# Coordinated Controls of Residential EV Chargers Considering High Power Appliances

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***Abstract*—In addition to electric vehicle (EV) adoption, the electricity demand of the modern grid is also under change from the replacement of resistive electric water heaters (EWHs) with high-efficiency heat pump electric water heaters (HPWH). Typical load of a HPWH has two parts: a low power compressor and a backup high power resistive boosting element. Within this paper, residential load from a large field demonstration for over one thousand homes is simulated in virtual power plant (VPP) operation with realistic HPWH and EV synthetic modules based on big data from the latest CBECC-Res and National Household Travel Survey (NHTS). Simultaneous uncontrolled EV charging and HPWH boosting element operation cause short duration residential transformer overload and increase peak demand. The coordinated control of EV charging power based on HPWH and heating ventilation and air-conditioning (HVAC) system loads using industry standard commands, including CTA-2045 protocol, to maintain human comfort and reduce the peak power experienced by residential transformers that supply multiple houses is proposed. It is shown that the coordinated controls may reduce peak power by temporarily suspending EV charging based on future HPWH operation.**

***Index Terms*—Electric vehicle (EV), resistive electric water heater (EWH), heat pump electric water heater (HPWH)**

## I. INTRODUCTION

There has been a rise in field deployment of electric vehicles (EVs) in recent years due to energy savings, cost reductions and technology maturity [1]. To satisfy the energy demand of growing EV ownership, infrastructure improvements may be needed. Further research to estimate the scale of infrastructure change and standardize transformer replacement criteria across utilities considering smart charging may be beneficial.

A directly relevant reference by Pacific Northwest National Laboratory (PNNL), employs EV growth forecasting from 2025-2050 to vary EV location on distribution systems through Monet Carlo scenarios [2]. Transformer replacement was recommended based on the number of long-term voltage violations found. Further studies indicate that it may be advisable to upgrade all transformers of 5, 7, 10kVA due to higher power EV charging at 10-20kW [3]. The ability to reduce the number of upgrades to transformers through smart charging was investigated through these works [4]–[6]. Further evaluation of coordination for all residential high power devices is needed with electrification of water heating and heating ventilation and air-conditioning systems (HVAC).

For example, studies have proposed the replacement of resistive electric water heaters (EWH) with heat pump electric water heaters (HPWH) [7]. The energy efficiency of an HPWH is significantly higher in comparison to a resistive electric water heater (EWH) [8]. Heat pumps have much lower heat output than EWH, so instances occur when the backup resistive element, or "boosting" element, is necessary to ensure availability of hot water. If HPWH boosting elements operate simultaneously with EV charging for multiple homes serviced by the same residential transformer, especially during peak hours, it may cause short duration transformer overload and increase peak demand.

Very few of the home energy management systems (HEMS) case studies conducted for model predictive controls (MPC) with high power appliances consider both EVs and HPWHs. Early examples with EVs, HPWH, battery energy storage systems (BESS), and solar PV include the load frequency control method and distribution system centralized load management [9], [10]. Studies of centralized controls for electric power distribution systems with smart homes, including appliances, charging and energy storage in stationary or EV batteries, have been published in recent years for example in [11], [12]. Due to the complexity of building modeling, assumptions were made for floor plan and hot water draw (HWD) profiles. These challenges are general across building energy modeling (BEM) with the difficulties of data collection.

The current study proposes coordinated controls of EV considering high power appliances such as water heaters and heating ventilation and air-conditioning (HVAC) to decrease peak demand and overload duration of residential transformers. The contributions include: 146 unique and realistic synthetically-generated HPWH power profiles from the CBECC-Res dataset as well as details and citations for other publicly-available residential load datasets; discussion of priority order for coordinated controls with EV, HVAC, and HPWH; assessment for residential transformers serving multiple EVs; and results for a simulation of the proposed coordinated control method on a distribution circuit with over one-thousand houses.

## II. VPP CONTROL FOR EV AND LARGE APPLIANCES

In residential communities, Virtual Power Plant (VPP) controls through CTA-2045 have been applied for thermal energy storage in EWHs and HVAC systems in co-simulation with electric power distribution systems [13], [14]. The CTA-2045 standard is an industry communication protocol that can be used for control of HPWH, EV, and HVAC [15]. When a "load-up" or "shed" command is issued for an appliance, individual setpoints are adjusted based on the estimated equivalent energy capacity. During an EV charging shed event, charging power level was reduced using variable control [16]. For HVAC

Authors' manuscript version accepted for publication. The final published version will be copyrighted by IEEE and available as: Poore, S., Alden, R., and Ionel, D. M., "Coordinated Controls of Residential EV Chargers Considering High Power Appliances" in 2024 IEEE Transportation Electrification Conference & Expo (ITEC 2024).

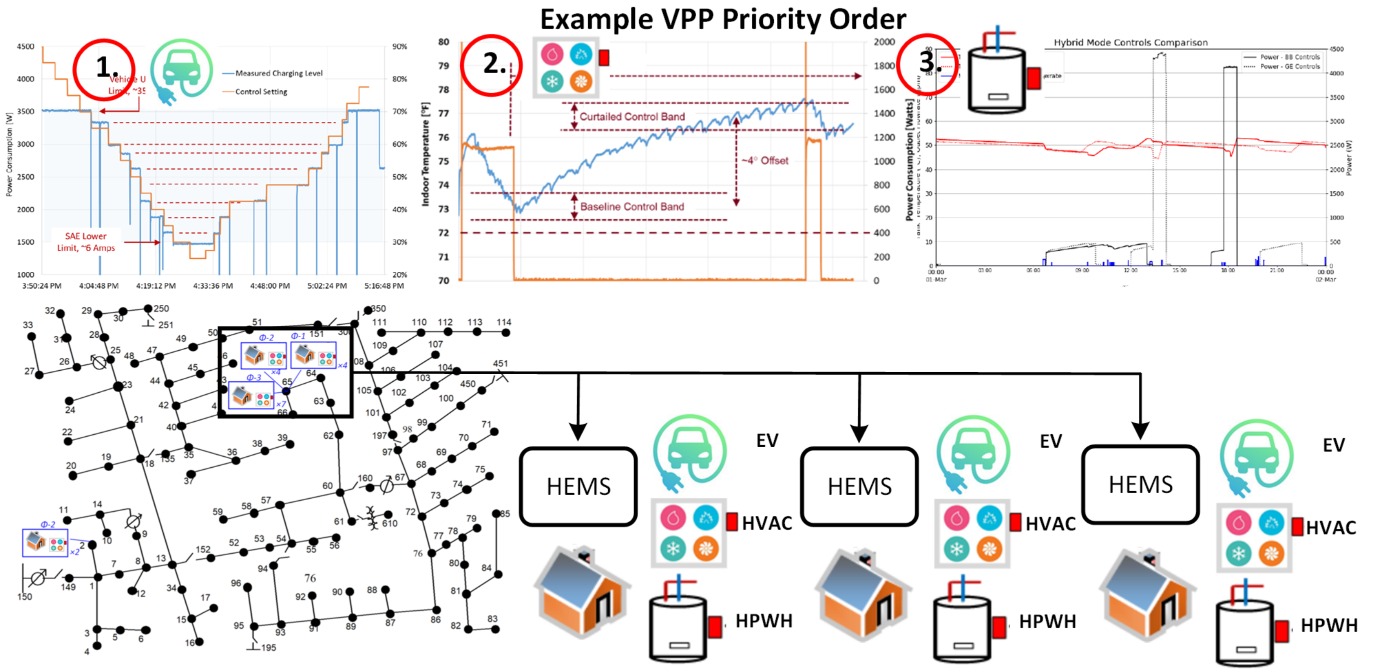

Fig. 1. Coordinated control of EV, HVAC, and HPWH can be directed with HEMS to supply grid service requests. From the perspective of VPP, control of EV charging comes first in the priority order so that control of HVAC and HPWH is avoided to maintain human comfort. Example VPP shed events for each device are shown.

and HPWH shed events, operation was stopped until human comfort limit on temperature was reached [17].

An example of CTA-2045 controls for EV charging, HVAC, and HPWH is illustrated in Fig. 1 along with the proposed priority order for shed commands. In the example priority order shown, the loads are ranked from first to third by the order in which they should be controlled in VPP, i.e. as the first and last devices to be issued shed commands, respectively. While the priority order may be changed based on customer preference, EV charging is recommended to be controlled first to avoid interfering inside the home. By employing CTA-2045 commands or equivalent industry controls from EV manufacturers, the EV charging could be temporarily suspended or the power level reduced until after short duration high loads.

## III. EFFECTS OF HPWHS AND VEHICLE ELECTRIFICATION ON RESIDENTIAL LOAD

If EV charging occurs simultaneously with HPWH boosting element operation for multiple homes on a distribution system, this may cause spikes in power demand and overload of residential transformers. To investigate, a stratified node temperature model was employed to simulate HPWH operation given HWD. Using power ratings of 0.45kW and 4.5kW for the heat pump and boosting element respectively, 146 unique HPWH power profiles were synthetically generated using the CBECC-Res 2019 and 2022 HWD data. The HPWH power profiles generated for three, four, and five-occupant houses from the 2019 CBECC-Res data are plotted in Fig. 2. While the highest peak demand is in the morning, the evening peak increases with number of occupants.

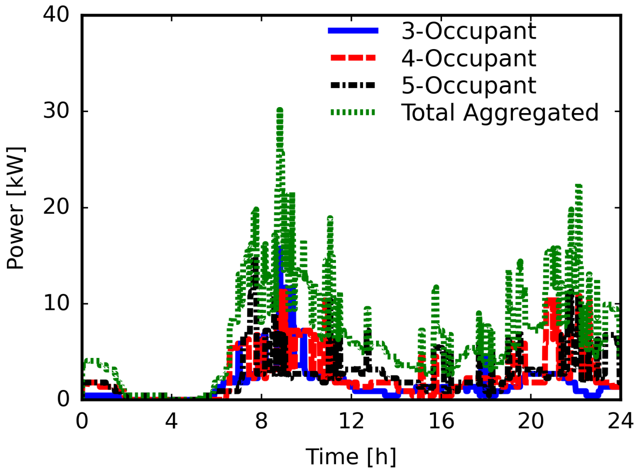

Fig. 2. Synthetically generated HPWH power profiles based on the CBECC-Res 2019 HWD data. Each category represents 10 aggregated power profiles grouped by number of building occupants.

Simultaneous operation of HPWH boosting element and EV charging may cause overload of residential distribution transformers. To illustrate a worst-case scenario of overlap, three HPWH profiles with high evening activity were intentionally selected and combined with three experimental EV charging power profiles from the Pecan Street dataset. These power demands are plotted in Fig. 3, where the combined total represents demand seen by a residential transformer serving three homes with EVs and HPWHs.

In this scenario, demand from EV and HPWH alone is more

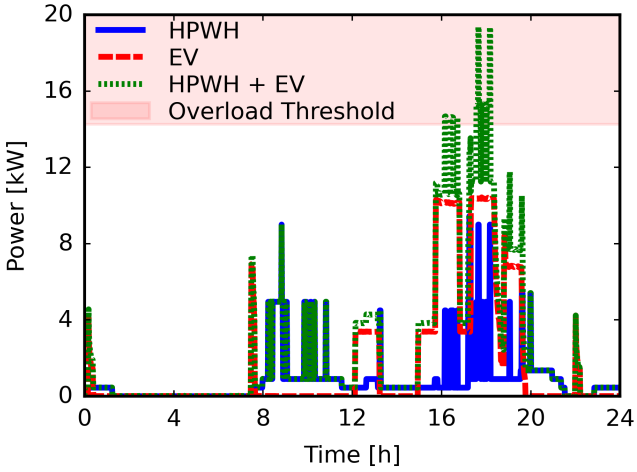

Fig. 3. Power demand for three EV and three HPWH in the scenario that the three homes are serviced by the same residential transformer. Around 6:00 PM, multiple HPWH boosting elements are active during EV charging, causing peak load high enough to overload a 15kVA distribution transformer even without other appliances considered.

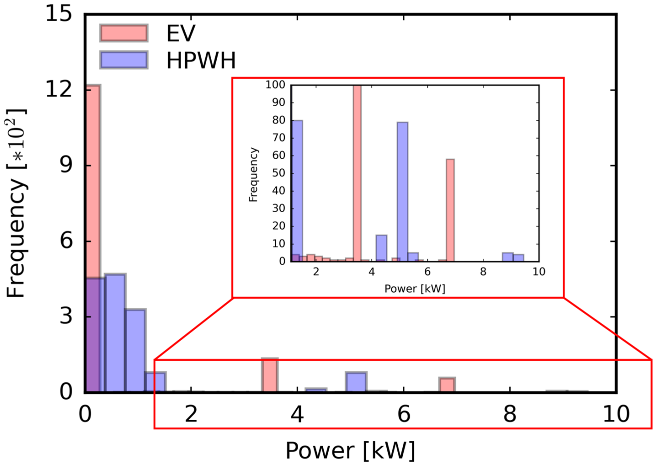

Fig. 4. Distribution of minutely power measurements for the HPWH and EV profiles in Fig. 3. While the number of instances with power draw above 2kW for HPWH and EV is low, simultaneous operation can cause large spikes in demand high enough to overload a transformer.

than enough to overload a 15kVA transformer in the evening without even considering other appliances, such as HVAC. The distribution of power demand for the day is shown in Fig. 4. While the EV and HPWH demand in this example is under 2kW for most of the day, the evening peak of high demand still causes short duration transformer overload due to simultaneous operation without considering potential high HVAC load.

Residential EV charging power profiles were generated using the California (CA) data from the 2017 National Household Travel Survey (NHTS). Details and citations for the CBECC-Res and NHTS datasets, along with other publicly available experimental and synthetic residential load datasets are included in Table I. The distribution of daily travel distance for the state of CA is comparable with the national data (Fig. 5) and it was selected because of higher adoption rates of smart controls and public data for residential loads is scarce in other regions of the USA.

For the case studies, charging times were determined based on vehicle arrival times and battery state-of-charge (SOC) upon arrival was calculated using distance traveled. Charging power profiles were generated by randomly sampling the distribution for home arrival and daily driving distance. Each EV was allowed to drive for seven days before the simulation and set to begin charging at its respective arrival time until battery SOC was 95%, and all EV charging levels and battery capacities were assumed to be 10kW and 100kWh respectively.

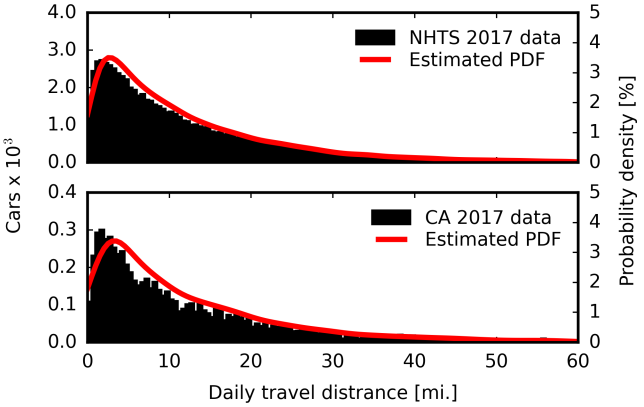

Fig. 5. Distribution of daily travel distances from the NHTS 2017 and CA 2017 data. While daily driving distance is not identical, it is comparable between the two datasets.

## IV. CASE STUDY: CONTROL OF EVS TO ENSURE CONTINUOUS HPWH OPERATION

To study overlap of EV charging and HPWH boosting element operation, an EV module was generated for each CBECC-Res profile and simulated at minute resolution across an entire day. The operation of the EVs and HPWHs is visualized in Fig. 6, where the red sections represent simultaneous operation of HPWH boosting element and EV charging at the same house. Most instances of overlapping operation happen during evening hours, when residential demand is highest. To decrease the likelihood of residential transformer overload, a control method that temporarily suspends EV charging or reduces the charger power level during HPWH boosting element operation is proposed.

An example VPP control implementation for the 146 synthetically-generated HPWH loads decreased demand from hours 17-21 by adjusting tank temperature setpoints (Fig. 7). Following CTA-2045 commands, temperature setpoints were increased from 51.7C to 55C during load-up in preparation for the shed event, and during the shed event they were decreased to 46C to avoid operation until the human comfort limit was reached. While energy consumption during the shed period was reduced by 45.4kWh for the VPP case, large, short-

Table I

PUBLIC DATASETS FOR HIGH POWER RESIDENTIAL APPLIANCES INCLUDING EVS.

| Data set | Type | Resolution | Length | Distinct entries [Cars, Tanks, HVAC Units] |
|---|---|---|---|---|
| Pecan Street [18] | EV, EWH, HPWH | 1s, 1m, 15m | 7 months | 4, 2, 1 |
| NREL PEV [19] | EV | 10m | 10 months | 100, 0, 0 |
| Honda Smart Home [20] | EV, EWH, HVAC | 1m | 7 years | 1-3, 1, 1 |
| CBECC-Res [21] | HWD | 1m | 24 hours | 0, 146, 0 |
| SHINES [22] | HPWH, HVAC | 15m | 4 years | 0, 2, 2 |

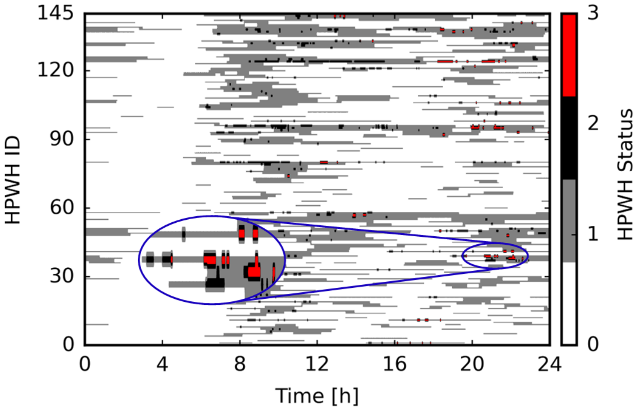

Fig. 6. Operation of the HPWH across all homes in the CBECC-Res 2019 and 2021 data. Statuses “1”, “2”, and “3” represent heat pump compressor, boosting element, and simultaneous operation of boosting element and EV charging respectively. As seen in the expanded portion, overlap of EV charging and HPWH boosting element operation is typically short duration.

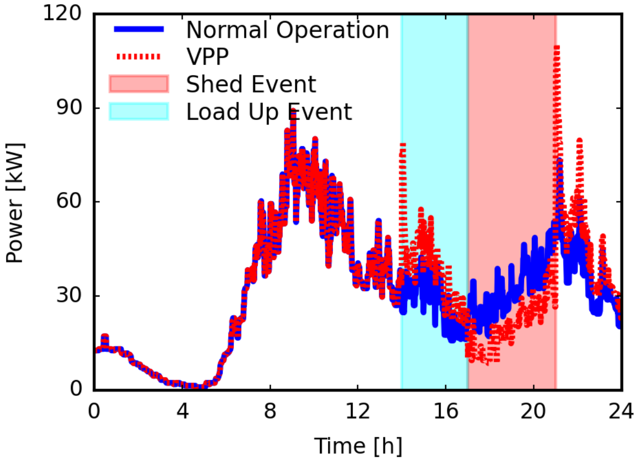

Fig. 7. Power demand of HPWHs only for normal operation and an example shed event implemented through VPP control of HPWH tank temperature setpoints. The VPP case has spikes in demand when temperature setpoints are decreased, i.e. at the beginning of load-up and at the end of shed. The proposed VPP method avoids this type of control to prioritize human comfort.

duration spikes in demand resulted when temperature setpoints were increased at the beginning of load-up and end of shed. From the perspective of VPP, control of temperature setpoints for appliances such as HVAC and HPWHs should be avoided if possible to prioritize human comfort. For this reason, EV comes first in the priority order for shed commands in the remaining case study.

A simulation of coordinated EV control was conducted on a modified IEEE 123-bus circuit populated with 1,765 home loads, including the 146 with CBECC-Res and NHTS based HPWH and EV modules for a penetration rate of 8%. This level of penetration represents a transition case to smart grid with low EV and smart appliance adoption. The proposed control method is implemented to temporarily suspend EV charging at a house if there would be simultaneous operation of its HPWH boosting element. As expected, the control method at 8% penetration has little impact on the system demand seen by the substation transformer in Fig. 8.

Residential transformers benefit more from this control method, especially during evening hours when residential demand is higher. The charging status in the evening hours for each EV on the system is shown in Fig. 9, and the red areas represent times when EV charging was suspended due to HPWH boosting element operation. Most of the instances of paused EV charging happen during hours 18-24 and only for a short duration. Since demand on the system is highest in the evening presumably when occupants arrive home from work, decreasing demand by up to 10kW for typical residential level 2 charging rates during HPWH boosting element operation may significantly decrease likelihood of transformer overload.

## V. CONCLUSION

The methods proposed employ multiple publicly available datasets for large residential loads, most notably the CBECC-Res and NHTS, which were used to synthetically generate unique and realistic HPWH and EV charging power profiles. Challenges that may result from EV adoption, especially, when multiple EVs are served by the same residential transformer, were illustrated. Due to overlap with multiple EV charging loads and operation of other high power appliances, coordinated controls may be necessary to prevent transformer overload as EV penetration increases. The proposed VPP priority order for shed events is EV first, followed by HVAC, then HPWH, to ensure human comfort.

The new VPP control method was simulated on a modified IEEE 123-bus circuit populated with base home loads as well as synthetically-generated EV and HPWH loads. The EV penetration on the system was 8%, representing a realistic transition case with low adoption. Charging of EVs were temporarily suspended when operation would be simultaneous with HPWH boosting elements to prevent overload of the residential transformers. As expected, the impact of aggregated HPWH and EV charging load on the demand seen by the

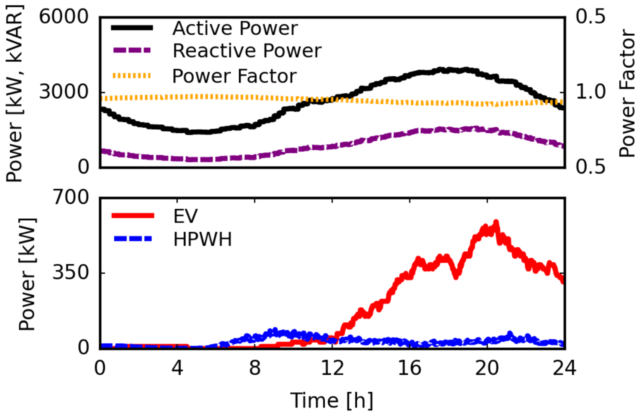

Fig. 8. Results for system power seen by the substation transformer for the VPP control case. As expected with a penetration rate of 8%, low impact on main substation power occurs. As shown in Fig. 9, EV charging is typically suspended only for very short durations representing low impact on the user.

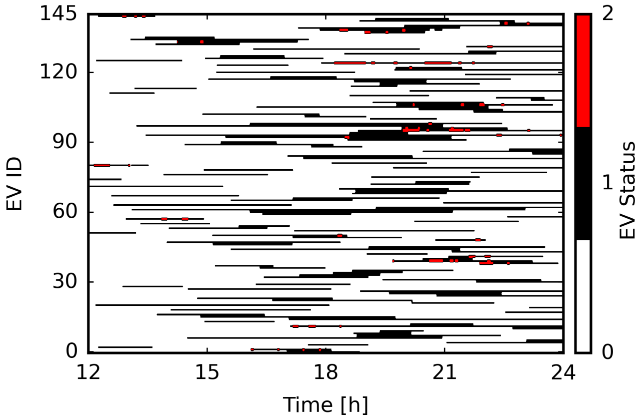

Fig. 9. Charging status of EVs on the system during the controlled scenario. Statuses "1" and "2" represent charging and suspended charging due to HPWH boosting element operation respectively. As shown through the length of the red lines, EV charging was resumed following the short periods of suspension.

substation transformer was minimal due to the short duration of boosting element operation and a more even distribution in comparison to EV. At higher penetration rates, the use of VPP commands to reduce the EV charging power level may be deployed as needed to maintain a low grid impact.

## ACKNOWLEDGMENT

This paper is based upon work supported by the National Science Foundation (NSF) under NSF Graduate Research Fellowship Grant No. 2023356979. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NSF. Special thanks are due to the industry collaborators from AO Smith Corporation Mr. Tim Rooney and Mr. Brian Branecky.

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