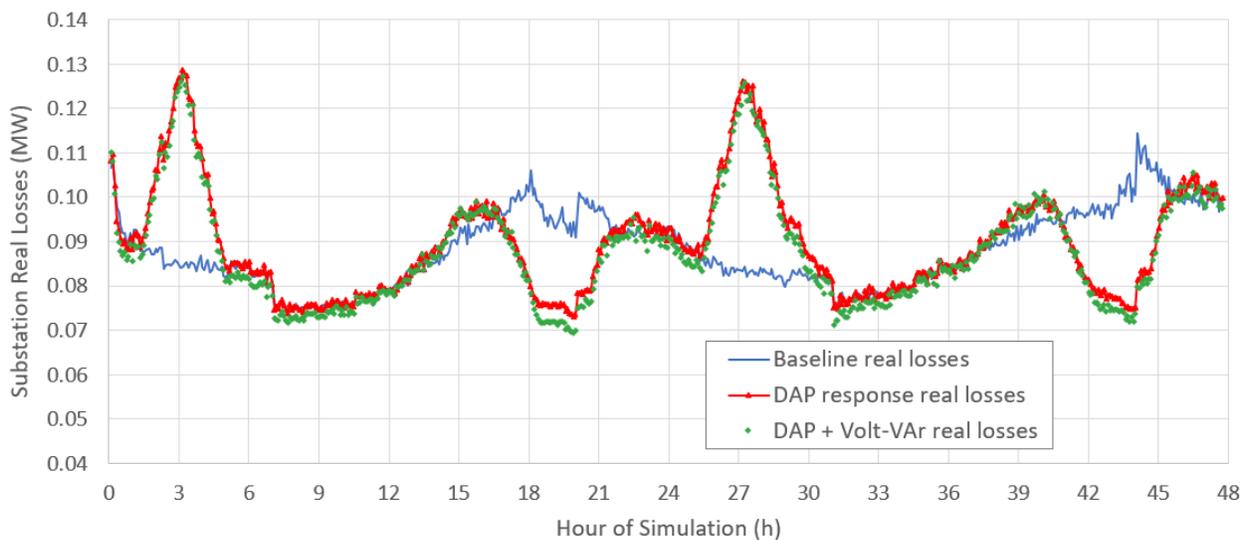
Fig. 27 Substation losses for baseline, DAP response and additional Volt-VAr, reg125 .

In conclusion, the loss analysis is complex. Overall, price-responsiveness leads to a reduction in power flow (averaged across the day), but potentially a small increase in losses. Volt-VAr further reduces the power flows and generally reduces losses, depending on device configuration. A PV

inverter may be configured to deliver max power and to do this by raising current while Volt-VAr reduces voltage, with the end result of increasing losses. In contrast, a heat pump will reduce power consumption with a voltage reduction, and thus losses also are reduced.

3.5. Customer Economics

How does the tariff, whether the customer is paying for power based on DAP or RTP, impact the customer cost for different price and voltage response approaches? For the purposes of illustration, the cost for houses behind transformer 123 will be shown along with the cost for the consumption of the average grid house. Fig. **28** shows the cumulative cost across the two days of simulation, along with the price signal at the bottom. The cost to the customer is on the left axis. The typical house on the grid would be charged $6 for the two days of energy under DAP prices while the houses behind Xfmr_123 would pay about half of that. Each of the Xfmr_123 houses have below average consumption due to very energy efficient walls and windows and above average efficiency heat pumps, which together contribute to the lower energy bills seen here. Looking at the customer cost if paying based on RTP, Fig. 29, one sees the average house paying close to $10 due to the price spikes on July 7. Both of these cost curves are for no price response, that is, baseline energy consumption and paying for that based on DAP or RTP.
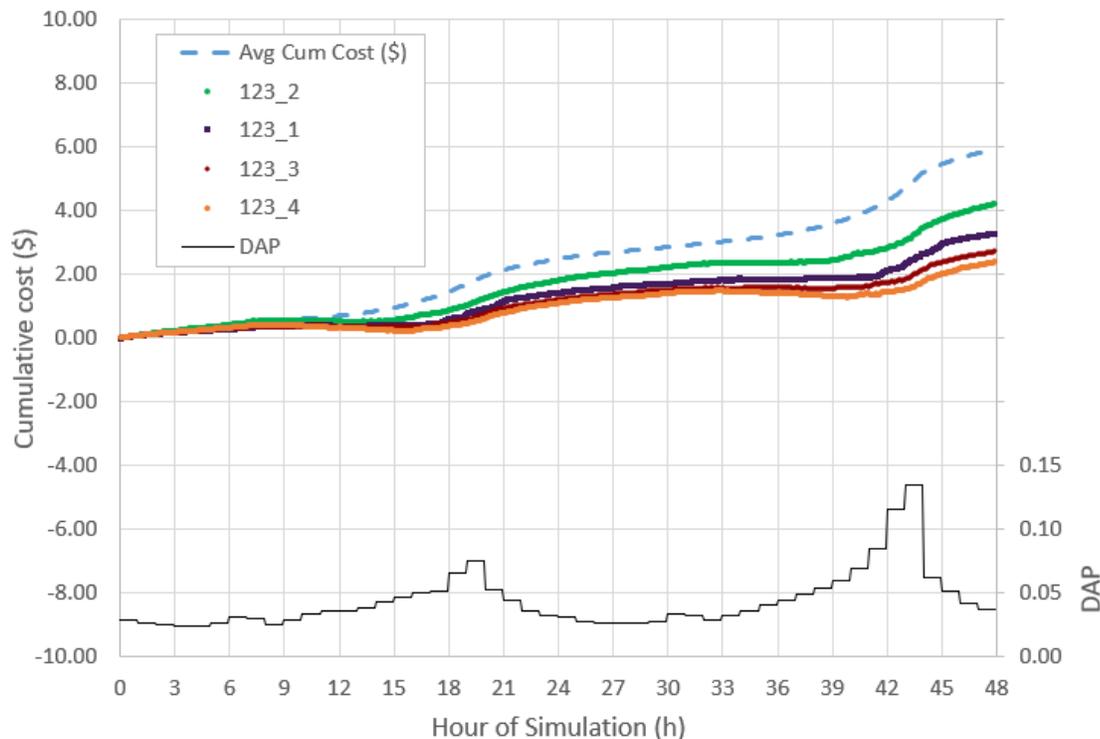
Fig. 28 Baseline cost (no price response) for customers behind Xfmr_123 paying all energy consumption at DAP, and comparison to distribution grid average house cost. DAP included on figure right axis.
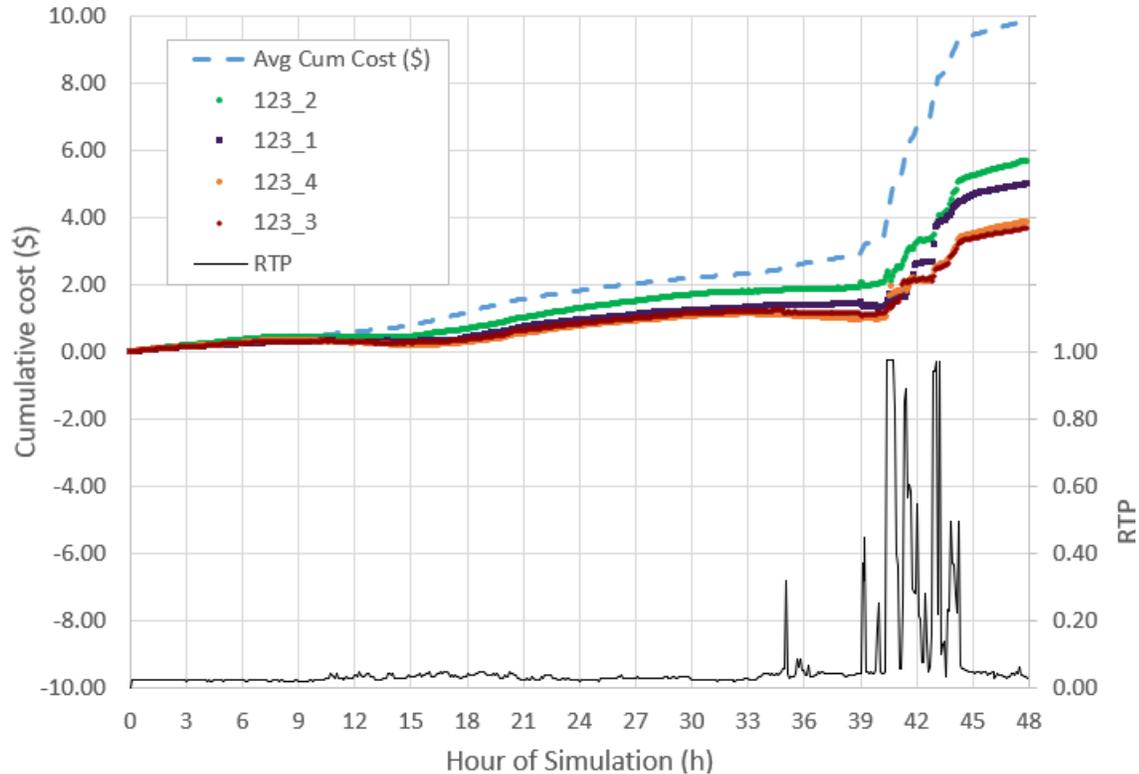
Fig. 29 Baseline cost for customers behind Xfmr_123 paying all energy consumption at RTP, and comparison to distribution grid average house cost. RTP included on figure right axis.

Using the FRC with DAP response significantly reduces the costs, Fig. 30, with a 30 % reduction in cost for the average house. The backflow from PV to the grid during the peak price time (assuming net metering) results in the cumulative cost coming down in the 6 p.m. to 9:00 p.m. window. The Xfmr_123 houses see costs that are less than half of the baseline costs. Paying at RTP for the energy used during DAP response results in higher costs for the average customer, Fig. 31 (compared to Fig. 30) while the Xfmr_123 houses see lower prices, even negative. Note that the DAP response causes HP precooling in the 3 p.m. to 6 p.m. window, but RTP spikes up during that time on July 7, peaking ahead of the DAP signal peak used for planning. This change contributes to the higher cost for the average house but has less impact on the more efficient Xfmr_123 houses. Adding Volt-VAr control to the inverters provides a small reduction in cost. The average house cost was reduced $0.02 across the two days while the highest voltage customer saved $0.04, indicating that the purpose of Volt-VAr is voltage control, not saving money.

Fig. 30 With DAP price response, cost for customers behind Xfmr_123 and average grid house when paying all energy consumption at DAP. DAP included on figure right axis.
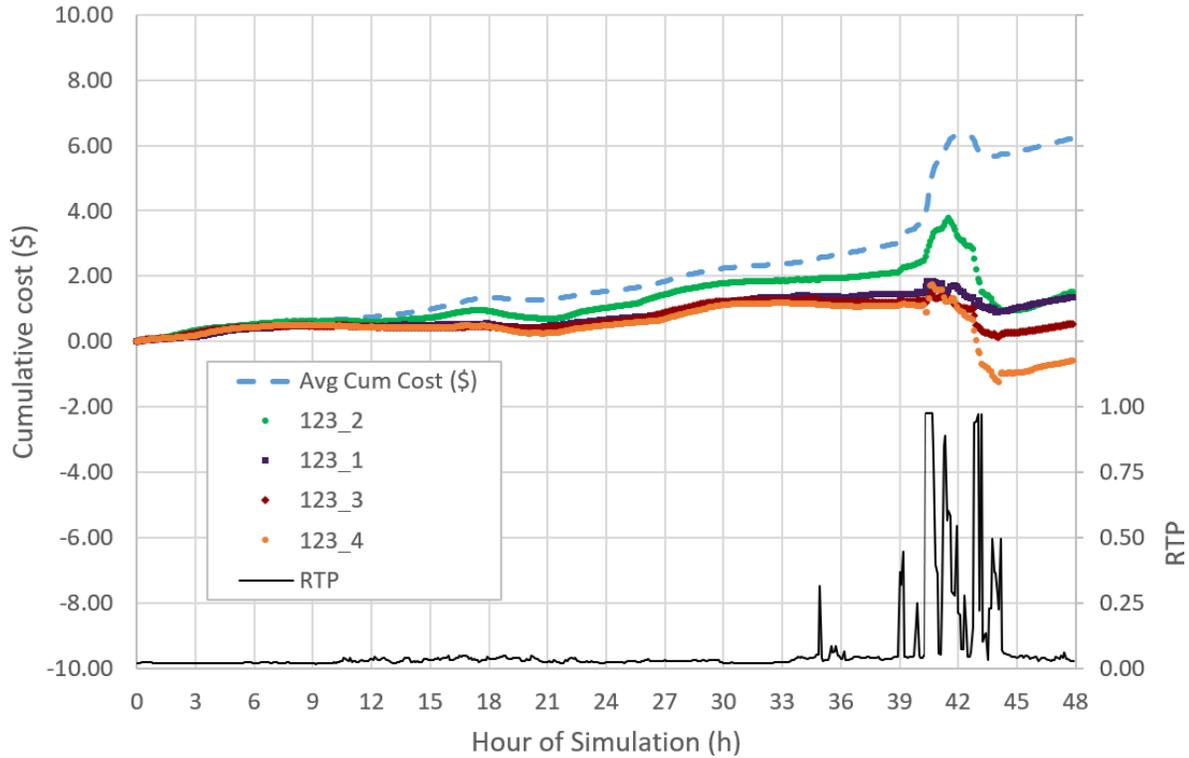
Fig. 31 With DAP response, cost for customers behind Xfmr_123 and average grid house when paying all energy consumption at RTP. RTP included on figure right axis.

Implementing the RTP-adjust function has a large impact on customer costs. During the price spikes, all the houses raise set points and set batteries to full discharge. The result is strong backflow to the bulk grid while the houses are credited for that power flow out at the high RTP price. The result is that the average Xfmr123 house gains about $6 during the afternoon of July 7, Fig. 32, while the average grid house had a $4.18 savings below the cost seen without RTP

adjust (Fig. 31). The customers in the houses behind Xfmr_123 were all paid by the utility for providing power when the real-time market marginal price was so high.

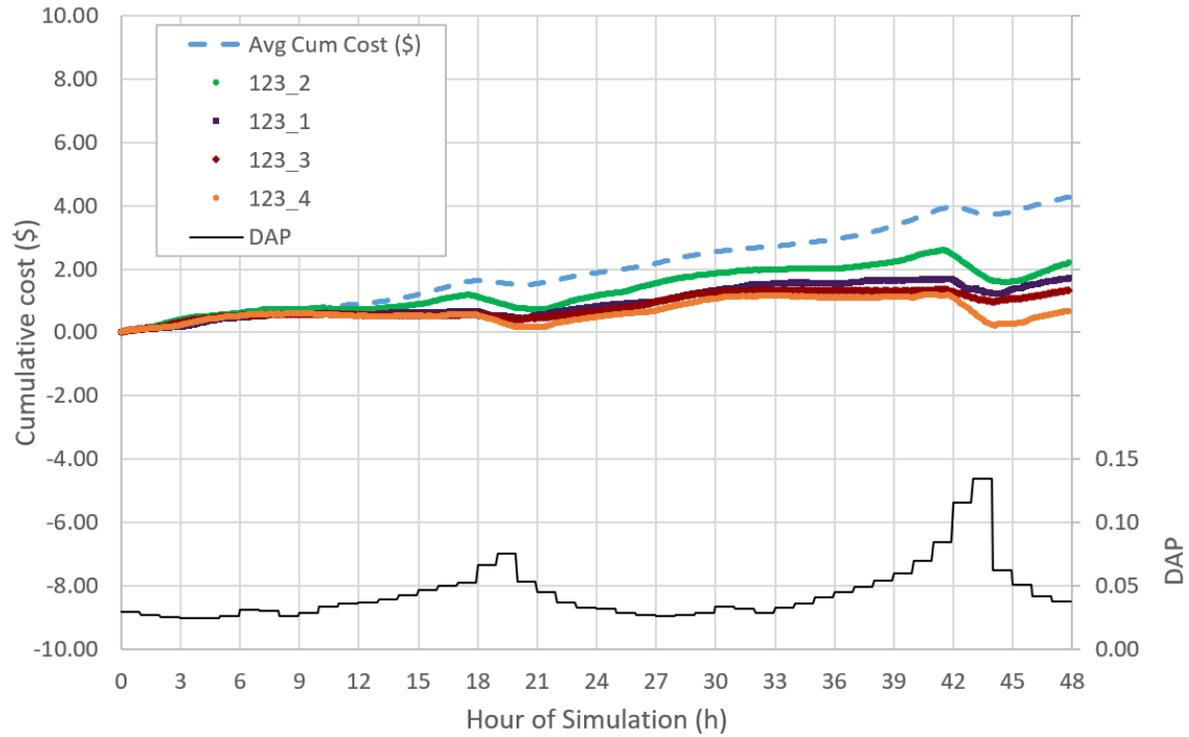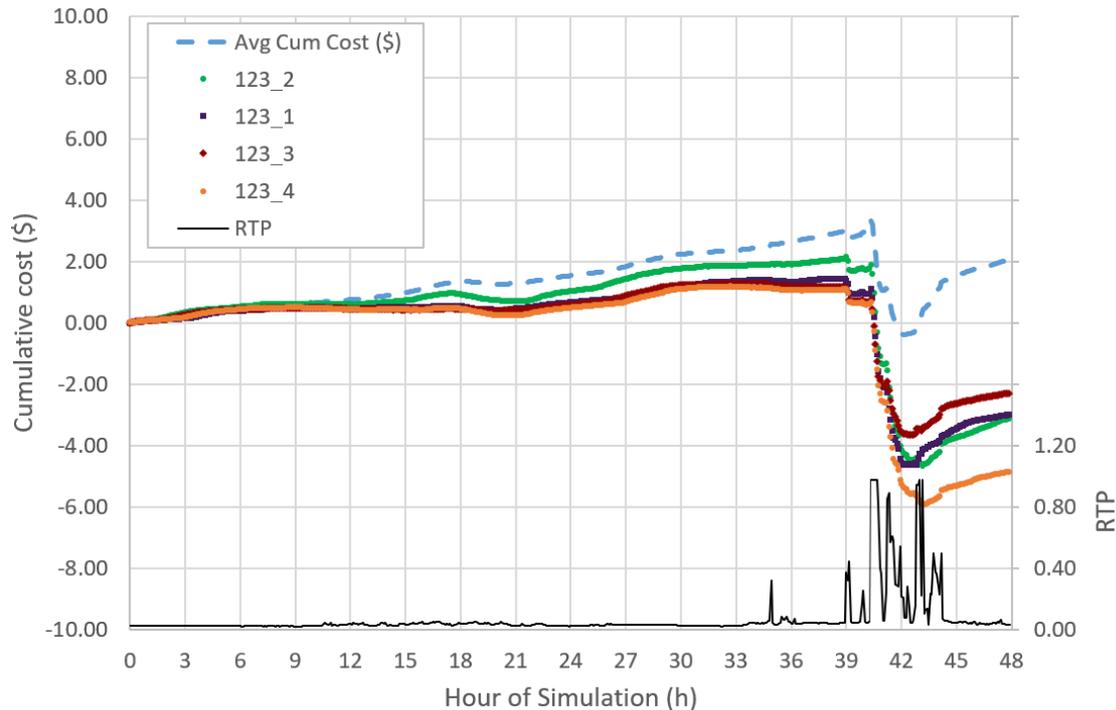**Fig. 32** With RTP adjust in addition to DAP response, cost for customers behind Xfmr_123 and average grid house when paying all energy consumption at RTP. RTP included on figure right axis.

4. Discussion

Flexible Resource Controller operation

The FRC is designed for customer energy cost savings, based on dynamic prices, and it succeeds at that. Customers save money by heat pump precooling and then raising the temperature setpoint higher during high price evening peak, by setpoint temperature adjustment of the water heater, and by battery arbitrage. Responsive loads can help reduce line voltage drop by reducing load. The data presented here show the potential for residential appliances (HP, DHW, batteries) to move much of the load off peak (Fig. Fig**. 13**, Fig**. 14**, Fig**. 15**).

The FRC focus on low and high price periods causes strong load reduction on price peak while shifting load to lower price time intervals. When this approach is combined with a very high percentage of responsive load, the result is large changes in demand and voltage. These changes are not locally beneficial, even if they may support bulk grid energy balance. Nonetheless, inverter Volt-VAr helps to significantly reduce voltage variation.

Is this behavior what we should expect from price-responsive controllers? As a first response, yes, if a price-responsive controller watches a price signal and controls a device to save the most money. However, there may be regulatory demands or other factors influencing a device owner

to pursue different goals despite loss of income. In addition, there may be different tariffs with different price signals (e.g., a TOU tariff versus one based on day-ahead markets). And there are other ways to control devices for providing grid services that don't involve a price signal, e.g., an aggregator may use control signals (a battery operator may send out "charge" or "discharge" commands) to provide ancillary services, which in turn dilutes the number of price-responsive devices. If the utility price signal is tied to the wholesale energy market, then FRC response behavior might be expected.

To be clear, the results presented here are NOT what we are likely to see in the future when we have much higher penetrations of DER and price-responsive loads on the distribution grid. In the future we can expect to have higher penetrations on many distribution grids. Then customer flexibility will in turn be reflected in the market price itself. That is, the market clearing prices will adjust to the presence of large amounts of price-responsive customer flexibility, leading (ideally) to a flatter load curve, not one that contains many sudden spikes. However, that is still speaking about the average grid, whereas a specific distribution grid or sectional with some concentration of a specific DER or device, may see increased voltage variability.

What, then, are we to learn from these experiments? The results give us insights to the impacts (magnified large) that price-responsive loads can have on distribution voltage when the infrastructure (wires, voltage regulators, etc.) are not designed for it, when wholesale markets are not accounting for the flexibility, and when price signals are not tuned to local conditions. This result is what we *could* see on a high-DER grid today if we load it up with price-responsive loads and pass it today's wholesale market clearing prices. The results teach us about price signal formation and controller design.

Hosting capacity

We know that hosting capacity (HC) is typically limited by high voltage due to PV generation at peak sun and minimum load, as well as limited by low voltage when load is high but there is no sunshine. And these out-of-limit voltages occur at specific spots on the distribution grid.

Simulations of the R4-1 grid show that a strong flexibility response to bulk grid energy market prices could hinder voltage management and lead to reduced HC. However, price signals could potentially be modified at a local level to minimize voltage variability while still supporting bulk grid capacity (or reserves or regulation) needs. The price signal could be smoothed or designed to consider voltage, both of which will likely increase HC.

To say it another way, the electricity tariff can impact hosting capacity. If the utility offers a dynamic price tariff based on the volatile wholesale real-time market (RTP), then it's possible that HC could be reduced, depending on grid congestion and amount of responsive load. A tariff that is locally tuned to voltage can boost HC but may be less beneficial to the customer in terms of cost savings even if the average price across the day does not change. In essence, voltage-tuned prices could optimize the use of flexibility within HC limits.

Alternatively, instead of modifying the price signal to be local voltage-aware, a utility could set up a program to use customer batteries for power quality management. The customer could be paid some incentive to allow the utility to implement Volt-VAr control and to give the utility charge and discharge control of the battery. In this case, the customer likely could not use the battery for arbitrage. For the R4-1 grid, the batteries have enough capacity to largely flatten the load curve, charging with peak sun to later supply peak load. With this approach, the utility-controlled batteries could help to better manage voltage.

In order to optimally address intermittent renewables, we need to incentivize customer DER flexibility. Dynamic pricing is an important tool for incentivizing load flexibility. The industry is currently in a transition phase, testing the use of different dynamic market price-based tariffs. Initially, with relatively low penetration of price-responsive load, there will be no large power flow changes in response to price. This study shows the potential for price changes to induce voltage volatility and utilities should consider carefully what the price signal looks like and how controllers will respond.

Possible Lessons for utilities

Voltage management: The distribution utility must plan for both full-sun and no-sun, full-load and no-load scenarios. While PV generally offsets and reduces peak load, it also is not dispatchable. Likewise, price response typically helps to move load off peak and raise voltage.

Prices taken from wholesale energy markets are disconnected from local voltage issues. They may encourage load response that worsens voltage stability, whether due to coordinated load changes at price changes, or over-compensation locally leading to voltage problems. Passing unmodified, volatile wholesale energy market prices to devices can lead to worse power quality [11].

As seen in this study, price response has the potential to hinder voltage control. Flexibility will always have some impact on distribution voltages depending on loading, PV and battery distribution, amount of load under control, device control strategies, tariffs, etc. A more congested grid will have more voltage problems, in general. The utility may use inverter Volt-VAr and Volt-Watt controls and dynamic conservation voltage reduction (CVR) in addition to traditional voltage control devices. A utility may also consider investing in community storage that can be used for voltage management via Volt-VAr as well as via voltage-sensitive charge and discharge.

Flexible devices could be made to support voltage if a local price (more granular than the feeder) is adjusted based on voltage and transformer loading.

Price signal formation: What kind of price signals should be passed to customers?

- If possible, it is desirable to have a day-ahead price to allow storage (thermal and electrical) to support the grid. A real-time price component can also allow a customer's facility or devices to respond to real-time grid events.

- The utility could monitor voltages at key points on a feeder to observe the impact of price signals in different seasons and times of day as more or less customers subscribe to one or another tariff and employ different price-responsive controllers. This action will inform incremental grid upgrades and alert to any concerns with the price signal itself.
- If and when price response induces voltage problems, the utility could consider smoothing the price signal, reducing intra-hourly volatility, etc. Ideally, the potential for volatility will be considered up front. The previous report [11] references several existing tariff examples. Multiple utilities and public utility commissions are now considering dynamic tariffs.
- A Time-of-Use tariff is a common pricing tariff but suffers from a sharp change in price, leading potentially to sharp power and voltage changes. Moving to a fixed hourly-averaged day-ahead price could be an improvement.
- Batteries and other storage will tend to charge at lowest price and discharge at highest price. Therefore, if there is a sharp peak or valley in the price signal, then charging and discharging will be concentrated in a short interval of time.
- Ideally, the tariff is communicated using standard price communications, such as OpenADR. This standard approach is important for controller vendors that need to understand different signals and do not want different signals used by different utilities.

5. Conclusion

This work builds on previous simulations now using a less-congested grid, with added flex load and including Volt-VAr. Results show the potential for flexible loads (heat pumps, water heaters, and batteries) to shift load and dramatically alter the power flow and voltage. The load shifting was guided by wholesale electric market price signals, primarily the day-ahead market clearing prices. The Flexible Resource Controller algorithms respond to the prices by shifting load off peak and moving heat pump cooling and battery charging to lower price times. The voltage stays within ANSI 84.1 Range A limits (for the case with adjusted substation voltage), but the voltage range is increased due to price response. Volt-VAr control was also applied to the battery and PV inverters and this control helped to reduce high voltages.

The results demonstrate that passing today's energy market prices to a distribution grid with most of the load on the grid being price-responsive, in addition to price-responsive batteries that charge and discharge based on price arbitrage, can lead to very strong power flow changes and resulting increases or decreases in local voltages. In practice, we don't think this situation will be realized, for a variety of reasons: there will not be a grid in the near future with such a high percentage of price-responsive loads and batteries, not all customers will subscribe to the dynamic price tariff, and energy markets themselves will adjust to the presence of more flex loads which, in turn, will moderate the flex load response.

It is not clear that bulk energy market prices should be passed to distribution grid devices if there is a large percentage of flexible load on a congested grid. Storage resources (thermal as well as electrical) seek to charge at lowest price and discharge at highest price, thus concentrating load to certain periods of the day. Additionally, flex loads may respond in unison, turning off/on, in response to a volatile price signal. The result may be unacceptable voltages at points on the

circuit. At some point, the value of the price signal may be negated by shortened life of utility hardware and customer equipment. Use of a price signal that is adjusted locally based on voltage may help to alleviate voltage problems. A heterogeneity of tariffs and controllers will also help.

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