Federated Power Plant Controls for Outage Resiliency in Distribution Grids with EVs

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***Abstract*—Tens of thousands of utility customers are affected by major outages every year. While many outages such as those due to extreme weather are inevitable, existing distributed energy resource (DER) infrastructure including electric vehicle (EV) batteries may be leveraged for communities to self-sustain during an outage. A market-free federated power plant (FPP) control approach is proposed to coordinate DER dispatch for sustained microgrid operation during an outage. Communication between a centralized controller and home energy management systems (HEMSs) allows responsive operation to grid conditions and occupant preferences, optimizing DER performance while avoiding curtailment of critical loads. Extensive experimental and synthetic data were employed, including thousands of EV charging profiles generated with travel survey data, to test outage resiliency potential of a very large distribution grid with over 5,000 homes and high DER penetration. Simulation results demonstrated potential for over 70 hours of self-sustained operation during an outage.**

***Index Terms*—Microgrid, resilience, reliability, distributed energy resource (DER), electric vehicle (EV)**

I. INTRODUCTION

The advancement of grid resilience and modernization represents a top research priority recognized by national laboratories and independent research organizations [1], [2]. In recent years, millions of utility customers were affected by major power outages in the United States (US) alone [3]. While some outages, such as those due to extreme weather, are inevitable, existing distributed energy resource (DER) infrastructure may be leveraged to provide self-sustained operation for communities during an outage event. Common DERs include electric vehicles (EVs), battery energy storage systems (BESSs), and solar photovoltaic (PV) arrays, all of which have already seen significant deployment in the US [4]–[6].

A previous study by our group found that an individual home equipped with an EV, BESS, and solar PV array could self sustain during an outage for up to 72 hours in some cases [7]. This potential could further increase when considering entire communities where each home is equipped with DERs. The Federated Power Plant (FPP) concept was originally proposed by the authors of [8] and refers to a network where DERs owned by utility customers are deployed to provide ancillary services through energy trading. In this paper, a market-free FPP approach is considered to provide the same dispatch and energy trading functions without associated cybersecurity risk [9].

Extensive experimental measurements and synthetic data were utilized to test the proposed FPP control in a community with high penetration of EVs, BESSs, and solar PV. Contributions include: synthetic generation of thousands of EV charging profiles using travel data; a proposed FPP framework with forecasting and user-defined inputs to optimize operation of DERs during an outage; development of a virtual testbed using extensive experimental and synthetic data; and a systematic resilience potential assessment of a distribution grid with over 5,000 homes, each equipped with DERs.

II. PROPOSED FEDERATED POWER PLANT CONTROL FOR OUTAGE RESILIENCE

A market-free FPP control method is proposed to optimize DER dispatch during outage events based on load forecasting and user-defined settings, as shown in Fig. 1. During normal operation, i.e., when there is no outage, solar PV generation will charge the BESSs. The controller would maintain the BESS SOC between 20% and 80% to minimize lifespan degradation as widely recommended in literature [10].

When an outage is detected, the community will island to operate as a microgrid and implement FPP control. During an outage, solar PV generation will directly supply local loads and BESS and EV batteries will discharge during times when system load exceeds solar generation. Home energy management systems (HEMSs) may operate as decentralized controllers for management of local loads, generators, and energy storage, where they will optimize operation based on forecasts from the cloud and user-defined inputs. Occupants may select an appliance priority order, allowing the HEMS to determine which loads should be curtailed first, if necessary.

At each timestep during an outage, HEMSs respond to current system conditions and forecasts to determine the charge and discharge setpoints for BESS and EVs. These setpoints are calculated based on the PV generation, load demand, and SOC constraints. If system demand exceeds solar PV generation and sufficient BESS capacity is available, BESSs will supply the load. If there is not sufficient BESS capacity, available EV batteries are then dispatched to supply the load. During times where PV generation is greater than the load, excess generation is utilized to charge BESSs.

III. SYNTHETIC GENERATION OF TRAVEL PATTERN-BASED EV CHARGING PROFILES

Due to the very limited availability of experimental EV charging data, synthetic EV charging profiles were generated for this study using the 2022 National Household Travel

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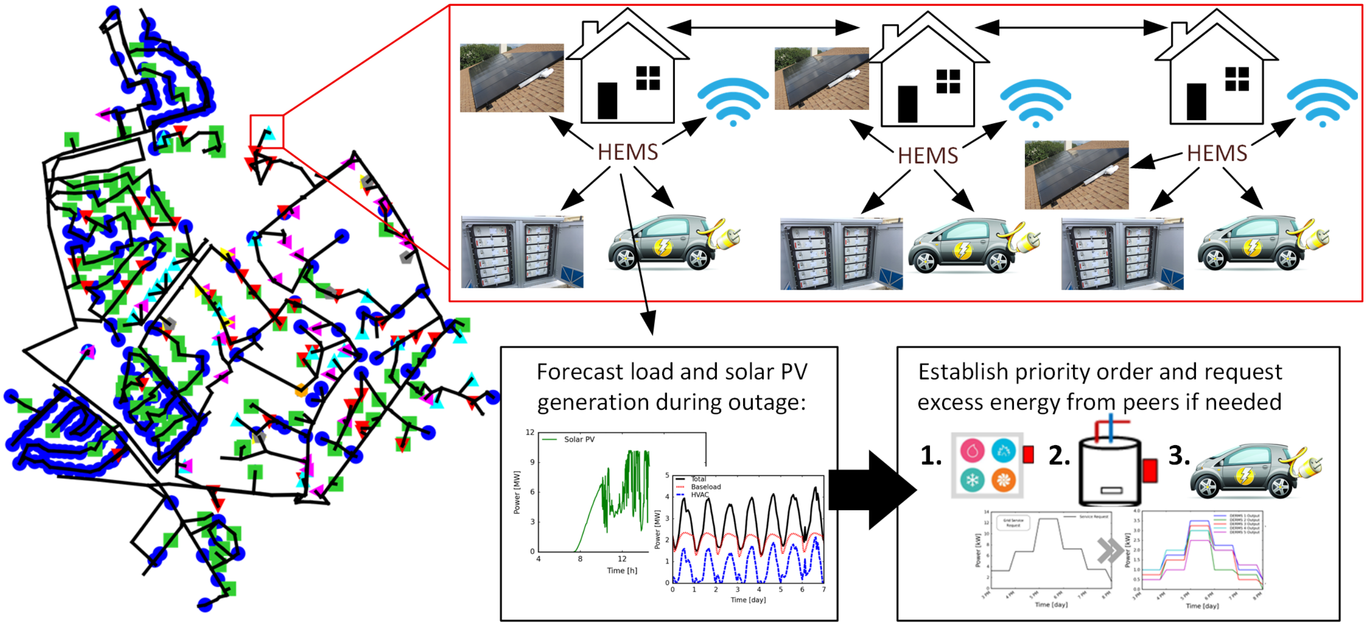

Fig. 1. During an outage, distribution grids can island to operate as a microgrid, where a centralized controller communicates to home energy management systems (HEMSs) to optimize DER operation and energy trading based on forecasting and occupant preferences to maintain operation of critical loads. The proposed FPP control may be applied to large-scale utility circuit models such as the one shown above with over 2,000 nodes and 8.65MW peak load.

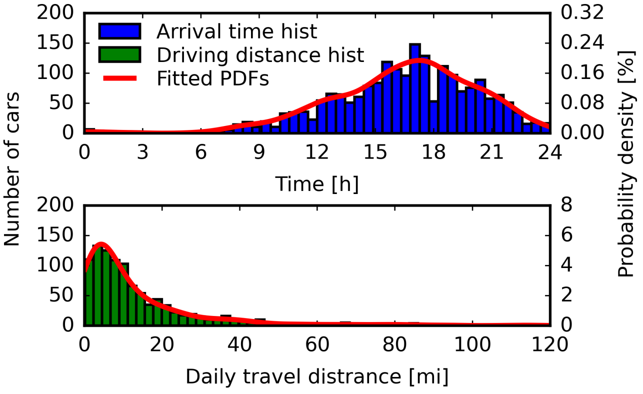

Fig. 2. Distribution of home arrival times (top) and daily travel distances (bottom) from the sampled 2022 NHTS data. The majority of commuters drove less than 20 miles total each day. Assuming a similar short commute for EV owners, much of the battery capacity would be available for dispatch should an outage occur during the evening hours.

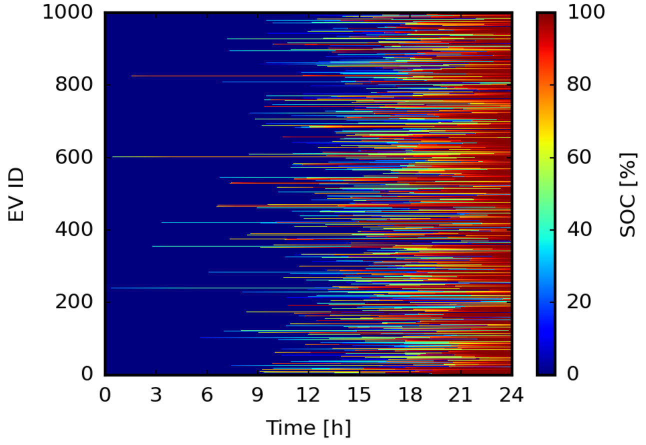

Fig. 3. Battery SOC for 1,000 example EV charging profiles generated from the sampled data of the 2022 NHTS. Majority of vehicles arrived home with high SOC due to the higher frequency of short-distance commutes. Battery SOC was shown as “0” for times when the EV was not parked at home.

Survey (NHTS) [11]. Gaussian Kernal Density Estimation (KDE) was used to estimate the probability density functions (PDFs) of driving distance and home arrival time for all 30,000+ responses in the dataset using the following formulas:

$$\hat{f}_{\mathbf{H}}(x) = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{det(\mathbf{H})}\kappa\{\mathbf{H^{-1}(x-X_i)}\}, \tag{1}$$

$$\mathbf{H} = \mathbf{n^{-1/(d+4)}\Sigma^{1/2}}, \tag{2}$$

where κ is the kernal function; n, the total number of data points; and $\mathbf{H}$, the bandwidth matrix in Equation 1. The Silverman rule was applied in Equation 2 where Σ is the covariance matrix and d the number of dimensions [12].

A group of 1,000 travel patterns were sampled based on the Gaussian KDE PDFs. The resulting distribution of arrival times and travel distances are shown in Fig. 2. The data showed that most vehicle owners arrived home from their daily commute in the afternoon and evening, with arrival peaking around 5PM. Additionally, the majority of occupants drove for less than 20 miles during their commute. The samples were used to generate 1,000 synthetic EV charging profiles

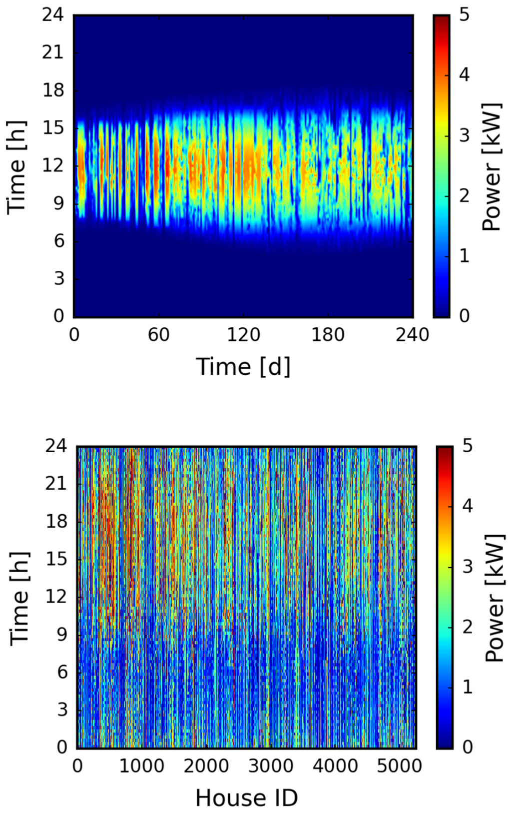

Fig. 4. Solar PV generation measurements from house 1 of the EPRI SHINES experimental field demonstration (top) and active power load measurements for over 5,000 homes from the Smart Energy Technologies (SET) field demonstration (bottom). This experimental data was utilized in the case study to emulate realistic home loads based on historical data.

where the following assumptions were made for each vehicle: a battery capacity of 100kWh; a 90% round trip efficiency; a 10kW charging power level; owners charged their vehicle on home arrival; and owners carried out the same commute for 7 days prior to charging.

Battery state-of-charge (SOC) at the time of home arrival was calculated based on miles driven prior to charging for each vehicle. The overwhelming majority of participants reported a short commute, so significant EV battery capacity would be available for dispatch, should an outage occur during the night or early morning. This is shown in Fig. 3, where even without charging for 7 days prior, 51% of EVs were parked at home with over 90% SOC at 7PM.

IV. CASE STUDY: FEDERATED POWER PLANT CONTROL ON A GRID WITH ELECTRIC VEHICLES

A case study was conducted to demonstrate FPP control for a distribution grid with over 5,000 homes, each equipped with one EV, one BESS, and one solar PV array. The electric load was modeled using experimental measurements from the Smart Energy Technologies (SET) field demonstration [13]. Since the homes in the SET project were equipped with gas water heaters, an electric heat pump water heater (HPWH) load was added for each home load.

The HPWH loads were synthetically generated with a stratified node temperature model from the hot water draw profiles in the 2019 and 2022 California Building Energy Code Compliance Residential (CBECC-Res) data set [14]. This method for generation of HPWH profiles is described in detail in a previous publication by our group [15].

The solar PV profile of each home was generated based on experimental measurements from the Electric Power Research Institute (EPRI) Sustainable and Holistic Integration of Energy Storage (SHINES) field demonstration [16]. Synthetic variation of +/- 10% was introduced to three sunny days of solar PV generation measurements collected from house 1 of the SHINES data set. The variation was added to account for differences in shading and positioning of solar PV arrays in the same general area. The SHINES house 1 solar PV generation and SET home load measurements are illustrated in Fig. 4.

The energy capacity of each BESS was assumed to be 13.5kWh, which is consistent with commercially available units designed for residential use. The following formulas were applied to calculate BESS and EV battery SOC for each time step:

$$SOC_{t+1} = SOC_t + \left[\frac{P * r * \eta}{E_{cap}}\right], \tag{3}$$

$$SOC_{t+1} = SOC_t + \left[\frac{P * r}{E_{cap} * \eta}\right], \tag{4}$$

where P is the power level (positive for charging, negative for discharging); r, the simulation resolution; η, the round trip efficiency; and E_{cap}, the maximum capacity. In the outage simulation, the SOC of each EV battery upon home arrival was calculated based on the commute distance as described in section III.

To evaluate a "best case" scenario while still accounting for travel behavior, the following assumptions were made: EVs remained at home following arrival from the daily commute on the first day of the outage; BESSs were fully charged at the start of the outage; each day of the outage was sunny, producing very high solar PV generation; and EV charging was suspended to supply critical loads. It is also important to note that nearly the full BESS range was utilized to implement a maximum use case, even though the recommendation is to operate between 20% and 80%. For the outage event, BESSs had an initial SOC of 100% and were discharged to 5%.

V. RESULTS AND DISCUSSION

The following results were obtained from a simulation of an outage starting at midnight. The system self-sustained for 70.4 hours while reserving 50% of EV battery SOC. As shown in Fig. 5, excess solar PV generation during midday was used to charge BESSs while system demand was low. The BESSs discharged later in the day when load was high and generation was low. The heat map in Fig. 6 illustrates the battery SOC of all EVs during the outage. Approximately 85.8% of vehicles arrived home from their commute with 90% battery SOC or

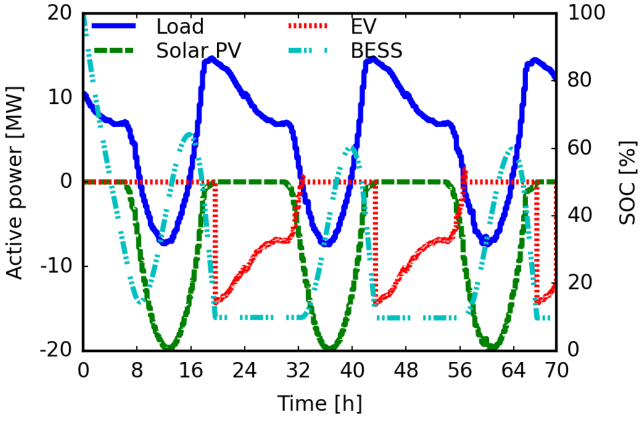

Fig. 5. System power and BESS SOC during the simulated outage. During midday when solar PV generation was high, excess energy was stored in BESSs then dispatched later in the day when load exceeded generation. Dispatch of EV batteries was initiated once BESS SOC was depleted. The system self-sustained for over 70 hours.

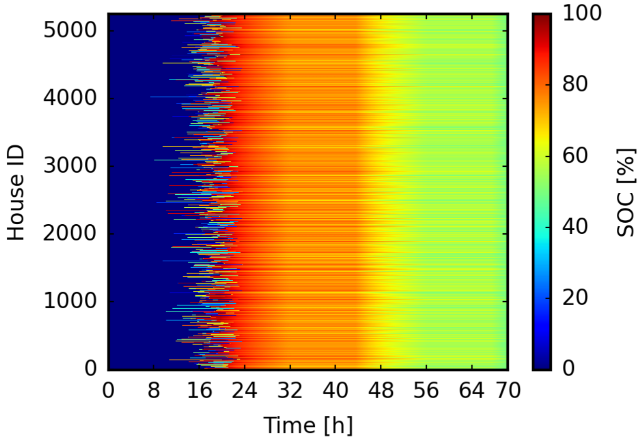

Fig. 6. Battery SOC for all EVs in the circuit during the outage simulation. An SOC of "0" is shown prior to drivers arriving home from their daily commute. Discharge power at each timestep was equally distributed across all available EVs to supply the load when needed. The system self-sustained for over 70 hours while reserving 50% of EV battery capacity.

higher, so there was significant capacity available for dispatch even when reserving 50% SOC for each EV battery.

The total energy dispatched by DERs during the outage was 930.06MWh. Of this energy, 7.24% was supplied by the initial discharge cycle of the BESSs, 57.77% was supplied by solar PV generation either directly or by charging the BESSs, and 34.99% was supplied through discharge of EV batteries.

VI. CONCLUSION

A new market-free federated power plant (FPP) control method was proposed and tested to provide outage resiliency in distribution grids through energy trading and leverage of existing electric vehicles (EVs) and other distributed energy resource (DER) infrastructure. Additionally, thousands of synthetic EV charging profiles were generated based on travel survey data. The extensive experimental and synthetic data were utilized to evaluate the potential of a community with high DER penetration to self-sustain during an outage. The results demonstrated that a distribution grid with over 5,000 homes, each with its own EV, BESS, and solar PV array, has potential to self-sustain an outage for over 70 hours while reserving 50% of EV battery SOC.

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