Resilience Evaluation for Power Distribution Systems Impacted by Winter Storms

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2023 IEEE Industry Applications Society Annual Meeting (IAS) | 979-8-3503-2016-9/23/$31.00 ©2023 IEEE | DOI: 10.1109/IAS54024.2023.10406368

***Abstract*-- Over the past years, electric power distribution blackouts have been caused by natural events, creating more than one trillion dollars in total damages in the U.S. These events mainly affect power distribution systems making them very vulnerable to extreme weather. Therefore, it is important to further study ways to enhance the resilience of power distribution systems impacted by dangerous weather, such as winter storms. This paper presents a new approach for resilience evaluation for a power distribution system composed of networked microgrids (MGs). This involves the integration of distributed roof-top photovoltaic systems (PV) and electric vehicles (EVs) into MGs for resilience enhancements. In the study, EVs are utilized as energy storage that can operate in vehicle-to-home (V2H) and vehicle-to-grid (V2G). To evaluate the utilization of EVs and roof-top PV as backup power sources, several case studies are shown and assessed with a variety of resilience metrics. Test results reveal that EVs, and roof-top PVs can meet the energy needs of residential users for up to 20 hours and provide distribution grid support through surplus energy of the EVs aggregated by the network MGs; enhancing the resilience of the power distribution system being impacted by extreme weather.**

***Index Terms*-- Distribution system resilience, electric vehicles (EVs), networked microgrids, roof-top photovoltaic (PV), vehicle to grid (V2G), vehicle to home (V2H).**

I. Introduction

WEATHER has been changing extremely fast over the past decade, making extreme weather events more common across the world. Climate change can have great effects on the electric power system, resulting in extreme weather-related blackouts, interrupting electrical service to thousands of users for multiple hours and in some cases several days or even weeks. Climate and weather-related threats to power systems can be and are not limited to heat waves, winter storms, droughts, wildfires, flooding, and severe thunderstorms. Extreme weather events have led to major power outages across power distribution systems, creating concerns regarding the power grid's resilience to these events. The economic costs and impacts of extreme weather leading to power grid blackouts are vast, although they are considered low-probability events [1]. For example, in 2021, there were many winter storms across the United States. One of the most devastating winter storms in 2021 was winter storm "Uri", which affected the Electric Reliability Council of Texas (ERCOT) system. Winter storm Uri caused over 35 GW of generation capacity to go off-line in the ERCOT system leading to load shedding of approximately 3.2 GW over several hours during the worst days of the storm [2]. The winter storm impacted millions of users, affecting daily activities and essential services. ERCOT reported that the loss of generation threatened the frequency balance on the electric grid and partially caused a complete blackout which could have taken weeks or months to repair [2]. The total cost of the outage was estimated at over $195 billion [3]. As the occurrence and severity of similar extreme weather is projected to rise, there is a demand to boost the distribution systems' resilience to these types of events.

In recent years, multiple technologies have emerged to enhance the resilience of power distribution systems, for instance, the application of microgrids (MGs), which are interconnected with the distribution network and can consist of several distributed energy resources (DERs) such as wind turbines, photovoltaics (PV), electric vehicles (EVs), hydro energy, and battery energy storage system (BESS). In the past, MGs have been deployed for enhancing the reliability and sustainability of the distribution grid. For example, MGs are deemed a feasible method to operating and managing demand-side DERs as they offer a diversity advantage, low-cost energy, clean energy, increased power quality, and enhanced system resilience. Prosumer based MGs that can collaborate and interact with the distribution grid have been well discussed in references [4]-[6]. Also, MGs are frequently utilized as a source to improve the resilience of power distribution systems during blackouts. In such a use case, during a disruption, the area or section experiencing an outage is detached from the primary grid and is isolated into self-sufficient MGs using tie lines and circuit breakers, known as "islanded mode," operation. In some cases, MGs have been coupled to maintain critical loads of other MGs [7] as well. MGs operating in this mode, can either be used as a local resource or as a public resource to increase the resilience of the power distribution system [8]-[10].

This work is based in part upon work supported by the National Science Foundation (NSF), Awards# 1941524 and 2021470.

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Additionally, when power is disrupted due to a natural disaster MGs can be used as a power source to start-up the main generators [11]. Some universities in the United States have incorporated MGs into their campuses as backup energy sources when there might be problems with the main electric grid. In 2012, when hurricane Sandy hit the east coast Princeton University and New York University, were able to operate in “islanded” mode with their own MGs providing energy to their respective campus for essential services for a couple of days. Similarly, the city of Berkeley designed an MG with solar, energy storage, and EVs to distribute energy to city buildings. Furthermore, UC-San Diego is undergoing testing of the operation of MGs while integrating EVs [12].

As EVs become more popular around the world, it is anticipated that by 2030 U.S roads will have over 26 million [13]. Nowadays, vehicle manufacturers are competing to advance EV technology by increasing driving range and incorporating high storage capacity and more efficient batteries. This improvement in EV technology can motivate EV owners to use their EVs not only for commuting but also as battery resources to power their homes when an outage occurs. For example, Pacific Gas and Electric Company (PG&E) has carried out testing of the Ford F-150 Lightning in vehicle-to-home (V2H)/vehicle-to-grid (V2G) to enable customers to provide backup power to their homes. Based on public information, the Ford F-150 Lightning will provide its owners the ability to use exchange power technology and power-up their homes for up to two weeks during a blackout [14]. V2H operation allows users to store energy in their EV battery by home-generated renewable power and/or from the grid when electricity demand rates are cheaper. Users can then power their homes when in need, or when electricity prices are high. This can result in reduced energy costs as demand can be shifted from high cost to low-cost time periods [15]. V2H mode of operation provides value stacking for EVs as they provide the user more capabilities besides transportation. Furthermore, V2H mode of operation allows EV users to utilize them as backup power resources when a distribution system is experiencing an outage [16]. The V2H mode of operation is suitable to integrate into home energy management systems (HEMS) [17]. In V2G operation, the EV provides power to the grid. Examples of benefits of V2G operation are but not limited to frequency regulation, peak shaving, generation smoothing, and energy backup during blackouts [18]. Therefore, it is expected that EV integration into MGs could become valuable assets of power distribution systems. EVs can provide many benefits to the electric grid by providing demand response (DR) services. In V2G mode, EVs have been demonstrated to be useful to reduce energy costs and shave peak demand [19]. From an economic standpoint EV users can be incentivized by electricity pricing plans to participate in V2G. According to Bibak *et al.* [20], EV owners participating in V2G is a win-win because they charge their EVs with low-priced tariffs during off-peak periods, and discharge during on-peak periods. This type of market participation could provide EVs owners additional savings. Also, the V2G mode could be used in charging stations and parking lots to support the integration of renewable energy resources as explained in [21].

Given that there is limited literature availability on EVs operating in V2H/V2G during grid contingencies caused by atypical weather events, a void remains to explore V2H/V2G operation in MGs to improve grid ride through capabilities and study of the effects these types of meteorological events have on electric power distribution systems. The principal focus of this paper is thus to explore and investigate the possibilities of incorporating roof-top solar PV and EVs within networked MGs as backup power supply. This paper further provides assessment of resilience metrics to quantify potential grid resilience enhancements that the aforementioned DERs can provide. The significant aspects and major contributions of this paper are listed as follows,

- Demonstrate the benefits that effective control of roof-top solar PVs and EVs in networked MGs can provide the distribution grid during an extreme weather event.
- Evaluate system resilience considering various case studies that demonstrate the benefits that could be achieved by utilizing EVs and PVs as backup energy resources. The considered metrics are resilience index, outage index, and total outage costs ($).
- Usage of different outage scenarios from historical data reported by U.S. electric utilities to compute the expected time periods that the EVs and PVs could support the power distribution grid under close to realistic-life scenarios.
- Present case studies combining weather, electric demand, PV power production, and commercially available EV battery characteristics to match the actual conditions of the power grid while being impacted by a winter storm.

The remainder of this paper has been organized as follows. Section II presents the network test system and other data assumptions. Resilience metrics and distribution system outage effects are described in Section III. Section IV presents results and discussion, and in Section V conclusion and future work are presented.

II. Data Assumptions

To simulate the cases studies, scenarios are recreated to represent power failure on the distribution network triggered by a winter storm causing multiple outages. The weather data selected for the cases studies were assumed for a winter period in 2021 from (December to February) in the U.S. Southwest, from which two of the coldest successive days were chosen [22]. For the cases studies, three locations were selected from the U.S. Southwest, i.e., Las Cruces, NM, Holloman Air Force Base, NM and El Paso, TX. These locations, present similar weather conditions and are all served by the same electric utility. In the same manner, weather data was utilized to estimate roof-top solar PV power production for the same time horizon and geographic locations [23]. It is assumed the residential households have roof-top PV installations of 4 kW, which represent an average solar array setting in the U.S. Southwest. For the household load data, load profiles were obtained from the Energy Open Data Catalog of U.S. Department, residential TMY3. To assess diverse situations in

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the case studies, load data has been divided into two crucial groups.

I. **Full demand:** all household loads e.g., lighting, appliances, and heating/ventilation and cooling (HVAC).
II. **Critical demand:** priority loads that are classified for essential activities of the users, i.e., interior lighting, essential appliances, and HVAC.

For simulation of the case studies, battery EV (BEV) models were chosen based on the top selling commercially available BEVs in the U.S., i.e., Chevrolet Bolt, Nissan Leaf, and Tesla Model 3. The aforementioned EVs represent nearly 60% of EVs sold in 2019 [24]. Also, for each case study EV models are allocated by residential households in the following manner 10% Chevy Bolt, 10% Nissan Leaf and 80% Tesla Model 3. The EV characteristics for the EV models are shown in Table I. The flow diagram shown in Fig.1 illustrates a complete representation of data inputs and simulations are executed to assess the proposed resilience metrics. The network data utilized for the simulations is shown in Table II where the assumption is that all houses in the MGs have an EV. For instance, on MG-1 where there are three buses it can be seen at bus-23, there are 10 EVs, i.e., 1 EV for every household.

III. Resilience Metrics and Distribution Network Outage Consequences

To assess the distribution systems resilience, a set of metrics have been implemented. The metrics were adopted from a report developed by the Pacific Northwest National Laboratory (PNNL) [25]. The study focused on measuring the resilience performance of the system when grid operating conditions are disrupted. This was achieved by estimating the cumulative resilience of each customer interconnected to the grid, and measuring the time of service during grid outages. This metric aligns with the objective of harmonizing reliability and resilience considerations in assessing system performance during grid disturbances. It is common for reliability and resilience to be confused, although both consider different metrics, events and system impacts. Power system reliability considers the impact on the system from high probability events, with low impacts. On the other hand, system resilience focuses on human impacts from low probability events, with high consequences [26].

A. Resilience Measurements

The resilience metrics utilized to quantify the impacts of the winter storm on the distribution grid for the different case studies are based on [25] and are the following:

a) **System Service Impact:** Assesses Resilience and Outage Indexes.
b) **Financial Impact:** Assessment of Total Outage Cost.

B. Electrical Interruption and Resilience Assessment

The primary threats considered for simulation purposes are blackouts produced by a winter storm creating service interruptions with the following durations: 3 hours, 6 hours, and 20 hours. The service interruption duration is based on historical data on interruptions reported by electric utility companies in the U.S. Southwest for the year 2020. The average service interruption across electric companies in the U.S. Southwest was 3-hours, the U.S nationwide average of all electric utilities was 6-hours, and the prolonged interruption identified in the U.S Southwest was 20-hours. The data was obtained from the Annual Electric Power Industry Report, Form EIA-861 under the reliability section for the year 2020 [27]. For the case studies, it is simulated that the winter storm causes damage to the local distribution system impacted by freezing temperatures leading to damage of transformers and feeders. To measure the system impacts, power flow simulation is utilized for the different case studies [28]. Analyzing the power flow results can provide the instances where bus voltages are below operating conditions and therefore define which loads would be affected during the service interruption. All simulations are carried out for a 48-hours period for diverse cases using power flow analysis. A detailed explanation of the case studies is provided in the following section.

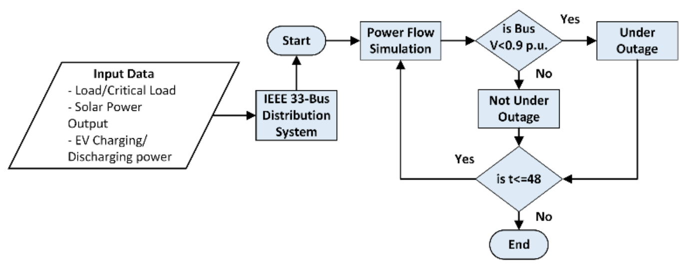

Fig. 1. Flow diagram of data inputs and simulation for resilience assessment.

TABLE I. BEV CHARACTERISTICS

Parameter	Tesla Model 3	Nissan Leaf	Chevrolet Bolt
Battery Size (kWh)	80	62	65
Roundtrip efficiency	90%	90%	90%
Max Power (kW)	11	7.2	7.2
Min State-of-charge (SOC)	10 %	10%	10%
Max State-of-charge (SOC)	90%	90%	90%

TABLE II. NETWORKED MGs SYSTEM TEST DATA

Bus	Houses	Load (kW)	No. BEVs	PV-Capacity (kW)	BEV-Capacity (kWh)	BEV-Input/Output (kW)
MG 1						
23	10	60	10	40	767	102.4
24	12	77	12	48	927	124.4
25	17	60	17	60	1312	175.6
MG 2						
19	10	60	10	40	767	102.4
20	11	71	11	44	847	113.4
21	12	48	12	48	927	124.4
22	12	73	12	48	927	124.4
MG 3						
7	40	70	40	160	3086	413.4
8	40	100	40	160	3086	413.4
9	20	48	20	80	1552	208.6
10	20	48	20	80	1552	208.6
11	20	35	20	80	1552	208.6
12	25	45	25	100	1934	259.8
MG 4						
29	48	290	48	192	3726	501.4
30	80	513	80	320	6187	830.6
31	60	239	60	240	4632	622
32	84	508	84	336	6507	874.6
33	24	154	24	96	1854	765.8

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C. Categorization of Resilience Measurements

The categorization of the resilience formulas and measurements that have been assessed in this paper are the following.

1) Consumer Resilience Index

$$R_i = \frac{T_{U,i}}{T_{U,i} + T_{D,i}} \tag{1}$$

where the resilience index of each consumer is R_i, i.e., electricity service availability for the respective consumer. $T_{U,i}$ and $T_{D,i}$ are time service is available and non-available for the i^{th} consumer during the simulation time period. The total resilience of the electrical power distribution network affected by an interruption, can be evaluated with the base resilience R_T. The Grid Resilience Index R_T. can be defined as the summation of the individual resilience of all consumers and is formulated as follows:

2) Grid Resilience Index

$$R_T = \frac{\sum_{i=1}^{n} T_{U,i}}{\sum_{i=1}^{n} (T_{U,i} + T_{D,i})} \tag{2}$$

where $R_T \in [0,1]$, with 0 meaning all consumers experiencing service interruption whereas a value of 1 would mean all consumers with service available. Another metric to quantify system performance during an interruption is by estimating the portion of consumers facing an interruption at any given time. This metric can be defined as a blackout index, θ_t, and is estimated as follows:

3) Blackout Index

$$\Theta_t = \frac{n_{0,t}}{N} \tag{3}$$

$$n_{0,t} = \sum_{i=1}^{n} (1 - S_{i,t})$$

where $n_{0,t}$ accounts for the number of consumers undergoing a blackout and $\theta_t \in [0,1]$, with 1 being all consumers facing blackout and 0 being no consumers under blackout conditions. The blackout index includes data around the state of each consumer $S_{i,} = \{0,1\}$ at a certain hour, i.e., $S_{i,t} = 1$ with service, 0 no service. With N representing the population of consumers interconnected to the electrical power distribution grid.

4) Blackout Cost

$$T_c = 0.33x^3 - 1.69x^2 + 3.17x + 2.1 \tag{4}$$

from which, T_c is the total blackout cost per time period ($/h). The total blackout cost has been estimated through the incremental cost of the duration of the service interruption and has been obtained from [29].

IV. Simulation Results and Discussion

To assess the resilience formulas described in the aforementioned section, two case studies are presented. This paper considers the following case studies: (1) the first case is tested utilizing the full demand of each household and (2) the second case considers only critical demand of each residential household. For the two cases, there is an assumption that sets of residential households have roof-top solar PV and EVs. Also, the IEEE 33-bus distribution grid composed by four MGs is utilized for the simulations as shown in Fig. 2. The impact of the extreme weather event leading to different interruption periods and locations are evaluated running the simulations for 2 days (48-hour).

A. Case Studies, Interruption Scenarios and Power Distribution Test System

Fig. 2 shows the modified IEEE 33-bus power distribution test network constituted by four MGs. Moreover, Fig. 2 illustrates the various loads that are being considered for each house. Table II summarizes the data for all MGs. The remaining system data is available in [30] and [31]. A key assumption for all simulations is that BEVs are equipped with bidirectional power capability to work in both V2G/V2H. All demand data for the distribution grid model was obtained from the U.S. Department of Energy Open Data Catalog, residential load at TMY3 [32]. The two cases under study are given by:

- **Case 1:** Full Demand and
- **Case 2:** Critical Demand

under the following three conditions:

1) Baseline without PVs and EVs in any of the MGs,
2) MGs with PVs and EVs functioning in V2H, and
3) MGs with PVs and EVs functioning in V2H and V2G.

The two scenarios in Table III, represent random interruptions at critical branches/laterals of the 33-bus distribution grid test system for both cases. The random faults are to account for the uncertainty of where the interruptions could happen and to account for various scenarios with similar levels of electrical interruption. All simulations are conducted for a two-day horizon considering the blackouts ensuing due to a winter storm. Also, to align the power being supplied by roof-top PV during the winter season, the same days are chosen for the PV power output profile [23]. Fig. 3 represents the winter weather PV power output profiles utilized for the case studies. Other assumptions that were made for the two cases are:

1) Blackout duration of 3-hours, 6-hours and 20-hours are used for both case studies and the multiple scenarios,
2) All blackouts initiate at hour 17:00,
3) EVs SOC is 90% at the beginning of each interruption,
4) EVs can function in V2H/V2G, and
5) Temperature effects on EV efficiency were neglected.

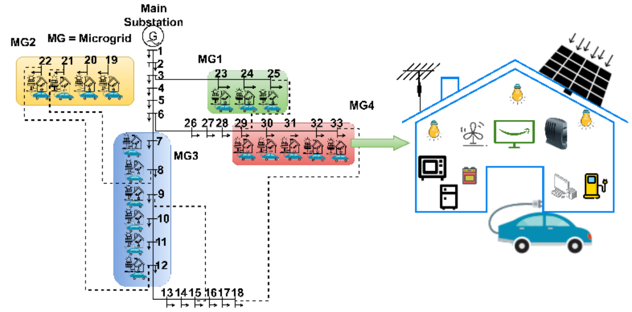

Fig. 2. IEEE 33-Bus test system with MGs and residential household loads.

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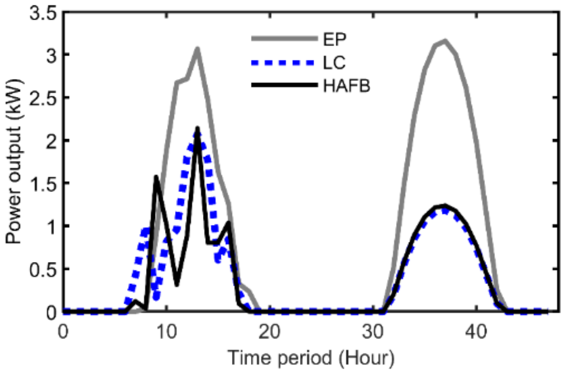

Fig. 3. Rooftop PV generation profile for U.S. Southwest households.

TABLE III. DISTRIBUTION GRID RANDOM BRANCH DAMAGE

Scenario	Branch		
1	2-19	3-23	6-26
2	2-19	6-7	6-26

B. Resilience Assessment Full Demand Condition

For this case study, the assumption is that winter weather ensues damage on the branches shown in Table III. Also, the interruption is expected to initiate at 5:00 pm and the length of the blackout ranges from 3-hours, 6-hours, and 20-hours. To alleviate the impact on the distribution network during the interruption, it is assumed tie-lines are utilized as shown in Fig. 2 to reconfigure the system and redirect power flow patterns.

The distribution grid simulations were executed running power flow including the system loads, power output of the PV systems and EVs. Following the simulation, bus voltages are analyzed to determine voltage violations throughout the distribution grid. In all cases and corresponding scenarios, any bus with a voltage below 0.9 p.u. is operating below rated conditions and is to be curtailed. To be able to provide an in-depth evaluation of the distribution system experiencing interruptions, different operating conditions are presented. First, a baseline condition with no DERs is simulated. A second operating condition is the inclusion of networked MGs with PVs and EVs functioning in V2H. The third condition is when the EVs are functioning in both V2H/V2G. When the EVs are functioning in V2H/V2G the priority is to fulfill the energy requirements of the household and subsequently if there is surplus energy from the EV it can be exported into the distribution system. This strategy ensures the local loads are met first and it allows the EV users to provide energy to the neighboring users. The three operating conditions presented in the case study resemble the most practical strategies EV users could be presented with.

The bus voltage profiles for the baseline condition operating under full demand with an interruption of 20 hours are shown in Fig. 4. From the figure we can identify the buses that would be curtailed in the shaded color of the graph during the blackout. In addition, Fig. 4 also shows that more than half of the buses are operating below 0.9 p.u. at the interruption time. Table IV provides a summary of the results for the case study. From the table, an estimated 57% of the users experienced a blackout in scenario 1. When EVs are functioning in V2H, the bus voltages are risen (Fig. 5), leading to a reduction in the blackout index and enhancing the resilience of the distribution network to 0.70 compared with the baseline of 0.53. In the case of EVs functioning in V2H/V2G the blackout index is reduced from 0.572 to 0.194 with respect to the baseline for scenario "1".

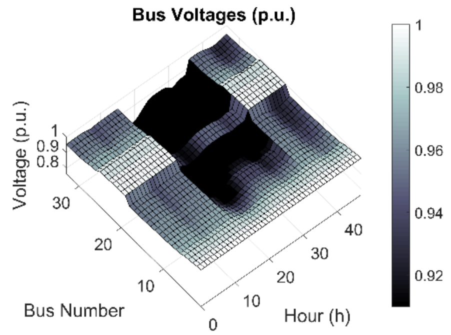

Fig. 4. Bus Voltages: Case 1, Scenario 1-20h blackout.

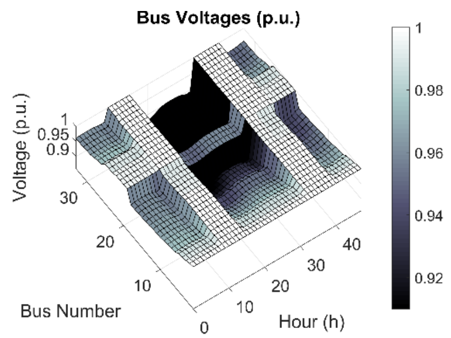

Fig. 5. Bus Voltages: Case 1, Scenario 1-20h blackout V2H.

The summary of the categories and corresponding resilience metrics that are utilized to assess the distribution system resilience is shown in Table IV. Comprehensive measurements of the resilience metrics provide an insight of the impacts that PVs and EVs could offer when effectively integrated in an electric power distribution system. Further dissecting the results in Table IV, resilience improvements are achieved in the two operational conditions where EVs are integrated in Case 1. The greatest improvement was with EVs operating V2H/V2G, reducing the blackout index by 37.8% and increasing the resilience index to 0.855 compared to 0.538 from the baseline.

Furthermore, under Scenario 2, the best resilience improvement was achieved as no user experienced an interruption when EVs functioned in V2H and V2H/V2G.

Table V presents the blackout cost assessment. Analyzing the overall costs when the EVs operate in V2H and V2H/V2G there is decrease in the economic impact by interruption cost. From Table V, when EVs function in V2H, the blackout cost is reduced $1,755,515, i.e., a 33% reduction compared to the baseline. Also, the greatest cost saving is when EVs were functioning in V2H/V2G with an associated reduction of $3,694,238 when compared to the baseline. The results indicate that when DERs are integrated to the power distribution system, specifically, EVs, overall blackout costs can be decreased as fewer users experience a service interruption.

C. Resilience Assessment Critical Demand Condition

Similarly, to the first case it is assumed the 33-bus distribution network with four MGs (Fig. 2) is impacted by a winter storm resulting in damage to infrastructure as shown in Table III. The principal characteristic of this case compared with Case 1, is only critical demand of the household will be

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prioritized while the interruption is ongoing. This case has been developed to analyze the differences and grid benefits of only supplying critical demand when interruptions may occur.

Table IV represents a summary of the resilience metrics assessment for Case 2, Sc. 1 and 2. Examining Scenario 1, when EVs operate in V2H there was an improvement of the resilience index between 18% (20-hours) and up to 23% (3-hours). In Case 1, the greatest resilience improvement is when the EVs function in V2H/V2G decreasing the blackout index 38% (20-hours), 61% (6-hours), and 63% (3-hours), with reference to the base condition under Scenario 1. Furthermore, in Scenario 2 for the V2H and V2H/V2G conditions no interruptions were encountered as the resilience index was 1.0.

Further analysis of Table IV shows that approximately 37% of the users were under blackout condition when the 20-hour interruption occurred in the V2H condition in Scenario 1, representing a 2% improvement compared to the identical operating condition of Case 1 where all household loads were fulfilled. Examining the V2H/V2G mode, the blackout index was reduced to 0.194, or equivalent to a 38% decrease compared to the baseline of Scenario 1. Likewise, no users observed an interruption in the 3 and 6-hour blackouts from Scenario 2 in the V2H/V2G condition.

The blackout cost evaluation through the financial service metric is shown in Table V. Comparing the blackout costs to those of Case 1, similar results were obtained, i.e., total blackout cost were reduced when EVs functioned in V2H and V2H/V2G. These results establish that when rooftop solar PV and EVs are present within networked MGs these could reduce the burden of financial impacts during distribution grid contingencies.

The results presented in this paper were simulated and implemented in MATLAB R2019a using MATPOWER version 7.1 [28]. All simulations were carried out utilizing a personal computer with 8 GB RAM and 2.4 GHz CPU.

V. Conclusion

This paper provided an in-depth description and evaluation of the effects that DERs (rooftop solar PVs and EVs) effectively managed in distributed residential networked MGs can have on the resilience of an electric power distribution grid that is being impacted by extreme weather.

A resilience assessment has been conducted with multiple case studies that tested different blackout duration scenarios and demand levels. The evaluation of the resilience of the power distribution network was achieved by applying resilience metrics that measure the impacts on electrical energy service and financial components. Evaluating the simulation results utilizing the IEEE 33-bus distribution system proved that when no DERs were interconnected to the distribution grid over 60% of the users experienced an outage. However, in cases where EVs were operated as a backup energy source they were able to supply power for over 20 hours while operating in V2H and V2H/V2G. Furthermore, the simulation results established that DERs such as solar PV and EVs can support local demand and provide bus voltage enhancements when system interruptions occur, significantly enhancing the resilience of the distribution network by providing benefits for all users improving the electrical service and minimizing negative economic impacts.

By analyzing the results for both cases (all loads and critical loads only) it can be determined that resilience enhancements were observed once EVs operated in both V2H and V2G for the 3-hour and 6-hour blackouts as the system reached 100% resilience and 0% of the power distribution system users suffered a blackout.

TABLE IV. CASE 1 AND 2: RESILIENCE INDEX (RI) AND BLACKOUT INDEX (BI) ANALYSIS FOR FULL DEMAND AND CRITICAL DEMAND CONDITIONS

		Case 1. Full Demand				Case 2. Critical Demand			
Scenario		1	1	2	2	1	1	2	2
Resilience Metrics		RI	BI	RI	BI	RI	BI	RI	BI
Base	3h	0.5	0.6	0.8	0.2	0.5	0.6	0.8	0.2
	6h	0.5	0.6	0.7	0.3	0.5	0.6	0.7	0.3
	20h	0.5	0.6	0.9	0.1	0.5	0.6	0.9	0.1
V2H	3h	0.6	0.5	1.0	0.0	0.7	0.3	1.0	0.0
	6h	0.6	0.5	1.0	0.0	0.7	0.4	1.0	0.0
	20h	0.7	0.4	1.0	0.0	0.7	0.4	1.0	0.0
V2H &V2G	3h	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0
	6h	1.0	0.0	1.0	0.0	1.0	0.0	1.0	0.0
	20h	0.9	0.2	1.0	0.0	0.9	0.2	1.0	0.0

TABLE V. TOTAL INTERRUPTION COST FOR FULL DEMAND AND CRITICAL DEMAND CONDITIONS

Operating Condition	**Outage Duration**	**Case 1. Full Demand**		**Case 2. Critical Demand**	
		Scenario		**Scenario**	
		1	2	1	2
Base	3h	7,693	2,359	7,693	2,359
	6h	42,438	17,057	42,438	17,057
	20h	5,593,363	855,319	5,593,363	855,319
V2H	3h	6,267	0	4,251	0
	6h	33,461	0	28,126	0
	20h	3,837,848	0	3,605,011	0
V2H & V2G	3h	0	0	0	0
	6h	0	0	0	0
	20h	1,899,125	0	1,899,125	0

While in the case of the longer duration interruption (20-hours), the system had an 85.5% resilience index, and only 19% of the system experienced an outage. Furthermore, results further improved when only critical loads were powered.

A key finding of the results is even though the V2H/V2G operation proved to be the best mode to increase system resilience, from the EV users' point of view this may not be the most beneficial operational approach as V2H/V2G can drastically decrease the backup support time for their household as well as the expected life of the battery of their EV. Consequently, except where there are strong monetary incentives for users to participate in V2H/V2G, users will have to decide which operational condition they want to perform with their EVs, i.e., if they provide grid support for a shorter period or use their EVs to supply their household demand only.

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It should be noted that the case study results described are case specific to the assumptions and conditions delimited throughout the paper. Nevertheless, the assessments and specific findings show the potential of roof-top solar PVs and EVs to improve the resilience of the electric distribution grid.

Future work will involve evaluating the energy exchange between EV users and electric utilities to determine the appropriate incentives for EV users to engage in V2H/V2G programs. Additionally, study of the utilization of Medium- and Heavy-duty EVs for power support of the distribution system and other ancillary services during blackouts.

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