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Abstract

The Flexible Resource Controller (FRC) is a multiple-objective controller that manages residential heat pumps (HP), electric water heaters (DHW) and batteries. The first objective is to manage energy use to save customers money—charging storage when electricity prices are low and avoiding energy use (or discharging the battery) when prices are high, while maintaining thermal comfort. A second objective is to implement reactive power control at the battery inverter based on local voltage levels (Volt-VAr) to minimize voltage excursions outside of acceptable limits.

The FRC has been developed as a federate for transactive energy co-simulations using the GridLAB-D distribution grid simulator to study the impact of price-responsive controls on voltage and other building and grid metrics. It takes as inputs the house thermal properties, weather and electricity price data and generates control variables (e.g., hot water temperature setpoint, battery real and reactive power settings) that are input to the GridLAB-D simulation engine on each time step. The FRC makes use of day-ahead hourly prices in addition to optional adjustment of control parameters in response to 5-min real-time prices. The FRC currently implements simple patterns that shift power usage based on prices. The FRC HP controller implements precooling prior to the evening price peak and then a raised house setpoint temperature during the price peak. The DHW controller lowers the tank setpoint in the afternoon. The battery is set to charge at night and discharge during the price peak. Battery inverter Volt-VAr voltage control is implemented independently of price response, operating at all hours of the day when activated. This document describes the control algorithms that were implemented in the Java programming language and provides an overview of a co-simulation that connects the controller to a GridLAB-D distribution grid simulation.

Keywords

DER flexibility; device controller; dynamic price; price response; voltage control; Volt-VAr.

1. Introduction

The Flexible Resource Controller was developed in the context of transactive energy (TE) simulation studies to understand the effect of different TE approaches (different markets, different dynamic price tariffs, different controllers) on customer economics, customer comfort, and grid power quality. Power quality metrics include voltage volatility and acceptable voltage levels, as well as power factor, losses, and transformer loadings. The FRC was developed to study the impact of price-responsive flexibility on distribution voltage and the value of voltage-responsive reactive power control (inverter Volt-VAr) relative to other voltage-control measures. The best sources of price-responsive flexibility include the largest loads in the house, electric heating and cooling equipment (e.g., electric heat pump) and electric domestic water heater (DWH), in addition to an electric vehicle or stationary battery. Each of these devices has thermal (i.e., building thermal mass) or electrical storage (i.e., battery) to enable load shifting.

Every house on the current test grid model (the same R4-12.47-1 GridLAB-D model used in [1]) has a heat pump, electric water heater and stationary battery. The capacities of the HPs and DHWs vary house to house, as do the thermal properties of each house. The FRC manages the HP and the DHW in each house in such a way as to maximize customer financial savings while staying within allowable comfort/performance boundaries. The battery is managed for energy arbitrage—charging during low price times and discharging during high price times. The purpose of the Volt-VAr control is to use inverter-based reactive power control to move voltage closer to the nominal 120 V level.

In previous experiments where devices responded to 5-min wholesale market real-time prices (RTP), the resulting power flow and voltage were volatile, due to synchronized response to price changes [1]. The FRC avoids this for the HP by creating a charge or discharge profile that is different for each house according to its thermal constants. For the DHW and battery, some randomization across houses is used to avoid synchronized response. The randomization may be similar to what would occur when different controllers are present with different control logic, responding in slightly different ways to the same price signal. The FRC control is primarily based on the wholesale market day-ahead hourly prices (DAP, taken from Tucson price data from July 2017 [1]) and assumes that the customer will be charged for power according to the DAP. Based on previous research [1], response to DAP allows planning for storage use (including load shifting) and avoids the larger power swings that occur when all devices react to a volatile RTP signal. On the other hand, the FRC also has logic that, if enabled, causes the controller to avoid using power during RTP price spikes, as may be applicable to a tariff where part of a customer's energy use is paid at the RTP while a baseline amount is paid at DAP.

The Volt-VAr control has been implemented to reduce voltage range of fluctuations on the grid as well as to reduce the count of voltage excursions outside of ANSI C84.1 Range A limits [2]. As voltage levels rise, inverter reactive power consumption increases to lower voltage. Likewise, as voltage drops, reactive power injection increases to raise voltage.

2. FRC Design

The FRC serves as a simple algorithmic controller that manages HP, DHW, and battery operation based on price. The FRC receives both wholesale market day-ahead hourly prices (DAP) in addition to 5-min real-time prices (RTP). The FRC uses a simple approach to manage load based on DAP, reducing load or discharging when the price is high, and charging when price is low. The FRC also implements standard Volt-VAr control to inject or consume reactive power based on local voltage and thereby move voltage closer to nominal.

The FRC has a configuration file that allows enabling or disabling control of 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 Figure 1.

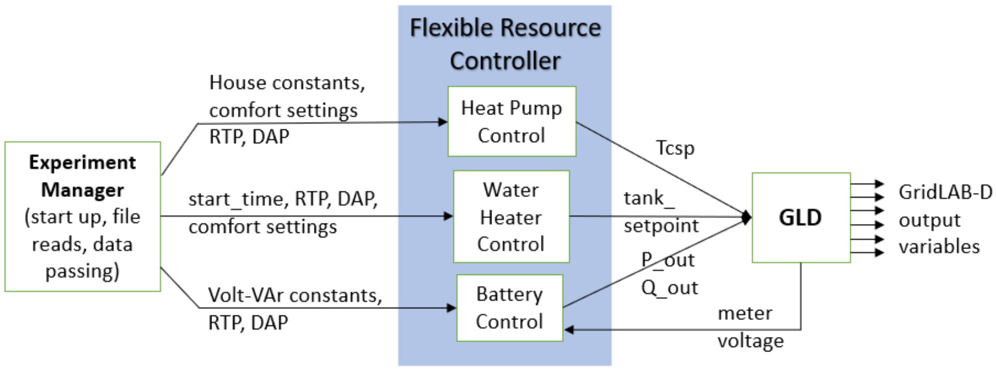

Figure 1 Flexible Resource Controller architecture within UCEF along with the data elements moving between UCEF components: Experiment Manager, FRC, and GridLAB-D (GLD).

The FRC acts as a single federate within the Universal CPS Environment for Federation (UCEF) [3]. UCEF is the co-simulation environment, and the Experiment Manager, FRC, and GridLAB-D (GLD) are federates (software components) in the co-simulation (Fig. 1). GridLAB-D simulates distribution grid power flows and the energy consumption of various loads in residential homes, taking control inputs from the FRC and generating power flow and house and device parameters as outputs.

As shown in Fig. 1, the FRC consumes price, inverter Volt-VAr constants, house thermal constants and occupant comfort parameters, and configuration options (i.e., which controls to use for each device). These are used to generate house temperature cooling setpoints (*Tcsp*) to drive HP operation, DHW tank setpoints to manage when DHW heats water, and the charge/discharge cycle for each battery. 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 inverter for Volt-VAr control. The specific design of each FRC component is provided below.

2.1. HP Controller

The primary goal of the FRC HP controller is to provide cost savings to the consumer within comfort requirements, responding to both DAP and RTP by avoiding running the HP during high-price times. There are two components: precooling based on DAP and adjustment based on RTP. The FRC logic currently only manages summer cooling season. Control variables are given in Table 1.

Table 1 Heat Pump Controller Variables

Variable Name	Description
Tau	House thermal mass time constant (h)
Ppeakda	Peak price for that day, using DAP ($)
Prtp	RTP 5 min price ($)
Rrtp	*Prtp/Ppeakda*, ratio of current RTP to DAP peak price
tpeak_ctr	Center of the DAP peak price hour (time)
tpeak_wid	Width of the peak time period (h)
tpeak_start	Start time for the peak period (time)
Hpp	Number of hours of precool preceding start of peak period (width of precool period, in hours)
tprecool_start	Start time for the precool
Tset	Baseline setpoint temp for each house before price adjustment (F)
Tset_pre	Setpoint temp during precooling (F)
Tset_peak	Setpoint temp during peak time period. When responding to DAP, this temperature will be set equal to *Tmaxλ* (F).
Tmaxλ	*Tset* ± *offset_limit* × (1-λ), where *offset_limit* is a maximum house temperature offset in response to price and λ is the customer comfort parameter.
Tminλ	*Tset - offset_limit* × (1-λ)
Tset_dap	Temperature before RTP adjust (could be *Tset*, *Tset_pre*, or *Tset_peak*)
Tcsp	Final house cooling setpoint temperature sent to GLD, including any adjustment based on RTP (F)

2.1.1. Precool based on DAP

The air conditioning in a typical house can be off for 1 to 3 hours while house temperatures rise during a peak price period, depending on house thermal parameters and customer comfort parameters. The temperature setpoint during this peak price period (*Tpeak_wid*) can be set to some *Tmaxλ* adjusted for customer comfort requirements. Likewise, before this peak period there can be a precool time to lower the house temperature (thermal mass temperature) to then enable a larger and longer temperature rise during the peak period. The setpoint during precool can be set to *Tminλ*. The FRC determines the length of a peak window and a precooling window. The peak *Tmaxλ* window is centered around the DAP peak price hour. Window sizes are determined based on house thermal constants. Determining *Tcsp* follows this progression.

1. Find *tpeak_ctr*. The Tucson July peak price is in the 7-8pm hour. Use 7:30pm.
2. Find *tpeak_wid*. This width varies with the thermal time constant of the home, just as the precool period varies.
    a. *Tpeak_wid* = 0.75 *Hpp*, and
    b. *Hpp* = 2 + *Tau*/6 (see discussion below)
3. Calculate *tpeak_start = tpeak_ctr – tpeak_wid*/2. For this simulation, *tpeak_start* will vary from (5:00 to 6:30) p.m. approximately.
4. Calculate the precool period start time such that precool period ends at *tpeak_start*
    a. *Tprecool_start = tpeak_start – Hpp*

5. Set temperature during the precool
    a. *Tcsp = Tset_dap = Tset_pre = Tminλ*
6. Set temperature during the peak time period
    a. *Tcsp = Tset_dap = Tset_peak = Tmaxλ*
7. Set temperature outside precool and peak periods at
    a. *Tcsp = Tset_dap = Tset*, if RTP adjust is not used.
    b. Else, if RTP adjust is used, see next section.

The FRC experiments on the R4-12.57-1 grid [1] used Tucson weather and CAISO prices we for June 23 to July 7 of 2017. The DAP peak is similar across all days with the peak price in the 7-8 p.m. hour and the highest prices from 6 – 9 p.m. Only the magnitude of the peak changes. The ideal *Hpp* (precool time) allows the house to cool to *Tminλ*, and this amount of time varies with house thermal time constant. GLD stores a thermal time constant, *Tau*[1], for each house. The R4-12.47-1 grid houses' average *Tau* is around 14 h, with a minimum of 4 h and maximum of 29 h. There is a trade-off between increased energy use to maintain *Tset-pre* at *Tminλ* and the amount of cooling of thermal mass that is achieved. The first few hours of cooling are the most valuable. The value of *Hpp* as a function of *Tau* was set to *Hpp* = 2+*Tau*/6. This relationship results in *Hpp* values from about 3 h for low *Tau* (*Tau* ≈ 6 h) to *Hpp* values of around 6 h for higher values of *Tau* (*Tau* ≈ 24 h). The varied peak width and precooling times also serve to stagger timing of heat pumps shutting off and turning on to minimize shock on the power flow.

2.1.2. Adjustment based on RTP

The availability of day-ahead prices allows effective use of storage, both thermal and electrical, to optimize load shedding during peak price times. At the same time, a tariff may charge the customer for power consumption based in part on RTP. In this case, it will be to the customer's advantage to avoid using power when prices are high and particularly during any price spike. For the CAISO RTP, the RTP signal is a more volatile version of the DAP, and the peak in the RTP signal aligns generally with the DAP peak, Fig. 2. However, the RTP has price spikes. The FRC's RTP adjust component raises the HP setpoint temperature during these price spikes.

This approach assumes that it is in the financial interest of the customer to minimize power use during the DAP peak period. If the RTP adjust algorithm responds to RTP at every instance, then it will no longer be responding to DAP. For this reason, the RTP adjust algorithm does not change the temperature setpoint unless RTP is greater than the peak DAP, that is, *Tcsp* is raised only when *Prtp* > *Ppeakda* (in other words, when *Rrtp* > 1). A ramp in *Tcsp* is implemented from the existing *Tcsp* up to a maximum of *Tmaxλ* + 1 as follows.

- If *Rrtp* ≤ 1, then *Tcsp* = *Tcsp-dap*
- If 1 < *Rrtp* < 2, then *Tcsp* = *Tcsp-dap* + (*Rrtp* - 1) (*Tmaxλ* - *Tcsp-dap* + 1 °F)
- If *Rrtp* ≥ 2, then *Tcsp* = *Tmaxλ* + 1 °F

The value of *Tmaxλ*+1 is arbitrary, but the assumption is that people will not want to run their air conditioner during a price spike and would be willing to slightly raise the temperature to avoid the extra marginal cost. The customer still has the option not to enable RTP adjust.

[1] *Tau* represents the time required for the thermal mass temperature of the house to change to a new value when *Tcsp* is changed, specifically the time to reach 63 % of the temp change from old to new value.

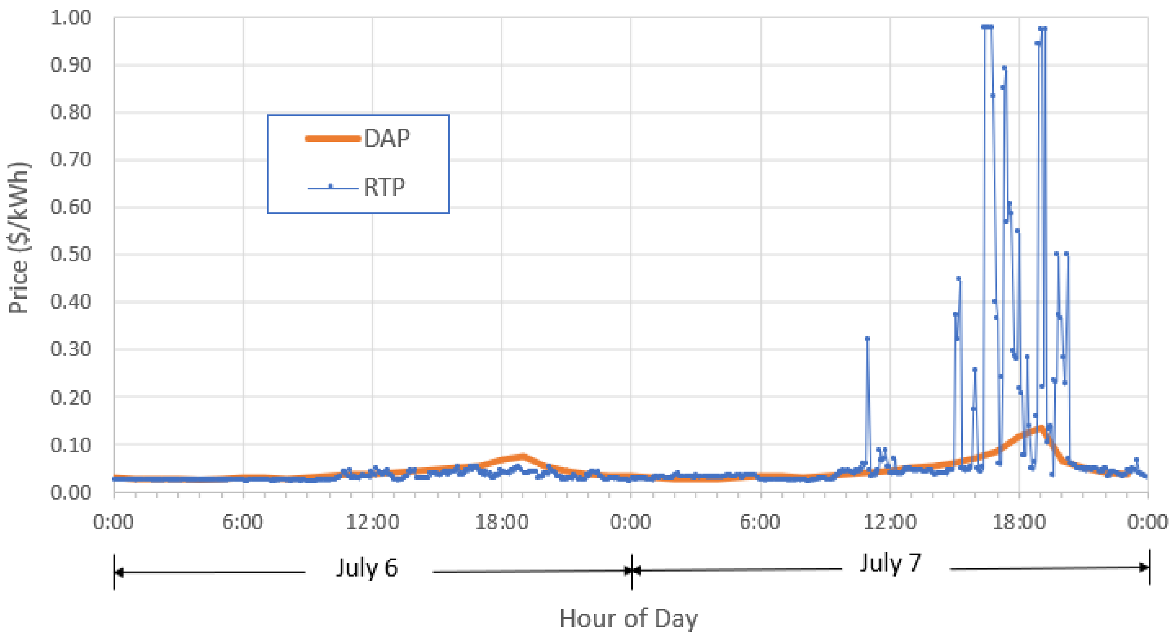

Figure 2 Real-time and day-ahead prices for test days in [1]. The FRC controls storage based on DAP peaks and valleys, but also allows response to price spikes as seen on July 7.

2.2. DHW Control

The water heaters in GLD have a distribution of sizes, water consumption per day, water temperature, and times of water consumption. In aggregate, there is a morning peak and afternoon peak in energy consumption. At the same time, price peaks in the late afternoon. In general, observing the amount of water in the tanks and amount of water drawn from these tanks in the afternoon, most customers would not need to heat water at all in the afternoon if the tank was fully heated after the morning peak. That is, a fully heated tank would serve the afternoon hot water demand of most customers without reheating before midnight.

Based on this information, a simple control strategy is used. The tank temperature is set to *Tmax* in the morning, and to *Tmin* in the afternoon. More specifically,

- *Tsetpoint* = *Tmax* from 2:00 am to noon, and
- *Tsetpoint* = *Tmin* from noon to 2:00 am.

The R4-12.47-1 grid model uses the "MULTILAYER" water heater from GridLAB-D with both "lower_tank_setpoint" and "upper_tank_setpoint". For the FRC implementation, these values were set equal to each other and to the tank_setpoint, *Tset*. The grid model DHW setpoints are uniformly distributed between 125 °F (51.7 °C) and 135 °F (57.2 °C). The setpoints are adjusted as follows.

- *Tmax* = *Tset* + 5 °F
- *Tmin* = *Tset* – (1-λ)×20 °F

The 2:00 am restart time is shifted by a random 0 min to 120 min, with one minute step (to match GLD step size) to avoid all water heaters turning on at the same time.

RTP Adjustment for the DHW works as follows. A large draw of water at any time of day will reduce the DHW tank temperature and generally cause the heating element to turn on. To reduce the likelihood of the heating element operating during a price spike, the DHW *Tset* is reduced to the GLD minimum allowed value of 90 °F (32 °C).

- If *Prtp* > 2×*Ppeakda*, then *Tset* = 90 °F

2.3. Battery Control

All batteries are the same in the R4-12.47-1 grid model, as implemented by the Pacific Northwest National Laboratory (PNNL) feeder_generator script 2022 [4] and are based on a Tesla Powerwall II with 13.5 kWh capacity, max 5 kW charge and discharge rate, minimum State off Charge of 20 % and maximum of 100 %, and with 85 % round trip efficiency.

The FRC battery control uses available GLD battery modes to enable both Volt-VAr (managing reactive power for voltage control) as well as charge and discharge of real power based on price. Since the goal is to manage the battery based on both price and voltage, the battery inverters use the GLD CONSTANT_PQ mode. In this mode, both the real power (*Pout*) and reactive power (*Qout*) values are passed into GLD from the FRC battery controller. *Pout* is used to indicate charge (-5 kW), discharge (5 kW) or no power flow (0 kW). *Qout* directs the amount of reactive power to inject or consume based on the local voltage. For this action, the FRC battery controller reads the GLD house meter real voltage output and determines *Qout* based on the Volt-VAr settings. If *Qout* is too high, such that the apparent power = SQRT($Pout^2$+$Qout^2$) > 5 kW, then *Pout* is reduced to keep apparent power at or below 5 kW. The resulting power values are passed back into GLD to direct the battery inverter.

The actual charge and discharge of the battery may be different than expected (i.e., realized *Pout* and *Qout* may differ from FRC control values) for a variety of reasons. It may be that the battery is fully charged and charging drops to zero even when the FRC battery controller is commanding continued charging. The GLD battery model will not allow overcharging. Similarly, discharge may be stopped when state of charge drops to minimum.

2.3.1. Battery price-responsive charge and discharge of real power

Price-responsive control is based on DAP. The nighttime charge, *Pcharge*, is activated during the low-price period from (2:00 to 8:00) a.m. Charging follows a 4.5 h triangular (ramp up, ramp down) pattern as follows:

- *Pcharge* ramps up from 0 kW to 4.8 kW over 0.5 hours then ramps back down to 0 kW over 4 hours with linear ramps.
- Start time is randomized for each house, uniformly distributed from (1:00 to 3:00) a.m.
- *Pout* = -*Pcharge*

The total energy added (assuming empty battery with SOC = 20 % to start) will be 10.8 kWh. This amount of charge fills the battery to SOC = 100 %. The afternoon discharge tracks the DAP peak hours.

- *Pdischarge* ramps up for 3 h from 0 kW to 3.6 kW peak at the middle of the peak hour, then back down to 0 kW over last three hours.
- *Pout* = *Pdischarge*

For the Tucson CAISO data, this algorithm means ramp up from (4:30 - 7:30) p.m. and ramp down from (7:30 - 10:30) p.m., with a total discharge of 10.8 kWh. The SOC is ignored because the GLD battery model will stop charging/discharging when full/empty.

2.3.2. Battery RTP adjust

The RTP adjust can be enabled independent of the DAP response. The battery will change state to discharge mode when the price spikes. This change will save money for the owner but have a sudden impact on power flow resulting in voltage disturbance. The discharge power, *Pout*, is unchanged (set according to charge/discharge plan based on DAP) until RTP increases above the *Ppeakda* price. The discharge power flow will then start to increase up to full discharge (5 kW) when RTP is at or above twice the peak DAP. The discharge logic is as follows.

- $Pout\_rtpadj = Pout$, for $Prtp/Ppeakda \leq 1$
- $Pout\_rtpadj = Pout + (Prtp/Ppeakda - 1)(5000 - Pout)$, for $1 < Prtp/Ppeakda < 2$
- $Pout\_rtpadj = 5000$, for $Prtp/Ppeakda \geq 2$

2.3.3. Battery reactive power control

The reactive power control (Volt-VAr) is a separate option that can toggled on or off independent of price-responsive real power control. Volt-VAr control adjusts the phase angle of voltage and current at the inverter which has the effect to change the measured voltage. The Volt-VAr dimensionless settings for IEEE 1547 Cat.B [5] (high-DER) default are as follows: *Qset*=0.44, *Vmin*=0.92, *Vlo*=0.98, *Vhi*=1.02, *Vmax*=1.08. The IEEE standard *Qset* value of 0.44 ensures that real power generation from photovoltaic inverters is not overly impacted by reactive power provision. *Qset*=0.44 corresponds to power factor near 0.9. The control logic is as follows.

1. Read house meter voltage, *V*, from GLD
    a. $Vpu = V/Vnom$, with $Vnom = 120$ V for triplex house meters
2. Set *Qout* based on voltage, where $Qout = Qpu \times Qmax$ and $Qmax = 5000$ VAr
    a. If $Vlo \leq Vpu \leq Vhi$, $Qpu = 0$
    b. If $Vmin \leq Vpu < Vlo$, then $Qpu = Qset\ (1 - \frac{Vpu - Vmin}{Vlo - Vmin})$
    c. If $Vhi < Vpu \leq Vmax$, then $Qpu = -Qset\ (1 - \frac{Vmax - Vpu}{Vmax - Vhi})$
    d. If $Vpu < Vmin$, then $Qpu = Qset$
    e. If $Vpu > Vmax$, then $Qpu = -Qset$
3. Check that $\sqrt{Pout^2 + Qout^2} \leq 5000$ VAr
4. If > 5000 VAr, then reduce Pout according to $Pout = \sqrt{5000^2 - Qout^2} \times \mathrm{SGN}(Pout)$

2.4. Implementation details

As was shown in Figure 1, the system has three components: a GridLAB-D distribution grid simulation that models (among other structures) residential houses and their energy resources, the FRC that controls these resources as described above, and an experiment manager that provides price data and other configurable settings. GridLAB-D was run in its server mode, which has a web application programming interface that allows external clients to access and modify model properties during the simulation execution. The FRC was implemented as a separate process using server mode to control the GridLAB-D model. For scalability, the FRC implementation controls multiple houses where each house has different control parameters, and one instance of the FRC controlled all the houses in GridLAB-D. The communication between the FRC and GridLAB-D was handled by a co-simulation standard called the High Level Architecture (HLA [6]).

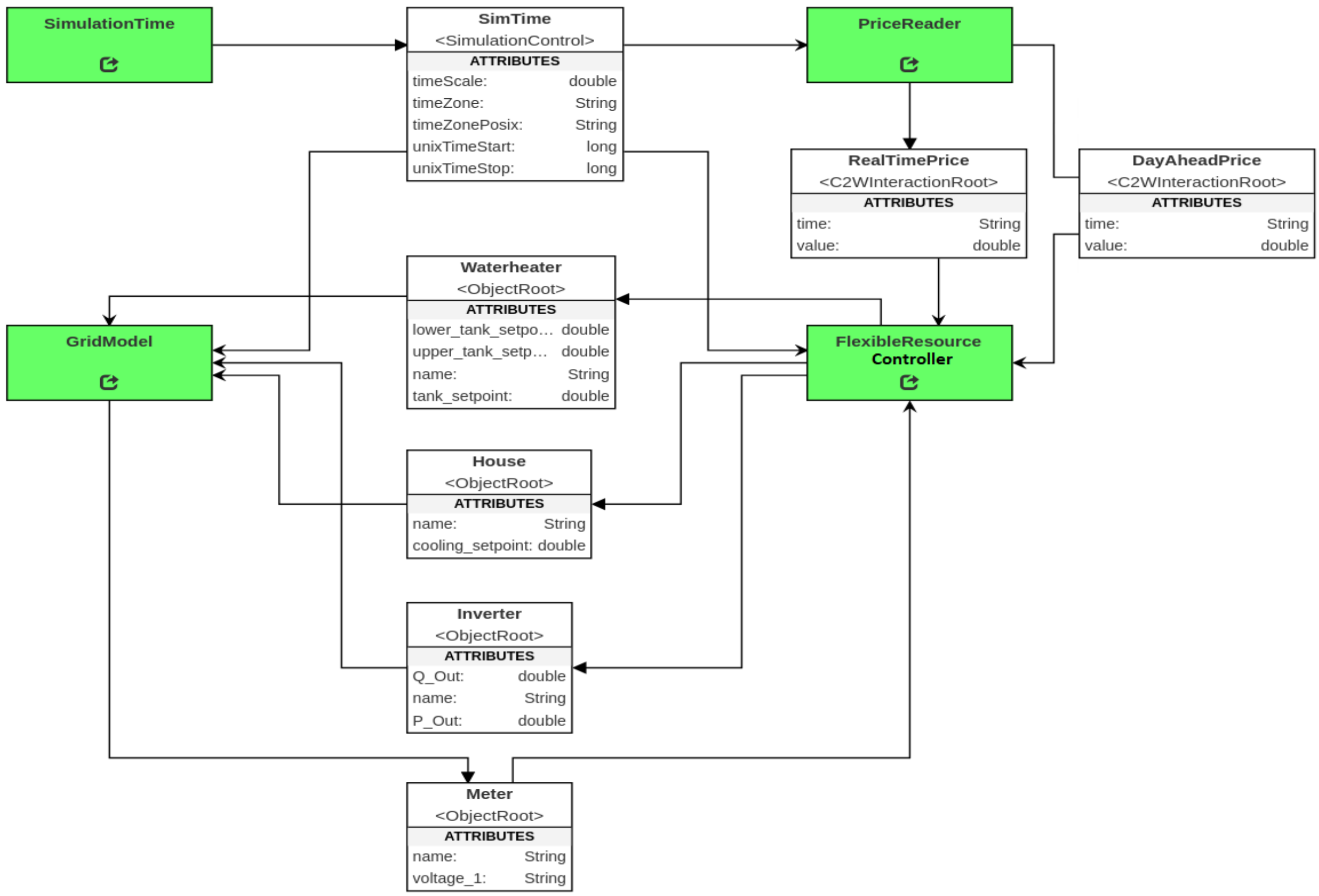

Figure 3 Model of the High Level Architecture (HLA) federation for the FRC modeled in WebGME.

Figure 3 shows the different processes (called federates) and their data exchanges in the Web-based Generic Modeling Environment (WebGME [7]). The federates (called a federation) include the GridLAB-D GridModel, the *FlexibleResourceController* implemented in Java, and two support federates called *SimulationTime* and *PriceReader* that represent the experiment manager. All the federates have a shared representation of scenario time[2], which they advance in lockstep with a configurable 60 s step size. This arrangement means that, from the perspective of scenario time, the FRC sends and receives data to its controlled devices every minute and does not interact at the timescale of seconds. The step size can be configured and was selected for improved performance given that price data is provided at the (5 to 15) min scale and the federation doesn't model the grid transient response. Both the data exchange between federates, and the synchronization of their execution, are managed by the HLA standard.

[2] The federation simulates a range of dates based on the available price and weather data (for instance, it could simulate from July 6, 2017 at midnight to July 8, 2017 at midnight). The scenario time refers to the current time being simulated within this range.

The *SimulationTime* federate specifies the scenario time reference using the *SimTime* message:

- timeScale: time step size between synchronization points (in floating point seconds)
- timeZone: default time zone for the federation represented in Olson format
- timeZonePosix: default time zone for the federation represented in POSIX format
- unixTimeStart: a unix time stamp that specifies experiment scenario start time
- unixStopTime: a unix time stamp that specifies experiment scenario end time

The *PriceReader* federate provides price data to the federation. The price data is configured using two CSV files, one for real-time price and one for day-ahead price, where each row contains an ISO 8601 time stamp (including date, time, and UTC offset) paired with the price in $/kWh. Because the federates only interact at multiples of the timeScale specified in the *SimTime* message, the time scale should be selected based on the price data to ensure the federation synchronizes as new price data is available. Real-time prices are provided each time step when new price data is available from the CSV file. Day-ahead (hourly) prices are provided at midnight, if available for the next day. In addition, as part of the initialization process when the federation starts, the *PriceReader* federate also provides the day-ahead prices for the day represented by unixTimeStart.

The FRC federate implements the heat pump control, water heater control, and battery control methods described in the previous sections. Controllers for each resource can be enabled or disabled through a configuration file, and the real and reactive power controls for batteries can be enabled or disabled independent of each other. In addition, the real-time price adjustment can be enabled or disabled per controller. Because the FRC federate controls all houses in the GridLAB-D simulation together, a CSV file configures the individual house parameters. These parameters include:

- house: the unique name of the house in GridLAB-D
- Tcsp: the cooling setpoint for the heat pump controller
- offset_limit: the maximum allowed deviation from the cooling setpoint for the heat pump
- tank_setpoint: the setpoint for the water heater controller
- lambda: the comfort parameter for the house
- tau: the thermal time constant for the house
- minute_delay: a random (0 to 120) min time offset to stagger control changes

The heat pump control, each day, computes the times for precool start, peak start, and peak end for each house based on its thermal time constant. The controller also computes three different setpoints for normal operation, precooling, and peak operation based on the house comfort parameter and offset limit. At each time step, the current scenario time is compared against these time values to determine the state (normal, precooling, peak) of each house. The corresponding heat pump setpoint is selected, and a real-time price adjustment is applied as necessary.

The water heater control, each day, computes a time interval for each house when the water heater operates at a higher setpoint. The default time range for all houses is from 2 am to 12 pm. The minute delay value configured for each house is added to the start time of this interval to stagger the heat pump operation to prevent a sudden spike of power consumption on the grid. This procedure results in individual intervals for each house that start in the range from 2 am to 4 am and end at 12 pm. During this interval, the water heater setpoint operates at the specified tank setpoint plus 5 °F (2.8 °C). Outside of this interval, it operates at a setpoint calculated based on the house comfort parameter. If a real-time price adjustment is necessary, regardless of the interval, the setpoint is set to 90 °F (32.2 °C)[3].

The battery real power control, each day, computes time intervals for each house to charge and discharge the batteries. The default charge interval starts at 1:00 a.m. with a duration of 270 min. The minute delay value configured for each house acts as a delay to the start time of this interval to spread out power consumption. This procedure results in charging intervals for houses that range from [1:00 a.m., 5:30 a.m.] to [3:00 a.m., 7:30 a.m.]. The discharge interval is the same for all houses and is the 6 h interval centered on the predicted peak hour[4]. If the peak hour for the current day is the hour beginning at 7:00 p.m., then this interval will be calculated as [4:30 p.m., 10:30 p.m.] which is centered around the time 7:30 pm. When the battery is not charging and the RTP exceeds a threshold (as given earlier), regardless of the discharge interval, the control will override the battery real power output based on the RTP adjustment. The batteries are charged and discharged according to this schedule or alternatively according to the RTP adjust mode, as described in the previous section.

The battery reactive power control for each house monitors the voltage at the house meter to set the reactive power output. This control is not time dependent and is implemented as described in the previous section. However, the batteries have a maximum charge and discharge rate of 5 kVA (apparent power) that depends on both the real and reactive parts of the battery output. To prevent the FRC from exceeding this 5 kVA limit, the reactive battery control calculates the magnitude of the complex power output after it computes the reactive power output. If the magnitude exceeds the limit, then the real power output is reduced to the maximum possible value that fits under the limit. To support this implementation, the reactive battery control runs sequentially after the real battery control to ensure the latest real power value is used in the magnitude calculation.

3. Conclusion

The Flexible Resource Controller implements heat pump, water heater and battery control based on prices. Each device adjusts power consumption in response to day-ahead prices, and optionally to real-time price spikes. Additionally, the FRC implements battery reactive power control based on local meter voltage. The FRC has been implemented in Java and deployed in the UCEF co-simulation environment to enable experiments examining the impact of customer device response to price signals.

The FRC has been tested in co-simulation with GridLAB-D using the R4-12.47-1 grid model to examine the impact of price response on distribution power quality. That report is in preparation.

[3] 90 °F is not an arbitrary value. In reality, the controller should turn off when the real-time price is too high, but there is no easy mechanism to disable the water heater control in GridLAB-D. Instead, while the prices are too high, the setpoint is set to a very low value (compared to the current water temperature in the tank) to prevent the water heater from operating. However, GridLAB-D does not allow for water heater setpoints less than 90 °F, and so the minimum allowed value for GridLAB-D was selected.

[4] The peak hour is computed each day, at midnight, based on the largest value from the day-ahead price data.

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