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Research on Power Grid Resilience and Power Supply Restoration during Disasters-A Review

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Abstract

Electric power system plays an indispensable role in modern society, which supplies the energy to residential, commercial, and industrial consumers. However, the high-impact and low-probability natural disasters (i.e., windstorm, typhoon, and flood) come more frequent because of the climate change in the recent years, which may sequentially cause devastating damages to the infrastructure of power systems. The aim of this paper is mainly to explore and review the resilience of power grid system during the disaster and the power supply management strategies to recover the power grid. Firstly, the category of natural disasters and different influences on power grid are discussed. Then, the definition of power grid resilience is explored and the supply management strategies coping with disasters are introduced, such as microgrids and distributed generation systems. Specially, the electric vehicles (EVs) equipped with large-capacity battery pack in the transportation network can also be considered as the distributed power sources with mobility. Thus, the conceptual frameworks of integrating large-scale EVs into the power grid to fasten restoration of the power systems in the pre-disaster/post-disaster are emphatically investigated in this paper. Finally, the opportunities and challenges in further research on employing EVs for emergency power supply in the extreme weather events are also discussed.

Keywords: power grid system, natural disasters, power grid resilience, electric vehicles (EVs), power system restoration

1. Introduction

Due to the climate change, the high-impact low-probability extreme weather events, such as hurricane, flood and ice storm, become more frequent and drastic in recent years, which lead to an enormous and irreversible damage to the people's daily life and the economy activity. One non-negligible damage caused by the natural disasters is the widespread power system outage since electric power provides the foundational support for all industry, from the manufacture production to the life-line energy warranty. Thus, the outage avoidance and fast recovery from the outage are the key factors for the power systems.

The ability of the power systems to cope with the natural disasters is usually seen as the power grid resilience. Since the uncertain characteristics of a disaster and the complexity of the power systems, the resilience enhancement measures should be

taken into account. Targeting the emission reduction of the transformation system on the road network, the electric vehicles (EVs), including battery electric vehicle, hybrid electric vehicle and plug-in electric vehicle, are gaining the worldwide attention increasingly. There is a revolutionary opportunity in improving resilience of power systems during the disaster provided by the EVs, due to the abilities of high electric capacity, mobility, and bidirectional charging of EVs.

Thus, this paper mainly makes a comprehensive review of the impacts of natural disasters to the power systems, the resilience improvement strategies, especially with consideration of the high increasing penetration of EVs. The remainder of this paper is organized as follows: In Section 2, the introduction of the high-impact low-probability natural disasters and the different impacts to power systems of corresponding natural disasters are given. Then, the definition of resilience and enhancement strategies for power grid, including hardening measures and operation actions are explored in Section 3. Section 4 shows the electric vehicles with characteristics of mobility and bidirectional charging and the utilization methods to improve power grid resilience performance in pre-disaster and post-disaster. Finally, the conclusion of this paper and challenge for future work are given in Section 5.

2. The vulnerability of power system to natural disasters

As the most basic and principal energy sources in the modern society, electric power plays an important role in promoting the development of social economic and improving the quality of people's life. A possible power outage can not only affect people's daily life and cause immeasurable losses of social economic, but also may lead to the breakdown of critical infrastructures, such as communication networks, police stations and hospitals, which provide essential services for the disaster relief.

Natural disasters can cause devastating damage to the modern society's infrastructures especially to the electric power system, with their main characteristics of unpredictable, large-scale and inevitable. Although the double circuit configuration for important circuits, automation equipment of distribution network, and a series of protection systems were adopted to improve the reliability of modern electric power system, the power system is still vulnerable to natural disasters. In recent decades, there were a number of large-scale power outages around the world due to the damage of the power system infrastructure caused by the high-impact low-probability natural disasters including hurricane, earthquake, tsunami and floods.

There has been numerous research on the analysis of damage to power system components or other infrastructures which are interdependent with power grids (e.g., transportation, telecommunications), due to natural disasters. It can be confirmed that the vulnerability of power system components to different types of natural disasters is not identical. Thus, the discussion of specific examples about the characteristics of damage to power system components caused by different types of natural disasters will be conducted below.

Compared with other natural disasters, substation equipment, which located in a low-lying area is more vulnerable to flood damage. Abi-Sarma and Henry [1] studied the impact of the flood on power substations, which occurred in the Mississippi River basin of the Midwestern US in the summer of 1993 and caused about 10–15 billion of dollars of property damage. Of Union Electric's (UE, now known as AmerenUE) 1300 stations, there were 19 substations affected by rushing waters and several suffered severely damage. **Figure 1** shows the flooded substations during the 1993 flood at UE. They indicated that the flooded substations were affected

very differently from those affected by other natural disasters, due to some electric equipment especially power circuit breakers and low-voltage control cabinets were easily affected by even tiny amounts of water and mud, which rendered it unable to function normally. In addition, restoring flooded substations required longer time and considerable manpower than restoring a downed power line damaged by ice or wind.

The impact of hurricane on power system is mainly reflected in the damage to transmission/distribution system and telecommunications. On August 29, 2005, Hurricane Katrina struck the United States Gulf Coast, generating an intense storm surge. Reed et al. [2] focused on the resilience of the electric power delivery systems after the Hurricane Katrina and investigated the correlations between power outage data and weather parameters such as wind speed, rainfall and storm surges. They counted that over 20,000 utility poles, 4000 transformer and 1300 transmission structures were destroyed directly by storm surge in the states of Alabama, Louisiana and Mississippi. **Figure 2** shows the damage to grid by Hurricane Katrina near Pt. A La Hache, LA. Kwasinski et al. [3] studied the impact of Hurricane Katrina on the telecommunications power infrastructure including damage in



Figure 1.
Flooded substations during the 1993 flood at UE.



Figure 2.
Damage to the electric distribution grid near Pt. A La Hache, LA.

wire-line and wireless networks. Their analysis showed that widespread telecommunications outages were mainly due to power shortages caused by fuel delivery disruptions, flooding and security issues. In addition, the damage to the electric grid was also extensive and severe, especially in the areas affected by the storm surge. The breakdown of above infrastructure has directly hampered the operations of disaster relief, and prevented people living in the hardest hit areas from appealing for assistance.

As a special meteorological disaster, ice storm has greatly affected the safe operation of many overhead lines worldwide. Zhang et al. [4] reviewed the procedure of the severe ice storm which took place in southern China in 2008, studied the process of the power grid hit by ice storm and the power restoration, and also summarized emergency strategies and the lesson from this natural disaster. They found that significant ice accumulated on overhead power lines and transmission towers, which led to broken power lines and collapsed towers. Xie and Zhu [5] provided detailed data about the impact of ice storms on Chinese power system. According to the State Grid Corporation of China, there were at least 36,740 transmission lines, 5420 transmission towers, and 2018 transformers damaged, and at least 1841 towers needed to be repaired. **Figure 3** shows the transmission tower collapse caused by ice accumulation in 2008.

Furthermore, the damage to modern power systems by earthquake has historically been enormous. Fujisaki et al. [6] discussed the observations of earthquake aftermath in Japan, New Zealand, US, Chile, China, and Haiti, and focused on high-voltage electric substation equipment and transmission lines in US, China, and Haiti. They indicated that the main reasons for the disruption of the power grid were the collapse of the transmission tower, the damage of transformers, circuit breakers and other high voltage equipment, and the local damage of broken poles and broken-down village transformers. And buried electric transmission and distribution cables may be vulnerable to liquefaction induced ground displacement in a number of earthquakes. Unquestionably, the damage of earthquake on the power system infrastructures was extensive and severe, and the damage to the telecommunication network was also devastating. During the Wenchuan Earthquake in 2008, cellular service was disrupted for more than 60 days in some parts of the earthquake-affected region [7]. **Figure 4** shows the damage to equipment in the Ertai Shan switchyard after Wenchuan Earthquake. In the Tohoku Earthquake in 2011, due to earthquake and massive tsunami, 18 telecom buildings were totally



Figure 3.
Transmission tower collapse caused by ice accumulation.

collapsed, 23 telecom buildings were submerged, 65,000 telecom poles were washed over or damaged and 90 relay transmission routes were cut-off [8].

Over the last two decades, under the influence of climate change, many countries and regions have abnormal weather conditions, with extreme weather events more frequent and harmful. And extreme weather events may increase the possibility that modern electric power systems are disrupted terrifically. For example, Typhoon No. 15 landed near Chiba, Japan on September 9, 2019, and led to a power outage in about 935,000 households in the Kanto region. It was reported from Tokyo Electric Power Company (TEPCO) that the large-scale power outage was caused by the blown down of two transmission towers in Kimitsu City, and the damage of about 2000 electric poles in various places. **Table 1** shows the major power outages caused by extreme weather events around the world from 2010 to 2019.

Therefore, it is essential for the power system to recover rapidly from the damage caused by the high-impact low-probability natural disasters including extreme weather events, due to continuous power supply being a prerequisite for the



Figure 4.
Damage to equipment in the Ertai Shan switchyard.

Date	Extreme weather event	Number of customers without power	Location
March 2010	Rainstorm	>10,0000	West Australia
March 2011	Tohoku Earthquake, Tsunami	8900,000 households	East Japan
October 2012	Hurricane Sandy	8100,000	United states
March 2013	Heavy snow	200,000	Northern Ireland
December 2013	Ice Storm	~300,000	Canada
July 2014	Typhoon Rammasun	13,000,000	Philippine
November 2015	Windstorm	700,00	Canada
September 2016	The Blyth Tornado	1700,000	South Australia
July 2018	Rainstorm	>180,000 households	West Japan
September 2019	Typhoon No.15	935,000 households	East Japan

Table 1.
Major power outages worldwide (2010–2019).

operation of other social infrastructures. Based on this background, the concepts of resilience and resilient power grids were proposed, and the research and construction of the resilient power system has gradually become a national strategy for the governments of various countries to focus on.

3. Power grid resilience

3.1 The definition of power grid resilience

The definition of resilience was presented by the National Infrastructure Advisory Council (NIAC) in 2010, which offered a broader definition for infrastructure resilience that the ability to mitigate the magnitude and/or duration of low-frequency high-effect events. The effectiveness of a resilient infrastructure depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event [9]. The Multidisciplinary Center for Earthquake Engineering Research (MCEER) presented a conceptual framework to define resilience, which can be useful to determine the resiliency of different systems in future research, with four main features: robustness, redundancy, resourcefulness, and rapidity [10].

The NIAC resilience definition was acknowledged by the North American Electric Reliability Corporation to be used in power systems [11]. Therefore, combining the definition mentioned above, a resilient grid can be described as a grid with four basic properties of resilience, which is the anticipation, absorption, recovery and adaptability after the destructive events [12]. Anticipation is the ability to avoid any potential damage due to natural disasters; absorption is the power grid's ability to minimize the damage caused by natural disasters; recovery refers to the ability of power grid to rebuild functions damaged by natural disasters; adaptability is the process by which a system learns from the past events, to improve its capabilities, and to prepare for the next event [12].

3.2 Resilience enhancement strategies for power grid

In this subsection, the hardening measure and operational actions for resilience enhancement will be reviewed.

3.2.1 Hardening measures

Vegetation management.

During a storm or strong wind event, trees touching or damaging transmission/distribution lines and poles are the most common cause of many power outages. Most and Weissman [13] proposed a range of solutions for vegetation management, including pruning/trimming trees around the transmission and distribution lines and replacing potentially problematic trees with species more appropriate for the location. They suggested revising municipal tree ordinances to define tall-growing trees planted under powerlines as "nuisance trees". In addition, Zahodiakin [14] recommended the utilization of Geographic Information System (GIS), sonic scanning and LIDAR (Light Imaging, Detection, and Ranging), to record pole locations, remove targeted trees, determine which trees are most likely to collapse in a storm, and measure the height of tree canopies to assess risks of trees falling into power line corridors.

Selective undergrounding.

The strategy of moving transmission and distribution lines underground can effectively reduce the vulnerability to damage of vegetation, wind, animals,

lightning, vandalism, and other natural disasters. However, the extensive use of this measures has been limited by the costs, because it is three times higher for underground systems than that for overhead systems. For instance, in urban areas, underground lines cost an average of \$559,293 per line mile, while overhead lines cost an average of \$196,628 per line mile [15]. Moreover, the complexity of these underground systems and the difficulty of directly observing damaged lines may increase their restoration time. Therefore, after appropriate risk and cost/benefit analysis, targeted or selective undergrounding of overhead lines may be more feasible than a total conversion, which provides benefits for both damage reduction and costs [16].

Upgrade infrastructure of power system.

Upgrading power grid components with stronger materials aims to increase the resilience of power grid in the high-impact low-probability natural disasters. Xu et al. [17] proposed a straightforward way that reinforcing utility poles and overhead distribution lines with stronger materials to improve the ability of distribution systems to ride through high-intensity winds, heavy ice storms and other extreme weather events. They also emphasized the importance of identifying and reinforcing vulnerable components for power sources to access critical loads during extreme events. Furthermore, for new distribution systems, using stronger poles for the entire system could reduce life-cycle costs in all cases. Relatively, for older systems, targeted hardening is more economical and effective than hardening the entire system [18].

Elevated substation and water barrier.

As mentioned earlier, the substation located in a low-lying area is more vulnerable to floods caused by natural disasters. Thus, elevating the substation above the flood levels could help provide protection against flood damage and maintain the normal substation operation. Boggess et al. [19] proposed to modularize substation equipment and install it on elevated foundation plates, platforms or stilts to help mitigate flood damage and avoid external impacts such as weather, contamination and wildlife. They indicated that elevating transmission substations with indoor GIS (gas-insulated switchgear) has proven to be an excellent solution to improve reliability and security of power grid, as well as life-cycle costs, especially in coastal areas. In addition, it is possible to install a permanent barrier at the side or sides of the substation most vulnerable to flooding, for existing substations [1].

Relocating facilities and rerouting transmission lines.

Relocating facilities, or rerouting transmission and distribution lines to low hazard areas also a practicable ways to reduce the negative impact of floods, storms and other extreme weather events on power systems. Considering the cost of relocating facilities and rerouting lines, a long-term cost-benefit analysis is necessary to determine the convenience of substation relocation or lines rerouting [16].

3.2.2 Operational actions

Emergency mobile substation

As reported by [1, 20], providing portable and mobile generators or substations to power supply in disaster-affected areas is one of the traditional emergency strategies of power supply. Mobile substation, composed of power transformer, switchgear and temporary control panel, has the advantages of convenient transportation, perfect equipment and reliable operation. The use of this equipment can quickly replace the damaged substation to maintain power supply in emergency situations such as natural disasters and sudden equipment accidents, especially for remote but critical loads. And the operation of mobile substation in high load season can overcome the shortage of power supply capacity in some areas. Meanwhile, mobile

substations can be flexibly used in the field, mountain areas, and other suitable locations where an extreme weather event is forecasted, due to the ease of moving and installing.

Natural-disaster-based grid predicting and monitoring system

Power systems are highly sensitive and demanding to meteorology, which lead to the production, construction and operation of power systems are greatly affected by meteorological factors. During natural disasters, through gathering the actual and real-time information to effectively predict and monitor potential damage to power grid components by disaster, is an important measure to minimize damage and improve power grid resilience. In [21], a machine learning based prediction method, using historical data of extreme weather events and damages of the grid, were proposed to determine the potential outage of power grid components in response to an imminent hurricane. Such machine learning-based algorithms can be applied to several power grid related problems such as security assessment, risk analysis, distributed fault identification and power outage duration prediction [22–25]. Furthermore, considering the condition of possibly damaged communication channels by natural disaster, a proposal of using unmanned aerial vehicles (UAV) to support Airborne Damage Assessment Module (ADAM) was presented in [26]. By using this method, on the one hand, it is possible to survey the disaster area to retrieve real-time data about the power poles and lines, and to determine the shortest possible route for the dispatch of repair personnel based on the information provided. On the other hand, the drones can reach areas that are inaccessible to other vehicles, especially when roads are blocked.

Spare part and repair crew management

During natural disaster, the availability of spare parts is critical to reducing the recovery time of power systems, due to requiring a lot of spare parts for the urgent repair of power grid [27]. However, the power system is complex, including power generation, transmission and distribution systems. When preparing spare parts, many factors have to be considered. Hence, it is suggested that decision-making and priority-confirming are determined by analyzing the components failure rates, consequences, investment cost, and the operation and installment difficulty level [28].

As the crucial response resources for power outage management against natural disasters, repair crews are expected to repair the damaged power components in an optimal order [29]. In [30], a co-optimization model for the repair and restoration of transmission systems was developed to coordinate generators and repair crews to maximize the picked-up loads after damages. The first step in this model was to locate optimal placement of the central station, which aims to locate the spare parts and repair crews, and to determine the optimal path for each crew to traverse to repair damaged components. Analogously, Lei et al. [31] proposed a co-optimization method for disaster recovery logistics, with adopting the dispatch of repair crews and mobile power sources, and operation of distribution system for electric service restoration.

Distributed Energy Systems and Microgrids

Facing with the hurricane and earthquake, the transmission lines and transmission towers may be destroyed, which can cause huge power outage to the customers. To deal with this problem, the microgrids connected with distributed energy resources, including the wind turbines, photovoltaic panels, fuel generators and electric vehicles, are becoming increasingly popular. This combination is located closer to the customers and delivers the power to them through a few or zero transmission lines. Moreover, when there is a failure of the transmission lines, an island grid can still be generated at a low-voltage level from the microgrid with distributed energy resources to supply electric power so that the power grid resilience can be enhanced. There are two aspects should be considered for microgrids

with distributed energy resources in the resilience improvement. On the one hand, the locations and power capacities of the distributed energy resources need to be optimized to achieve the minimization of the investment cost, operation cost and the risk level of unacceptable reliability [31, 32]. On the other hand, the real-time power flow of the microgrid/island grid after the disaster should be optimized to minimize the energy consumption on the grid line and the voltage fluctuation [33].

4. Electric vehicle

In this section, the characteristics of electric vehicle will be introduced firstly; then the review of electric vehicles to grid for the resilience of power grid during disaster will be conducted.

4.1 Electric vehicle characteristics

In recent years, the renewable energy vehicles have been gaining increasingly attention in the fields of the public, the industry and the government due to its advantage in the independence on fossil energy and emission reduction for establishing an environment-friendly society. In this chapter the electric vehicle powered by the battery is mainly represented for the renewable energy vehicle. Generally, EVs include pure battery electric vehicles (BEVs), hybrid electric vehicle (HEV) and the plug-in hybrid electric vehicles (PHEVs). Since the first HEV was launched into the market in 1997, the sales of EVs increase year by year. **Figure 5** shows the projections of EVs sales in US from 2020 to 2050 and it is clear that the battery powered vehicles will become more popular in the automotive market, especially the long-range pure electric vehicles with large-capacity battery.

Both BEVs and PHEVs are equipped with the devices to charge electric energy from the grid and discharge the energy back to grid with a bi-directional charger. And there is an internal combustion engine, which can be forced to work in high-efficiency and green-emission zone because of the addition electric motor to propel the (P)HEV. Compared to the conventional HEVs, there is a larger-capacity battery package in PHEVs so as to store more electric energy for propelling vehicle during the daily trip. The main physical structures of powertrain of (P)HEV can

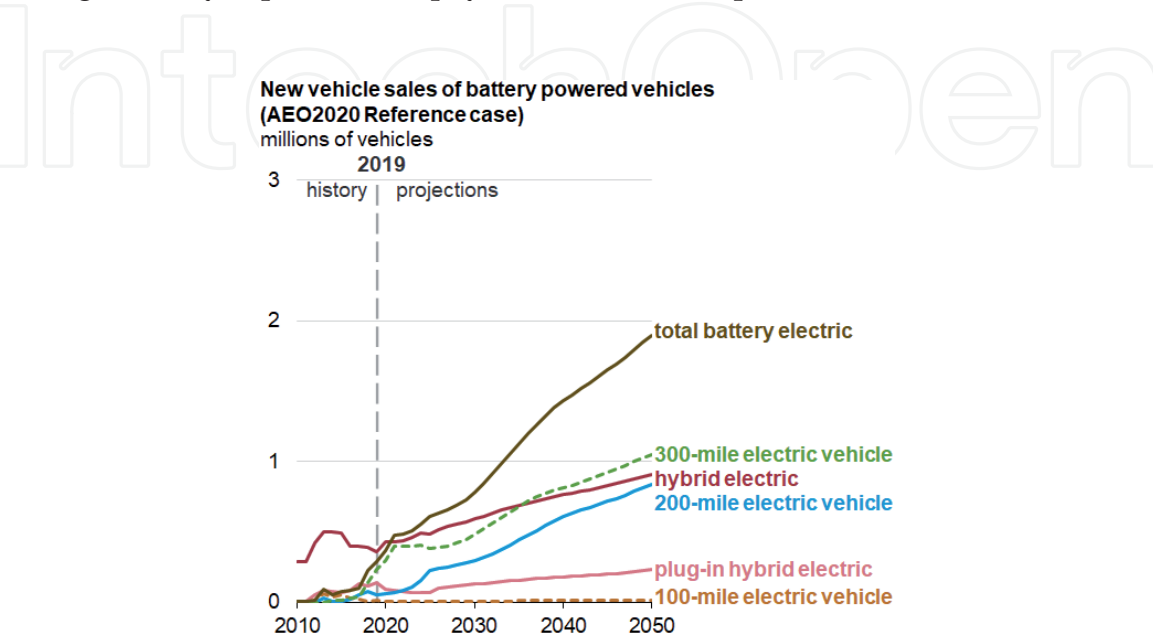


Figure 5.
Projections of EVs sales in US from 2020 to 2050 [34].

be classified into parallel, series and power split, as shown in Configuration A, Configuration B and Configuration C of **Figure 6**, respectively. The mechanical powers from engine and motor by using electricity from battery can propel the vehicle separately since there are two power flows. However, it not possible to use engine to propel motor in regeneration mode without vehicle running since the motor and tires are connected through a gear. In the series structure, there is a generator connecting the engine mechanically and connecting the battery electrically so that the engine can only be used to generate electricity in high efficiency zone. The vehicle is only driven by the motor using power from generator or battery. The third popular powertrain structure is power split, where a planetary gear is equipped to connect the engine, generator and motor through sun gear, ring gear and planet gear, respectively. Like the series structure, the motor is also connected to the tire through a gear. The engine torque can always be in the high-efficiency zone during propelling vehicle mechanically through using the generator to force the engine speed. As the engine and tire (motor) decoupled mechanically in series and power-split structures, it is possible to use engine for electricity generation.

Table 2 lists parameters comparison of the main passenger electric vehicles in the automotive market. Since there is a fuel tank in the vehicle, the running distance of PHEVs are much higher than the BEVs, except for the Tesla with supper large battery package. The reason is that the energy density in the battery is also an open problem for BEVs, which leads it not suitable for long distance trip. On the other hand, the temperature management of battery in winter and summer should be taken into consideration since the temperature can influence the battery performance deeply. Even though with disadvantage in above aspects, the BEV is still the most promising vehicle in the future market because of its zero-emission performance.

4.2 Electric vehicle to grid in disaster

With increasing BEVs on the road, the issue of BEVs charging needs to be considered since it may influence the power grid, such as the voltage stability and frequency on the nodes, which play virtual role to industrial manufactory users. Moreover, the peak cut and valley filling of power grid can be achieved by the large-scales BEVs due to its advantage of the large battery storage capacity and the bi-directional charging flexibility. An illustrative conceptual resilience framework of the

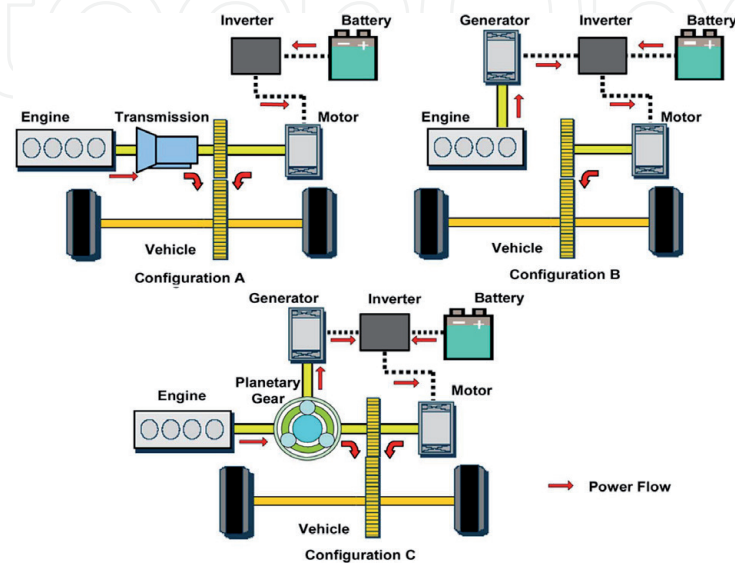


Figure 6.
Physical structures of powertrain of (P)HEV [35].

Vehicle	Type	Tank size (Gallons)	Battery capacity (kWh)	Distance (mile)	Electric distance (mile)
Toyota prius prime	PHEV	11.3	8.8	640	24
Nissan leaf	BEV	NA	40/62	149/226	149/226
Tesla model S	BEV	NA	100	348	348
BMW i3	BEV	NA	42.2	153	153
Audi A3	PHEV	10.6	8.8	580	31
Ford fusion energy	PHEV	16.5	9	610	26

Table 2.
Parameters comparison of the main passenger electric vehicles.

power grid associated with a disaster is shown in **Figure 7**, where the horizontal axis and vertical axis denote the time and system performance, respectively. Six states are divided in this figure, which are the resilient, event, post-event, restoration, post-restoration, and recovery. In this article, resilient is called as the pre-disaster period, and post-event, restoration and post-restoration are together named as the post-disaster period. The recovery state is only dependent on the power grid system characteristics. In this part, the beneficial of EVs as mobility of power resource to the power grid when facing the extreme events in pre-disaster and post-disaster times, especially to the distribution grid are discussed.

4.2.1 Pre-disaster strategies

The power grid recovery after a huge disaster is dependent on the quality and quantity of the resource that can be used at the beginning of recovery. However, during and post disaster, the road network may be destroyed so that it is of importance to allocate the resource for recovery in advance, such as oil of diesel generators and the batteries. With consideration of power grid device failure, the probability of it can be estimated through the analysis of weather records and the historical data by using the data-based learning approaches, such as linear regression, Bayesian learning and Monte Carlo simulation. EV, as a part of the mobility of the power sources, has been widely explored for the power system resilience under the natural disasters.

Considering the uncertain of the fault locations, a stochastic mixed integer non-linear program -based resource allocation problem is formulated to maximize the benefit obtained by difference between serving critical load in restoration and the total allocation cost. Meanwhile, the transportation cost is also calculated through the distance and the amount of the resources [36]. With consideration of the battery degradation cost and the estimation of fault locations, a two-stage stochastic mixed integer second order conic program with binary recourse decisions are developed to optimize the investments in the first stage and re-route the installed mobile energy resource in the second stage. The optimal solutions are derived by the progressive hedging algorithm [37]. On the other hand, a two-stage optimization problem is formulated, where a proactive pro-positioning of mobility power system strategy is developed to enhance the survivability before the disaster, and a dynamic dispatch of mobility power system strategy is developed to coordinate with restoration and infrastructure recovery effort. It is noted that the optimal solution is obtained through the column and constraint generation algorithm in the first stage [38]. Under the inspiration of [38, 39] developed a two-stage restoration strategy to deal with the power grid resilience problem under seismic scenario by employing the

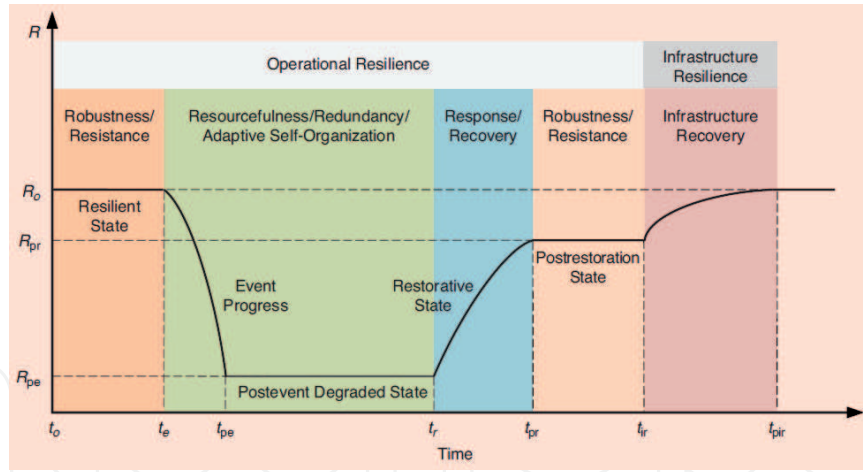


Figure 7.
Conceptual resilience framework of power grid associated with a disaster [16].

mobility of power sources. In the first stage, uncertainty of the seismic scenario is simulated through the Monte Carlo simulation. A mixed integer nonlinear program optimization problem is formulated in the second stage for routing and scheduling the mobility of power sources. Furthermore, for the purpose of co-optimization of power resource dispatch with mobility and repair crew to achieve the minimization of restoration time, a non-convex mixed integer nonlinear program optimization problem is formulated. The simulation validations under IEEE 33 node show the effectiveness of the proposed strategy [39].

4.2.2 Post-disaster strategies

When a disaster event happens, the blackout in the urban city can cause significant damage to the citizens and critical infrastructures. For example, unused of traffic signals leads to traffic accidents for vehicles and pedestrians and traffic disturbance. The aggressive BEVs on the road also mean large-scales second-hand battery packs that are not performance enough for BEVs, but they can be used as the distributed energy infrastructure after the disaster even happens. It is estimated that the end-of-life batteries in Berlin, Germany by 2040 can provide power for emergency traffic signals in the intersections for more than 380 hours, which is time enough for the repair crew to repair the electric power system [40]. On the other hand, the earthquake happened in Fukushima Japan in 2011 damaged the nuclear power plant and only the ships in the sea were survived from the tsunami. In this case, [41] proposed an emergency power supply strategy by using EVs to transform the electricity from ships to the land for hospitals and shelters.

Due to the storage capacity and charging flexibility of EVs, they can be used as grid supporting for the microgrid restoration and simulation results show that the active integration of the EV into the microgrid can make a contribution in reducing MG frequency deviations and reducing the unwanted negative and zero sequence voltage components [42]. Further, by utilizing the battery technologies connected to the grid, during the restoration period, [43] proposed a feedback optimal frequency controller with the frequency deviation and SOC deviation as state variables and individual battery charging/discharging power as control input. After the natural disaster, the transmission grid may be destroyed and the power from major grid cannot be transmitted to the distribution grid. Only the remnant equipment of battery and photovoltaic and the EVs are available for power generation. Since the resistance of the distribution line is larger, the power loss in the grid should be taken into account. In [33], an optimization problem of minimizing the distribution grid

loss by determining the discharging power nodes from EVs is proposed and both the active power and reactive of the EVs on the nodes are employed.

There are also some strategies focusing on the vehicle to home (V2H) for the resilience improvement of residential customers by providing power from EVs after the disaster. Specially, some PHEV powertrain structures, such as series and power-split, the gasoline engine can be applied for generation of electric power and transform it back for home's electric appliances. [44] developed a power system management scheme for emergency scenario to energize the small microgrid (V2G) together with other generators, such as wind turbine and solar panels, or the individual house (V2H) by employing the mobility and energy capacity of PHEVs. Moreover, the PHEV structure, where the fossil energy that is available to converted into electricity, is discussed. In [45], the simulation results of different type of EVs under the different cases of summer and winter show that the PHEV, especially with larger tank size, is the better choice than BEV in term of the long-time electric power supply for the house electric appliances and it is suitable as an emergency power supply to be popularized. For example, even without the pre-preparation before the disaster, the Prius with half gasoline and half battery can also provide power for more than 2 days in the emergency scenario. [46] described the problem that maximizes the time duration of V2H supporting residential load in an islanded mode after the disaster as a mixed integer quadratically constrained programming problem, which is solved through the numerical solver. Meanwhile the proposed algorithm is extended to the multi-homes and multi-PHEVs as a microgrid.

5. Conclusions and future work

In this paper, the state-of-the-art of the high-impact low-probability natural disasters influence on the electric power system is reviewed from the scientific and technical perspectives. By the analysis of the impacts of different natural disasters to the power grid, it is concluded that the substation equipment in the low-lying area and the transmission lines are susceptible destroyed by the flood and hurricane, respectively. Whereas the destroy caused by the earthquake is all-around, including the power grid network, communication network and the road network. Further, the definition of the power grid resilience under different natural disasters is explored and the power grid resilience enhancement approaches to deal with these disasters are reviewed from the hardening measures in advance to the real-time operation actions. Moreover, the utilization of the EVs, seen as the mobility energy systems, to improve the power grid resilience performance that aims to reduce the restoration time of the power grid after the disasters, is investigated in periods of both pre-disaster and post-disaster.

Although, a comprehensive investigation on the power grid resilience has been conducted, there still exist some research areas that are not included in this chapter. Meanwhile, there are unsolved researches and opportunities in the future, and they will be explained in detail in the following parts:

1. Forecasting the natural disasters

Through the review in this paper, there are some data-based machine learning algorithms to forecast the probability of a natural disasters, however, it may be unsuitable by just employing a black-box model and applying it to a specific disaster event without consideration of the physical mechanisms. The principles in different kinds of natural disasters should be considered and the prediction performance can be improved by the acknowledge combined with the power grid and the meteorology.

2. Transportation network and communication network

Dealing with the power grid restoration, the distributed generators play a virtual role in providing the power for the microgrid when the transmission line is destroyed. In the current research, only the power grid network performance is taken into account for fast restoration; however, the transportation network and the communication network that support lifeline sustainment may be also destroyed by the disaster, such as the flood and the earthquake. On the one hand, the large-scale rescuing and transportation vehicles may cause congestion. On the other hand, it is unreachable to allocate the restoration materials reasonably if there is not real-time communication in the disaster area.

3. EVs' proportion increasement

With the fast proportion increasement of EVs on the transportation network, the exploration of EVs to improve the resilience performance of power grid should be conducted further. Specially, the bidirectional charge property providing electric power back to the grid can be achieved both at home and at the charge station, which should be optimized for different targets and through different strategies. When EVs are treated as the distributed generators, the optimal route planning is needed since the power in the battery used for transportation is necessary. Moreover, the fuel availability for PHEVs to increase the power supplement for power resilience in island mode should also be considered.

4. Inter-disciplinary techniques

To achieve the best power grid resilience performance facing with the natural disasters, it is not enough if only power system technology is employed due to the complexity of this issue. The researchers in the communities of statistics, optimization, control, communication, hydraulic, and policy can make contribution to this issue. For example, the proposed strategies to deal with the pre-disaster mobile power resources allocation with too many constraints may lead to no solution and the dynamics model should be considered.

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