

Review on Resilience-Oriented Strategies Power Systems Facing Extreme Natural Disaster

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ABSTRACT

Natural disasters significantly impact electricity services worldwide, making power grid resilience a crucial research topic. This article presents a literature review focusing on resilience-oriented strategies for electric power systems facing extreme natural disasters. Employing the Preferred Reporting items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, fifty-eight relevant articles were selected and analyzed. The reviewed literature was categorized into three distinct operational stages of disasters: pre-disaster, during-disaster, and post-disaster. In the pre-disaster stage, the focus was placed on proactive infrastructure hardening and robust planning. During disasters, the priority shifted to real-time threat monitoring and active risk mitigation. Post-disaster recovery relied heavily on functional technologies, including distributed generation islanding, microgrid clustering, and optimal energy management coordinated with the deployment of emergency repair crews. The analysis revealed critical challenges, such as the lack of standardized metrics, limited transmission-distribution coordination studies, and a scarcity of multi-disaster modeling. Finally, future research directions were identified, emphasizing control stability in low-inertia microgrids and the integration of interconnected civil infrastructures to accelerate power system restoration.



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1. INTRODUCTION

The ability of an electric power system to withstand, respond to, and recover from catastrophic events is a basic criterion for defining power system resilience. Resilience is frequently characterized by high-impact low-probability (HILP) [1]. Environmental and human threats, including cyberattacks, can trigger this type of event. As the driving force behind all living activities worldwide, the electrical system plays a vital role but is highly susceptible to natural calamities such as hurricanes, earthquakes, floods, geomagnetic storms, etc. [2]. Many countries are now grappling with efforts to strengthen the resilience of power grids that have been operating for decades and were not originally designed to withstand extreme weather or natural disasters. Research reveals that natural disasters are the primary source of extensive blackouts, representing approximately 52% of occurrences [1]. An analysis of major power outages in the US in 2008 showed that out of 933 power outage incidents between 1984 and 2006, approximately 44% were weather-related [3,4]. In February 2021, the southern US experienced a catastrophic winter storm that caused generator outages and rolling blackouts in Texas and neighboring states. The devastating impact was economic damage to communities and loss of life due to the power grid. Consequently, measures must be taken to address these vulnerabilities and mitigate future losses. Motivated by this, the authors aim to review strategies for maintaining power system resilience in the

face of extreme natural disasters.

Natural disasters pose a significant concern to the continuity of electricity services in Europe and worldwide, as evidenced by data from the 2003, 2011, and 2014 flood centers, that consequently prompted Europeans to start doubting their dependability and safety of their electricity grids facing natural disasters [5]. Similar concerns are occurring in Asia [6], and Africa [7]. Global climate change is affecting electrical availability throughout the continent, with natural disasters damaging economies [8]. The impact of these disasters on electricity system service will jeopardize the activities of other important sectors such as industry and transportation, public health, security, communications, businesses, and households [3]. Figure 1 shows the importance of electricity services in supporting the operation of important sectors in improving a country's economy.

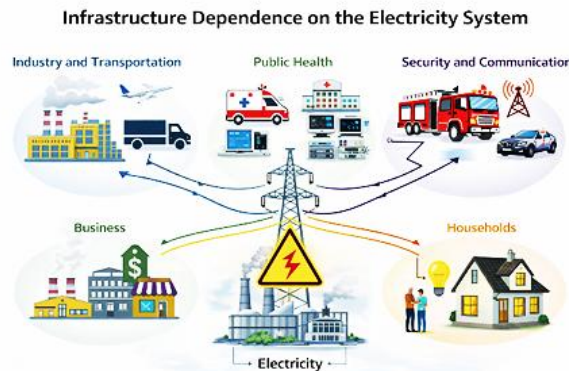


Figure 1. A visual depiction of the interdependence between electricity services and other infrastructure

With the increasing incidence of a natural disaster and extreme weather events, the resilience of the electricity grid infrastructure to deal with them has become crucial [9]. Since, it is not possible for humans to control all extreme events from natural disasters that will impact the occurrence of contingencies in the transmission and distribution system. Therefore, it is essential to implement additional strategic efforts beside the existing electricity master plans to maintain electricity supply during a disaster and to facilitate quick recovery [10]. By modernizing infrastructure using technologies cutting-edge smart grid, such as distributed energy resources (DER), isolated microgrid formation, and resource allocation for recovery, along with an agile team of technicians, the electrical system resilience can be significantly enhanced [11]. This article provides an outline of the essential systematic strategies that can achieve grid resilience during the preparation phase, during, and post-emergency incident phases [9].

This paper aims to deliver a comprehensive analysis of power system resilience by: (1) integrating notions the resilience stage, (2) classifying resilience strategies based on pre-, during-, and post-disaster phases, (3) assessing modeling and evaluation methodologies in transmission and distribution systems, and (4) pinpointing potential research directions. In understanding the meaning of resilience, several related sources are reviewed.

Various sources [12, 13], [10] demonstrate how difficult to describe the meaning of power system resilience. There is no globally accepted definition. However, it is generally understood that initiatives to enhance power system resilience seek to make the electricity network resilient to external disturbances. The concept and analysis related to this subject are presented by the author in [14]. Meanwhile, a review of the concept and assessment of resilience generally is available in [10], [14, 15]. These articles provide a strong foundation for developing research concepts on power resilience in the future. Figure 2 represents the concept of power systems resilience value using a trapezoidal graph. Classify resilience strategies based on pre-disaster, during-disaster, and post-disaster phases, depicted according to time periods (t). From time t_0 to t_1 , system is predicated on the N-1 reliability criterion. At t_1 , a natural disaster strikes the grid. The period from t_1 to t_2 indicates resilience period, which is expected be able to handle power supply disruptions more effectively than conventional reliability systems. From t_2 to t_3 , rapid response and adaptation strategies to the natural disaster are implemented; then, period t_3 to t_4 , further recovery strategies involving microgrid clustering can be immediately applied in an effort to approach the optimal condition of the system performance levels, while full recovery occurs from t_4 to t_n period after the existence of repair teams and the most efficient allocation of repair resources.

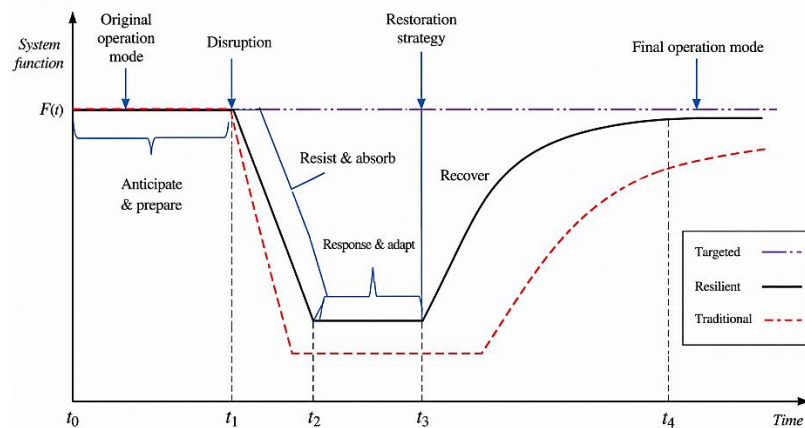


Figure 2. Performance of the trapezoidal system resistance to time [9], [16]

Based on this, resilience is defined as the ability of an electric power system to anticipate, withstand, adapt to, and rapidly recover from high-impact, low-probability (HILP) catastrophic events. As stated in [10], there are many studies on resilience uses reliability measures, such as the system mean duration of interruption (SAIDI), the system mean frequency of interruption (SAIFI), and the customer mean duration of interruption (CAIDI). These measures were taken without taking into account major outages disruption caused by extreme weather. The reliability of the electricity in stable weather conditions may not be sufficient to handle natural disasters. Therefore, it is important to implement standard resilience measures that can handle all possible disruptions due to extreme weather on critical infrastructure, based on a three-stage improvement strategy as illustrated in Figure 2, the resilience trapezoid graph. Therefore, having a robust electricity system that is able to efficiently prepare for future emergency conditions and its impact on increasing the effectiveness of operational scheduling. The strategy aims to naturally respond occurrences affecting the grid and mitigating the impact of future extreme weather events to improve network operational services.

2. RESEARCH METHOD

The applied method focuses on power system resilience evaluating. Strength assessment or evaluation is the initial strategies that needs to be taken before achieving power grid resilience. The evaluation methods used consist of qualitative and quantitative approaches. The quantitative approach includes three types: analytical techniques, statistical analysis of blackout history, and simulation method to improving the system resilient from natural disasters, as described in [10]. The results of the assessment the electric system resilience can be a guide in realizing concrete efforts and assisting system operators in planning and making operational decisions. Table 1 shows operational strategies planning for system resilience. As a basic concept in defining power system resilience, the aspects covered start from the operational period of the power system, as illustrated Fig.1 to the resilience measures implemented following a crisis. When a natural disaster impacts the grid, the subsequent frequently asked questions often yield insights for enhancing power resilience system.[9].

Question 1: What are the categories of resilience stage, and what types of measures are used in resilience assessment are needed to evaluate the power system grid in an emergency situation? These categories can provide information for formulating indicators to assess resilience improvement.

Question 2: At what level in the power system hierarchy can a power flow disturbance occur?

Question 3: What model can appropriate to address this issue to make problem-solving?

Question 4: Which phases does the resilience need to be improved?

All these questions serve as assesment criteria for research focused on increased power system resilience. Operational Strategies Planning, as shown in Table 1.

Table 1. Operational strategies planning for resilience of power system [9]

Term	Formulating operational strategies	
	Fortification measures	Strategies for operational resilience
Short term	Planning for reserves	Accuracy of location and intensity estimates.
	Installed black-start capabilities	Demand-side management
	Mobilization of repair team members	Rapid topology system reconfiguration
	Installation of Distributed Energy Resources (DER)	Microgridisland
	Collaboration with neighboring networks and repair teams	The existence of an automated protection and control system: generation and load shedding, system segmentation
Long term	Arboricultural pruning / vegetation control	Monitoring: enhancement situational awareness; sophisticated information systems and visualization.
	Underground installation of distribution and transmission cables	Guarantee communications capability
	Enhancing poles and structures with more durable, resilient materials	Microgrids with local generation (PV, wind, biomass)
	Improve the performance of substations and place them in areas that are not prone to flooding.	Using protection mechanisms and advanced control, including system integrity protection schemes (SIPS)
	The existence of backup transmission lines is carried out through additionally on transmission facilities.	Evaluation of disasters & establishment of priorities. Risk management and assessment to detect and mitigate the threats posed by disaster.

Assessing modeling and evaluation methodologies in transmission and distribution systems as shown in Table 2 below:

Table 2. Detailed list of the selected references

Disaster	References Number	Papers Overview				
		Classification	Lines		Model	
			Transmission	Distribution	Power Flow	Multi Agent
Before	[17] [18] [19] [20] [21] [22][23] [24] [25] [26]	Planning	✓	✓	✓	
	[27] [28]	Operation	✓	✓		✓
During	[29]	Operation		✓		
After	[7] [10] [24] [30] [31] [32] [33]	Evaluation		✓	✓	
	[34] [35] [36]	Strategy	✓	✓		

3. RESULT AND DISCUSSION

To directly answer the main research question (RQ1 to RQ4), this section provides a systematic literature analysis. The discussion is divided into three stages of system resilience, each providing: methodology, power vulnerability hierarchy, optimization and modeling techniques, and resilience strategies. Based on Figure 2, resilience is classified into three stages, as described below.

3.1. Pre-Interruption Stage

This stage represents the conditions before a disaster occurs, and is crucial for achieving power system resilience, it includes the following:

1. Role in Power System Resilience

This stage serves as a critical first layer in power system resilience, influencing its ability to withstand disaster-induced disruptions with a low probability of failure. Strategic implementation can realize a reduction in the frequency and duration of disruptions which will result in an increase in the system reliability index [37], lowering operational and recovery costs, and enhancing system

readiness to be able to face extreme disasters such as earthquakes, floods, storms, and cyber threats. Increasing renewable energy penetration. At this stage will also support the transition to a smart, adaptive, and self-sufficient grid. This procedure enables the anticipation, mitigation, and absorption of disruptions without interrupting power flow system services.

2. The Electricity Transmission Systems Pre-Interruption Phase

This section answers RQ 2, and in this stage, system planners will think about possible failures and to make the system ready. The research problem is frequently structured into two optimization phases. The first phase is all about making system parts stronger against expected weather conditions. The second phase looks at how the fortification strategies have improved network performance after "if scenarios" simulations to find system weaknesses during emergencies. The method for this phase is explained in the literature [23], [27], [24] recently made the electricity grid more resilient by doing a risk-based security evaluation. This evaluation method makes it easier to include risk or vulnerability analysis in security assessments that focus on risk. It uses what we know about current threats to understand important system scenarios and improve operator readiness. Phase 1 mainly uses this method, as shown in Figure 1. Researchers around the world are putting more and more effort into predicting the most dangerous possible events and finding the parts that are most likely to fail. You can find more models that are similar in references [39–41].

3. Prevention of Initial Power Supply Interruption on Distribution Systems level

This section answers RQ 2. The application of the defender-attacker-defender (DAD) model to distribution networks in [19], [20], [22] represents a decision in an effort to strengthen the distribution network. This model was developed in response to the maximum attack in research [41] correlated with the increasing frequency of disturbances caused by natural weather events. Optimal network reconfiguration and distributed energy resource (DER) island optimization are techniques for strengthening the system; therefore, considering the occurrence of natural disasters in relation to distribution line strengthening is very important. Various efforts can be made such as the placement of distributed energy resources (DER), pile excavation in robust construction efforts, vegetation management, and the application of resilience-enhancing techniques. Distribution system reconfiguration can be effectively carried out by changing the islanding procedure which will provide the opportunity to supply more electrical energy as needed and have an impact on reducing distribution system losses. [20].

3.2. During-Interruption Stage

This stage represents the conditions during a disaster occurs that people who plan and run electricity transmission and distribution systems try to figure out how often and in what ways their networks are attacked. This thorough understanding is essential for identifying the severity and nature of these attacks as a foundation for developing effective and resilient strategies [9]. Consequently, this phase examines research from two overarching viewpoints: natural occurrences and anthropogenic assaults. System planners look at the effects of natural disasters like storms, earthquakes, and floods on damage to components. They then come up with models to manage these attacks. Another way to get ready is to figure out what the worst things that could happen to the electricity system are and which parts of the network are most likely to be attacked. The literature and these sources contain more detailed explanations [43–46].

3.3. Post-Interruption Stage

At this stage, the rapid recovery of the electrical system becomes the most crucial aspect of the resilience enhancement strategy and need to be improved (this section answers RQ 3 and RQ 4). The distribution system area is directly impacted by disasters from several events. Therefore, the main research focus for post-disaster recovery conditions is on the distribution network. Through the growth of smart network technology, strategic innovations can be generated to address disruptions caused by disasters. From several studies, three main recovery schemes have been formulated that can be used to achieve optimal load recovery after a contingency occurs, which will be briefly discussed below:

1. Efficient Network Reconfiguration and DG Islanding:

In the face of unexpected disruptions, effective long-term measures are needed, such as grid reconfiguration and the implementation of distributed generation islanding (DG islanding) on power system lines. This method has been proven to be an effective strategy in avoiding and

repairing power outages to critical areas during emergencies [41], [17], [46]. A study [45], [47] has produced a network reconfiguration algorithm that considers "electrical connectivity" by prioritizing "non-black-start generators" and critical load to accelerate the recovery the transmission network after a natural disaster. Another researcher [48] introduces a model with "a sequential Monte Carlo" risk-based approach, through the separation strategies with creating gaps in the transmission line that require the least power exchange. The black-start component on each island will ensure a sufficient power supply to meet load demands. This concept also represents a strategic effort to restore power distribution during emergencies, reduce the risk of power loss, utilize renewable energy, and power quality improving [17], [41]. Restructuring the network and establishing interconnected distributed generation islands has demonstrated increasing the resiliency of the electric power systems network to harsh weather by alleviating cascading disturbances on power lines during natural catastrophes via the creation of microgrids [49]. Additional information concerning the diverse methodologies employed for this work within the electric power distribution system is available in publications [51, 52], offering a more comprehensive insight for interested readers.

2. Optimal Energy Management Scheme (OEMS):

The use of OEMS is an effort to restore power from an outage without changing the network configuration. This system uses advanced energy managements system (EMS) to improve network performance after a power outage. The OEMS can manage various resilience resources in the electrical system, from power generation, energy storage, and demand response to electrical loads, to ensure the microgrid functions properly. The algorithms used in energy management are divided into two categories. There are centralized and decentralized EMS [9]. The centralized energy management model was created using mathematical calculations and run through numerical simulations. Efforts to restore electricity supply services through mixed integer programming modeling that can be adapted to various operational constraints have been developed in previous research [52]. This model helps system operators plan and make decisions about how to run the system by creating a well-coordinated sequence of steps for controlling adjustable switches, energy storage systems, and distributed resources. The capability of such a tool has been demonstrated in other studies [54, 55] which indicate that the electricity system can be more robust if it considers the coordination of microgrids in isolation mode to maintain critical loads during emergencies. Conversely, in a decentralized energy management approach, each party making improvements, such as DERs and microgrids, independently optimize its operations and exchange information within local entities. Chen and his colleagues [52] addressing different operational restrictions on distributed generation and economic efficiency in the electrical market using a second-order conical programming paradigm. Abdelhamid et al. [54] examined the administration of extensive electrical networks extending hundreds of kilometers through the integration of multiple microgrids, employing a decentralized multi-agent control strategy to tackle the complexities inherent in large power systems. This study shows that adding a microgrid with multi-agent-based control makes the power system more resilient. Another study [55] said that the integration of multiple microgrids into a distribution system can substantially improve the utilization of distributed energy resources (DERs). This strategy is an effort to optimize operations through the implementation of microgrids connected to a system bus that has been modeled as a cyber communication network that is regulated in the form of an algorithm that has the ability to withstand disturbance conditions. This network would allocate the necessary power to local entities during emergency power supply situations, distribution systems use an EMS to lower network operating costs by adding tiered microgrids [17], [57].

3. Efficiency Allocation of Repair Resources with Teams

The last phase simulation, designed to assist the transmission and distribution system restore power as quickly as possible after a disruption, is to deploy the best recovery resources and repair teams. This is because power restoration involves efficient network restructuring and the separation of distributed generation systems, which are still not optimal as seen in the period t_3 to t_4 in Figure 2. The most effective deployment of resources and repair teams is associated with the end of the resilience graph, namely from t_4 to t_n . Reliability analysis often assumes that damaged components have recovered after a specific repair period. However, in an effort to increase resilience, Power supply can be restored better and faster through the deployment of repair teams that act proactively using limited restoration resources [58]. The integration of "mobile emergency generators" (MEGs)

and “prosumer communities” (PCs) is a combination of heat and power generation (CHP) units, electric boilers (EB), photovoltaic (PV) sources, and demand response (DR) is a strategy to improve recovery to post-disaster demand by looking at the capacity of resource capabilities to respond to demand more flexibly. Currently, efforts to accelerate emergency power recovery when extreme circumstances occur include risk-based evaluations to strengthen resilience, repair team dispatch arrangements, and resource deployment. In this phase, the identified challenge is a two-stage dispatch model with initial placement and real-time allocation, in realizing the efficiency of time delivery of repair resources using mixed integer linear programming, for example the use of mobile generators.

4. CONCLUSION

This article presents a comprehensive analysis of power system resilience strategies against extreme natural disasters, based on 58 studies identified through a thorough review using the PRISMA method. Addressing four research questions, the review classifies various resilience strategies into three critical stages. In the pre-disaster stage, actions focus on proactive infrastructure fortification and robust planning optimization to minimize the risk of initial failure. The during-disaster stage prioritizes real-time threat monitoring and immediate risk mitigation. For the post-disaster stage, rapid load restoration is achieved through functional technologies such as distributed generation islanding, microgrid clustering, and the implementation of Optimal Energy Management Schemes (OEMS) integrated with the efficient deployment of emergency repair teams. This comprehensive synthesis establishes a structured framework to guide both academics and practitioners. Future research should aim to address remaining critical challenges, including the standardization of resilience metrics, the expansion of transmission-distribution coordination studies, the development of multi-hazard modeling, the resolution of control stability issues in low-inertia microgrids, and the integration of interconnected civil infrastructure such as telecommunications and transportation systems to accelerate overall power restoration.

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