Research on Resilience of Power Systems Under Natural Disasters—A Review

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***Abstract*—Natural disasters can cause large blackouts. Research into natural disaster impacts on electric power systems is emerging to understand the causes of the blackouts, explore ways to prepare and harden the grid, and increase the resilience of the power grid under such events. At the same time, new technologies such as smart grid, micro grid, and wide area monitoring applications could increase situational awareness as well as enable faster restoration of the system. This paper aims to consolidate and review the progress of the research field towards methods and tools of forecasting natural disaster related power system disturbances, hardening and pre-storm operations, and restoration models. Challenges and future research opportunities are also presented in the paper.**

***Index Terms*—Blackout restoration, natural disasters, power systems operation.**

I. Introduction

SECURE and reliable electric power grid operation is important to social wellbeing. Recent years have seen many blackouts due to natural disasters such as the 2005 Hurricane Katrina blackouts, 2011 Japan Earthquake blackouts, and 2012 Hurricane Sandy blackouts. Between 2003 and 2012, roughly 679 power outages, each affecting at least 50 000 customers, occurred due to weather events in the U.S. [1]. Hines *et al.* [2] describes 933 events causing outages from the years 1984 to 2006, and the data is presented in Table I.[1] The study of natural disaster impacts on power grid can be traced back to the 1930s, when the 1938 New England Hurricane struck the Boston Area [3]. In the last decades, there has been considerable progress in advancing methods for analyzing natural disaster-related issues in power systems. At the same time, due to the complexity of the issue and its interdisciplinary nature, research activities are conducted sparsely across different domains. We summarize the natural disaster characteristics based on multiple sources such as [2] and [4] in Table II. The research on the issue of natural disasters on power systems can therefore be viewed in different aspects. To define the scope of this paper, we first summarize the timeline of the response in the electric grid under natural disasters in Fig. 1.

TABLE I
LARGE BLACKOUTS CAUSES IN THE UNITED STATES [2]

Cause	% of events	Mean size in MW	Mean size in customers
Earthquake	0.8	1,408	375,900
Tornado	2.8	367	115,439
Hurricane/tropical storm	4.2	1,309	782,695
Ice storm	5.0	1,152	343,448
Lightning	11.3	270	70,944
Wind/rain	14.8	793	185,199
Other cold weather	5.5	542	150,255
Fire	5.2	431	111,244
Intentional attack	1.6	340	24,572
Supply shortage	5.3	341	138,957
Other external cause	4.8	710	246,071
Equipment failure	29.7	379	57,140
Operator error	10.1	489	105,322
Voltage reduction	7.7	153	212,900
Volunteer reduction	5.9	190	134,543

Paralleling the issues illustrated in Fig. 1, we review the forecast models that are used to estimate the power outages as well as the asset damages; the corrective actions and emergency response, hardening and pre-storm preparation models; and the restoration models that organize activities happening during or after the occurrence of the natural disasters. The scope of this paper does not consider meteorological or geographical analyses of the natural disasters. While some traditional planning, operation, and restoration issues are discussed in the literature, we try to select and discuss the models and methods that could be applicable and relevant to natural disaster scenarios. The references we review are mainly academic, especially in forecast models and restoration techniques. On current hardening practices, some of the references are from industry. The models, methodologies, and frameworks we review could be applied with no geographical restrictions. However, the examples shown in this paper are mostly U.S. concentrated.

The remainder of this paper is divided as follows. Section II reviews the forecast models. Section III describes the experiences and practices for corrective actions, storm

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[1]The totals are greater than 100% because some events fall into multiple initiating-event categories.

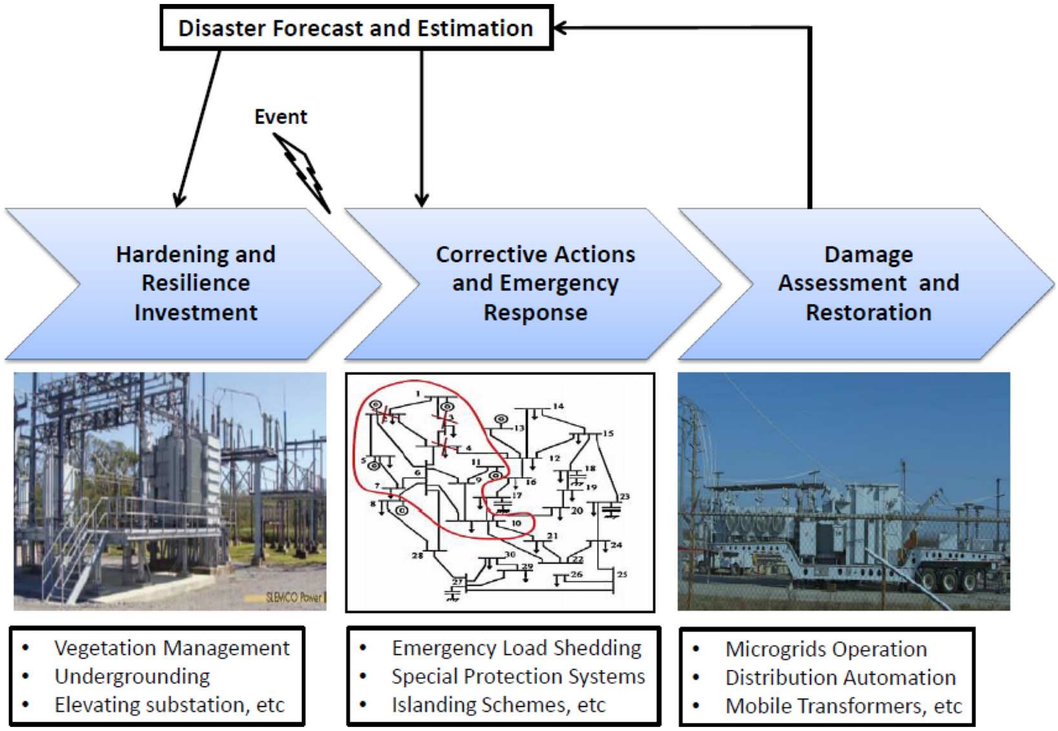

Fig. 1. Timeline of the response in electric grid under natural disasters.

TABLE II
ILLUSTRATION OF DISASTER CHARACTERISTICS BASED ON MULTIPLE SOURCES

Type	Impact Region	Predictability	Span/area	Affecting time
Hurricane, tropical storm	Coastal regions	24-72 hours, moderate to good	Large (radius up to 1,000 miles)	Hours to days
Tornado	Inland plains	0-2 hours, bad to moderate	Small (radius up to 5 miles)	Minutes to hours
Blizzard, Ice Storm	High latitude regions	24-72 hours, moderate to good	large, up to 1,000 miles	Hours to days
Earthquake	Regions on fault lines	Seconds to minutes, bad	Small to large	Minutes to days (after-shock)
Tsunami	Coastal regions	Minutes to hours, moderate	Small to large	Minutes to hours
Drought, Wild Fire	Inland regions	Days, good	Medium to large	Days to months

hardening programs, and pre-storm preparation activities. Section IV discusses the models used to advance restoration processes. Section V provides challenges and suggestions for future work in the area of natural disaster impacts on power systems.

II. FORECAST MODELS

A. Statistical Models

A range of models have been proposed in the literature to model power system damage, outage duration, and restoration after natural disasters [4]–[8]. Most of the proposed methods, however, rely on damage assessments made after the occurrence of the extreme events [9], [10]. In this section, we discuss some of the frequently used datasets, models, and validation methods.[2]

1) Data and Parameters: Many factors influence the susceptibility of electric power systems in a given geographic area to outages during natural disasters. Data required for statistical models can be divided into two categories, namely power system data and environmental data. The power system data usually includes the location and number of the customers, topology of the system, availability of the protection devices, etc. The Transmission Availability Data System (TADS) managed by North American Electric Reliability Corporation (NERC) as well as its outage reports have collected outage data in a common format for U.S. transmission systems [12]. Other reports [13], [14] also provide some aggregated data for natural disasters.

Environmental data may vary with the disaster scenarios. Examples of such parameters as well as the possible source are listed as follows:

- land and geometric characteristics of the area such as land use and land cover data, soil moisture levels, elevation characteristics, land slopes, and compound topographic index [15], [16];

[2]Most of the existing models emphasize finding the explanatory factors in power outages. While these factors and models could be used in both long-term hardening suggestions and short-term forecasting before the natural disasters, the online applications of short-term forecasting are challenging due to the difficulties to obtain updates and validate real-time data. At the same time, different models stated in this paper may suit some purposes better than the others. One example of the online prediction framework can be found in [11].

- disaster variables such as hurricane duration and intensity, approaching angle, landfall position, translation velocity, etc. [17];
- climatic characteristics, such as standardized precipitation index (SPI), annual and monthly precipitation [18].

2) Data Fitting Models: Generalized linear models (GLM): GLM has been used in [4] and [8] to estimate the storm damage to power systems and the effects of tree trimming programs on power systems resilience under hurricanes. For example, [8] uses a negative binomial GLM to model power system failures, represented by (1) and (2):

$$f_Y(y|\alpha,\lambda) \sim \frac{\Gamma(y_i+\alpha)}{\Gamma(y_i+1)\Gamma(\alpha^{-1})} \times \left(\frac{\alpha^{-1}}{\alpha^{-1}+\lambda_i}\right)^{\alpha^{-1}} \left(\frac{\lambda_i}{\alpha^{-1}+\lambda_i}\right), \quad (1)$$

$$log(\lambda_i) = \beta_0 + \sum_i \beta_i x_i \quad (2)$$

where the vector x_i represents the explanatory variables, the vector β is the regression parameters to be estimated, and α is the overdispersion parameter of the negative binomial distribution that is observed in power system performance data.

Generalized Additive Models (GAM): The structure of a GAM differs from the structure of a GLM only in how the parameters of the conditional distribution are related to the covariates. For example, the link function shown in (2) can be changed to (3) to represent a non-linear smoothing function:

$$log(\lambda_i) = \beta_0 + \sum_i s(x_i). \quad (3)$$

Accelerated failure time (AFT) models: AFT models have been used by [5] and [6] to estimate the power outage durations. The model relates the survival time to the explanatory variables through a linear relationship, as shown in (4):

$$ln(T_i) = X_t^T \beta + \sigma_i \quad (4)$$

where T_i is the survival time random variable, X_i is the vector of covariates, β is the vector of parameters, and σ_i is the vector errors that are assumed to be independently distributed. AFT is most typically fit using the method of maximum likelihood.

Tree Based Data Mining models (Classification And Regression Trees (CART) and Bayesian Additive Regression Trees (BART model)) [5]: CART are built by binary splitting of the data space into terminal nodes. In building regression trees, the best splits s are chosen such that the sum of squared errors (or least absolute deviation) within each node t is minimized. A BART model comprises a set of small trees with each tree constrained by a prior to restrict each tree's contribution to the final model, making each individual tree a "weak leaner". Fit and inference in BART are achieved through a Markov chain Monte Carlo algorithm.

Some other methods including Fuzzy Inference System (FIS) [19], Multivariate Adaptive Regression Splines method (MARS), and Cox Proportional Hazard models (COX PH) have also been used in the statistical forecast of the natural disaster impacts on power systems.

TABLE III
COMPARISON OF HOLDOUT MEAN ABSOLUTE ERRORS (MAEs)

Model	MAE
BART	11.5
CART	11.7
GLM	21.4
GAM	13.6
BART/CART	10.3
BART/CART/GAM	10.4
BART/CART/GAM/GLM	12.0
Prediction by the Mean	20.0

3) Measurement of Fitting Goodness and Example: A typical way to measure the fitting goodness of a certain model is to compare the prediction results with the observed data. The mean absolute error (MAE), mean absolute deviation (MAD), mean squared error (MSE), and root mean squared error (RMSE) are often used as metrics to this comparison.

An example of the model implementation can be found in [8], where model validation has been performed across four basic models, namely BART, CART, GLM, and GAM, as well as a combination of the methods to assess the pre-storm estimation of number of damaged poles in a distribution system. The variables used in the example include the parameters discussed in Section II-A1. The pole replacement data consisted of the number of poles that were replaced in 456 grid cells (12 000 feet by 8000 feet) due to damage in parts of Mississippi during Hurricane Katrina. There were 8698 total pole replacements in this data set with 2308 of these being poles owned by a telephone company but used by the power company and 6390 being poles owned by the power company. The Comparison of Holdout MAEs based on detailed pole-level damage data on the basis of 150 random pre-selected samples (or "holdout" samples) is provided in Table III.

B. Simulation Based Models

While most of the forecast models for power outages use statistical analysis, the accuracy of the estimates of the statistical approaches are critically dependent on 1) the appropriateness of the model used and 2) the sufficiency of the underlying data [5]. If an inappropriate or inappropriately developed model is used or if the data are insufficient to support the model development effort, the predictive accuracy of the statistical approach will be poor. At the same time, climate changes and other variances in natural occurrence could deviate the prediction results further from the future reality. Therefore, there is a value to understand the physical mechanisms of the damage, build simulation models that replicate the disaster occurrence and system response, and determine the proper preparation and hardening procedures.

One of the major causes of the equipment failures in natural disasters is due to the impacts of wind on transmission and distribution structures. There is a wide literature discussing the models and design of transmission and distribution structures subject to wind loading [20]–[24]. When designing transmission towers with conventional geometries and conductor arrangements, the engineer has some design codes and guides available [25]–[27].

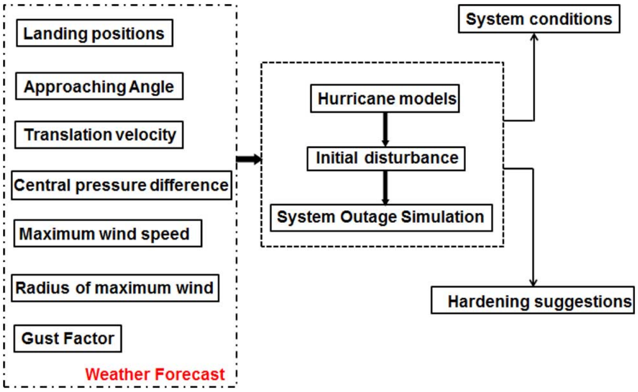

Fig. 2. Example simulation framework for hurricane outage forecast.

A simulation based approach to estimate the power outages or natural disaster related asset damages has been discussed in [28] and an illustration of the approach is shown in Fig. 2. The core of the framework is the simulator that consists of 1) hurricane models, which associates the weather forecast parameters with the estimation of local environment for each power system components; 2) a set of generated initial disturbance following the hurricane models[3]; 3) a system outage simulator (Cascading Outage Analyzer) that evaluates the system condition following the initial disturbances. The output of the simulator could be system conditions such as power outages and damaged assets, as well as a series of hardening suggestions that help utilities to identify critical assets.

Numerous hurricane, transmission failure, and outage models have been used in the previous research demonstrated in Fig. 2 [13], [28]. The simulation tool has the inputs of available weather forecast information, such as the landing positions, approaching angle, translation velocity, central pressure difference, maximum wind speed, and gust factor, to feed in to sample a failure rate-wind speed curve that generates the failed transmission line information as initial disturbances. This sampling processes can be replicated in a Monte Carlo simulation framework. The initial disturbances, i.e., a set of failed transmission lines, are used in a developed Cascading Outage Analyzer, to produce the outage data under such a forecasted scenario. The hardening decisions are made to upgrade the most frequently observed outage paths.

III. Corrective Actions, Hardening, and Resiliency Activities

We define the corrective actions and emergency response as actions that are deployed during and right after natural disasters. When the natural disaster happens, due to the severity and uncertainty of the event, few corrective actions and emergency response actions are currently being deployed by utilities. Several papers discuss traditional measures to prevent large scale blackouts due to “multiple contingencies”, which could potentially be used to help immediate natural disaster relief. Such activities may include deployment of Special Protection Schemes [29], [30] and Islanding Schemes [31], [32].

[3]Many transmission and distribution failure models are developed by the statistical models or observations discussed in Section II-A

TABLE IV
Power Grid Hardening and Resiliency Activities [33]

Hardening	Activities
Flood Protection	Elevating Substations/control rooms/pump stations Relocating/constructing new lines and facilities
Wind Protection	Upgrading damaged poles and structures Strengthening poles with guy wires Burying power lines underground
Modernization	Deploying sensors and control technology Installing asset databases/tools
Resiliency	**Activities**
General Readiness	Conducting preparedness planning & training Complying with inspection protocols Managing vegetation Participating in mutual assistance groups Purchasing/leasing mobile transformers & substations Procuring spare T&D equipment
Storm-Specific Readiness	Facilitating employee evacuation & reentry Securing emergency fuel contracts Supplying logistics to staging areas

According to the U.S. Department of Energy [33], hardening refers to physically changing the infrastructure to make it less susceptible to damage from extreme wind, flooding, or flying debris. Resiliency refers to the ability of an energy facility to recover quickly from damage to any of its components or to any of the external systems on which it depends. A summary of the existing practices to harden and increase resiliency of electric transmission and distribution system is shown in Table IV.

Among the activities, elevating substations, upgrading and under-grounding existing lines, and vegetation management are commonly used in current utility programs. We show some of the examples reported by the utilities in the following section.

Example 1: To prevent future flooding, as part of Southwest Louisiana Electric Membership Corporation's hardening plan, three substations that were flooded by Hurricanes Rita and Ike were elevated above the storm surge plus 5 feet, for a total of 13 feet above sea level. The cost of elevating the three substations was estimated at \$5.2 million [33].

Example 2: To upgrade and harden the T&D lines against high wind, the public utility council of Texas (PUCT) has recommended that all new and replacement transmission structures installed within 10 miles of the Texas coastline be designed to meet the current National Electric Safety Code (NESC) wind loading standards, assuming a maximum wind speed of 140 mph. For 2009, Tampa Electric budgeted \$10.7 million to replace 584 structures with steel or concrete poles, and 99 sets of insulators with polymer replacements [34]. Strengthening poles and towers by installing guy wires and upgrading crossarm materials is another common hardening method. Guying for extreme winds can cost \$1500–\$3100 per pole [33].

According to [35], the estimated cost for constructing underground transmission lines ranges from 4 to 14 times more expensive than overhead lines of the same voltage and same distance. For example, a new 138-kV overhead line costs approximately \$390 000 per mile as opposed to \$2 million per mile for underground (without the terminals) [35].

Tree trimming is also the primary way that trees near distribution lines are managed [36]. In 2006, NERC introduced the Transmission Vegetation Management Program (Standard FAC-003-1) [37]. There are a number of papers discussing the vegetation maintenance scheduling models and techniques of overhead lines [36], [38]–[41]. While these models do not directly consider natural disaster scenarios, they may be helpful for utilities to determine optimal strategy to allocate hardening resources.

Preparation of sufficient emergency generation units and blackstart units also plays a critical role in improving power grid resilience. Generation planning normally does not consider the benefit of providing blackstart capability and reduction of restoration time after natural disasters. However, optimal allocation of blackstart units and the restoration procedure has been discussed in [42] and [43]. Such planning activities could significantly reduce the system restoration time, thus enhancing the system resilience.

IV. Power System Restoration Techniques

After a power outage happens due to the damage from a natural disaster, the most important task for system operators is to restore the power system as quickly as possible to restore critical loads and minimize the economic loss to customers. In this section, we will first review the conventional power system restoration strategies and discuss new challenges for restoration from natural disasters. Then we will discuss two strategies to tackle these challenges, i.e., distributed generation and microgrids integration, and distribution automation with decentralized restoration.

A. Conventional Restoration Strategies

Power system restoration methods have been studied extensively in the literature [45], [44]. In general, the restoration process can be divided into three temporal stages: preparation, system restoration, and load restoration [46], [47]. In the first stage, the system status is assessed, initial cranking sources are identified and critical loads are located. During the second stage, the overall goal is reintegration of the bulk power network by designing an optimal generator start-up strategy utilizing black start (BS) and non-black start (NBS) units. Mathematical programming provides a powerful tool to tackle this problem, e.g., [42], [43]. In the third stage, the primary objective of restoration is to restore critical loads and minimize the unserved load, and the scheduling of load pickup will be based on the capabilities of available generators. This stage takes place after a part of the transmission system has been restored and electrical parameters such as frequency and voltage profiles have been stabilized. Several approaches and analytical tools have been developed for load restoration strategies such as: expert systems [48], [49], fuzzy logic [50], [51], heuristic approaches [52], [53], and mathematical programming [54]–[56]. With emerging smart grid technologies, a phasor measurement units (PMUs) based wide area monitoring system (WAMS) can enhance the information transmission as well as the system stability monitoring in the load restoration process [57].

TABLE V
Differences Between Typical Outages and Natural Disaster Related Outages

Typical Outages	Outages due to Natural Disasters
• Single fault due to one component failure	• Multiple faults due to catastrophic damage
• No stocastic feature involved in general analysis	• Uncertainty & stochasticity with the process of natural disasters
• No spatiotemporal correlation for the fault; fault happens randomly	• Spatiotemporal correlation for the faults due to natural disasters
• Most power generation units are working and stay connected	• Power generation units may be out of service
• Transmission & distribution network remain intact	• Transmission & distribution network are damaged and incomplete
• Only involve power grids infrastructure	• Have interdependence with other infrastructures
• Quickly repair and restore	• Difficult to repair and restore, e.g., debris after the disaster

However, power outages due to natural disasters have their unique features, which are different from those in typical outages, as shown in Table V. These features are highly related to the characteristics of the natural disasters. For example, a storm may topple trees at several locations that snap utility poles to cause multiple faults causing a wide spreading outage, and these locations are dependent on the path of the storm, while in a typical outage, usually only one random fault causes the outage. Some severe disasters can even damage the transmission network, substations, and generators to cause the outage such that conventional restoration methods may not work effectively. In addition, natural disasters may also destroy other infrastructures which are interdependent with power grids (e.g., transportation, communications, water) so that the restoration will face even more difficulties. In comparison, a typical power outage usually does not have such issues. In this sense, conventional power system restoration strategies, which are designed for typical outages, may have more challenges for the recovery from outages as a result of natural disasters.

To cope with these challenges, new techniques, such as distributed generation, microgrids, distribution automation, and decentralized restoration strategies, may provide promising solutions to enhance the resilience of the grids, which will be discussed in the following section. A few existing works have been done, e.g., using microgrids for system restoration after natural disasters, which will also be described.

B. DGs and Microgrids for Load Restoration

Generation availability is fundamental for all stages of power system restoration: stabilizing the system, establishing the transmission path, and picking up load [42]. As shown in Table V, the lack of power availability during outages due to natural disasters casts huge challenges for conventional restoration strategies, which are based on the condition that most power sources are working and stay connected. To cope with generation unavailability during and after the natural disaster, distributed generation units (DGs) can be utilized to enhance the grid resilience by improving generation availability (e.g., fuel cells, microturbines, wind turbines, photovoltaic panels) [58]. Furthermore, microgrids can be employed to efficiently manage these DGs as well as other resources to improve the restoration for natural

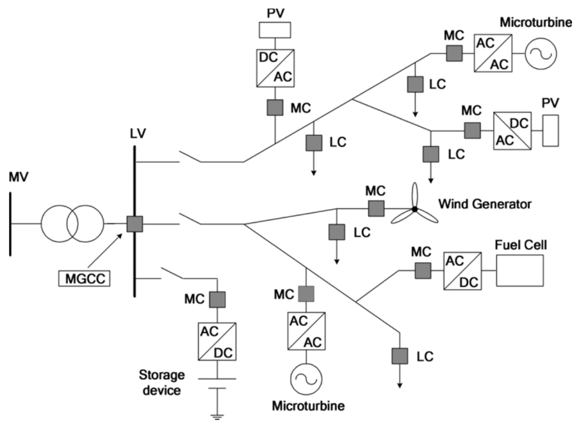

Fig. 3. Microgrid architecture comprising microsources, storage devices, loads, and control devices [59].

disasters. A microgrid is a small-scale power system typically on the medium- or low-voltage distribution feeder that includes distributed load and generation together with storage (e.g., flywheels, batteries) and protection devices, which are synchronized through an embedded management and control system [59]–[61]. Fig. 3 is a typical architecture of the microgrid that comprises different kinds of components [59].

A key fundamental difference of microgrids with respect to conventional grids is that microgrids add active network components (i.e., DGs) at the distribution level, which provide more operational flexibility and reduce conventional power grid vulnerabilities caused by centralized generation and control architecture and long distances between power sources and loads [62]. This feature is even more important for the power system restoration after natural disasters. In addition, the observed uneven damage distribution of the natural disaster on distribution systems increases the resilience when applying microgrids for load restoration, as the chances of all microgrids being damaged are very low [62]. In this sense, microgrids will enhance the power system restoration after the disastrous event. The value of microgrids to achieve grid resilience has been recognized, and they are being adopted by some state governments and industries, and their technical, regulatory, and financial barriers for implementations are being studied, e.g., [63], [64].

Microgrids are utilized in power system restoration in the following three ways, depending on how the microgrids can be used:

1) Microgrids Aiding the Conventional Load Restoration: In this scenario, the microgrids can serve as extra resource to enhance the conventional load restoration. This is especially useful for the area where no other suitable restoration path or source is available. In [65], the authors proposed graph-theoretic distribution system restoration strategy to embed the emerging microgrids that enhance the self-healing capability and allow the distribution system to recover faster in the event of an outage. The proposed method applies the spanning tree search algorithm to maximize the restored load and minimizes the number of switching operations without violations of operational constraints. The microgrids in the distribution system are modeled as virtual feeders. The authors in [66] present a mathematical model to utilize microgrids to alleviate the outage in the absence of suitable restoration path/source.

2) Microgrids Providing Resources for Bulk System Restoration: In this scenario, the microgrids operate in the grid-connected mode, and can provide ancillary services such as blackstart to the bulk system restoration. For example, the authors in [67] develop a stochastic mixed integer linear program to assess the impact of coordinating microgrids as a blackstart resource to the regional grid or regional transmission organization (RTO) after a natural disaster.

3) Microgrids in Island Mode for Load Restoration: In this scenario, the microgrids act in island mode in the event of disasters and serve critical loads like data center, hospital communities, and campuses by utilizing local generation and storage facilities. This operation mode requires special control for the frequency and voltage since no support is from the main grids. The power electronics inverters in this case act as voltage source inverter (VSI) to control the frequency and voltage [59]. In [68], the authors describe the sequence of actions for a microgrid central controller (MGCC) to perform service restoration, which is briefly described as the following steps: 1) sectionalize the microgrid around each microsource (MS) with BS capability; 2) build the low voltage (LV) network utilizing storage device; 3) synchronize small islands energized by MS; 4) connect the controllable lads to the LV network; 5) connect noncontrollable MS or MS without BS capability; 6) connect other loads; 7) change the control mode of MS inverters; and 8) synchronize the microgrid with the medium voltage network. In [69], the authors further propose a new distribution system architecture that allows the coordination among multiple microgrids for load restoration, and the corresponding sequence of actions are defined. Reference [70] discusses the role of electric vehicles (EVs) as grid-supporting units to take advantage of their storage capacity and charging flexibility in the microgrids restoration. In [71], the authors propose a microgrids formation scheme by utilizing the distributed generation to restore the critical loads after the natural disaster. Reference [72] proposes a self-healing strategy after natural disasters by sectionlization of the distribution system into microgrids. Other regional experiences such as shown in [73]–[75] can also be utilized.

These three functions for power system restoration can be integrated in the microgrid energy management system (EMS). In [76], the authors introduce the hierarchical control of the Illinois Institute of Technology (IIT) microgrid, in which primary control is based on droop characteristics of distributed energy resources for the sharing the microgrid load; secondary control performs corrective action to mitigate frequency and voltage errors introduced by droop control; tertiary control manages the flow between the microgrid and the utility grid and provides normal operation as well as emergency restoration services.

C. Advanced Distribution Automation Techniques and Decentralized Restoration Strategies

Current power distribution system are mostly with radial topology and limited number of line switches. However, to improve the reliability of distribution system, network topology with a large number remotely controlled automatic switches will be implemented [77]. With the Smart Grid Investment

Grant (SGIG) by the U.S. Department of Energy (DOE) under the American Recovery and Reinvestment Act of 2009, several utilities have installed a large number of remotely controlled switches to enhance the topology flexibility of the distribution system, so-called distribution automation [78]. These distribution automation pilot projects largely increase the reliability (e.g., System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI)) of the distribution system [78], by reducing the number of customers affected and the restoration time via the operation of these automatic switches. During the restoration after the natural disaster, distribution automation can be extremely helpful since several distribution lines may be destroyed due to the disaster. Reconfiguration of the topology of the network with remotely controlled switches provides opportunities to restore the outaged loads more quickly. This flexibility can also enhance the integration of distributed generation and storage, i.e., microgrids, into the distribution system for restoration. The authors in [58] propose a method for integration of large scale of distributed generation into power system restoration by utilizing the fully implementation of remotely controlled switches.

Generally, the approaches to study service restoration in distribution system can be roughly grouped into two categories: centralized methods and distributed methods [79]. The centralized methods normally depend on a powerful central facility to handle large amount of data with high communication capability requirement. This dependency is not suitable for next-generation resilient distribution system in two aspects. Firstly, large amount of remotely controlled devices installed in the system would be an extensive burden on computation and communication will exert on the central controller. Secondly, the centralized strategy is prone to a single-point-of-failure of the central controller, especially in the scenario of the natural disaster. In this sense, decentralized power system restoration strategies are needed to achieve grid resilience.

Several decentralized methods have been proposed for the power system restoration in the literature, e.g., [80]–[84], and they are based on multi-agent coordination schemes. In [80], a multi-agent system for load restoration is proposed, where description of the types of agents and their behaviors to exchange information and determine a feasible restoration path is specified. The authors in [82] propose a distributed information discovery process for load restoration applying the average consensus algorithm, in which agents only communicate with their direct neighbors. In [81], the authors propose a distributed algorithm for service restoration with distributed energy storage support following fault detection, location and isolation, as well as load restoration. The authors in [83] present a conceptual multi-agent system design for autonomous bulk power system restoration. A dynamic team forming mechanism was proposed for agent coordination purposes. The authors in [84] propose a cooperative two-layer multi-agent system to locate and isolate faults and decide and implement the switch operations to restore the out-of-service loads. Besides these research works, the decentralized methods have already been implemented in some distribution automation products, e.g., [85], [86]. With the decentralized methods, these remotely controlled automatic switch devices of distribution automation can, in principle, achieve more resilient power system restoration scheme to mitigate the impact of natural disasters on customers.

V. Conclusion and Future Research Directions

This paper reviews the state-of-the-art of the impacts of natural disasters on power systems, and how the advanced smart grid technologies can be utilized to enhance the grid resilience. Due to the complexity of the issue, it involves interdisciplinary techniques such as statistics, meteorology, power engineering, optimization, communication and control, as well as policies and regulations. Based on the review, we observe several challenges and opportunities in future research, and this paper lists three of them which we think are important.

A. Natural Disaster Impact Forecast, Hardening, and Resilience Optimization

There lacks a clear link from the modeling of damages/outages to the future prediction and hardening guidance. The statistical methods described in Section II-A heavily rely on the information that is localized (meaning heavily associated with the local geographies and power system structure) and subject to a specific event. Such case-dependent variance and uncertainty prevent the use of the model for future predictions. At the same time, the statistical methods do not look into the mechanisms of the development process of the blackouts/damages. Simulation based models may be able to provide more insights into causes of outages. But they are substantially more complex when detailed power system transmission and distribution information, as well as the other factors (e.g., vegetation information, accurate wind forecast, etc.) are required. Such requirements may be hard to obtain, and subject to uncertainties.

Future research on forecast models is needed in two direction: 1) Enhancing the accuracy of the forecast by developing new statistical and simulation based models. This may require more data analytical models to be incorporated, as well as more open source data to be provided by the utilities. 2) Establishing models that link the forecast and the hardening investment guidance. For example, [13] provides some insights on the cost-benefit analysis of the infrastructure upgrades based on increasing NESC standard requirements. Such analysis may also be used in other types of hardening techniques, guided by the more accurate statistical and simulation models.

When designing the hardening and resilience programs, utilities typically do not use systematic and rigorous optimization techniques. A common way of deploying the investment is to upgrade the previously damaged facilities, or choose certain techniques based on experience. Therefore, the identification and allocation of the budget may not be the most efficient. More research on how to optimize the hardening program investments could potentially save a large amount of money, as well as increase the resilience of the program. Some optimization methods and applications in the conventional power system research, such as [36], [38]–[41], and [87] may be a helpful starting point.

B. Interdependence Among Different Infrastructures

As discussed in Table V, during a natural disaster, the resilience of the power system does not solely depend on the infrastructure of the power grids, but is also related to other infrastructures such as communication network, natural gas pipelines, transportation network, etc. For example, distributed generation such as internal combustion engine generator or microturbines will not work if the fuel or natural gas availability (also called lifeline infrastructures [62]) are destroyed by the natural disaster. To achieve a resilient power system, these lifeline infrastructures should be considered in the overall planning and operation before and after the natural disaster.

To do so, the impacts of lifeline infrastructures on the power system regarding the natural disaster need to be analyzed first. Several papers in the literature have already analyzed the interdependence between the power grids and natural gas infrastructure in the normal operation [88], [89]; however, the extension of these interdependence analyses from a resilience perspective has not been well studied. The co-simulation framework for the interdependent infrastructure is useful to evaluate the correlation between them. For example, based on the assessment, the optimization problem for planning of the infrastructure considering these dependencies can be formulated, in which the uncertainty of the infrastructure subject to the natural disaster can be integrated using stochastic or robust optimization techniques. At the operation level, optimal strategies utilizing the flexibility of the infrastructure (e.g., reconfiguration of network topology, demand response, distributed energy storage) can be designed using optimization techniques.

C. Operation and Control for Power System Restoration With DGs, Microgrids, and Distribution Automation

Integrating microgrids and distribution automation provide potential to improve the restoration process of the power system; however, challenges exist on the operation and control of the distributed generation and the remotely controlled switch devices to achieve the restoration goal while maintaining the frequency and voltage profile of the distribution system, especially in the island mode of the microgrids. During the disaster, the distributed generation and the remotely controlled switches may also be fully or partially damaged, so operation and control under this stringent condition need to be considered.

Advances in distributed optimization techniques [90] can be utilized to design the decentralized restoration scheme which is suitable for the natural disaster scenario. The impact of the device failure can be analyzed based on this decentralized framework which serves as the tertiary control level. The coordination between this scheme and primary and secondary control scheme need to be investigated accordingly.

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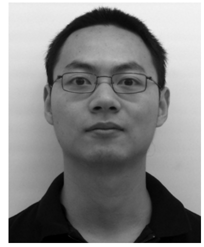

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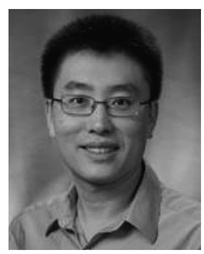

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