Enhancing Distribution Grid Resilience to Power Outages Using Electric Vehicles in Residential Microgrids

Orlando Quezada Simental, *Student Member, IEEE,* Dept. of Electrical and Computer Engineering
University of Texas at El Paso
El Paso, TX 79968, USA
oquezadasi@miners.utep.edu

Paras Mandal, *Senior Member, IEEE*
Dept. of Electrical and Computer Engineering
University of Texas at El Paso
El Paso, TX 79968, USA
pmandal@utep.edu

Eric Galvan, *Member, IEEE*
Load Research and Data Analytics Dept.
El Paso Electric
El Paso, TX 79901, USA
eric.galvan@epelectric.com

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Abstract—**The transition to electric vehicles (EVs) is underway globally and EVs are expected to become more widely adopted in the coming years. One of the main characteristics of EVs is that they are not only seen as mean for transportation but also potentially as a flexible energy storage resource in vehicle-to-grid (V2G) applications. This paper proposes a resilience analysis on the feasibility of using EVs for power restoration and supply of residential networked microgrids (MGs) experiencing a power outage due to extreme weather. In order to evaluate the effectiveness of utilizing EVs as a backup power supply during an outage, various case studies are presented considering different scenarios and resilience metrics. Test results demonstrate that EVs can satisfy the energy requirements of a residential household for more than 6 hours but, also provide power to the distribution grid through MG aggregation.**

Keywords— Electric grid resilience, electric vehicle, microgrid, vehicle-to-grid, vehicle-to-home.

I. INTRODUCTION

Electric companies are nowadays facing frequent power outages in their distribution systems due to extreme weather such as winter storms and heat waves. Although blackouts are considered low-probability events, the socioeconomic costs and impacts can be extensive [1]. In February 2021, the Electric Reliability Council of Texas (ERCOT) system was affected by a winter storm that left thousands of customers without electrical service for more than two weeks causing an estimated total cost of over $195 billion [2]. Over the past five years (2015-2020), The National Oceanic and Atmospheric Administration (NOAA) reported more than 10 billion dollars in damage due to 22 weather/climate events that occurred in the United States [3]. The number of severe storm events as well as their intensity has increased in recent years affecting electrical power systems. These recent events have provided valuable lessons on the need to improve electric grid resilience.

To improve the resilience of power distribution systems to external events can be enhanced by implementing microgrids (MGs), which can be constituted by a group of distributed energy resources (DERs) such as hydro energy, solar energy, wind energy, electric vehicles (EVs), energy storage, and many others.

MGs are considered a viable approach to manage and control demand-side DERs as it offers a variety of benefits, such as, improved power quality, zero-emissions energy sources, reduction in transmission and distribution costs, and improve grid resilience to extreme weather.

EVs are becoming more popular in the US with more than 18 million EVs anticipated to be on the road by 2030 [4]. Advancements in battery technology are allowing EVs to have higher energy capacity. An increased battery capacity not only benefits customers by having and extended driving range, but also creates the potential opportunity to use the EV as an energy resource. This mode of operation is referred to as vehicle-to-grid (V2G). V2G applications can be, but not limited to, the following: peak load shaving, smoothing generation from non- dispatchable renewable energy resources, and acting as a reserve against unexpected outages [5]. Therefore, given the prior potential of EVs as an energy resource, it is expected that the EVs will become an integral part in the operation of MGs and power distribution systems of the future.

The EV-V2G operation has been evaluated in the literature for a variety of purposes such as frequency regulation [6], economic operation of the power grid [7], mitigate renewable energy resources' effects, and charging demand fluctuation reduction. The V2G operation mode can also be used to study the power grid as well as to support large-scale renewable energy integration, as presented in [8]. However, very limited literature is available in which EVs are used as an emergency backup during power outages.

Similarly, to V2G, vehicle-to-home (V2H) operation is ideal for value stacking of EVs. In this operation mode, the vehicle is connected to the residential household, and it is capable to provide energy to the house or receive energy when necessary. Such operation can help shift the demand from expensive to none-expensive time-intervals resulting in a reduced amount of energy cost [9]. Under V2H operation, the EVs can be used as backup power resource following a contingency [10]. The V2H can be properly incorporated in home energy management system (HEMS) as a flexible option [11],[12].

Therefore, given limited literature availability in V2G operation during power grid contingencies and the impacts these events have on the distribution side, the proposed resilience analysis as proposed in this paper aims to investigate

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the potential of using EVs as a backup power supply for networked MGs during an outage. This paper contributes to the state-of-the-art in the operations of power distribution grid by evaluating resilience enhancements and its capability to withstand moderate damage and heavy damage events caused by severe weather. The major contributions of this paper are:

1. Presenting a resilience analysis with case studies that demonstrate the main advantages that EVs, when effectively controlled in networked MGs, can deliver to the power distribution grid.
2. The computation of resilience metrics for electrical service and monetary impacts using EVs as a backup resource. The evaluated metrics are: total user hours of outage (h), total user energy not provided (kWh), total and average number of users experiencing outages, total outage costs ($), and total loss of service revenue ($).

The rest of the paper is organized as follows. Section II presents the distribution system model and resilience metrics methodology. Simulation results are discussed in Section III that presents the two major case studies and associated scenarios. Finally, Section IV concludes the paper.

II. DISTRUBITION SYSTEM CONSEQUENCES AND RESILIENCE METRICS

To perform the evaluation of resilience metrics for the distribution system with MGs and distributed energy resources (DERs), a study following the Resilience Analysis Process (RAP) is performed. The RAP was presented by SANDIA national laboratories to contribute with a method and a set of metrics to evaluate the resilience of energy systems [12]. Commonly, resilience and reliability are often confused as being alike, however, they account for various types of events and use different measurements, i.e., reliability analysis considers high probability, low impact events, and the focus is on system impacts. While resilience analysis considers low probability, high consequence events, and the resilience metrics focus on the impacts on humans [12].

A. Disruption Effects and Resilience Metrics

In this paper, the effects and resilience metrics that are evaluated for the case studies are presented in Table I. The metrics classification shown in Table I are based on the results and resilience metrics reported in [13].

The primary threats considered for simulation purposes are outages caused by weather events of different magnitudes, i.e., moderate magnitude and high magnitude. Under different scenarios, the expected level of grid damage is associated to the hazard's intensity, i.e., similar damages will be considered (moderate damage and high damage). In particular, the damages that are expected to take place in the distribution grid are feeders and transformers that are overloaded due to high temperatures.

The data results of the threats for the case studies are obtained through power flow simulation [14]. During the simulation, the power flow analysis, bus voltages, and power outputs of the EVs are calculated to determine which loads would be unserved during the outage. In this paper, power flow was carried out for the case studies for a time-period of 1-day under the different scenarios that are described in the following section. The simulations allow the estimation and quantification of the impacts the threats will have on the users that are being supplied energy and the capability of the utility or system operator to be able to deliver electrical energy to its users.

TABLE I: RESILIENCE METRICS

Effects Category	Resilience Metric
Energy Service	Total user-hours of outages (h) Total user energy not provided (kWh) Total and average outages during of users experiencing outage.
Economic	Total outage costs ($) Total loss of service revenue ($)

B. Hazard's Impact and Resilience Metrics Formulation

The resilience metrics that have been evaluated for the case studies presented in Section III are listed in Table I. The mathematical formulas of the resilience metrics were obtained from our previous work [15] where the authors analyzed the impacts on the distribution networks' resilience to thunderstorms by using roof-top solar and stationary battery energy storage. In contrast to [15], this paper utilizes the resilience metrics to evaluate the resilience improvements EVs can have on the distribution grid. Each metric is calculated as follows.

Total user-hours of outage

$$\sum_{t=1}^{n} \sum_{i=1}^{k} x_i \cdot (t) \tag{1}$$

where $xi \cdot (t)$ is the number of user-hours without power of user i for the duration of event n, for all user k experiencing an outage.

Total client energy not served

$$\sum_{t=1}^{n} \sum_{i=1}^{k} E_i \cdot (t) \tag{2}$$

Where $E_i \cdot (t)$ is the total energy not served per user.

Total and average number of users experiencing outages

$$\bar{X} = \frac{\sum_{s=1}^{T_S} \sum_{i=1}^{K} x_{i,s}}{T_s} \tag{3}$$

where $\bar{X}$ is the average number of users experiencing an outage during scenarios and Ts the total number of scenarios.

Total outage costs

$$C_{out,s} = C_o * \left(\sum_{t=1}^{n} \sum_{i=1}^{k} x_{i,s} \cdot (t) \right) \tag{4}$$

where $C_{out,s}$ is the total outage cost ($) and C_o is the outage cost per hour($/h).

Total Service loss of revenue

$$C_{LUR,s} = C_e * (\sum_{t=1}^{n} \sum_{i=1}^{k} E_{i,s} \cdot (t)) \tag{5}$$

where $C_{LUR,s}$ is the loss of service revenue ($), C_e is the cost of energy ($/kWh), and $E_{i,s} \cdot (t)$ is the total energy not served for the duration of the event.

III. SIMULATION RESULTS AND ANALYSIS

In this section, case studies are presented to evaluate the resilience metrics described in the previous sections. This paper considers two case studies: (1) first case, where the power distribution system suffers moderate damage, and (2) second case, where heavy damage occurs to the system. Both cases are assumed to be caused by a heat wave. The IEEE 33-bus distribution system with three MGs presented in Fig. 1 is used for simulation purposes with minor modifications to the system data [15]. For both cases, it is assumed that all households within the microgrids own an EV. For example, in bus-23, there are 10 households with one EV per household. The EVs considered for this study are Tesla Model 3, Nissan Leaf, and Chevrolet Bolt. These three battery EV (BEV) models are commercially available and are the highest selling EVs in the US market. According to the U.S. Department of Energy, these EV models accounted for approximately 60% of EV sales in 2019 [16]. Furthermore, the BEVs are assumed to have the following distribution, 80% Tesla, 10% Chevy Bolt, and 10% Nissan Leaf. This distribution has been estimated according to EVs sales in the U.S during 2019 [16]. The BEV penetration level is based on NREL's electrification futures study-medium adoption scenario, that considers 60% BEV penetration level by 2040 [17]. Table II presents the MGs data. The rest of the system data can be found in [15]. Three scenarios were considered for each case study, i.e., base scenario, energy conservation scenario, and energy sharing scenario. A detailed analysis comparison is carried out for each case and among scenarios to determine the advantages/disadvantages of the BEV operation as a backup energy source. Table III presents the battery capacity of the BEVs and the power that can be charged/discharged per vehicle. For the simulations, the BEVs were assumed to have the capability to operate in V2H and V2G during the outage period. Load data was obtained from the U.S. Department of Energy Open Data Catalog, residential load at TMY3 locations for the surrounding region of El Paso, Texas, and other locations in the U.S. southwest [18]. Three load profiles that were selected from the specific locations are El Paso, TX, Las Cruces, NM, and Holloman AFB, NM. Below is a description of each case study and the corresponding scenarios of each case study.

Case 1: Moderate Damage

- **Scenario 1.1:** Base case with no BEVs in the MGs,
- **Scenario 1.2:** BEVs connected to MGs and operating in V2H, and
- **Scenario 1.3:** BEVs connected to MGs and operating in V2H/V2G.

Case 2: High Damage

- **Scenario 2.1:** Base case with no BEVs in the MGs,
- **Scenario 2.2:** EVs connected to MGs and operating in V2H, and
- **Scenario 2.3:** EVs connected to MGs and operating in V2H/V2G.

The base scenarios consider that there are no BEVs interconnected with the power distribution system. Scenarios 1.2 and 2.2 consider the BEVs are available within the MGs and operate in V2H fulfilling the energy demand of the user's household during the outages. In Scenario 1.3 and 2.3, the BEVs operate in V2H within the MGs and provide surplus power in V2G operation to the rest of the power distribution grid.

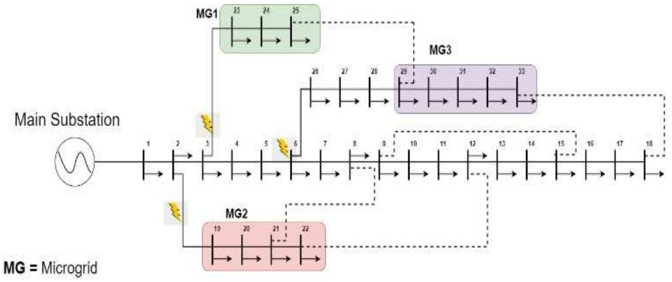

Fig 1. Networked microgrids in an IEEE 33-bus distribution network.

TABLE II. SYSTEM STUDY DATA FOR RESILIENCE ANALYSIS

	Households	Load(kW)	BEV		
			No. BEVs	Capacity (kWh)	Input/Output (kW)
Microgrid 1					
Bus 23	10	60	10	767	102.4
Bus 24	12	77	12	927	124.4
Bus 25	17	60	17	1312	175.6
Microgrid 2					
Bus 19	10	60	10	767	102.4
Bus 20	11	71	11	847	113.4
Bus 21	12	48	12	927	124.4
Bus 22	12	73	12	927	124.4
Microgrid 3					
Bus 29	48	290	48	3726	501.4
Bus 30	80	513	80	6187	830.6
Bus 31	60	239	60	4632	622
Bus 32	84	508	84	6507	874.6
Bus 33	24	154	24	1854	765.8

TABLE III. BATTERY ELECTRIC VEHICLE DATA

Battery Electric Vehicle (BEV) Parameter	**Tesla Model 3**	**Nissan Leaf**	**Chevrolet Bolt**
BEV Battery Size (kWh)	80	62	65
BEV Battery efficiency	90%	90%	90%
Maximum Charger Power (kW)	11	7.2	7.2
Minimum State-of-charge (SOC)	10 %	10%	10%
Maximum State-of-charge (SOC)	100%	100%	100%

The simulations are carried out for a day assuming the outages occur due to extreme weather (heat wave) on a summer day. To calculate the price of energy not served, a fixed energy rate is assumed [19]. To calculate the outage costs, a value of 5.1 $/h is used to compute the total outages costs [20]. The following assumptions are made for the case studies:

- Moderate damage case assumes a 4-hour interruption period.
- High damage case assumes a 6-hour interruption period.
- The outages occur at 5:00 PM.
- EVs initial state of charge is 90%.
- EVs minimum state of charge is 10%.
- It is assumed that all necessary infrastructure (hardware and software) are available for the operation of the EVs in V2H and V2G.

A. *Resilience Analysis of the Distribution System Under Moderate Damage Case*

In this case, it is assumed that an outage occurred and created moderate damage to the feeders of the system, specifically, to branches 2–19, 3–23, and 6–26 (see Fig. 1). The contingency is considered to have occurred at 17:00 and the duration of the event is 4 h (17:00 to 21:00). The 4-hour time-period is based on the average duration of an outage in the U.S. [21]. To mitigate the impact of the damaged branches, the normally-open tie lines 8–21, 12–22, 18–33, and 25–29 are closed. The use of tie-lines for network reconfiguration during contingencies is a normal practice in most power distribution systems, when available.

For the moderate damage case, three scenarios are considered. The base scenario 1.1 represents a conventional power distribution system that enables available tie-lines to maintain the service of its customers when an outage occurs. Under Scenario 1.2, EVs are available in the MGs where EVs only supply power to the user's household in V2H operation. For Scenario 1.3, it is considered that the EVs cannot only supply the demand of the residential household but also provide power to grid. For all simulations in this paper, power flow analysis is utilized to simulate the operation of the power distribution system. When power flow is executed, the power output of the EVs as well as the bus voltages of the distribution network are determined. For all scenarios, it is assumed that the load at any bus with a voltage below 0.9 p.u. will be curtailed. This premise is made because loads cannot work under normal conditions with voltages under this value. Tables IV and V present a summary of the two resilience metrics categories that are used to measure the resilience impacts that EVs can have on the power distribution grid. Table IV presents the resilience metrics for the electrical service impact category. The metrics for this category are the total user-hours of outage, the total user energy not served, and the total number and percentage of users experiencing an outage.

TABLE IV. RESILIENCE METRICS FOR ENERGY SERVICE: CASE 1 MODERATE DAMAGE.

Scenario	**Total User-Hours of Outage (h)**	**Total User Energy Not Provided (kWh)**	**Total Number and Percentage of Users Experiencing Outage**
1.1	2,998	16,161	723 (78%)
1.2	2,192	8,620	345 (37%)
1.3	0	0	0 (0%)

TABLE V. RESILIENCE METRICS FOR ECONOMIC IMPACT: CASE 1 MODERATE DAMAGE

Scenario	**Total Outage Costs ($)**	**Total Avoided Outage Costs ($)**	**Loss of Service Revenue ($)**
1.1	15,239	0	1,678
1.2	11,179	4,060	895
1.3	0	15,239	0

Comparing the results of different scenarios, Scenario 1.3 displayed the best performance out of all the scenarios for all resilience metrics, i.e., no user service was interrupted and therefore no energy demand was unserved. The average number of users experiencing an outage when the EVs are used as a backup is reduced from 78% to 25% when compared to the base scenario (see Table IV).

However, it should be noted that the outage duration was limited to 4 hours, in cases where the outage extends to longer time-periods, prioritizing the supply of critical loads could be more beneficial. From an economic impact perspective (Table V), a similar outcome is seen, i.e., Scenario 1.3 had the best performance as the avoided outage cost is $15,239 compared to the base scenario. In the case of loss of service revenue, the best outcome was also obtained in Scenario 1.3. An interesting observation is the great differences between the loss of service revenue and outage costs, i.e., it offers a good perspective of the economic impacts that prolonged electric power outages can have.

Fig. 2 shows the net load (NL) of a residential household and an EV operating in V2H under Scenario 1.2. Furthermore, Fig. 2 illustrates how the EV is able to provide power (PEVS) to the house during the outage from hours 17:00 to 21:00.

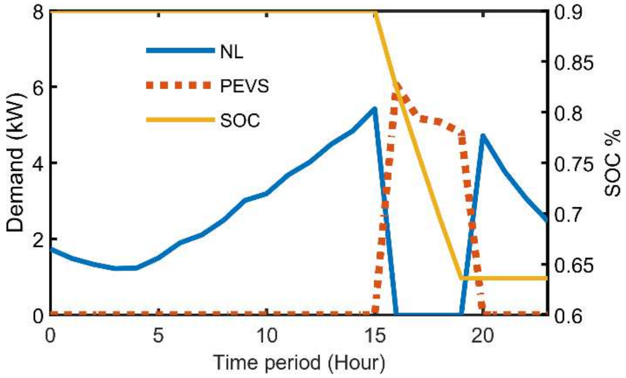

Fig. 2. Residential Household and EV in V2H Operation during power outage - Case 1, Scenario 1.2.

Fig. 3 shows the EV operating in V2H and V2G for the same household under scenario 1.3. We can observe in Fig. 3 that the EV can not only provide power to the house (PEVS), but also deliver power to the grid (PE) during the outage period from 17:00 to 21:00.

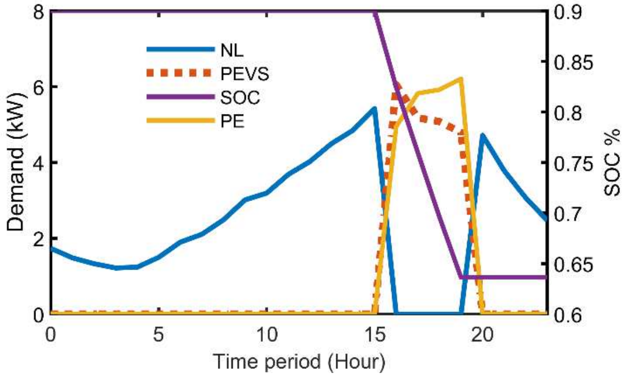

Fig. 3. Residential Household and EV in V2H/V2G Operation during power outage - Case 1, Scenario 1.3.

Based on the results presented in Tables IV and V, operating the EVs in V2G during an outage benefits all users of the system as they significantly provide support to not only the neighboring buses, but also to other buses of the distribution networks. The tradeoff for users that operate their EVs in V2G is that it reduces the time they could power their own household. Providing good incentives for customers to offer their EVs to participate in V2G during outages is a key to achieving high customer participation.

B. *Resilience Analysis of the Distribution System Under High Damage Case*

For the high damage case, it is assumed that the heat wave damaged branches 2–19, 3–23, and 6–26 as shown in Fig. 1. The event is assumed to have occurred at 17:00 and the duration of the outage is 6 h (17:00 to 23:00). The 6-hour time-period is based on the highest average duration of an outage in the U.S. due to extreme weather [20]. For the system under failure, three scenarios are also considered. Tables VI and VII present a summary of the two resilience metrics categories that are used to measure the resilience impacts that EVs can have on the power distribution grid. Table VI presents the resilience metrics for the electrical service consequence category.

TABLE VI. RESILIENCE METRICS FOR ENERGY SERVICE: CASE 2 HIGH DAMAGE.

Scenario	**Total User-Hours of Outage (h)**	**Total User Energy Not Provided (kWh)**	**Total Number and Percentage of Users Experiencing Outage**
2.1	4,482	22,791	723 (78%)
2.2	2,070	12,179	345 (37%)
2.3	0	0	0 (0%)

TABLE VII. RESILIENCE METRITCS FOR ECONOMIC IMPACT: CASE 2 HIGH DAMAGE

Scenario	**Total Outage Costs ($)**	**Total Avoided Outage Costs ($)**	**Loss of Service Revenue ($)**
2.1	22,858	0	2,367
2.2	10,557	12,301	1,265
2.3	0	22,858	0

Comparing the results obtained from different scenarios, Scenario 2.3 displayed the best performance out of all the scenarios for all resilience metrics, i.e., no user service was interrupted and therefore no energy demand was unserved. The average number of users (Scenarios 2.2 and 2.3) experiencing an outage is reduced by 24% when compared to the base scenario (see Table VI). From an economic consequence perspective (Table VII), a similar outcome is observed, i.e., Scenario 2.3 presented the best performance as the avoided outage cost presented a $22,858 reduction compared to the base scenario. In the case of loss of service revenue, the best outcome was also obtained in Scenario 2.3 with no utility loss of revenue. Test results clearly demonstrate the positive impact the EV operation in V2H and V2G can have during an outage at the local level (household and MG), and at a higher system level (bus and feeder). Having a high customer participation in programs where EVs provide V2G operation could provide utilities and/or system operators flexibility to manage power outages. The creation of attractive incentives for customers to participate in such programs will be of high value to ensure high customer participation.

The results presented in Section III clearly show the benefits of using EVs to improve the resilience of power distribution networks to extreme weather events, in particular heat wave. Using EVs could provide an economic advantage compared to stationary energy storage. Given the frequency of these extreme events, large financial investments for stationary energy storage for resilience purposes only might not be justified without value stacking. Therefore, maximizing the use of EVs during extreme weather events could defer, and in some cases, help avoid costly electrical infrastructure investments. The simulation results presented in this paper are obtained using MATLAB R2019a and MATPOWER version 7.1 [14]. All simulations are conducted using a personal computer with 2.4 GHz CPU, 8 GB RAM.

IV. CONCLUSION

This paper analyzed the significance of EVs to enhance the resilience of electric power distribution systems to power outages. A resilience analysis approach was presented considering two case studies having two levels of damages, i.e., heavy and moderate, to the system that was tested under a variety of scenarios and evaluated by applying resilience metrics. This paper contributed to provide an insight into the advantages that EVs, when efficiently operated in networked MGs, can provide energy support to the distribution grid. Test results demonstrated that EVs can provide power generation support up to 6 hours in V2G mode and provide improvements to the power distribution system during outages. For the specific case studies, EVs supplied the load of residential households in V2H operation and provided surplus power to the distribution system in V2G operation demonstrating the high potential impacts EVs could have on the power grid. In the case of EVs operating within a residential MG, test results showed the number of users experiencing an outage could be reduced to between 41% and 0%, i.e., power outages could be avoided by using EVs as a backup power source and allow power to be restored more rapidly across the distribution network. Furthermore, the avoided outage cost was between 53% and 100% translating to a total savings between $4,060 and $12,301. It is to be noted that the results presented were obtained for the specific case studies and scenarios described in this paper. However, the appraisal of the resilience metrics presented in this paper can be performed in case studies with different scenarios. Nonetheless, the analysis and results indicate that EVs can significantly improve the resilience of power distribution systems.

Future work would be interesting to consider longer duration faults to test the ability of the EVs to support the distribution system during extended outage periods. Furthermore, the development of economic incentives to encourage customer participation could also be considered in future studies.

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