A Review on Resilience Studies in Active Distribution Systems

Dillip Kumar Mishra [a,*], Mojtaba Jabbari Ghadi [a], Ali Azizivahed [a], Li Li [a], Jiangfeng Zhang [b]

[a] School of Electrical and Data Engineering, University of Technology, Sydney, NSW 2007, Australia

[b] Department of Automotive Engineering, Clemson University, Greenville, SC 29607, United States

Abstract: The world has been experiencing natural disasters and man-made attacks on power system networks over the past few decades. These occurrences directly affect electricity infrastructures, thereby resulting in immense economic loss. The electric infrastructure is the backbone and one of the most essential components of human life. Thus, a resilient infrastructure must be constructed to cope with events of high-impact, low-possibility. Moreover, achieving resilience in the active distribution system (ADS) has been a vital research field of planning and operation of electric power systems. The incorporation of recent breakthrough technologies, such as micro- and smart grids, can make the distribution system become considerably resilient through planning-operation activities prior, during, and after an extreme event. This study offers the concepts premised on a systematic review of available literature by distinguishing characteristics between reliability and resiliency. Thereafter, the most relevant proceedings in conformity with an overview of the major blackouts, hardening and its guidelines, weather-related scenarios, taxonomies, and remedial actions are discussed. In addition, this research presents the planning, operational, and planning-operational attributes in response to catastrophes. Furthermore, a case study is conducted to support the review work, where the reliability and resilience of the ADS (IEEE 33-bus test system) are evaluated as performance indices with and without the addition of PV units. The performed research is laying out the importance of the distributed generation, such as PV, in the context of resilience, with the inclusion of different faults.

Keywords: Active distribution system (ADS), Planning-operational activities, Resilience.

Nomenclatures:

ADS: Active distribution system

BD: Benders-decomposition

DAD: Defender-attacker-defender

DS: Distribution system

DG: Distributed generation

DSO: Distribution system operator

ESS: Energy storage system

EDNS: Expected demand not served

IIDG: Inverter-interfaced distributed generator

LOLP: Loss of load probability

LP: Linear programming

MMC: Markov–Monte Carlo

MILP: Mixed-integer linear program

MINP: Mixed-integer non-linear program

MPC: Model predictive control

MIP: Mixed integer programming

MC: Monte Carlo

MG: Microgrid

MMGs: Multi Microgrids

NB: Naïve Bayes

OPF: Optimal power flow

PS: Power system

PSR: Power system resilience

R&D: Research and development

RESs: Renewable energy sources

SG: Smart grid

1. INTRODUCTION

1.1 Background study

In the new global economy, the modern power system has become essential owing to its reliable and efficient operation. Considering a huge investment is required to build an electrical infrastructure, the recovery cost is extremely high if this infrastructure collapses, which will directly impact the economy [1]. These philosophies can suitably deal with the acknowledged disruptive events in an entire power system infrastructure. Power system networks are designed under the N-1 security criteria to address unpredictable events [2, 3]. However, the increasing frequency of natural disasters and cyber-physical attacks has led to remarkable challenges to the electricity structure in the modern era [4]. This situation indicates a need to understand the various characteristics of the power outage in different environments. Over the past decade, the majority of the studies on power outage have emphasized the analysis of reliability and sustainability. To understand the reliability concept, two important factors that should be considered are adequacy and security [5, 6]. Adequacy refers to the uninterrupted power supply that will continuously provide *light on* facilities to end-users. Security is the capability to withstand unexpected disruptions, such as sudden power loss caused by component failure and bad weather [7]. Furthermore, the continuous exploration of enhancing a sustainable, safe, and robust power system has resulted in the continuous development of complex and large-scale power system networks [8]. The normal operation of a power system becomes abnormal due to unpredictable and turbulent conditions. Thus, system design may need extremely high safety provisions considering natural disasters and uncontrollable faults. However, only minimal attention has been provided to the concepts of robust systems in early planning stages that consider all probable failure modes. Consequently, increasing attention has been given to resilience study to withstand system complexities and unpredictable failure modes.

The word resilience originates from the Latin word *resilio*, which means to “spring back” [9]. The dictionary meaning indicates that this term refers to the capability to immediately recover from disruptive events. It identifies that extensive planning and operating level is taken to decrease the susceptibility to unexpected events. Although various definitions of “resilience” have been suggested, Holing et al. defined it as the perseverance of systems and their capability to resist, perturb, and uphold identical interactions among people and state variables [10]. The theories of resilience have enlightened significantly in various domains such as finance, engineering, socio-ecological, safety, and infrastructure [11, 12]. Hence, resilience could be hypothesized to refer to high-impact, low-possibility events. The main idea behind resilience theory is not merely to battle all-natural disasters but also to have immediate recovery operational measures. For low-probability and extreme events, the post-disruption stage is considered vital.

In the power system perspective, resilience is related to the capability to continuously maintain power supply even after highly disruptive events, such as a hurricane, tornado, tsunami, earthquake, and cyber-physical attack [13, 14]. Over the past decade, the majority of the studies on power systems have emphasized *reliability* and *resiliency*. Therefore, the current study aims to investigate the key issues of reliability and resiliency. Such essential factors like robust structures, cost-efficiency, reliable power supply, and smart networks can reconfigure a power system to be resilient and supply power to prosumers without any interruptions. For the first time, the UK Energy Research Center and Power Systems Engineering Research Center have defined resilience and distinguished it from reliability [15]. Furthermore, the UK Cabinet Office stated that resilience includes reliability and encompasses resistances, severance, restoration, and action [16]. In 2018, the US Federal Energy Regulatory Commission defined resilience in terms of the bulk power system as "The capability to endure, and curtail the degree of enormity and/or period of disruptive actions, which comprises the three main factors such as absorb, adapt and recover from natural disasters, manmade attacks, and severe technical faults" [17].

1.2 Resilience study

1.2.1. Reliability and resiliency

In the power system domain, reliability and resilience are two important factors that must be considered while designing a new structure or renovating an existing one. These two terms are often considered the same, but they differ in terms of probability and effect. Although extensive research has been conducted on these issues, considerable uncertainty remains related to their relationship. The main distinguishing characteristic between reliability and resiliency is, high-probability and low-impact, and low-probability, and high-impact events, respectively, as shown in Fig. 1 and other key aspects are highlighted in Table 1.

Table-1 Reliability versus resiliency characteristics

Key↓ Factor→	**Reliability**	**Resiliency**
Probability of faults	High	Low
Impacts of event	Low	High
Process or system	Static	Dynamic
Objective of concerns	Consumer interruption time	Consumer interruption time and infrastructure recovery time
Restoration time	Low	High
Number of faults	High	Low
Level of events predictability	High	Low
Targeted loads for restoration	All connected loads	Critical loads
Duration of power outages	Short duration	Long duration
Scenario	Controllable fault, overload, short circuit, maintenance.	Hurricane, earthquake, Tsunami, tornado, ice-storm, cyber-physical attack.
Level of predictability	Predictable	Un-predictable
Needed devices for compensation	Using FACTS, filter, solid-state transformer, load forecasting, smart grid	Robust design, mobile DG, more micro-grid (MG) formation, repair crews, black start capabilities, tree trimming, underground cables.
Performance evaluation indices	SAIFI, CAIFI, ENS, SAIDI, CAIDI	Need to be addressed.

Despite some studies that have been conducted with a minimal scientific understanding of the definition of resilience, the significance of this concept is broadly similar to the reliability. Therefore, the term resilience can refer to withstanding any extreme event, responding immediately to restore and adapt to unexpected events, and finally prevent future occurrences [18]. The four factors of resilience are illustrated in Fig. 2.

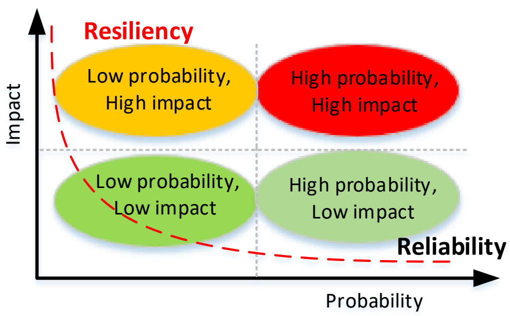


Fig. 1. Reliability versus Resiliency

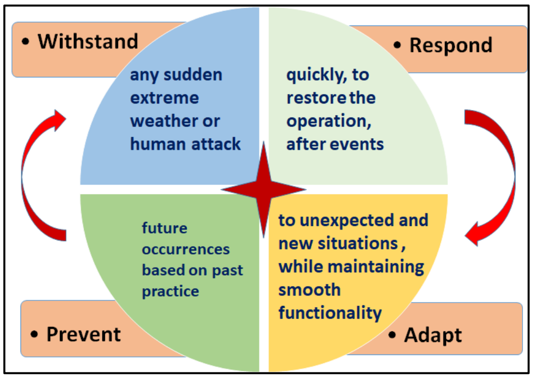


Fig. 2. Resilient system

1.2.2. Resilience characteristics

At present, research studies focusing specifically on the resilience curve is evidently lacking. Researchers draw an extensive range of sources and describe the different ways in which the resilience state can be obtained. Several studies have reported the resilience triangle, in which two different states are presented [19-21] and shown in Fig. 3. Furthermore, a systematic understanding of each stage of the resiliency operation and resilience trapezoid is studied in [15, 20, 22]. The resilience trapezoid is the detailed analysis of the resilience state during disruptive events through Phases I, II, and III. In Phase-I, the event hits the network, and the state goes to a disruptive phase. Emergency coordination is needed to survive the load demand in Phase-II. Lastly, restorative action can take place in Phase-III to reach the normal operation state. In Figs. 3 and 4, the authors of [20] present the two expressions in terms of robustness and rapidness. Robustness can be defined as permeable capability by measuring the least percentage of functionality. Rapidness refers to the capability to attain prioritized objectives in a given time frame to encompass threats and evade further disturbance. Thus, the resilience performance level can be estimated as a function of robustness and rapidness [20]. To enhance the resilience characteristics, corrective planning-operational measures are key areas that can facilitate the shifting of the resilience level with a short restoration time to reach a normal operating condition, as shown in Fig. 5. As can be seen in Fig. 5, phase-II, and phase-III are the response to the disaster and recover operation, respectively, showing improvement characteristics in terms of time duration and load recovery.

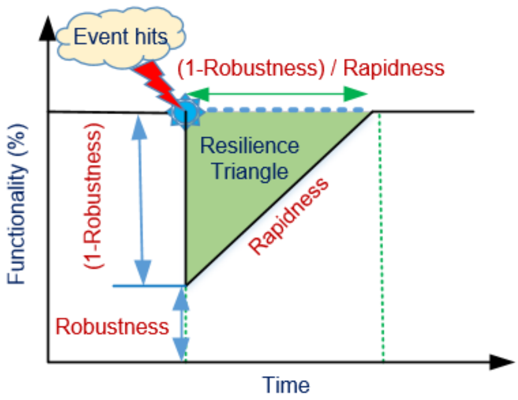


Fig. 3. Resilience triangle [20]

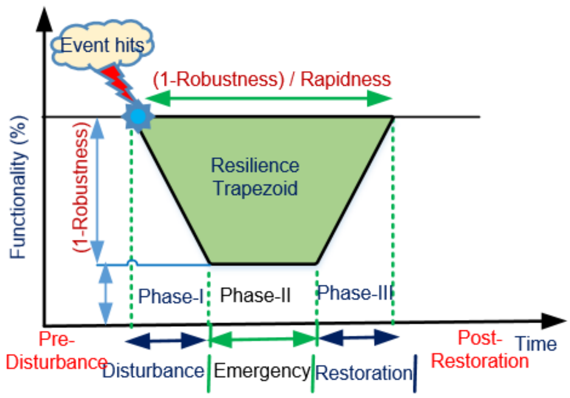


Fig. 4. Resilience trapezoid [20]

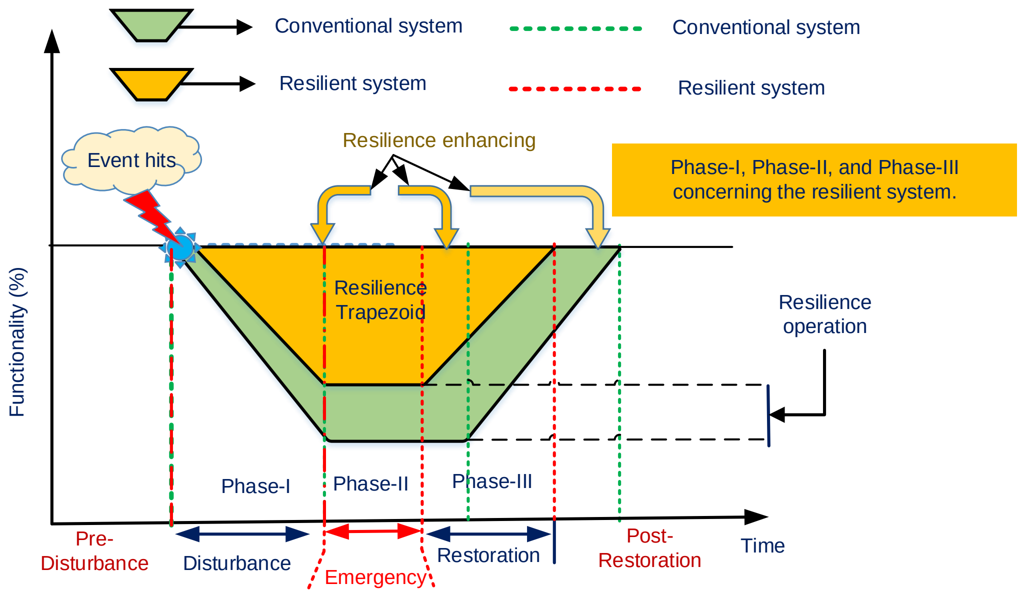


Fig. 5. Resilience performance curve

1.3 Highlights

The planning-operational movements of an active distribution system (ADS) in the power system resiliency context are the recently emerging areas for the short- and long-term improvements of electric infrastructures. A large number of studies have been undertaken to emphasize various distribution planning methods and operational measures to enhance the resilience characteristics of ADSs. The general architecture of the ADS is shown in Fig. 6. As the name suggests, ADS has distributed energy sources as a means of an active network that can manage the entire grid to improve the reliability of the distribution system.

The current study conducts a detailed review of the resilience study of ADS collected from the available literature. First, we summarize the overview of the various weather-related scenarios, hardening overview, various taxonomies, and future plans. Second, planning, operational, and planning-operational studies of resiliency are reviewed. Third, the major contributions, models used, and the objective function of reviewed papers are also presented in tabular form. Accordingly, readers may obtain knowledge from the following perspectives.

- What are the special planning schemes to enhance the resilience of distribution systems?
- What are the actions required to obtain the optimal operation of resiliency?
- What planning-operation frameworks and measures are required for the immediate recovery and response during/after an event?

The remainder of this paper is organized as follows. Section 2 outlines a summary of the different planning-operational reviews. The resilience-based ADS planning approaches and operational activities are presented in Section 3 and Section 4, respectively. Subsequently, the planning-operational based study is discussed in Section 5. Section 6 presents a resilience case study, and finally, Section 7 provides a conclusion.

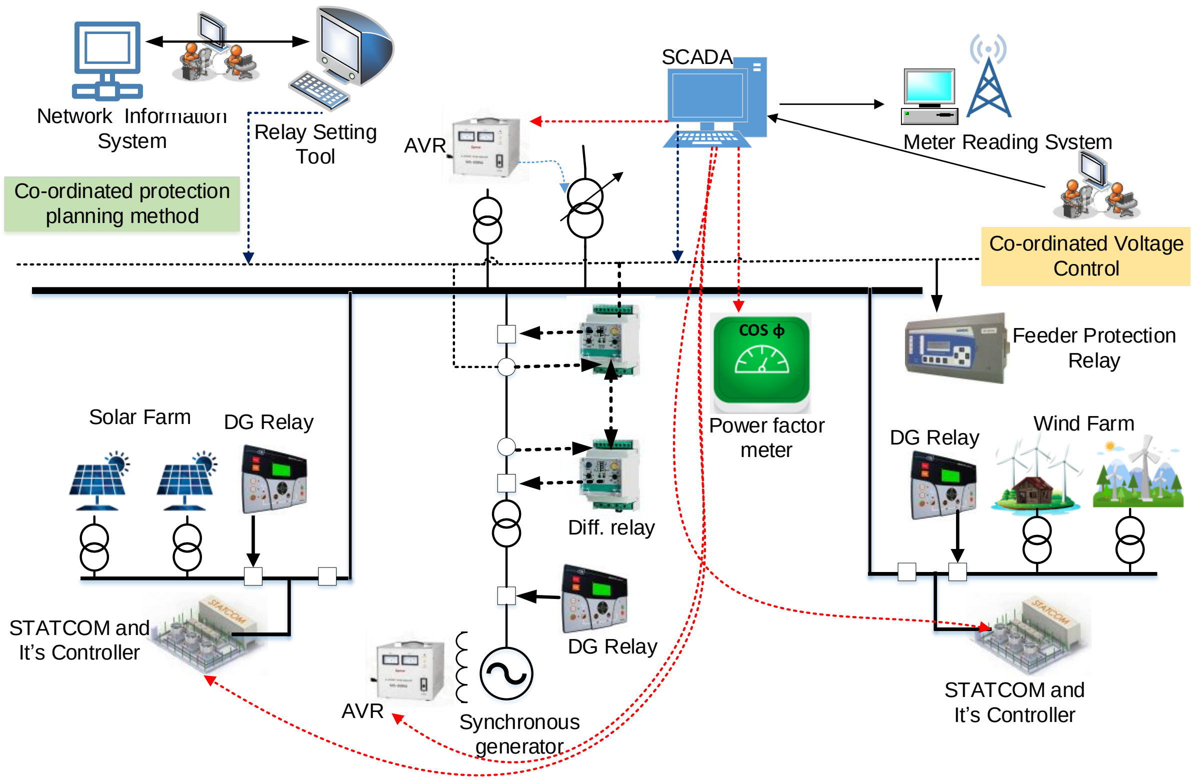


Fig. 6. Active distribution network

2. Overview

This section generally reports concerns with the overall vision of resilience in various contexts. Numerous studies have explored the factors influencing resilience [19, 23-26]. The probabilistic resilience study with different weather conditions is proposed in [24]. The application of artificial neural networks in the resilience analysis evolved to match load shedding in response to the failure probability with their load profiles is discussed in [25]. Substantial analysis and discussion of resilience metrics are presented in [23], which focus on endurance and recovery time. Subsequently, Ref. [26] proposes several resilience metrics considering past threat experiences and future probability of threats for a complex power system network.

Several possible solutions related to the resilience metrics are discussed in [27-29]. Moreover, Ref. [28] analyzes the resilience metric estimation of a dynamic power system considering energy storage devices, renewable energy sources, and demand-side management. The strategy of enhancing resiliency is presented in [29], which discusses the association between disaster organization members and critical infrastructure that is crucial in a power system. On the other hand, Ref. [27] reports the major limitations of the preliminary analysis considering the sustainability of low-income households. A clear understanding of the hardening measure and guiding principle for the migration of present DSs to MGs is presented in [30]. Retrospectively, the hardening and operational measures toward the distribution resiliency scheme are discussed in [31-33]. Meanwhile, Refs. [34] and [35] report the major power outages and their consequences worldwide and identified the improved strategy of DS resiliency against storms. Moreover, Refs. [36-40] investigate the differential study and remedial action in response to floods, storms, earthquakes, and other weather-related catastrophes. A future projected plan is outlined to indicate the subtle distinctions between reliable DSs and resilient grids. The benefits of each research and development (R&D) practices are also discussed in [1].

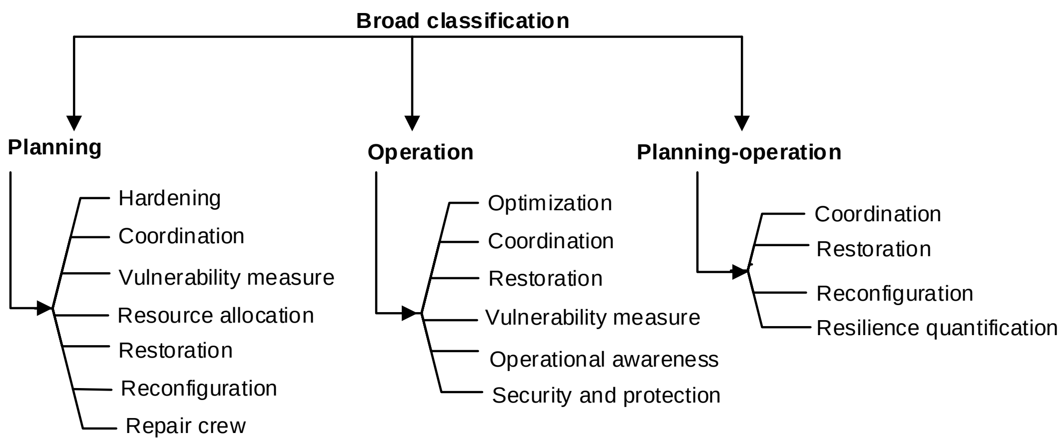


Fig. 7. Broad classification of a power distribution system in the resilience context

Moreover, Ref. [41] identifies major contributing factors for the defensive planning of DSs to enhance grid resiliency. A broad perspective is outlined in [42], which holds the view of cyber-physical attainment in the PS resilience context to address natural disasters. Energy regulators and infrastructure planning bodies are examined in [39, 43] to understand the climate adaptation strategy on resiliency. A recent study by [44] involves various classifications of resilience in the power system context. The contribution and the key area of the aforementioned literature are presented in Table-2, which mainly focuses on outage history, hardening plan, various taxonomies, and future perspectives. The study related to the planning-operational measure of ADS in resilience context is classified through various means, as categorized in Fig. 7. By following Fig. 7, the planning (Section 3), operational (Section 4), and planning-operational (Section 5) activities with the model used, and the main contributions are shown in Table 3, Table 4, and Table 5, respectively.

Table 2: An overview of the resilience factors from review literature

Category	Areas of study (Overview)	Contributions	Year	Ref.
Hardening overview	Hardening measure	Brief discussion of hardening measures for the metamorphosis of present DSs to future MGs	2007	[30]
	Hardening guidelines	Detailed discussion of distribution system resiliency in contrast with protection, hardening, guidelines, and innovations.	2010	[31]
	Hardening operation	Key area of distribution resiliency toward hardening, and operational measures.	2014	[32]
	Hardening enhancement strategy	Brief discussion of enhancement strategy by hardening and smartening power systems for improved resiliency characteristics.	2017	[33]
Blackout study	Blackout summary	Concise summary of blackouts against natural catastrophic events that lead to power outages.	2014	[34]
	Outages and impacts	Reporting major power outages worldwide and their impact on pole structure and also discussing robust pole structures to enhance potential actions in response to future storms.	2007	[35]
Weather-related study	Protection against flood	Reporting a flood-related study and remedial action from the perspective of substation protection.	2011	[36]
	Protection against storm	Listing various weather- and storm-related blackouts worldwide, their causes, and the corresponding remedial actions.	2012	[37]
	Protection against earthquakes	Outlining the study of power system resilience against earthquakes using a two-phase stochastic method.	2015	[38]
	Climate adaptation strategy	Providing an overview of the key function of microgrids and examining the resiliency among energy regulators and infrastructure planning bodies.	2017	[39]
Future projection	Grid transformation	Future development plan report toward reliable DSs to sustainable and resilient grids and the need for R&D.	2015	[1]
	Defensive planning of DSs	Presenting comprehensive planning to improve the resiliency of power systems against highly disruptive scenarios.	2015	[41]
Cyber-physical based study	DGs withstand against extreme events	Key concepts of PS resilience in terms of cyber-physical attainment to address unfavorable events and leveraging by DGs.	2016	[42]
Resilience framework and taxonomies	Energy infrastructure	Outlining the modeling framework of energy infrastructure regarding resilience outlook.	2019	[43]
	Classification	General understanding of resilience and its classification in the context of the power system.	2018	[44]

3. Resilience-based ADS planning approaches

Before the occurrence of unfavorable events, such as natural disasters and man-made attacks, some planning actions must be implemented in accordance with weather scenarios to prepare for and minimize the consequences of forthcoming catastrophes [45]. The step includes hardening, resource allocation, coordination, reconfiguration, restoration, and repair crew planning schemes for disastrous hazards and responses. Pre-planning strategy in ADS is significantly beneficial in minimizing the adverse effects of catastrophes [46], enhancing the effectiveness of network recovery, reducing the restoration cost, and improving the resilience of ADS. The summary of ADS planning methods is presented in Table 3.

3.1 Distribution system hardening

Hardening measures refer to physically improving electric infrastructure to minimize its vulnerability to interruptions. Among all the steps, hardening DS is one of the supreme effective plans to decrease the susceptibility of PS [47]. Hardening DS is generally implemented through undergrounding or strengthening the structure materials, such as poles, substations, and distribution lines. However, the hardening is expensive. Therefore, numerous studies have been conducted to make cost-effective hardening decisions. Meanwhile, Ref. [48] proposes the Benders–decomposition (BD) model with the worst-case interdiction study, which provides the hardening decision. The defender–attacker–defender (DAD) technique is introduced in [49] and used to withstand the critical infrastructure against man-made attacks, which shows that the DS component is susceptible to the attack until and unless hardened or protected. The modeling of the optimal and hardening-based MMG structures of DSs with reference to N–k events is explained in [50], where the BD method is used. The objective is to reduce the hardening cost of DSs. In [51], the reconfiguration planning and DG islanding mode are demonstrated through a tri-level DAD model. Through the DAD model, cost-effective hardening decisions with respect to the majority of dreadful attacks are presented. Thereafter, the distribution system operator (DSO), in addition to considering the uncertainties of renewable energies like wind [52, 53], solar [54], and etc., will execute all desirable remedial schedules to recover the DS after the attack happens [55, 56]. Overall, the preceding studies have revealed that hardening planning must be undertaken to minimize the power system damage.

3.2 Resilience based coordination of MGs

Coordination is one of the significant components of the DS planning stage. The main objective of this type of planning is to organize or manage the system through the improvement of control units (i.e., centralized or decentralized), improved fault detection, energy scheduling, power reserve, and interconnected MGs. A wide range of studies has described coordination planning as follows. A single and double bus partition-based DC MG is studied in [57], where authors mainly focus on components (for instance, during the drop-outs due to solar/wind sources) survivability through controlling the range of loads. In addition, energy exchange cost is considered as the objective function for minimization through a neighborhood optimization algorithm, while this resilience enhancement scheme shows the self-sustainability of DSs. In [58-61], a distinct test network is studied through centralized and decentralized MMG structure, considering flexibility, reliability, and resiliency. The purpose of the current study is to reduce the overall cost of DSs using a decentralized algorithm with a proper energy management strategy. A dynamic MG structure has been proposed in [62], which examines the self-healing strategy during unfavorable events considering DGs and random load change. One of the main concerns of the dynamic MGs is reliability maximization. Therefore, the power disturbance can be minimized even during and after the fault. Active multi-loop control with the design principle of MG has also been established to show the critical area of DSs, like optimal fault isolation, energy balance, and power quality improvement [63, 64]. An appropriate energy management scheduling of DSs can reduce costs and improve the resiliency through the dual-mode property, such as stand-alone and grid-connected mode; this concept has been examined and tested through an analytical model presented in [65]. Recent trends in DS planning have led to the proliferation of MG formation to withstand disruptive events and immediate restoration of facilities regarding critical load restoration [66]. The power reserve is one of the most intense requirements during disastrous events to manage power failure. In [67], a mixed-integer linear programming (MILP) method is employed to maintain the power balance in DSs. Thus, the coordination planning scheme particularly involves an energy management strategy during extreme events.

3.3 Vulnerability measures

The term vulnerability is related to instability or risk. System vulnerability can be defined as a system's inability to cope with a disturbing situation, restrict the impact, restore, and stabilize after the event [68]. Vulnerability depends on weather conditions, which often differ from one region to another, and the most critical events are identified as wind storms, lightning, and ice storm [69]. Moreover, the vulnerability analysis of PS using reliability and the hazard-based scheme is introduced on account of high voltage levels [70]. The consequence of extreme wind events in the DS is investigated with reliability indicators in [71].

In [72], different system conditions are analyzed, apart from weather-related conditions, and measured the reliability indices. A comparative analysis has been performed considering the risk studies from different states using quantitative reliability indices. The key purpose of [72] is to provide an optimal allocation of manpower and system components in ADS, which could be preferred for DS planning as preparedness and security measures based on weather forecasts. A sequential attack scenario-based study is proposed to identify the vulnerable nodes and point out the priority of removal for the robust system design, reduce the complexity of the network, and minimize power outage [73]. In [74], the DAD model is employed to improve grid survivability with the objective of minimal load shedding. Column–constraint generation-based algorithm is applied to provide the optimal solution for the protection planning of ADSs, which significantly enhances system resilience against terrorist attacks. In [75], a bi-level mathematical formulation is developed to identify the vulnerable components, where multiple attacks are applied with less computation time used, and consequently, the results show the improved reliability and resiliency response.

3.4 Resource allocation

During and after a catastrophic event, DS resources are generally restricted and difficult to supply because of the affected transportation link. Hence, the functioning of the system recovery action relies on available resources with good quality and surplus quantity[76]. Thus, pre-event resource allocation significantly affects the pro-activeness of system recovery and is a crucial phase in disaster promptness in DS. Several types of resource allocation are reviewed in [77], where three optimization paradigms are likewise discussed (e.g., tactical method and short- and long-term strategic frameworks). The framework in [77] can support the power system components to detect and dispatch mobile units and effectively recover from power outages. In [78], the triangulation model is applied to find the key issues influencing resource accessibility in post-event reconfiguration states. Moreover, various factors, such as rules, policy, regulations, and transfer, have been deliberated, which immensely influence the practicability and exertion of resource allocation. A combined simulation optimization method is explained in [79], which schedules an energy restoration network. Thereafter, the simulation-based model is introduced to assist emergency loads during high-disruptive events. This model also enables the disaster response-based system to maximize operational capacity [80]. Furthermore, a planning procedure using a proactive network decision enabling tool considering the unit commitment problem has been demonstrated to reduce the overall cost [81]. This solution can facilitate the reduction of the outage time, minimize the service interruption cost, and maximize the critical load supply in response to disasters or man-made attacks. Additionally, demand response units can perform a significant role in such situations, which have attracted less attention in this regard [82-85].

3.5 Restoration planning

Restoration planning is a crucial phase of a resilient power system. This phase is enacted when disaster hits the network (i.e., post-disruption stage), and a major blackout occurs, thereby resulting in damage to the distribution network. Therefore, immediate restorative actions should be planned by using resource allocation in ADS. The allocated resources are used to promptly restore emergency loads not supplied in the DS. However, a part of load restoration is served directly through allocated uninterrupted power supply facilities by DGs, MGs, and charging stations for recovery [86]. The critical issue of DS restoration has been investigated in numerous studies, particularly identifying the restoration order of loads after a system blackout [87]. In [79], a power restoration planning scheme is pioneered through an integrated simulation approach, which aims to reduce the workforce cost and minimize customer interruption time. Workforce planning is related to “right” repair crews in the “right” moment and “right” location to achieve the organizational goals [88].

A slow coherency theory is developed in [89] to minimize the power outage by the use of black-start capabilities of island operation to reduce transient oscillation. In [90], a novel key area in the restoration framework is defined through mixed-integer programming (MIP) to minimize load curtailment and maximize the functional capacity. Recent studies have examined the restoration planning methods in the form of transportable storage units with MG scheduling, specifically to respond to eventualities, reduce the interruption cost, and maximize the reliability of DSs [91].

3.6 Reconfiguration planning

In ADS, expansion planning extensively focuses on the efficiency, reliability, and financial sustainability of power transfer to prosumers [92, 93]. However, such a focus has predominantly been in the claim of disastrous events. Hence, reconfiguration planning related to resilience in response to natural disasters and man-made attacks has been considered an emerging research trend. In addition, the enhancement of resilience against disasters has become a key economic factor in reducing damage in power systems, recovery costs, and provide reliable power supply to the end-users, which is crucial for distribution planning. Several approaches are used to reconfigure DS in terms of new installation of power system components, such as energy storage units, on-site DG units, smart transformers, fault protection devices, and integration of renewable energies [94-96]. MMG formation is also part of the reconfiguration phase. In [97], an energy storage-based grid reconfiguration of ADS is proposed, with voltage magnitude deviance as objective function through the BD model. Moreover, Ref. [97] concludes that infrastructure deployment and grid reinforcement should be developed for optimal operation. In [98], a two-phase reconfiguration planning framework is established through MMG formation to achieve a resilient structure. Moreover, the aforementioned research has shown that resilience quantification can benefit planning engineers to validate control actions, relate various reconfiguration techniques, and improve effective control actions to evade blackout in response to extreme weather conditions. A probabilistic framework for ADSs to achieve a resilience structure based on on-site generation premises, such as solar and wind generation, is demonstrated in [99]. Its objective is to enhance grid survivability against unfavorable events and accelerate the restoration period.

3.7 Repair crew planning

Repair crew planning in ADS can enhance system reliability during and after disastrous events. Various factors are considered in crew planning, such as immediate crew actions, decreasing failure rates, and specific protective measures [100, 101]. For the planning stage, the deployment of the repair crew needs particular modeling of the maintenance practice in ADSs. For the maintenance endeavors, DS is divided into various regions or control zones, with each allocated to a repair crew [102], as shown in Fig. 8.

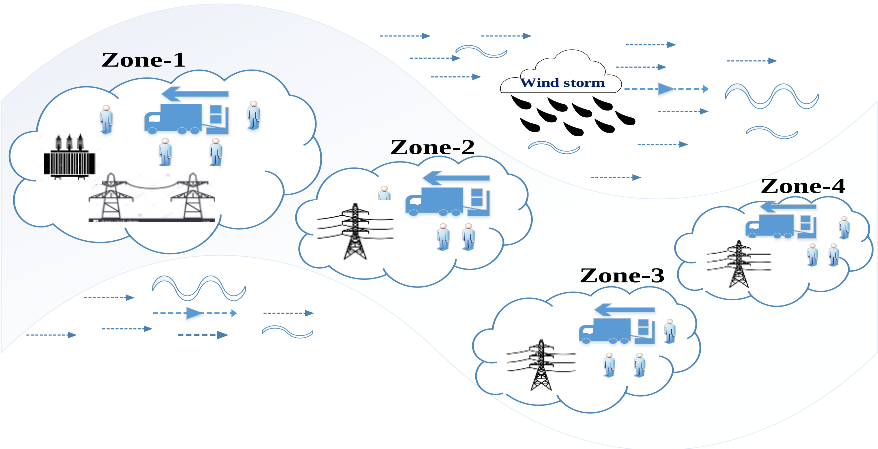


Fig. 8. Repair crew allocation

The repair crew resources include individuals, tools, spare parts, and trucks, which are important for the restoration of ADS. After an event, the crew starts the repair process in the order of maintenance received from control centers or distribution operators, and it can be done either manually (customer call) or automatically identifying the system failures.

Therefore, the repair process in each zone is a queuing process. Hence, the input is the sequence of element faults, which cause power disruptions that should be addressed by the crew. The output result is power restoration. This process depends on the quantitative and qualitative terms of the logistical resources from a system performance perspective. Such logistical resources are restricted and must be sensibly coordinated to follow the step of element failures to attain reasonable outage times. Traditionally, the repair process of ADS is not modeled. However, several studies have modeled the repair process with various procedures. In [103], a queuing theory-based repair model and stochastic point method are established to reduce outage time and maximize reliability. A synthetic model to optimally dispatch the crew in ADS is investigated in [104]. Short- and long-term tactical models have been demonstrated to give the optimal placement of crew during catastrophes [77].

Table 3: Resilience-based planning methods of ADSs

Area of Study	Contribution	Techniques/ Model	Objective function	Year	Ref
Hardening planning	Modeling of optimal hardening structure and MMG formation scheme of DSs on account of N–k events.	BD method with the iterative relaxation process	Hardening cost minimization	2017	[50]
	Reporting the enhancement scheme of DSs through reconfiguration planning and DG islanding with a tri-level DAD model.	DAD model	Load curtailment minimization	2018	[51]
Coordination planning	Introducing single and double bus partitioning-based DC microgrids to enhance the unit's survivability, self-sustainability, and control.	Neighborhood optimization	Energy exchange cost minimization	2014	[57]
	Contrasting a case study of centralized and de-centralized control-based MMGs to show adaptability, suitability, reliability, and resiliency of the grid.	Decentralized Algorithm	Overall cost minimization	2015	[58]
	Outlining a brief discussion of a centralized and decentralized model of two neighboring MGs and measuring the stability of MMGs.	Centralized and decentralized approach	Load curtailment minimization	2015	[59]
	Proposing a dynamic microgrid structure to enable the self-adequacy during extreme events considering stochastic load and distributed generations (DGs.)	MC method	Reliability maximization	2016	[62]
	Demonstrating the design principle and active multi-loop control of MG for good fault isolation, energy balance, and power quality management.	Analytical models	Power extract (peak power) maximization	2016	[63]
	Energy management scheduling of grid-connected and stand-alone modes, which points out the operation costs and resiliency.	Load shedding and ramp down techniques	Energy exchange cost minimization	2018	[65]
	Formulating the MG formation plan to quickly restore the critical load against extreme disruptions.	MILP	Load pickup maximization	2018	[66]
	Aiming to manage the power shortage during the events with the incorporation of power reserve facilities.	MILP	Load curtailment minimization	2019	[67]
Vulnerability measure	Demonstrating a vulnerability analysis to help operators make decisions, which enhances distribution reliability, security, and flexibility.	Considering various weather scenarios	Reliability maximization	2012	[72]
	Building a sequential attacking model and its resilience analysis in response to various attack scenarios.	Sequential attack procedure	Power outage minimization	2014	[73]
	Optimal solution with a sensible time toward the enhancement of grid survivability during unfavorable events.	DAD model	Grid disruption minimization	2014	[74]
	Addressing the plan on hardening measures and improving grid security in relation to the	Interdiction Algorithm	Cost minimization	2004	[75]

	identification of vulnerable components through IEEE reliability test system.				
Resource allocation planning	Introducing a simulation-based model to support critical loads in optimal DSs during catastrophic events.	Disaster-response network-enabled environment	Operational capacity maximization	2014	[80]
	Defining a proactive decision-enabling tool for the efficient restoration of DSs to minimize the overall cost incorporating with unit commitment challenge.	Stochastic linear-programming	Restoration cost minimization	2015	[81]
Restoration planning	Introducing workforce planning for outage management to minimize the cost and consumer interruption time.	Integer programming	Workforce cost minimization	2012	[79]
	Addressing the minimization strategy of blackout using black-start capabilities in responding to eventualities.	Slow coherency theory	Transient oscillation minimization	2012	[89]
	Defining a key area of the load restoration model to maximize the functional capacity of critical infrastructures.	MIP	Load curtailment minimization	2014	[90]
	Distinguishing the overall system cost and reliability between transportable storage systems and fixed storage units in MMGs.	MILP	Overall cost minimization	2019	[91]
Reconfiguration planning	Proposing grid reconfiguration planning of ADS by means of energy storage devices and aiming to reduce the cost and voltage deviation.	BD model	Total cost and energy storage installation cost minimization	2018	[97]
	Developed a two-phase reconfiguration planning model for MMGs to achieve a cost-effective and resilient structure.	Pre-location theory	Load pickup maximization	2016	[98]
	Establishing a probabilistic model of DS considering the integration of solar and wind energies to improve the survivability and reduce restoration period.	Moment-based design	Total cost minimization	2018	[99]
Repair crew planning	Demonstrating the disaster restoration logistic model considering repair crew and mobile storage into the location before and during events.	Co-optimization	Improve service restoration	2019	[101]
	The optimal designing of crew actions regarding failed units and the aims for reliability measures.	Queuing theory	Reliability maximization	2008	[103]
	Introducing a synthetic model for optimal dispatch of crews in ADS for service restoration.	Synthetic model	Unserved energy minimization	2019	[104]

4. Resilience-based ADS Operation

During unfavorable events, such as natural disasters or man-made attacks, operational activities should withstand and optimally coordinate system operation with minimal vulnerability and lowest restoration time. To obtain an improved understanding of the operational activities against catastrophes, various methods have been described, such as the optimal operation, coordinated operation, restoration, vulnerability measures, operational awareness, and software-defined actions. Moreover, in the case of operational activities during the events in the DS, these actions can extensively improve the resilience characteristics, which further re-establish the power system for the prosumers. The operational activities of the ADS operation considering the resilience are discussed as follows and the summary of this section is presented in Table 4.

4.1 Optimal operation

The optimal operation of DS has a significant impact on the overall cost, which is in the form of operational cost minimization during the events. Optimal operation preferably manages the load demand and generation balance to meet the continuity of the supply for the prosumers and particularly for emergency loads. Moreover, this operation includes unit commitment, generation scheduling, optimal dispatch, and optimization algorithms. A large and growing body of research has investigated this area. In [105], a scheduling model of MG to ascertain self-sustainability during the events through a feasible islanding method is demonstrated. In recent years, a proactive scheduling and stochastic programming based optimal power flow (OPF) model has been established through a load curtailment minimization approach during events [106].

Moreover, this model considers the renewable sources to highlight socio-economic benefits. In [107], a proactive operation scheme has been developed through a Markov process to minimize the probability of failure against extreme events. In this regard, MG-based studies have been presented, which mainly focuses on operation cost minimization through a hierarchical control scheme [108], graph theory [109], linear programming (LP) [110], and robust optimization [111] in response to various catastrophes. The optimal operation method by means of a voltage and frequency minimization model is also demonstrated to improve system stability and resiliency [112].

4.2 Coordinated operation

In the case of operational actions, the coordination activity plays a key role in managing the power system operation through centralized/decentralized control practice, grid-connected/stand-alone mode[113], single-/multi-agent approach, and the integration of RESs [114]. In [115-118], the decentralized control based operation is established to minimize the operation cost of interconnected MGs. The same primitive cost minimization technique is applied using mixed-integer bi-level programming, considering the MMG structure [119], a consensus algorithm for self-healing operation [120], MIP for proper coordination between MGs [121], and robust optimization for islanding feasibility and proactive operation in [122, 123], respectively. To ensure the power supply to the critical or emergency loads, a priority load maximization model is introduced in [120, 124-126] through an agent and linear programming methods by means of MG and MMGs. To extend the service continuity to emergency and non-emergency loads, load curtailment minimization techniques are pioneered through a Markov–Monte Carlo (MMC) model [7], and a fuzzy logic control technique [127] considering the MMG formation. Furthermore, a recovery model is established to minimize the power outage duration in response to highly disruptive events [128]. A probability model is formulated in [129] through the Naïve Bayes technique for the maximization of forecast probability by means of MG energy management strategy. In spite of all these methods, the coordinated operation is also concerned with power system stability, which is discussed in [130, 131], and demonstrates the multi-agent-based DSs through active energy-sharing units. A reliability assessment concerning various outage management schemes is generalized in [132]. Note that these operational activities can enhance resilience characteristics through proper coordination.

4.3 Restoration operation

The resilient operation, particularly during the restoration period, is essential to minimize power outages during highly disruptive events. Several extensive cross-sectional studies of therapeutic actions have been conducted for rapid and optimal system recovery. In the restoration phase, the maximization of a list of priority loads is a major concern, which is formulated through different algorithms, such as mixed-integer non-linear programming (MINP) [133-135] and linearized distribution flow model [136, 137]. The list of priority loads considers the optimal switching operation and MMG formation against natural disasters. Furthermore, the list of priority loads is used to stabilize dynamic performances with different fault scenarios during restoration [138].

An optimal dispatching model considering the storage units and DGs is introduced in [134], which mainly focuses on the maximization of restored energy through MINP. A defensive islanding procedure has been adopted to restore DS and minimize load shedding [139] immediately. In [140], crew member deployment with on-site generation unit dispatching schemes for service restoration is presented. To estimate the accessibility of MG for recovery, considering RESs, dispatchable DGs are reported in [141]. The energy cost should be minimized during the restoration phase. Therefore, [142] established an optimization model to maximize the energy capacity in response to extreme weather conditions.

4.4 Vulnerability measure

Power system failure means that an electric infrastructure sustained considerable damage, which directly impacts the socio-economic life of people. Thus, the vulnerability of the component and system must be analyzed to cope with any eventuality. Various studies have assessed performed vulnerability analysis to detect and address the infirmity of DSs to improve survivability and resilience. In [143], the graph theory-based model is used to measure the vulnerability of interdependent electric infrastructure. A machine learning algorithm is applied to predict the power outage and components' state for vulnerability measure evaluation in [144-146]. An outline of fundamental methods to assess the vulnerability in the power system is recently discussed in [147].

4.5 Operational awareness

Given the practical constraints of modern DSs, DSOs have to cope with various challenges to sustain reliable supply. Hence, establishing and updating a necessary situation awareness (SA) is a strategic factor in maintaining this reliability, although it is a complex process because of the various factors that regulate its formation in the energy control center. Therefore, operational awareness is definitely needed to support human operators. In [148], the Markov model is used to minimize the probability of man-made errors by enabling executive decisions in response to power outages. Similarly, advanced visualization procedures are applied in [149] to minimize the probability of failure using relevant alertness of power outages. The main concern of [148, 149] is to maintain system reliability through operational awareness activities.

4.6 Security and protection

The continually increasing installation of protection devices in DSs has prompted particular phase tripping orders at the distribution phase [150]. Accurate phase preference denotes the capability of protective relays to detect faulty phase(s). Conversely, many control algorithms have been developed to improve efficiency, reliability, and resiliency of the system. Therefore, the components and the entire system should be protected during the operation to significantly reduce outage duration and enhance DS resilience in response to catastrophes. In [151-153], a software-based network is discussed to maximize reliability and reduce the communication cost after considering the software enabling technology to reach a better and more secure control of DSs' operation. Moreover, an inverter interfaced-based algorithm is introduced and integrated with DGs to minimize fault current during the operation [154].

Furthermore, security against intentional attacks and redundancy have been programmed in [155] through the geometric progression rule to minimize the probability of destroying DSs. Moreover, a decision model also plays a vital role in the security and protection of DSs during the operation. Only [156, 157] have endeavored to study the protection employing a decision model to minimize the investment and operation costs against disruptive events.

Table 4: Operational study of ADS

Area of Study	Contribution	Techniques/ Model	Objective function	Year	Ref
Optimal operation of DSs	Introducing a scheduling model of hybrid MGs to ensure survivability during events by means of feasible islanding	–	Minimization of overall cost during events	2017	[105]
	Formulating the optimal power flow (OPF) during catastrophic events to reduce the adverse effects of flooding on DSs.	Proactive scheduling	Load curtailment minimization	2018	[106]
	Identifying the socioeconomic benefits of MMGs through a developed mathematical model incorporated with RESs and EVs in DSs	Stochastic programming	Minimization of load curtailment	2016	[158]
	Presenting proactive operation schemes of DSs to minimize load failure because of highly disruptive events.	Markov process and MINP	Probability of failure	2017	[107]
	Modelling and analysis of DC-MG to provide improved energy management capability and economic operation of DSs compared with AC-MG.	Hierarchical control scheme	Operation cost minimization	2014	[108]
	Utilizing graph theory-based methods for the optimal operation of MGs considering microturbine and ESSs and addressing the energy management strategy to operate DS in normal and self-healing modes	Graph theory	Minimization of operation cost	2017	[109]
	Developing an optimal energy management framework to minimize operational cost in the presence of ESSs	LP	Minimization of operation cost	2018	[110]
	Describing the imperative formulation of MG for optimal programming in response to islanding modes against extreme events	Robust optimization	Minimization of operation	2019	[111]
	Modelling and analysis of MG considering electric springs to enhance the stability of DSs against intermittent renewable sources	–	Voltage and frequency minimization	2018	[112]
Coordinated operation	Decentralizing controlled operation of MMGs through coordinated actions	Decentralized bi-level technique	Minimization of operation cost	2016	[115]
	Investigating the optimal and self-healing operation of MMGs via energy management techniques in a decentralized manner	-	Minimization of operation cost	2016	[116]
	Modelling of decentralized DSs, which comprise a non-linear assumption, capacity extension, N-1 security, and long-term operation	Decomposition algorithm	Minimization of operational and installation costs	2017	[117]
	Establishing a robust distributed regulation scheme to manage power flow considering STATCOM and ESSs	Distributed control scheme	Stability enhancement	2016	[118]

	Designing disruption as an event of intentional attacks on MMGs by taking the interconnection of electrical structures and natural gas into account	Mixed-integer bi-level linear programming	Minimization of operation cost	2015	[119]
	Proposing a dynamic formation of MGs to maintain power supply of emergency loads after an inevitable accident	MILP	Maximization of priority load	2016	[120]
	Proposing a generalized framework of outage management practices in MMGs for an appropriate coordination among MGs through MPC and DSO	MILP	Minimization of the overall cost	2016	[121]
	Presenting a scheduling model of MGs that took the islanding feasibility and survivability of emergency loads into account	Robust optimization	Minimization of operation cost	2019	[122]
	Offering deterministic techniques in response to fragility curves to achieve the proactive operation of DSs	Robust optimization	Minimization of operation cost	2019	[123]
	Reporting distributive MMGs to realize resilient autonomous power DSs using independent operation of MGs.	Agent algorithm	Maximization of priority load	2011	[124]
	Highlighting the benefits of MMGs for load restoration and coordination mechanism in consideration of intermittent loads and DGs	MILP	Maximization of priority load	2017	[125]
	Establishing an effective management strategy for MGs to withstand intense windstorms to protect vulnerable components	LP model	Maximization of priority load	2018	[126]
	Introducing a fuzzy logic control (FLC)-based model of MG considering ESS units, which follows the management commands for proper scheduling and operation in normal and non-normal conditions.	FLC	Minimization of load curtailment	2017	[127]
	Pioneering a three-phase MG recovery model after disruptive events to balance the DSs	Linear relaxation	Minimization of outage duration	2018	[128]
	Focusing an energy management strategy of MG on the basis of renewable energy prediction and battery state of charge (SOC).	NB model	Maximization of forecast probability	2016	[129]
	Pioneering regulated multi-agent-based DSs to stabilize frequency and voltage deviation through proportional active energy sharing units	Stochastic programming	Minimization of changes in voltage and frequency	2018	[130]
	Comprehensive architecture of MMGs for reliability assessment with various outage management tactics	MC model	Minimization of operation cost	2018	[132]
Restoration operation of DSs	Proposing a comprehensive mathematical model for load restoration by means of optimal switching operation in ADS	MINP	Maximization of priority load	2016	[133]
	Modelling of a resilient MG operation taking account of a master–slave-based DG application.	MINP	Maximization of priority load	2017	[134]

	Establishing dynamic MGs to provided uninterrupted supply to critical loads immediately after events hit the network	MINP	Maximization of priority load	2016	[135]
	Providing a detailed mathematical formulation of MMGs to restore critical loads during natural disasters	Linearized distribution low	Maximization of priority load	2017	[136]
	Providing an integrated solution on the basis of a decision-making tool to improve situational alertness and survivability	Generalized linear model	Maximization of priority load	2017	[137]
	Measuring the stability and dynamic performances of MGs in the process of restoration with regard to different fault states	LP model	Maximization of priority load	2018	[138]
	Developing an enhancement strategy of DSs through defensive islanding to address severe wind contingencies	Defensive islanding-algorithm	Minimization of load shedding	2016	[139]
	Exemplifying the repair crew and restoration operations of DSs after unfavorable events through multiple-vehicle and on-site generation to reduce recovery times	Randomized adaptive vehicle decomposition	Minimization of total outage	2012	[140]
	Describing a service restoration scheme incorporated with RESs, dispatchable DGs and ESSs and introduced a continuous operating time to estimate the accessibility of MG with limited source	MM	Minimization of load curtailment	2016	[141]
	Pioneering an optimization model of MGs to maximize energy capacity during an emergency in response to disruptive events	MM	Minimization of energy cost	2018	[142]
Vulnerability measure	Discussing two models, namely, network and functional, as interfaces to various DSs and performance evaluations correspondingly for measuring the vulnerability of bulk interdependent electrical infrastructures	Graph theory	Consequence measure with single/double/multiple faults	2010	[143]
	Presenting a predictive model of DSs to determine component states for vulnerability measures through the machine learning algorithm to address extreme incidents	Machine learning method	Outage prediction	2017	[144]
	Proposing an outage prediction paradigm through machine learning technique to identify vulnerable components against forthcoming hurricanes	Machine learning method	Outage prediction	2017	[145]
	Performing a vulnerability comparison analysis of two models to measure the effectiveness of DS operation under man-made attacks	Topological and betweenness basis models	Measuring power grid vulnerability with different attack intensity	2014	[146]

Operational awareness study	Providing a brief description of SA, man-made errors, operational decision enabling, and the MM for proactive SA in response to power system outages	MM	Minimizing the probability of man-made errors	2013	[148]
	Presenting a brief synopsis of relevant alertness of power outages and its main sources to provide operators with an efficient provision in maintaining system reliability	Advanced visualization procedures	Minimization of probability of failure data	2013	[149]
Security and protection	Maximizing software-based programming to enable the networks to identify and respond to failures and obstruction during the run period of MG operations.	Software-based network	Maximization of reliability	2017	[151]
	Presenting a software-enabled architecture for MG operations to utilize global perceptibility, programmability and enhanced controllability for security implications	Software-based network	Maximization of reliability	2016	[152]
	Presenting fast-powered reinforcement models between MMGs through a software-enabled algorithm to improve efficiency, reliability, flexibility, and resiliency	Software-based network	Minimization of communication cost	2018	[153]
	Formulating a new control algorithm for a fault protection	Inverter interface DG model	Minimization of fault current	2018	[154]
	Providing optimal solutions for resource allocation in view of redundancy and security against intentional threats	Geometric progression rule	Minimization of destruction probability	2015	[155]
	Designing a two-level stochastic model for DSs in response to hardening decisions against catastrophic consequences	Progressive hedging optimization	Minimization investment co	2016	[156]
	Formulating a resiliency-cut index to ensure survivability of emergency loads after events hit the network	Robust optimization	Minimization of operation cost	2018	[157]

5. Resilience-based ADS planning- operation

Distribution system planning-operation is an increasingly complex and information-intensive procedure. Thus, seeking for perceptibility across the continuum of power supply has expanded over intermittencies, update technology expenses, price signals, response sensitivities, and socioeconomic impact [159]. However, deployment and allocation of novel breakthrough technologies suffer from many issues that differ by means of technology and critical function in the power delivery system. The electricity power supply has been continuously and highly reliable since the last few decades because of enhanced expansion planning and uninterrupted power supply of DSs across the globe. In the event of natural disasters or other unfavorable occurrences, the operation of power systems may fail to achieve desired reliability. Hence, planning-operation schemes should consider a number of possible adverse events, which demands a more resilient electric infrastructure.

During these events, the planning-operation phases play crucial roles in disaster concerns, which require simultaneous resource and crew allocation, restoration, and coordinated planning-operation schemes to make some decisions about the optimal operation of the power system. It also facilitates the reduction of restoration time after low-power system damages. The study of these schemes is described as follows, and the summary of this section is presented in Table 5.

5.1 Coordination

In the resilience planning-operation procedures of DSs, coordination, which is also called energy management, plays a vital role. Changes experienced in energy management methods of DSs over the past decade have become unprecedented, thereby enhancing the resiliency of power systems. Various models have been employed to coordinate some components of the power systems in the planning-operational phases. In [160], a scenario decomposition-based algorithm is introduced to minimize power outage considering transportable on-site generation facilities in pursuance to installation and proper allocation before and during events. Moreover, the preparedness index is a major concern in the study of resilience against eventualities in enhancing the performance of DSs and minimizing load curtailment. Given these objectives, [161] established a linear approximation model to maximize the preparedness index through MMG in response to hurricane events. To maximize load pickup, Ref. [134] proposed a master-slave operation of DGs and crew routing. By contrast, Ref. [162] suggested a DG dispatch. However, MMG formation has been regarded recently as one of the key survival factors to resiliency, which is discussed in [163].

5.2 Restoration

In the restoration phase, planning can be implemented via the proper allocation of storage units and crew members, identifying vulnerable components and mobile generation units, and using islanding mode. These methods can restore the system immediately. Conversely, the same units are used in the operational phase during events to recover the system from low distribution system damage with minimal recovery time. Numerous studies have intended to explain the restoration planning-operation of DSs in view of resilience. In [164], a sectionalized MMG for the optimal operation of DSs is proposed to minimize costs during outages. The importance of sectionalized MMG is that it can cope with highly disruptive events and is capable of isolating the section individually when DSO predicts the consequences. To further discuss this concept, Ref. [165] proposed a deterministic and stochastic model to spring the DS back to normal operation after events. In [146], a network partitioning method is introduced to maintain continuity of electricity supply in the context of planning-operational movements. To maximize restored energy during events, a mathematical formulation has been developed through MINP, as presented in [166].

5.3 Reconfiguration

Reconfiguration is an increasingly important area in DS resilience because reconfiguration planning and rapid operation should be conducted during events to immediately address the outage. The majority of the current studies on reconfiguration particularly focus on minimizing the overall and life cycle costs. To enable the optimal operation of DSs during events, thermal stability and reliability are major factors that should be assessed, in which DSs should be designed and operated accordingly [167]. Apart from the aforementioned aspects, enhanced voltage profile, low power loss, and load adjusting should also be considered, as described in [168]; it introduced a power electronic-based module that re-establishes performance using a soft-open point framework. Note that the geometric progression rule is applied to minimize the destruction probability of DSs and address issues in redundancy and security against intentional threats [155].

5.4 Resilience quantification

To measure the performance of the DSs, resilience quantification plays a crucial role in decision making in the cases of load switching, DG allocation, and crew position. Accordingly, Ref. [169] concentrates on the distinctive metrics of resilience in the perspective of system design, extreme weather, and repair crew, which aims at maximization of sensitivity. In [170], a quantitative model for resilience estimation and preventive measures is developed in the face of windstorms. This model mainly aims to minimize the probability of failure. Furthermore, a multi-criteria-based decision-making model is pioneered through the graph and pre-location theory to reduce switching operations and maximize load operation [98]. One of the most significant discussions in the study on resilience quantification is that various quantifications can introduce a new resilience index, which can further improve reliability and resiliency characteristics.

Table 5: Planning-operational method of ADS

Area of study	Contributions	Techniques /Model	Objective function	Year	Ref
Coordination	Proposing a novel load restoration scheme of the MG to improve the reliability and resiliency of DSs through master-slave DGs during natural disasters	Mixed integer second order cone method	Maximization of critical load pickup	2017	[134]
	Establishing an optimal planning strategy for an emergency load restoration using transportable on-site generation facilities in accordance with pre-positioning and practical constraints to reduce outage during emergency operations	Scenario decomposition algorithm	Minimization of power outage	2018	[160]
	Presenting a multi-objective oriented architecture to enhance the effective preparedness of MMGs and cope with forthcoming hurricanes	Linear approximation model	Maximization of the preparedness index	2019	[161]
	Proposing a co-optimization model for crew routing, system reconfiguration, and DG dispatch to enrich the DSs from outage under disruptive events	MILP	Maximization of load pickup	2018	[162]
	Enhancing strategy of MMG formation for survival in extreme events in terms of critical service restoration.	MILP	Minimization of MG scale	2018	[163]
Restoration	Proposing the extensive structure of a distribution system via two modes of operation in relation to sectionalized MMGs for optimal restoration of an outage	Rolling-horizon algorithm	Minimization of operation cost and maximization of profit	2015	[164]
	Designing a deterministic and stochastic model of DSs on account of component failure during events and spring back to normal operation	Probabilistic and deterministic approach	Minimization of overall cost	2018	[165]
	Developing a successive service restoration model of DSs and MGs using DGs as well as formulating a mathematical power flow model	MINP	Maximization of total restored energy	2018	[166]
	Using network partition-based techniques for survival after a power disruption in terms of planning-operational movements	Network partition method	Minimization of restoration time	2018	[171]
Reconfiguration	Providing optimal solutions for resource allocation in view of redundancy and security against intentional threats	Geometric progression rule	Minimization of destruction probability	2015	[155]
	Addressing the thermal stability and reliability measure of wind-based plants with FACT functionality in MGs to provide optimal operation and better assessment of DSs.	Coffin–Manson model	Minimization of overall cost	2017	[167]

	Developing a network reconfiguration planning scheme with power electronic modules to enhance voltage profile, lessen power loss and adjust load during operation	Soft-open-points paradigm	Optimization of the life cycle cost	2016	[168]
Resilience quantification	Proposing new resilience metrics with corresponding estimation approach considering the system design, catastrophe, and repair crews	Dynamic Bayesian networks	Maximization of sensitivity	2018	[169]
	Introducing a quantitative model to estimate DS resilience and approach in preventive measures against windstorms.	Degradation model	Minimization of failure of probability	2019	[170]
	Introducing resilience quantification techniques through percolation theory and multi-criteria decision model using an analytical hierarchical procedure	Graph theory and percolation theory	Load maximization and switching operation minimization	2016	[98]

6. Case study

In this section, resilience studies are carried out and applied to an IEEE 33-bus system [172]. The findings from this study provide two contributions to the current literature, *i.e.*, firstly, without assuming the emergency load in Study-1; and secondly, with the consideration of emergency loads in Study-2 and Study-3. In this study, four different scenarios (such as no PV, with PV, considering PV power increase, and optimal allocation of PV units) are discussed. In contrast, Study-1 and 2 are simulated with energy-not-supplied (ENS) as an objective function. While, in Study-3, the loss index is measured in response to extreme events.

This study aims to investigate the importance of the penetration of DGs like PV and wind, which play key roles in migrating the system infrastructure from conventional to a resilient system. With this objective, the PV unit is shown on how it will increase system reliability and resiliency. Thus, a conventional system is taken as the base case where no PV unit is considered, and three more cases are studied in a resilient system with the inclusion of single-phase and double-phase to ground fault. Besides, the islanding mode is modeled here to supply the local loads during the event according to the available PV capacity. The formulation of the ENS and islanding mode modeling are presented in (1) and (2), respectively.

The ENS can be formulated with two main categories of consumers: first, consumers should consider the switching time (i.e., the time took to form the islanding mode), and second, consumers experiencing the rate of failure and repair time.

The ENS can be expressed by (1) while considering each state of generation and load [173]:

$ENS = \sum_{i=1}^{N_{br}} \lambda_i \, L_i \left(t_{rpr} + t_{swc}\right) \sum_{j \in \Omega_i} P_j$ (1)

where

N_{br} : Number of branches

λ_i: Failure rate of branch *i* (f /km yr)

L_i : Length of a branch *i* (km)

P_j : Demand power of the j^{th} load

t_{rpr} : Fault repair time (hours)

t_{swc} : Switching time (hours)

Ω_i: The set of buses located at the upstream of branch *i*

In this case study, four PV units are installed along with four distinct islanding mode, and each unit has a specific capacity. In the estimation method of ENS, the output of the DG power can be formulated as (2), which is the prerequisite to forming an island.

$P_{DG} \geq P_{load} + P_{loss}$ (2)

where, P_{DG}, P_{load}, and P_{loss} are the DG power, active power load (exist in the island mode), and network power loss. In (2), it is assumed that the power loss of the grid equals 5% of the hourly total load demand of the network.

6.1 Study-1

In this study, the four types of scenarios are discussed. Scenario-1 considers a base case where no DG unit is considered, and then four PV units are installed in scenario-2. In scenario-3, PV power is increased, and finally, the optimal allocation of the PV unit is addressed in scenario-4. Moreover, the single fault and double phase to ground fault are applied to the test system, and ENS is calculated. However, this test system does not consider an emergency load.

6.1.1 Scenario-1: Base case

In this scenario, the conventional operation of the grid is considered as the base case where no DG is incorporated into the IEEE 33-bus test system [172]. The base scenario is simulated with a single fault, and the ENS profile is shown in Fig. 9. From Fig. 9, it is observed that the ENS value is high, which is because that there is no backup unit. If any fault occurs, the grid supply might not be available to the whole load. Hence, to overcome this issue, the penetration of the DGs is increasing, which can improve the reliability and resiliency of the system. Further details are discussed as follows.

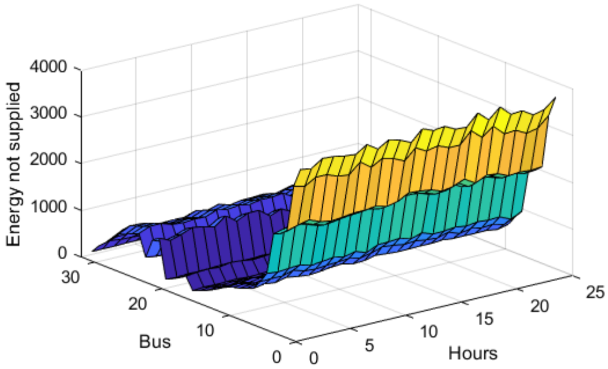


Fig. 9. Single fault without PV unit

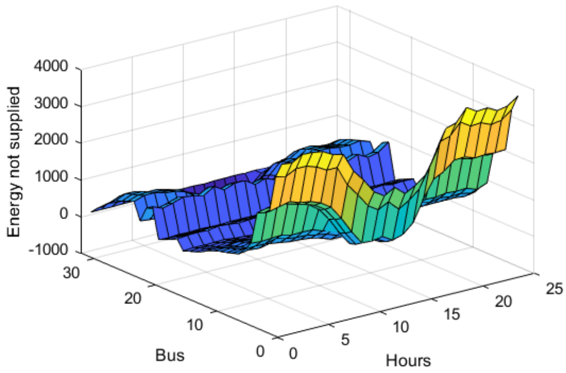


Fig. 10. Single fault with PV unit

6.1.2 Scenario-2: PV unit set-up

This study takes four solar units with a capacity of 100 kW, 200 kW, 500 kW, and 1000 kW are installed at the buses 12, 18, 22, and 32 respectively to make the system resilient. The ENS profile of such a scenario is shown in Fig. 10, which, in comparison with the conventional network, is reduced after installing the PVs to the 33-bus system.

Noticeably, such a decrease gives a better situation to the end-users during the contingency period. Notwithstanding, during peak hours of load demand, the ENS value is also minimum because solar power has its highest generation and is able to meet the major part of the load demand.

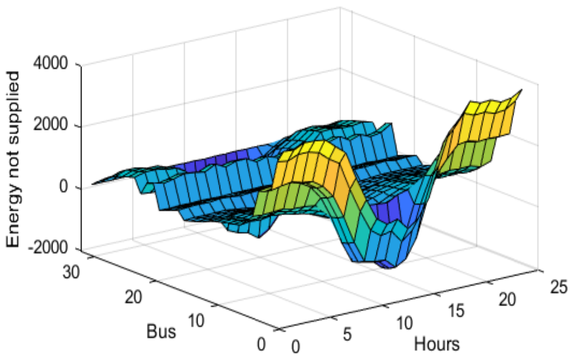


Fig. 11. Single fault with PV power enhance units

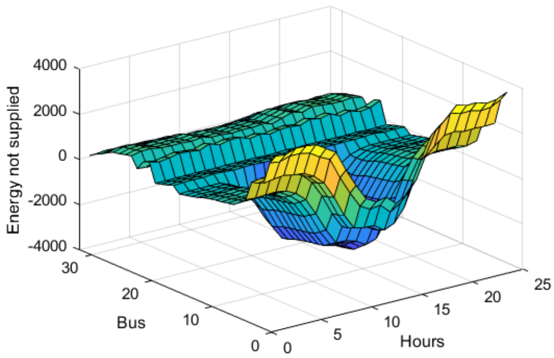


Fig. 12. Single fault with optimal allocation of PV units

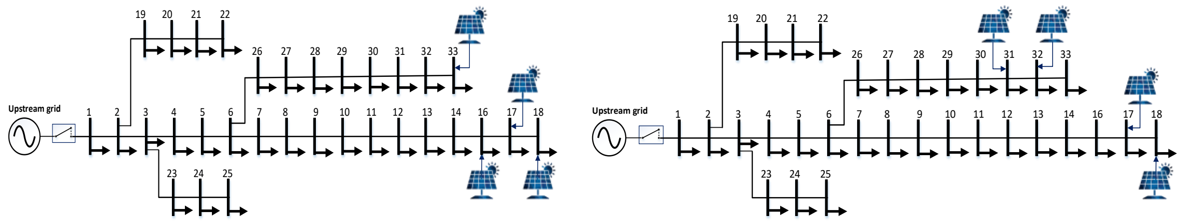
6.1.3 Scenario-3: PV power enhance

Considering the four PVs in the 33-bus system, and let us increase the output power of four PV units to 200 kW, 400 kW, 500 kW, and 1500 kW, respectively, at the bus locations 12, 18, 22, and 32 respectively, and the ENS performance is assessed. It is clear that using the proposed approach, the ENS value is reduced, which means that the system is more reliable and resilient than the above two scenarios with the single fault inclusion, as shown in Fig. 11.

6.1.4 Scenario-4: PV optimal allocation

It is important to note that the proper DG allocation can achieve increased system reliability and resiliency as well as reduced operating costs before and during the contingencies [174, 175]. The Swarm Robotics Search & Rescue (SRSR) [176] optimization method is applied here to optimize the location of PVs, which are 16, 17, 18, and 33, with a capacity of 200 kW, 400 kW, 500 kW, and 1500 kW, respectively. The ENS performance with the single-phase fault and the optimal location of PV units are shown in Fig. 12, and Fig. 13(a), correspondingly.

Furthermore, to show the robustness of the system, the double phase to ground fault is applied to the IEEE 33-bus system, and the ENS is measured with all four scenarios. The optimum location of the PVs in response to the double phase to ground fault is shown in Fig. 13(b) with a capacity of 200 kW, 400 kW, 500 kW, and 1500 kW at bus locations 17, 18, 31, and 32, respectively. Subsequently, the ENS performance is measured and compared for all four scenarios, as shown in Fig. 14. A comparison of the findings with those of other scenarios such as without PV and with PV confirms the better result, which means it can supply more power during the faults. Besides, it is clear that from scenario-3, the DG capacity also plays a key role in minimizing the ENS of the system, and eventually, after the optimal allocation of PV unit it reveals that there is a significant performance improvement compared to scenario-1 to scenario-3.



(a) (b)

Fig. 13. (a) Optimal location of DGs considering single fault, (b) Optimal location of DGs considering double fault

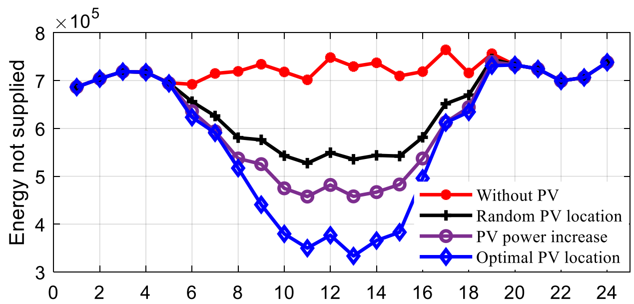


Fig. 14. Comparison characteristics of ENS for a double phase to ground fault

6.2 Study-2

In the response of unfavorable events, the consideration of emergency loads (e.g., first responders) is also a part of resiliency to minimize the life at risk. For that, there is a need for DGs to maintain the power supply to critical loads such as health institutions, financial institutions, process industries, communication centers, etc.

Hence, in order to make a priority level, this case study includes four emergency loads in a modified IEEE 33-bus system. The modified values of load are 300 kW, 500 kW, 800 kW, and 600 kW at bus 16, 20, 24, and 31, respectively, which are considered as emergency loads. This study also considers all four scenarios, as in Study-1.

6.2.1 Scenario-1: Base case

In this scenario, the base case refers to the conventional operation of the system, where no DG is incorporated. Moreover, the single fault and double fault are applied to the system, and then the ENS value is calculated as a performance index. The ENS profile for a single fault is shown in Fig. 15, and it is noted that the value of ENS is the same as the base case in Study-1.

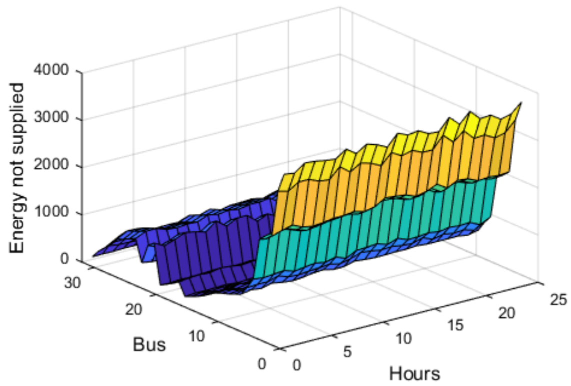


Fig. 15. Single fault without PV unit

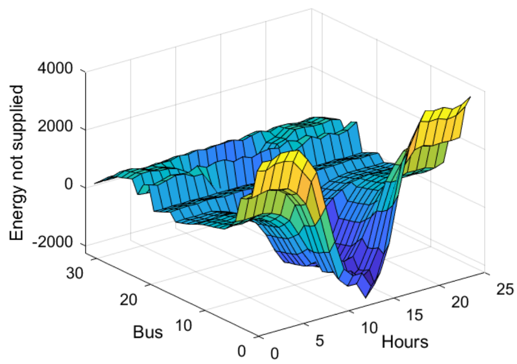


Fig. 16. Single fault with PV unit

6.2.2 Scenario-2: DG set-up

This scenario considers the four solar units (200 kW, 500 kW, 1000 kW, and 500 kW), which are incorporated into the 33-bus test system at the bus location 13, 18, 23, and 28, respectively. The ENS of the proposed system, in comparison with the conventional system, is reduced. As can be seen, the PVs could help to reduce the load curtailment of the system, which further minimizes the ENS as depicted in Fig. 16 in response to the single phase fault. In addition, considering the emergency load, PV can supply power in the face of a catastrophic event or grid failure, which increases the resiliency of the system.

6.2.3 Scenario-3: PV power enhance

In order to increase the resiliency of the system, the capacity of the PV unit should be increased to maximize the load recovery during the emergency or after the event hits the network. Therefore, this scenario presents the ENS profile with increased PV capacity, such as 1000 kW, 500 kW, 1500 kW, and 1000 kW at the same bus location, as mentioned in scenario-2. It can be seen from Fig. 17 that the ENS decreases further, which has a better solution for resiliency.

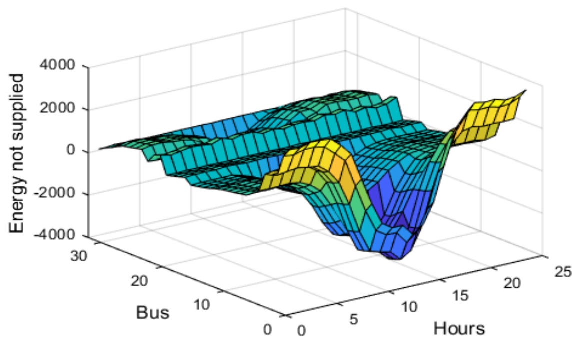


Fig. 17. Single phase fault with increased PV power

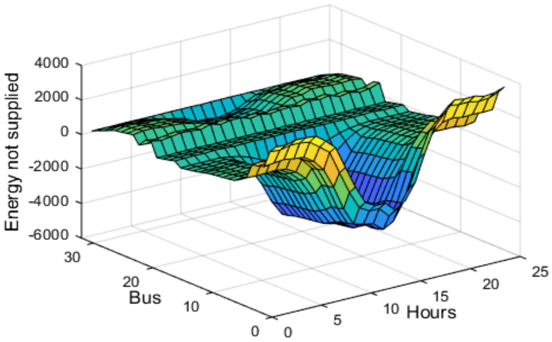


Fig. 18. Single phase fault with optimal PV allocation

6.2.4 Scenario-4: PV optimal allocation

The objective of this scenario is to minimize the ENS considering the emergency loads; hence, the optimal allocation of the PV unit is presented, where the result shows a lower value of ENS and better management of the PV unit to the emergency loads. The SRSR optimization method is applied here to optimize the location of PVs. A single phase fault is applied to the test system, and the ENS performance is shown in Fig. 18. It is noted that the ENS is greatly reduced as compared to the other two scenarios, which means that the system reliability and resiliency is enhanced. The random and optimal locations of the PV unit in the proposed system are presented in Fig. 19(a) and Fig. 19(b), respectively.

Finally, the comparison characteristics of ENS in the response of the double phase to the ground fault of Study-2 is illustrated in Fig. 20. Notwithstanding the foregoing scenario, optimal location of PV unit is vital for a real-world network, because in the face of extreme events, the most priority is to meet the critical load demand. To this end, the power system planner should consider the DG units near the emergency loads, which can supply power after the events with a less time horizon, and then such a system can be treated as resilient. Thus, this scenario is simulated considering the PV, increased PV power and optimal location of PV, and it is demonstrated in Fig. 20. It is clear that from Fig. 20, ENS is minimum as compared to other three scenarios as mentioned above.

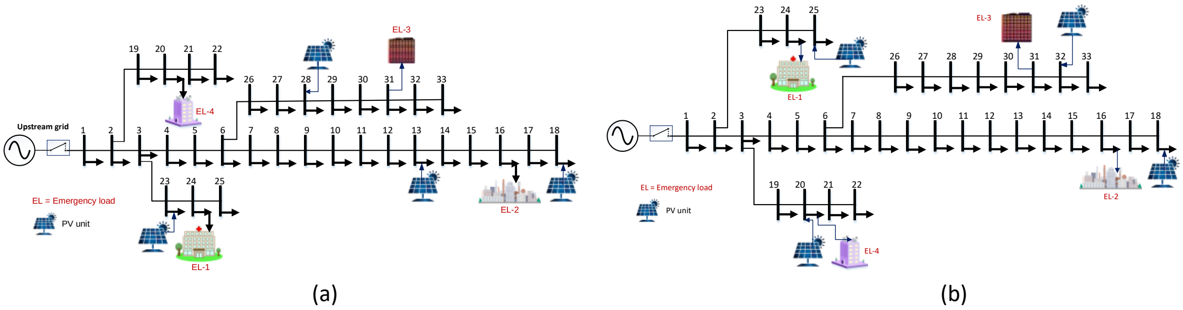


Fig. 19. (a) Random location of PVs considering emergency loads, (b) Optimal location of PVs considering emergency loads

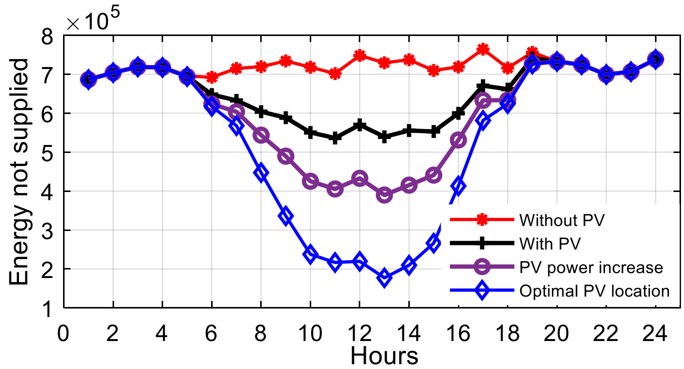


Fig. 20. Comparison characteristics of ENS for a double fault

6.3 Study-3

The catastrophic events that hit a network could inevitably need a prolonged period of recovery time and high recovery costs. In addition, the system generation loss increases, which further decreases the resiliency. Therefore, the system should be planned to have low loss and high resilience. To this end, the installation of DGs and their placement can play a crucial role in reducing generation loss and increasing the resiliency of the system. With these objectives, this Study-3 is presented here, with four different scenarios, as mentioned above.

The resilience of the system on account of a catastrophic event can be estimated as the reciprocal of the system's loss performance [177], which can be defined as (3)

$$\text{Resilience} = \frac{1}{\text{Loss}} \tag{3}$$

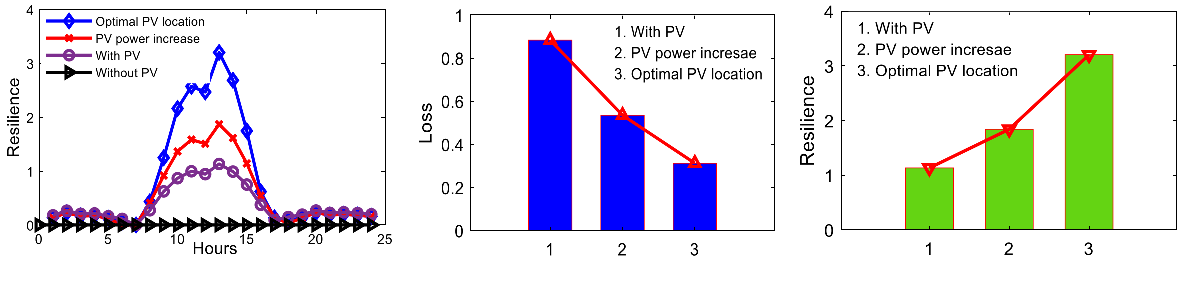
In this case, a loss means the amount of generation power is not available to the test system. Hence, the loss can be estimated as (4)

$$\text{Loss} = \frac{P_0 - P_{min}}{P_{min}} \tag{4}$$

where, P_0 and P_{min} are the total load and active load in the system after the event, respectively.

The resilience can be estimated in the range of zero (no resilience) to infinity (maximum resilience). The significance of the range is explained below. Zero resilience refers to the system that does not have the coping capacity to recover the load after the events, which means the system is completely collapsed. On the other hand, infinity resilience refers to the system that can recover all the loads after the event [177].

In this study, PV units are taken as DG sources to show the resiliency of the system in the face of a double phase to ground fault. Moreover, the limitation of the PV unit is that it can only supply power when there is solar insolation available, e.g., from 8 am to 5 pm. With this assumption, if a fault happens during this time, the system can meet the load demand partially or fully according to the available capacity. As can be seen in Fig. 21(a), the resilience is increased by PV installation, PV power increase, and optimal PV allocation. The resilience and loss can be measured by assuming that the maximum PV capacity is reached at 1 pm. Accordingly, loss and resilience values are estimated and presented in Figs. 21(b), and (c), respectively.



(a) (b) (c)

Fig. 21. (a) Comparison characteristics of resilience, (b) Loss at peak hour, (c) Resilience at peak hour

The case studies presented thus far provide testimony that the integration of DGs into the conventional system can be mentioned as a cornerstone for the endurance of the DS to evade the total system failure. On the other hand, during the unfavourable events, the critical load must be supplied, and this can be done by the incorporation of DG units. This case study is limited to the solar unit only; however, other alternative DG units like wind, storage unit, micro-turbine, etc., can also be studied in a similar way.

7. Conclusion

This paper has systematically reviewed the existing research of ADSs in case of resiliency. It firstly highlights the concept and differences between reliability and resiliency. Then, three major categories, including planning, operation, and planning-operation methods, are formed, and current literature is thoroughly discussed accordingly in terms of models used and contributions.

As reviewed in the literature, the implementation of resilient ADSs and their enhancement is considered as inevitable necessities for DSs. Nevertheless, resilience is acknowledged as a requirement that represents critical infrastructure and lifeline systems in view of extreme events. However, increasing concerns over resilient structures have also emerged along with the increase in the number of extreme events. In a nutshell, the following conclusions are made from presented review work:

- The most crucial issue in resilience is the restoration during/after the events, which can be achieved by coordinated planning and operational approaches to enhance the load recovery profile and reduce the restoration time.
- Some activities in different stages are essential to make a system resilient, firstly an appropriate planning approach, which can increase the robustness of the system when designing. Secondly, an improved operational scheme can provide better supply security; and finally, a coordinated planning and operational approach can prevent the system collapse.

A case study is demonstrated through the IEEE 33-bus test system with and without the incorporation of PV units, where the main aim is to show the system resiliency with two objective functions, including ENS and energy loss. The case study is presented in this paper with the following conclusion and limitations.

- Initially, the incorporation of PV units into the distribution system is presented, which shows that the value of ENS is decreased. Indeed, the reduced value of ENS demonstrates better resilience characteristics. Given this objective, the case study-1 and case study-2 are simulated separately through Matlab software, without and with considering the emergency loads, respectively.
- Secondly, in study-3, energy loss and resiliency are formulated, which states an inverse relationship between them. In fact, it is demonstrated that the energy loss is decreasing, while the resilience factor is conversely increasing.
- The study reveals that the addition of DGs like PV units becomes crucial for making the system resilient and, accordingly, load restoration can be enhanced.
- This case study is based on the PV units, but not limited to PV only; other DGs like wind, fuel cell, microturbine, and storage unit can be added to enhance the system resiliency. On the other hand, solar power during peak hours is considered here; however, the extreme event can happen at any time of the day, where only solar energy might not be feasible to restore the load. Thus, from a practical perspective, considering the uncertainties is vital.

In the future, the resilience study needs to move a step forward in following directions, for example:

- A resilience quantification framework is needed considering different natural hazards;

- An expansion/reconfiguration planning and improved coordination planning and operation is desirable to enhance the survivability and quick load recovery of the distribution systems;
- Considering all kind of power system thefts is challenging nowadays, which must be taken into account to make the system cyber-resilient; and
- The trade-off between resilience and cost has not explored yet, which needs to be considered in the future according to the different types of load demands (e.g., residential, industrial, and commercial).

8. References

[1] D. T. Ton and W. P. Wang, "A More Resilient Grid: The U.S. Department of Energy Joins with Stakeholders in an R&D Plan," *IEEE Power and Energy Magazine,* vol. 13, no. 3, pp. 26-34, 2015.

[2] M. J. Ghadi, A. Rajabi, S. Ghavidel, A. Azizivahed, L. Li, and J. Zhang, "From active distribution systems to decentralized microgrids: A review on regulations and planning approaches based on operational factors," *Applied Energy,* vol. 253, p. 113543, 2019.

[3] M. J. Ghadi, S. Ghavidel, A. Rajabi, A. Azizivahed, L. Li, and J. Zhang, "A review on economic and technical operation of active distribution systems," *Renewable and Sustainable Energy Reviews,* vol. 104, pp. 38-53, 2019.

[4] F. H. Jufri, V. Widiputra, and J. Jung, "State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies," *Applied Energy,* vol. 239, pp. 1049-1065, 2019.

[5] W. Li, *Risk assessment of power systems: models, methods, and applications*. John Wiley & Sons, 2014.

[6] A. Azizivahed, S. Ghavidel, M. J. Ghadi, L. Li, and J. Zhang, "A novel reliability oriented bi-objective unit commitment problem," in *2017 Australasian Universities Power Engineering Conference (AUPEC)*, 2017, pp. 1-6: IEEE.

[7] X. Liu, M. Shahidehpour, Z. Li, X. Liu, Y. Cao, and Z. Bie, "Microgrids for enhancing the power grid resilience in extreme conditions," *IEEE Transactions on Smart Grid,* vol. 8, no. 2, pp. 589-597, 2017.

[8] R. Neches and A. M. Madni, "Towards affordably adaptable and effective systems," *Systems Engineering,* vol. 16, no. 2, pp. 224-234, 2013.

[9] D. E. Alexander, "Resilience and disaster risk reduction: an etymological journey," *Natural hazards and earth system sciences,* vol. 13, no. 11, pp. 2707-2716, 2013.

[10] C. S. Holling, "Resilience and stability of ecological systems," *Annual review of ecology and systematics,* vol. 4, no. 1, pp. 1-23, 1973.

[11] C. Folke, "Resilience: The emergence of a perspective for social–ecological systems analyses," *Global environmental change,* vol. 16, no. 3, pp. 253-267, 2006.

[12] L. Seeliger and I. Turok, "Towards sustainable cities: extending resilience with insights from vulnerability and transition theory," *Sustainability,* vol. 5, no. 5, pp. 2108-2128, 2013.

[13] Z. Bie, Y. Lin, G. Li, and F. Li, "Battling the extreme: A study on the power system resilience," *Proceedings of the IEEE,* vol. 105, no. 7, pp. 1253-1266, 2017.

[14] R. Jena and B. Pradhan, "Integrated ANN-cross-validation and AHP-TOPSIS model to improve earthquake risk assessment," *International Journal of Disaster Risk Reduction,* p. 101723, 2020.

[15] M. Panteli and P. Mancarella, "The grid: Stronger bigger smarter?: Presenting a conceptual framework of power system resilience," *IEEE Power Energy Mag,* vol. 13, no. 3, pp. 58-66, 2015.

[16] D. Sage, P. Fussey, and A. Dainty, "Securing and scaling resilient futures: neoliberalization, infrastructure, and topologies of power," *Environment and Planning D: Society and Space,* vol. 33, no. 3, pp. 494-511, 2015.

[17] S. Shetty, G. Kamdem, B. Krishnappa, and D. Nikol, "Cyber Resilience Metrics for Bulk Power System," *Risk Analysis Journal*, 2018.

[18] D. K. Mishra, M. J. Ghadi, L. Li, and J. Zhang, "Proposing a Framework for Resilient Active Distribution Systems using Withstand, Respond, Adapt, and Prevent Element," in *2019 29th Australasian Universities Power Engineering Conference (AUPEC)*, 2019, pp. 1-6: IEEE.

[19] M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides, and N. D. Hatziargyriou, "Metrics and quantification of operational and infrastructure resilience in power systems," *IEEE Transactions on Power Systems,* vol. 32, no. 6, pp. 4732-4742, 2017.
[20] W. Kröger, "Achieving Resilience of Large-Scale Engineered Infrastructure Systems," in *Resilient Structures and Infrastructure*: Springer, 2019, pp. 289-313.
[21] Y. Liu, X. Li, and L. Xiao, "Service Oriented Resilience Strategy for Cloud Data Center," in *2018 IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C)*, 2018, pp. 269-274: IEEE.
[22] A. Hussain, V.-H. Bui, and H.-M. Kim, "Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience," *Applied energy,* vol. 240, pp. 56-72, 2019.
[23] A. Kwasinski, "Quantitative model and metrics of electrical grids' resilience evaluated at a power distribution level," *Energies,* vol. 9, no. 2, p. 93, 2016.
[24] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson, and P. Mancarella, "Power system resilience to extreme weather: fragility modeling, probabilistic impact assessment, and adaptation measures," *IEEE Transactions on Power Systems,* vol. 32, no. 5, pp. 3747-3757, 2016.
[25] R. Rocchetta, E. Zio, and E. Patelli, "A power-flow emulator approach for resilience assessment of repairable power grids subject to weather-induced failures and data deficiency," *Applied energy,* vol. 210, pp. 339-350, 2018.
[26] J.-P. Watson *et al.*, "Conceptual framework for developing resilience metrics for the electricity oil and gas sectors in the United States," *Sandia National Laboratories, Albuquerque, NM (United States), Tech. Rep,* 2014.
[27] S. Charoenkit and S. Kumar, "Environmental sustainability assessment tools for low carbon and climate resilient low income housing settlements," *Renewable and sustainable energy reviews,* vol. 38, pp. 509-525, 2014.
[28] S. Mousavizadeh, M.-R. Haghifam, and M.-H. Shariatkhah, "A linear two-stage method for resiliency analysis in distribution systems considering renewable energy and demand response resources," *Applied energy,* vol. 211, pp. 443-460, 2018.
[29] T. Münzberg, M. Wiens, and F. Schultmann, "A spatial-temporal vulnerability assessment to support the building of community resilience against power outage impacts," *Technological Forecasting and Social Change,* vol. 121, pp. 99-118, 2017.
[30] J. Mitra and S. J. Ranade, "Power System Hardening through Autonomous, Customer-driven Microgrids," in *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1-4.
[31] P. Hoffman, W. Bryan, M. Farber-DeAnda, M. Cleaver, C. Lewandowski, and K. Young, "Hardening and Resiliency, US Energy Industry Response to Recent Hurricane Seasons," *Office of Electricity Delivery and Energy Reliability, US Department of Energy, OE/ISER Final Report,* 2010.
[32] G. Davis, A. F. Snyder, and J. Mader, "The future of distribution system resiliency," in *2014 Clemson University Power Systems Conference*, 2014, pp. 1-8: IEEE.
[33] M. Panteli, D. N. Trakas, P. Mancarella, and N. D. Hatziargyriou, "Power systems resilience assessment: Hardening and smart operational enhancement strategies," *Proceedings of the IEEE,* vol. 105, no. 7, pp. 1202-1213, 2017.
[34] A. Kenward and U. Raja, "Blackout: Extreme weather climate change and power outages," *Climate central,* vol. 10, 2014.
[35] M. Rollins, "The hardening of utilitiy lines-implications for utility pole design and use," ed: Technical report, North American Wood Pole Council, 2007.
[36] N. Abi-Samra and W. Henry, "Actions Before... and After a Flood," *IEEE Power and Energy Magazine,* vol. 9, no. 2, pp. 52-58, 2011.
[37] R. J. Campbell, "Weather-related power outages and electric system resiliency," 2012: Congressional Research Service, Library of Congress Washington, DC.
[38] N. Romero, L. K. Nozick, I. Dobson, N. Xu, and D. A. Jones, "Seismic retrofit for electric power systems," *Earthquake Spectra,* vol. 31, no. 2, pp. 1157-1176, 2015.
[39] S. C. Madathil *et al.*, "Resilient off-grid microgrids: Capacity planning and N-1 security," *IEEE Transactions on Smart Grid,* vol. 9, no. 6, pp. 6511-6521, 2017.
[40] R. Jena, B. Pradhan, G. Beydoun, H. Sofyan, and M. Affan, "Integrated model for earthquake risk assessment using neural network and analytic hierarchy process: Aceh province, Indonesia," *Geoscience Frontiers,* vol. 11, no. 2, pp. 613-634, 2020.
[41] M. Panteli and P. Mancarella, "Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies," *Electric Power Systems Research,* Review vol. 127, pp. 259-270, 2015.
[42] R. Arghandeh, A. Von Meier, L. Mehrmanesh, and L. Mili, "On the definition of cyber-physical resilience in power systems," *Renewable and Sustainable Energy Reviews,* vol. 58, pp. 1060-1069, 2016.

[43] J. Wang, W. Zuo, L. Rhode-Barbarigos, X. Lu, J. Wang, and Y. Lin, "Literature review on modeling and simulation of energy infrastructures from a resilience perspective," *Reliability Engineering & System Safety*, 2018.
[44] A. Gholami, T. Shekari, M. H. Amirioun, F. Aminifar, M. H. Amini, and A. Sargolzaei, "Toward a consensus on the definition and taxonomy of power system resilience," *IEEE Access*, vol. 6, pp. 32035-32053, 2018.
[45] A. M. Caunhye, X. Nie, and S. Pokharel, "Optimization models in emergency logistics: A literature review," *Socio-economic planning sciences*, vol. 46, no. 1, pp. 4-13, 2012.
[46] F. He and J. Zhuang, "Balancing pre-disaster preparedness and post-disaster relief," *European Journal of Operational Research*, vol. 252, no. 1, pp. 246-256, 2016.
[47] A. M. Salman, Y. Li, and M. G. Stewart, "Evaluating system reliability and targeted hardening strategies of power distribution systems subjected to hurricanes," *Reliability Engineering & System Safety*, vol. 144, pp. 319-333, 2015.
[48] J. Salmeron, K. Wood, and R. Baldick, "Worst-case interdiction analysis of large-scale electric power grids," *IEEE Transactions on power systems*, vol. 24, no. 1, pp. 96-104, 2009.
[49] G. Brown, M. Carlyle, J. Salmerón, and K. Wood, "Defending critical infrastructure," *Interfaces*, vol. 36, no. 6, pp. 530-544, 2006.
[50] X. Wang, Z. Li, M. Shahidehpour, and C. Jiang, "Robust line hardening strategies for improving the resilience of distribution systems with variable renewable resources," *IEEE Transactions on Sustainable Energy*, 2017.
[51] Y. Lin and Z. Bie, "Tri-level optimal hardening plan for a resilient distribution system considering reconfiguration and DG islanding," *Applied Energy*, vol. 210, pp. 1266-1279, 2018.
[52] M. J. Ghadi, S. H. Gilani, H. Afrakhte, and A. Baghramian, "A novel heuristic method for wind farm power prediction: A case study," *International Journal of Electrical Power & Energy Systems*, vol. 63, pp. 962-970, 2014.
[53] A. Sharifian, M. J. Ghadi, S. Ghavidel, L. Li, and J. Zhang, "A new method based on Type-2 fuzzy neural network for accurate wind power forecasting under uncertain data," *Renewable energy*, vol. 120, pp. 220-230, 2018.
[54] M. J. Ghadi, L. Li, J. Zhan, L. Chen, Q. Huang, and C. Li, "A Review on the Development of Concentrated Solar Power and its Integration in Coal-Fired Power Plants," in *2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, 2019, pp. 1106-1111: IEEE.
[55] S. Wang and J. Yu, "Optimal sizing of the CAES system in a power system with high wind power penetration," *International Journal of Electrical Power & Energy Systems*, vol. 37, no. 1, pp. 117-125, 2012.
[56] S. Wang, D. Yu, and J. Yu, "A coordinated dispatching strategy for wind power rapid ramp events in power systems with high wind power penetration," *International Journal of Electrical Power & Energy Systems*, vol. 64, pp. 986-995, 2015.
[57] M. Simonov, "Dynamic Partitioning of DC Microgrid in Resilient Clusters Using Event-Driven Approach," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2618-2625, 2014.
[58] M. He and M. Giesselmann, "Reliability-constrained self-organization and energy management towards a resilient microgrid cluster," in *2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2015, pp. 1-5.
[59] E. Pashajavid, F. Shahnia, and A. Ghosh, "Development of a self-healing strategy to enhance the overloading resilience of islanded microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 868-880, 2015.
[60] M. Samadi, M. Aghamohamadi, and A. Mahmoudi, "Optimal time period clustering of time-of-use schemes based on elastic loads' responsiveness," *International Transactions on Electrical Energy Systems*, vol. 30, no. 4, p. e12275, 2020.
[61] M. Aghamohamadi, A. Mahmoudi, and M. Haque, "Two-stage Robust Sizing and Operation Co-optimization for Residential PV-battery Systems Considering the Uncertainty of PV Generation and Load," *IEEE Transactions on Industrial Informatics*, 2020.
[62] M. E. Nassar and M. M. A. Salama, "Adaptive Self-Adequate Microgrids Using Dynamic Boundaries," *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 105-113, 2016.
[63] D. Tan, D. Baxter, S. Foroozan, and S. Crane, "A First Resilient DC-Dominated Microgrid for Mission-Critical Space Applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 4, pp. 1147-1157, 2016.
[64] A. K. Mishra, S. R. Das, P. K. Ray, R. K. Mallick, A. Mohanty, and D. K. Mishra, "PSO-GWO Optimized Fractional Order PID Based Hybrid Shunt Active Power Filter for Power Quality Improvements," *IEEE Access*, vol. 8, pp. 74497-74512, 2020.

[65] A. Hussain, V.-H. Bui, and H.-M. Kim, "A resilient and privacy-preserving energy management strategy for networked microgrids," *IEEE Transactions on Smart Grid,* vol. 9, no. 3, pp. 2127-2139, 2016.

[66] K. S. A. Sedzro, A. J. Lamadrid, and L. F. Zuluaga, "Allocation of resources using a microgrid formation approach for resilient electric grids," *IEEE Transactions on Power Systems,* vol. 33, no. 3, pp. 2633-2643, 2017.

[67] H. Lee *et al.*, "An energy management system with optimum reserve power procurement function for microgrid resilience improvement," *IEEE Access,* vol. 7, pp. 42577-42585, 2019.

[68] G. L. Doorman, K. Uhlen, G. Kjolle, and E. S. Huse, "Vulnerability analysis of the Nordic power system," *IEEE Transactions on Power Systems,* vol. 21, no. 1, pp. 402-410, 2006.

[69] Y. Zhou, A. Pahwa, and S.-S. Yang, "Modeling weather-related failures of overhead distribution lines," *IEEE Transactions on power systems,* vol. 21, no. 4, pp. 1683-1690, 2006.

[70] X. Yu and C. Singh, "A practical approach for integrated power system vulnerability analysis with protection failures," *IEEE Transactions on Power Systems,* vol. 19, no. 4, pp. 1811-1820, 2004.

[71] D. A. Reed, "Electric utility distribution analysis for extreme winds," *Journal of Wind Engineering and Industrial Aerodynamics,* vol. 96, no. 1, pp. 123-140, 2008.

[72] C. J. Wallnerstrom and P. Hilber, "Vulnerability Analysis of Power Distribution Systems for Cost-Effective Resource Allocation," *IEEE Transactions on Power Systems,* vol. 27, no. 1, pp. 224-232, 2012.

[73] Y. Zhu, J. Yan, Y. Tang, Y. L. Sun, and H. He, "Resilience analysis of power grids under the sequential attack," *IEEE Transactions on Information Forensics and Security,* vol. 9, no. 12, pp. 2340-2354, 2014.

[74] W. Yuan, L. Zhao, and B. Zeng, "Optimal power grid protection through a defender–attacker–defender model," *Reliability Engineering & System Safety,* vol. 121, pp. 83-89, 2014.

[75] J. Salmeron, K. Wood, and R. Baldick, "Analysis of electric grid security under terrorist threat," *IEEE Transactions on power systems,* vol. 19, no. 2, pp. 905-912, 2004.

[76] M. Aghamohamadi, A. Mahmoudi, and M. H. Haque, "Robust Allocation of Residential Solar Photovoltaic Systems Paired with Battery Units in South Australia," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 6673-6679: IEEE.

[77] Y. Ming-Jong and K. J. Min, "Repair-unit location models for power failures," *IEEE Transactions on Engineering Management,* vol. 45, no. 1, pp. 57-65, 1998.

[78] Y. Chang, S. Wilkinson, E. Seville, and R. Potangaroa, "Resourcing for a resilient post-disaster reconstruction environment," *International Journal of Disaster Resilience in the Built Environment,* vol. 1, no. 1, pp. 65-83, 2010.

[79] N. Safaei, D. Banjevic, and A. K. S. Jardine, "Workforce Planning for Power Restoration: An Integrated Simulation-Optimization Approach," *IEEE Transactions on Power Systems,* vol. 27, no. 1, pp. 442-449, 2012.

[80] A. Alsubaie, J. Marti, K. Alutaibi, A. D. Pietro, and A. Tofani, "Resources allocation in disaster response using Ordinal Optimization based approach," in *2014 IEEE Canada International Humanitarian Technology Conference - (IHTC)*, 2014, pp. 1-5.

[81] A. Arab, A. Khodaei, S. K. Khator, K. Ding, V. A. Emesih, and Z. Han, "Stochastic Pre-hurricane Restoration Planning for Electric Power Systems Infrastructure," *IEEE Transactions on Smart Grid,* vol. 6, no. 2, pp. 1046-1054, 2015.

[82] M. H. Imani, K. Yousefpour, M. T. Andani, and M. J. Ghadi, "Effect of Changes in Incentives and Penalties on Interruptible/Curtailable Demand Response Program in Microgrid Operation," in *2019 IEEE Texas Power and Energy Conference (TPEC)*, 2019, pp. 1-6: IEEE.

[83] M. H. Abbasi *et al.*, "Risk-constrained offering strategies for a price-maker demand response aggregator," in *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*, 2017, pp. 1-6: IEEE.

[84] S. Ghavidel, A. Rajabi, M. J. Ghadi, A. Azizivahed, L. Li, and J. Zhang, "Risk-constrained demand response and wind energy systems integration to handle stochastic nature and wind power outage," *IET Energy Systems Integration,* 2019.

[85] A. Rajabi *et al.*, "A pattern recognition methodology for analyzing residential customers load data and targeting demand response applications," *Energy and Buildings,* vol. 203, p. 109455, 2019.

[86] H. Gao, Y. Chen, Y. Xu, and C.-C. Liu, "Resilience-oriented critical load restoration using microgrids in distribution systems," *IEEE Transactions on Smart Grid,* vol. 7, no. 6, pp. 2837-2848, 2016.

[87] R. Pérez-Guerrero, G. T. Heydt, N. J. Jack, B. K. Keel, and A. R. Castelhano, "Optimal restoration of distribution systems using dynamic programming," *IEEE Transactions on Power Delivery,* vol. 23, no. 3, pp. 1589-1596, 2008.

[88] T. Wegner, "Discrete simulation modelling for corporate manpower planning," *Omega,* vol. 13, no. 3, pp. 201-210, 1985.

[89] J. Q. Tortós and V. Terzija, "Controlled islanding strategy considering power system restoration constraints," in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1-8: IEEE.

[90] H. Ahmadi, A. Alsubaie, and J. R. Martí, "Distribution system restoration considering critical infrastructures interdependencies," in *2014 IEEE PES General Meeting | Conference & Exposition*, 2014, pp. 1-5.

[91] S. Yao, P. Wang, and T. Zhao, "Transportable energy storage for more resilient distribution systems with multiple microgrids," *IEEE Transactions on Smart Grid*, 2018.

[92] K. Aoki, K. Nara, T. Satoh, M. Kitagawa, and K. Yamanaka, "New approximate optimization method for distribution system planning," *IEEE Transactions on power systems*, vol. 5, no. 1, pp. 126-132, 1990.

[93] P. Carvalho, L. Ferreira, F. Lobo, and L. Barruncho, "Optimal distribution network expansion planning under uncertainty by evolutionary decision convergence," *International Journal of Electrical Power & Energy Systems*, vol. 20, no. 2, pp. 125-129, 1998.

[94] D. K. Mishra, T. K. Panigrahi, A. Mohanty, and P. K. Ray, "Impact of wind/solar integration on frequency control in two-area power system," in *2018 19th International Carpathian Control Conference (ICCC)*, 2018, pp. 580-584: IEEE.

[95] M. Sedaghat, E. Rokrok, and M. Bakhshipour, "A Novel Method Based on Biogeography-Based Optimization for DG Planning in Distribution System," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 15, no. 1, pp. 1-13, 2015.

[96] F. Namdari, S. Samadinasab, N. Shojaei, and M. Bakhshipour, "Optimal coordination of overcurrent and distance relays using cuckoo optimization algorithm," *TELKOMNIKA Indones J Electr Eng*, vol. 16, no. 3, p. 389, 2015.

[97] M. Nick, R. Cherkaoui, and M. Paolone, "Optimal planning of distributed energy storage systems in active distribution networks embedding grid reconfiguration," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1577-1590, 2017.

[98] S. Chanda and A. K. Srivastava, "Defining and enabling resiliency of electric distribution systems with multiple microgrids," *IEEE Transactions on Smart Grid*, vol. 7, no. 6, pp. 2859-2868, 2016.

[99] T. Jin, N. Mai, Y. Ding, L. Vo, and R. Dawud, "Planning for Distribution Resilience under Variable Generation: Prevention, Surviving and Recovery," in *2018 IEEE Green Technologies Conference (GreenTech)*, 2018, pp. 49-56.

[100] R. E. Brown, "Electric Power Distribution Reliability, Marcel Decker," *Inc, New York*, 2002.

[101] S. Lei, C. Chen, Y. Li, and Y. Hou, "Resilient disaster recovery logistics of distribution systems: Co-optimize service restoration with repair crew and mobile power source dispatch," *IEEE Transactions on Smart Grid*, vol. 10, no. 6, pp. 6187-6202, 2019.

[102] K. G. Zografos, C. Douligeris, and P. Tsoumpas, "An integrated framework for managing emergency-response logistics: The case of the electric utility companies," *IEEE Transactions on Engineering Management*, vol. 45, no. 2, pp. 115-126, 1998.

[103] C. J. Zapata, S. C. Silva, H. I. Gonzalez, O. L. Burbano, and J. A. Hernandez, "Modeling the repair process of a power distribution system," in *2008 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, 2008, pp. 1-7.

[104] B. Chen, Z. Ye, C. Chen, J. Wang, T. Ding, and Z. Bie, "Toward a Synthetic Model for Distribution System Restoration and Crew Dispatch," *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 2228-2239, 2018.

[105] A. Hussain, V.-H. Bui, and H.-M. Kim, "Optimal operation of hybrid microgrids for enhancing resiliency considering feasible islanding and survivability," *IET Renewable Power Generation*, vol. 11, no. 6, pp. 846-857, 2017.

[106] M. H. Amirioun, F. Aminifar, and H. Lesani, "Towards Proactive Scheduling of Microgrids Against Extreme Floods," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3900-3902, 2018.

[107] C. Wang, Y. Hou, F. Qiu, S. Lei, and K. Liu, "Resilience Enhancement With Sequentially Proactive Operation Strategies," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 2847-2857, 2017.

[108] L. Che and M. Shahidehpour, "DC Microgrids: Economic Operation and Enhancement of Resilience by Hierarchical Control," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2517-2526, 2014.

[109] M. Zadsar, M. R. Haghifam, and S. M. M. Larimi, "Approach for self-healing resilient operation of active distribution network with microgrid," *IET Generation, Transmission & Distribution*, vol. 11, no. 18, pp. 4633-4643, 2017.

[110] M. Tavakoli, F. Shokridehaki, M. F. Akorede, M. Marzband, I. Vechiu, and E. Pouresmaeil, "CVaR-based energy management scheme for optimal resilience and operational cost in commercial building microgrids," *International Journal of Electrical Power & Energy Systems*, vol. 100, pp. 1-9, 2018.

[111] A. Gholami, T. Shekari, and S. Grijalva, "Proactive management of microgrids for resiliency enhancement: An adaptive robust approach," *IEEE Transactions on Sustainable Energy*, 2017.

[112] L. Liang, Y. Hou, D. J. Hill, and S. Y. R. Hui, "Enhancing resilience of microgrids with electric springs," *IEEE Transactions on Smart Grid*, vol. 9, no. 3, pp. 2235-2247, 2016.

[113] A. Mohanty, M. Viswavandya, S. Mohanty, and D. K. Mishra, "Reactive power compensation in a stand-alone wind-diesel-tidal hybrid system by a fuzzy logic based UPFC," *Procedia Computer Science,* vol. 57, pp. 1281-1288, 2015.
[114] A. Mohanty, M. Viswavandya, D. Mishra, P. Paramita, and S. P. Mohanty, "Intelligent voltage and reactive power management in a standalone PV based microgrid," *Procedia Technology,* vol. 21, pp. 443-451, 2015.
[115] Z. Wang, B. Chen, and J. Wang, "Decentralized energy management system for networked microgrids in grid-connected and islanded modes," *IEEE Transactions on Smart Grid,* vol. 7, no. 2, pp. 1097-1105, 2015.
[116] Z. Wang, B. Chen, J. Wang, and C. Chen, "Networked microgrids for self-healing power systems," *IEEE Transactions on smart grid,* vol. 7, no. 1, pp. 310-319, 2015.
[117] K. M. Kelly-Pitou, A. Ostroski, B. Contino, B. Grainger, A. Kwasinski, and G. Reed, "Microgrids and resilience: Using a systems approach to achieve climate adaptation and mitigation goals," *The Electricity Journal,* vol. 30, no. 10, pp. 23-31, 2017.
[118] M. J. Hossain, M. A. Mahmud, F. Milano, S. Bacha, and A. Hably, "Design of Robust Distributed Control for Interconnected Microgrids," *IEEE Transactions on Smart Grid,* vol. 7, no. 6, pp. 2724-2735, 2016.
[119] S. D. Manshadi and M. E. Khodayar, "Resilient Operation of Multiple Energy Carrier Microgrids," *IEEE Transactions on Smart Grid,* vol. 6, no. 5, pp. 2283-2292, 2015.
[120] Z. Wang, B. Chen, J. Wang, and C. Chen, "Networked Microgrids for Self-Healing Power Systems," *IEEE Transactions on Smart Grid,* vol. 7, no. 1, pp. 310-319, 2016.
[121] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Enhancing Power System Resilience Through Hierarchical Outage Management in Multi-Microgrids," *IEEE Transactions on Smart Grid,* vol. 7, no. 6, pp. 2869-2879, 2016.
[122] A. Hussain, V.-H. Bui, and H.-M. Kim, "Resilience-oriented optimal operation of networked hybrid microgrids," *IEEE Transactions on Smart Grid,* 2017.
[123] A. Hussain, A. O. Rousis, I. Konstantelos, G. Strbac, J. Jeon, and H.-M. Kim, "Impact of Uncertainties on Resilient Operation of Microgrids: A Data-Driven Approach," *IEEE Access,* vol. 7, pp. 14924-14937, 2019.
[124] C. Colson, M. Nehrir, and R. Gunderson, "Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing," in *2011 4th International Symposium on Resilient Control Systems*, 2011, pp. 83-88: IEEE.
[125] A. Arif and Z. Wang, "Networked microgrids for service restoration in resilient distribution systems," *IET Generation, Transmission & Distribution,* vol. 11, no. 14, pp. 3612-3619, 2017.
[126] M. Amirioun, F. Aminifar, and H. Lesani, "Resilience-oriented proactive management of microgrids against windstorms," *IEEE Transactions on Power Systems,* vol. 33, no. 4, pp. 4275-4284, 2017.
[127] A. Hussain, V.-H. Bui, and H.-M. Kim, "Fuzzy logic-based operation of battery energy storage systems (BESSs) for enhancing the resiliency of hybrid microgrids," *Energies,* vol. 10, no. 3, p. 271, 2017.
[128] Z. Wang, J. Wang, and C. Chen, "A three-phase microgrid restoration model considering unbalanced operation of distributed generation," *IEEE Transactions on Smart Grid,* vol. 9, no. 4, pp. 3594-3604, 2016.
[129] Y. Kwon, A. Kwasinski, and A. Kwasinski, "Coordinated Energy Management in Resilient Microgrids for Wireless Communication Networks," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 4, no. 4, pp. 1158-1173, 2016.
[130] N. M. Dehkordi, H. R. Baghaee, N. Sadati, and J. M. Guerrero, "Distributed noise-resilient secondary voltage and frequency control for islanded microgrids," *IEEE Transactions on Smart Grid,* 2018.
[131] D. K. Mishra, T. K. Panigrahi, A. Mohanty, P. K. Ray, and M. Viswavandya, "Design and Analysis of Renewable Energy based Generation Control in a Restructured Power System," in *2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2018, pp. 1-6: IEEE.
[132] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Role of outage management strategy in reliability performance of multi-microgrid distribution systems," *IEEE Transactions on Power Systems,* vol. 33, no. 3, pp. 2359-2369, 2017.
[133] R. Romero, J. F. Franco, F. B. Leão, M. J. Rider, and E. S. De Souza, "A new mathematical model for the restoration problem in balanced radial distribution systems," *IEEE Transactions on Power Systems,* vol. 31, no. 2, pp. 1259-1268, 2015.
[134] T. Ding, Y. Lin, Z. Bie, and C. Chen, "A resilient microgrid formation strategy for load restoration considering master-slave distributed generators and topology reconfiguration," *Applied energy,* vol. 199, pp. 205-216, 2017.
[135] C. Chen, J. Wang, F. Qiu, and D. Zhao, "Resilient distribution system by microgrids formation after natural disasters," *IEEE Transactions on smart grid,* vol. 7, no. 2, pp. 958-966, 2015.

[136] T. Ding, Y. Lin, G. Li, and Z. Bie, "A new model for resilient distribution systems by microgrids formation," *IEEE Transactions on Power Systems,* vol. 32, no. 5, pp. 4145-4147, 2017.
[137] C. Chen, J. Wang, and D. Ton, "Modernizing distribution system restoration to achieve grid resiliency against extreme weather events: an integrated solution," *Proceedings of the IEEE,* vol. 105, no. 7, pp. 1267-1288, 2017.
[138] Y. Xu, C.-C. Liu, K. P. Schneider, F. K. Tuffner, and D. T. Ton, "Microgrids for service restoration to critical load in a resilient distribution system," *IEEE Transactions on Smart Grid,* vol. 9, no. 1, pp. 426-437, 2016.
[139] M. Panteli, D. N. Trakas, P. Mancarella, and N. D. Hatziargyriou, "Boosting the Power Grid Resilience to Extreme Weather Events Using Defensive Islanding," *IEEE Transactions on Smart Grid,* vol. 7, no. 6, pp. 2913-2922, 2016.
[140] B. Simon, C. Coffrin, and P. Van Hentenryck, "Randomized adaptive vehicle decomposition for large-scale power restoration," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* vol. 7298 LNCS, ed, 2012, pp. 379-394.
[141] H. Gao, Y. Chen, Y. Xu, and C. Liu, "Resilience-Oriented Critical Load Restoration Using Microgrids in Distribution Systems," *IEEE Transactions on Smart Grid,* vol. 7, no. 6, pp. 2837-2848, 2016.
[142] Y. Liu, N. U. Hassan, S. Huang, and C. Yuen, "Electricity cost minimization for a residential smart grid with distributed generation and bidirectional power transactions," in *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT),* 2013, pp. 1-6: IEEE.
[143] J. Johansson and H. Hassel, "An approach for modelling interdependent infrastructures in the context of vulnerability analysis," *Reliability Engineering & System Safety,* vol. 95, no. 12, pp. 1335-1344, 2010.
[144] R. Eskandarpour, A. Khodaei, and A. Arab, "Improving power grid resilience through predictive outage estimation," in *2017 North American Power Symposium (NAPS)*, 2017, pp. 1-5.
[145] R. Eskandarpour and A. Khodaei, "Machine Learning Based Power Grid Outage Prediction in Response to Extreme Events," *IEEE Transactions on Power Systems,* vol. 32, no. 4, pp. 3315-3316, 2017.
[146] M. Ouyang, L. Zhao, Z. Pan, and L. Hong, "Comparisons of complex network based models and direct current power flow model to analyze power grid vulnerability under intentional attacks," *Physica A: Statistical Mechanics and its Applications,* vol. 403, pp. 45-53, 2014.
[147] A. Abedi, L. Gaudard, and F. Romerio, "Review of major approaches to analyze vulnerability in power system," *Reliability Engineering & System Safety,* 2018.
[148] M. Panteli, P. A. Crossley, D. S. Kirschen, and D. J. Sobajic, "Assessing the Impact of Insufficient Situation Awareness on Power System Operation," *IEEE Transactions on Power Systems,* vol. 28, no. 3, pp. 2967-2977, 2013.
[149] M. Panteli, D. S. Kirschen, P. A. Crossley, and D. J. Sobajic, "Enhancing situation awareness in power system control centers," in *2013 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision Support (CogSIMA)*, 2013, pp. 254-261.
[150] J. R. Agüero, J. Wang, and J. J. Burke, "Improving the reliability of power distribution systems through single-phase tripping," in *IEEE PES T&D 2010*, 2010, pp. 1-7: IEEE.
[151] L. Ren, Y. Qin, B. Wang, P. Zhang, P. B. Luh, and R. Jin, "Enabling resilient microgrid through programmable network," *IEEE Transactions on Smart Grid,* vol. 8, no. 6, pp. 2826-2836, 2016.
[152] D. Jin *et al.*, "Toward a cyber resilient and secure microgrid using software-defined networking," *IEEE Transactions on Smart Grid,* vol. 8, no. 5, pp. 2494-2504, 2017.
[153] L. Ren *et al.*, "Enabling resilient distributed power sharing in networked microgrids through software defined networking," *Applied Energy,* vol. 210, pp. 1251-1265, 2018.
[154] M. A. Azzouz, A. Hooshyar, and E. F. El-Saadany, "Resilience enhancement of microgrids with inverter-interfaced DGs by enabling faulty phase selection," *IEEE Transactions on Smart Grid,* vol. 9, no. 6, pp. 6578-6589, 2017.
[155] H. Mo, M. Xie, and G. Levitin, "Optimal resource distribution between protection and redundancy considering the time and uncertainties of attacks," *European Journal of Operational Research,* vol. 243, no. 1, pp. 200-210, 2015.
[156] S. Ma, L. Su, Z. Wang, F. Qiu, and G. Guo, "Resilience enhancement of distribution grids against extreme weather events," *IEEE Transactions on Power Systems,* vol. 33, no. 5, pp. 4842-4853, 2018.
[157] A. Hussain, V.-H. Bui, and H.-M. Kim, "A proactive and survivability-constrained operation strategy for enhancing resilience of microgrids using energy storage system," *IEEE Access,* vol. 6, pp. 75495-75507, 2018.
[158] A. Gholami, T. Shekari, F. Aminifar, and M. Shahidehpour, "Microgrid Scheduling With Uncertainty: The Quest for Resilience," *IEEE Transactions on Smart Grid,* vol. 7, no. 6, pp. 2849-2858, 2016.
[159] M. Aghamohamadi, M. Samadi, and I. Rahmati, "Energy generation cost in multi-energy systems; an application to a non-merchant energy hub in supplying price responsive loads," *Energy,* vol. 161, pp. 878-891, 2018.

[160] S. Lei, J. Wang, C. Chen, and Y. Hou, "Mobile Emergency Generator Pre-Positioning and Real-Time Allocation for Resilient Response to Natural Disasters," *IEEE Transactions on Smart Grid,* vol. 9, no. 3, pp. 2030-2041, 2018.
[161] M. H. Amirioun, F. Aminifar, and M. Shahidehpour, "Resilience-Promoting Proactive Scheduling against Hurricanes in Multiple Energy Carrier Microgrids," *IEEE Transactions on Power Systems,* 2018.
[162] A. Arif, Z. Wang, J. Wang, and C. Chen, "Power distribution system outage management with co-optimization of repairs, reconfiguration, and DG dispatch," *IEEE Transactions on Smart Grid,* vol. 9, no. 5, pp. 4109-4118, 2017.
[163] L. Che and M. Shahidehpour, "Adaptive formation of microgrids with mobile emergency resources for critical service restoration in extreme conditions," *IEEE Transactions on Power Systems,* vol. 34, no. 1, pp. 742-753, 2018.
[164] Z. Wang and J. Wang, "Self-healing resilient distribution systems based on sectionalization into microgrids," *IEEE Transactions on Power Systems,* vol. 30, no. 6, pp. 3139-3149, 2015.
[165] X. Zhang, S. Mahadevan, S. Sankararaman, and K. Goebel, "Resilience-based network design under uncertainty," *Reliability Engineering & System Safety,* vol. 169, pp. 364-379, 2018.
[166] B. Chen, C. Chen, J. Wang, and K. L. Butler-Purry, "Sequential service restoration for unbalanced distribution systems and microgrids," *IEEE Transactions on Power Systems,* vol. 33, no. 2, pp. 1507-1520, 2017.
[167] M. Aly, E. M. Ahmed, and M. Shoyama, "Thermal and reliability assessment for wind energy systems with DSTATCOM functionality in resilient microgrids," *IEEE Transactions on Sustainable Energy,* vol. 8, no. 3, pp. 953-965, 2016.
[168] W. Cao, J. Wu, N. Jenkins, C. Wang, and T. Green, "Benefits analysis of Soft Open Points for electrical distribution network operation," *Applied Energy,* vol. 165, pp. 36-47, 2016.
[169] B. Cai, M. Xie, Y. Liu, Y. Liu, and Q. Feng, "Availability-based engineering resilience metric and its corresponding evaluation methodology," *Reliability Engineering & System Safety,* vol. 172, pp. 216-224, 2018.
[170] M. Amirioun, F. Aminifar, H. Lesani, and M. Shahidehpour, "Metrics and quantitative framework for assessing microgrid resilience against windstorms," *International Journal of Electrical Power & Energy Systems,* vol. 104, pp. 716-723, 2019.
[171] J. E. Ramirez-Marquez, C. M. Rocco, K. Barker, and J. Moronta, "Quantifying the resilience of community structures in networks," *Reliability Engineering & System Safety,* vol. 169, pp. 466-474, 2018.
[172] W. Sheng, K.-Y. Liu, Y. Liu, X. Meng, and Y. Li, "Optimal placement and sizing of distributed generation via an improved nondominated sorting genetic algorithm II," *IEEE Transactions on Power Delivery,* vol. 30, no. 2, pp. 569-578, 2014.
[173] S. H. Gilani, M. J. Ghadi, and H. Afrakhte, "Optimal allocation of wind turbines considering different costs for interruption aiming at power loss reduction and reliability improvement using imperialistic competitive algorithm," *International Review of Electrical Engineering,* vol. 8, no. 1, pp. 284-296, 2013.
[174] J. C. Whitson and J. E. Ramirez-Marquez, "Resiliency as a component importance measure in network reliability," *Reliability Engineering & System Safety,* vol. 94, no. 10, pp. 1685-1693, 2009.
[175] S. Jain, S. Kalambe, G. Agnihotri, and A. Mishra, "Distributed generation deployment: State-of-the-art of distribution system planning in sustainable era," *Renewable and Sustainable Energy Reviews,* vol. 77, pp. 363-385, 2017.
[176] M. Bakhshipour, M. J. Ghadi, and F. Namdari, "Swarm robotics search & rescue: A novel artificial intelligence-inspired optimization approach," *Applied Soft Computing,* vol. 57, pp. 708-726, 2017.
[177] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, "Networked microgrids for enhancing the power system resilience," *Proceedings of the IEEE,* vol. 105, no. 7, pp. 1289-1310, 2017.